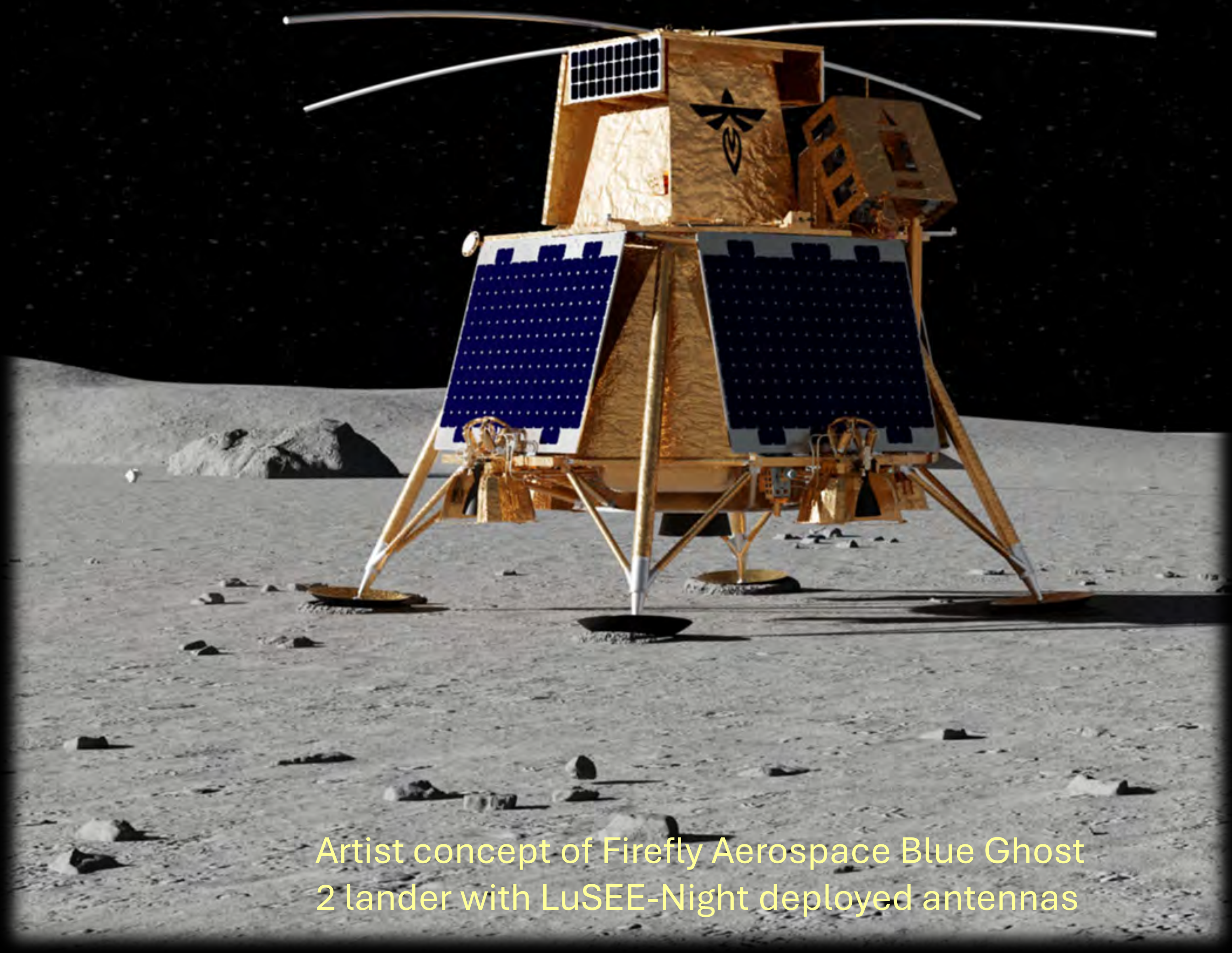
LOW FREQUENCY RADIO TELESCOPES ON THE MOON

Jack O. Burns

University of Colorado Boulder

Key Non-Polar Destinations Across the Moon to Address Decadal-level Science Objectives with Human Explorers: Panel on Heliophysics, Physics, and Physical Science

10 June 2025



Artist concept of Firefly Aerospace Blue Ghost 2 lander with LuSEE-Night deployed antennas

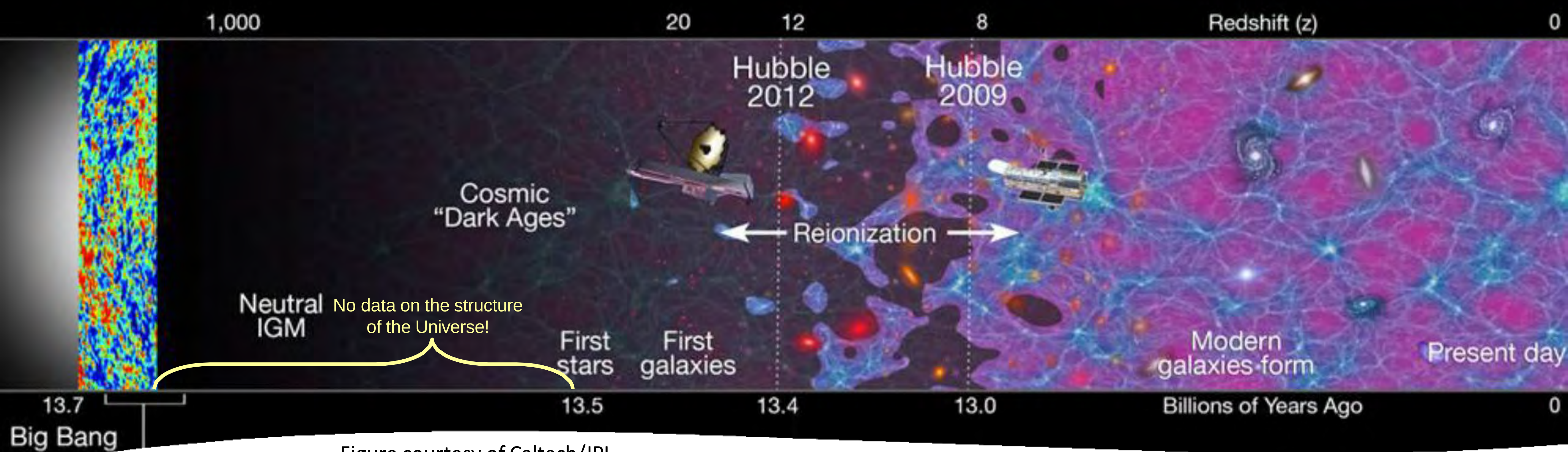
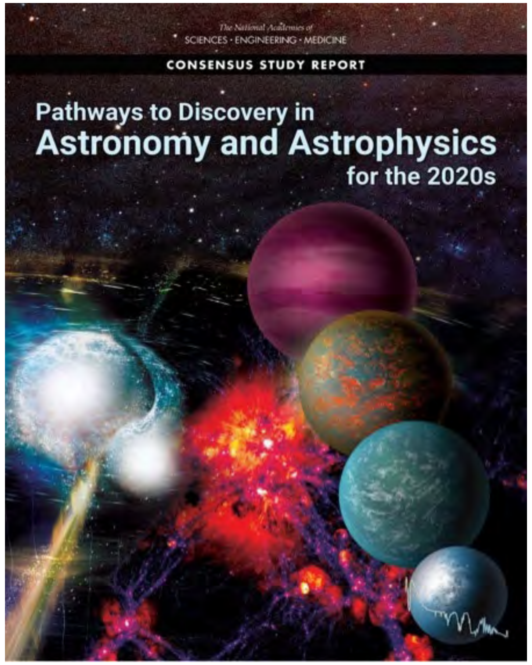


Figure courtesy of Caltech/JPL

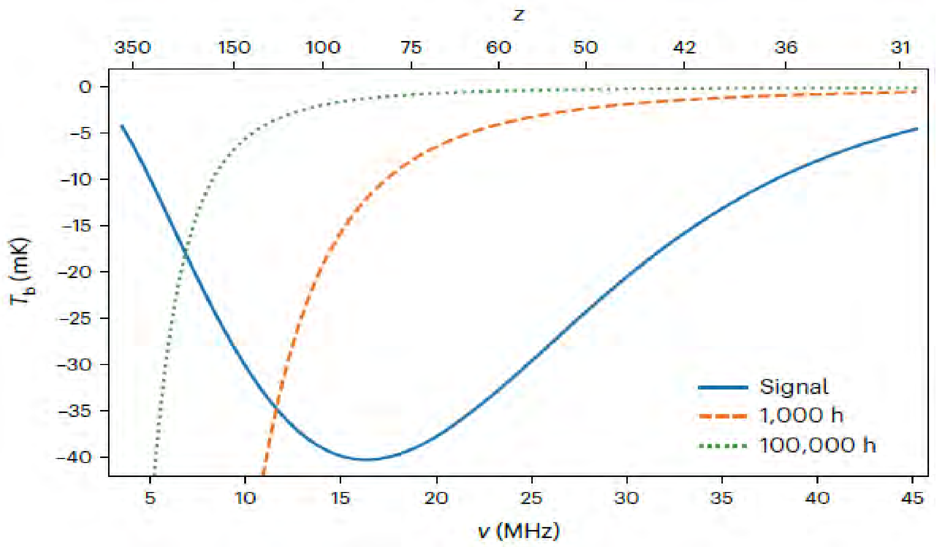
The Astro2020 Decadal Survey cosmology panel singled out the Dark Ages as THE Discovery Area in Cosmology; and identified "needed capabilities to include… both higher sensitivity and a better understanding of instrumental systematics and astrophysical couplings."

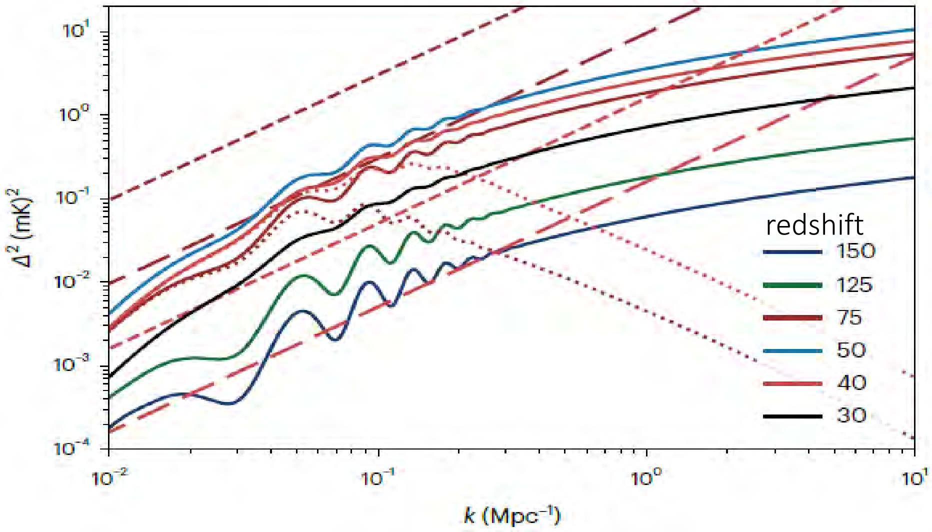
The Dark Ages is part of the Universe where JWST & other missions cannot explore – when the universe was filled with just neutral hydrogen – no stars or galaxies.



Exploring the Dark Ages of the Early Universe

- Global 21-cm spectrum can be measured by single antenna.
- Using an interferometer, structure power spectra & tomographic maps trace evolution of Universe from before/during birth of first stars.
- Spatial fluctuations, governed by linear structure formation, allows precise predictions for standard cosmology.
- Departure from these well-constrained predictions will provide insights into new physics possibly including:
    - Nature of Dark Matter (e.g., warm dark matter, sterile neutrinos)
    - Early Dark Energy
    - Masses of neutrinos and their hierarchy
    - Non-Gaussianity of initial density perturbations
    - Imprints of gravitational waves to reveal the energy scale of cosmic inflation.



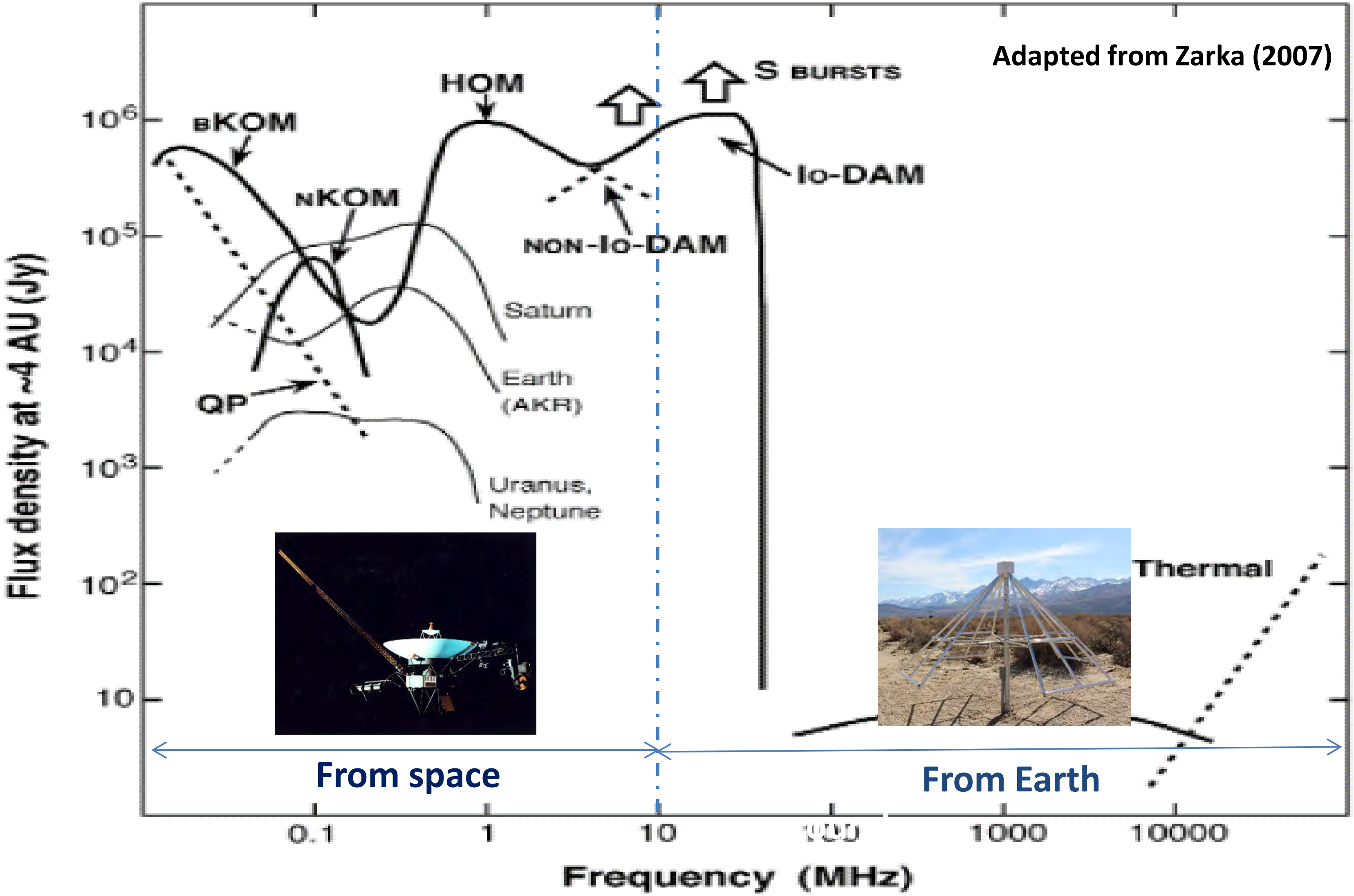


Mondal & Barkana, 2023, *Nature Astronomy*, 7, 10

Measuring B-fields for Exoplanets

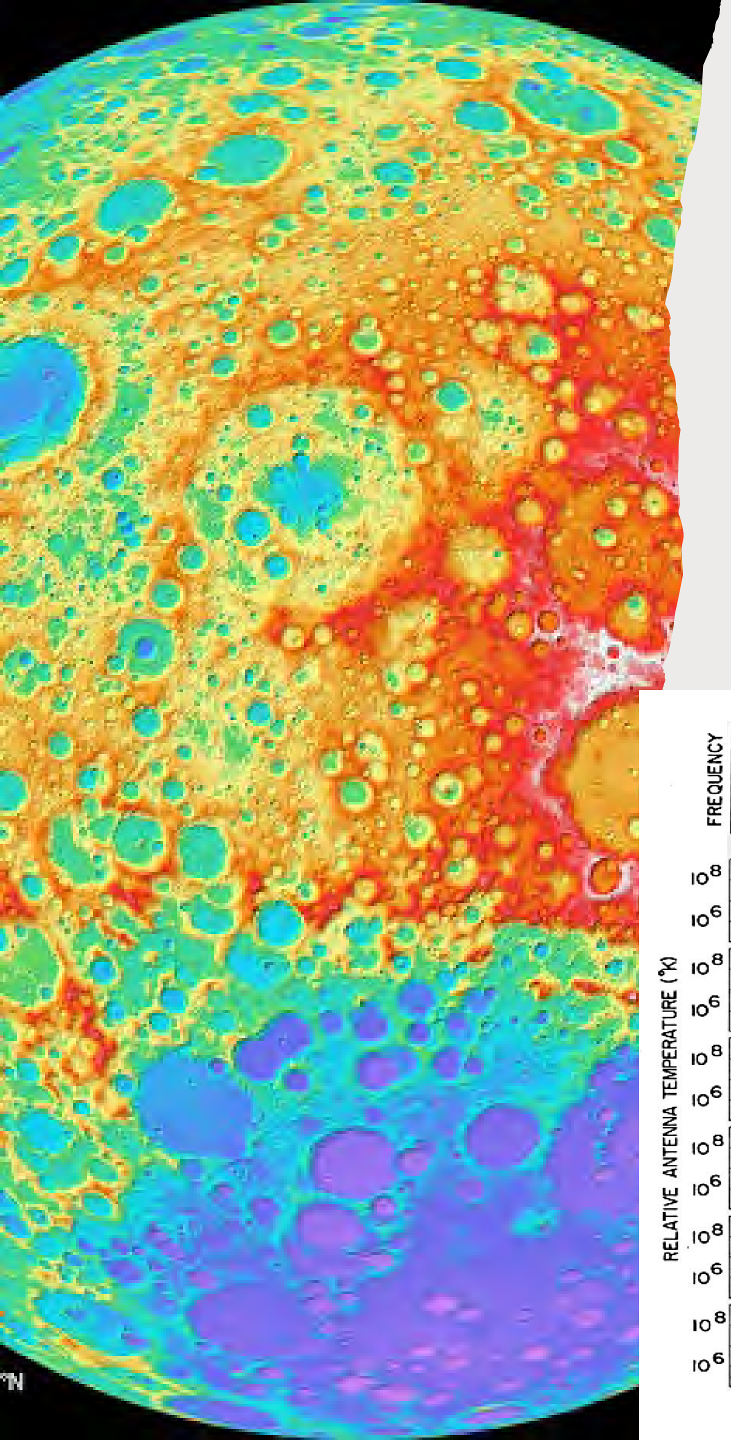
Electron cyclotron maser emission

Frequency (MHz) = $B_{Gauss} \times 2.8$



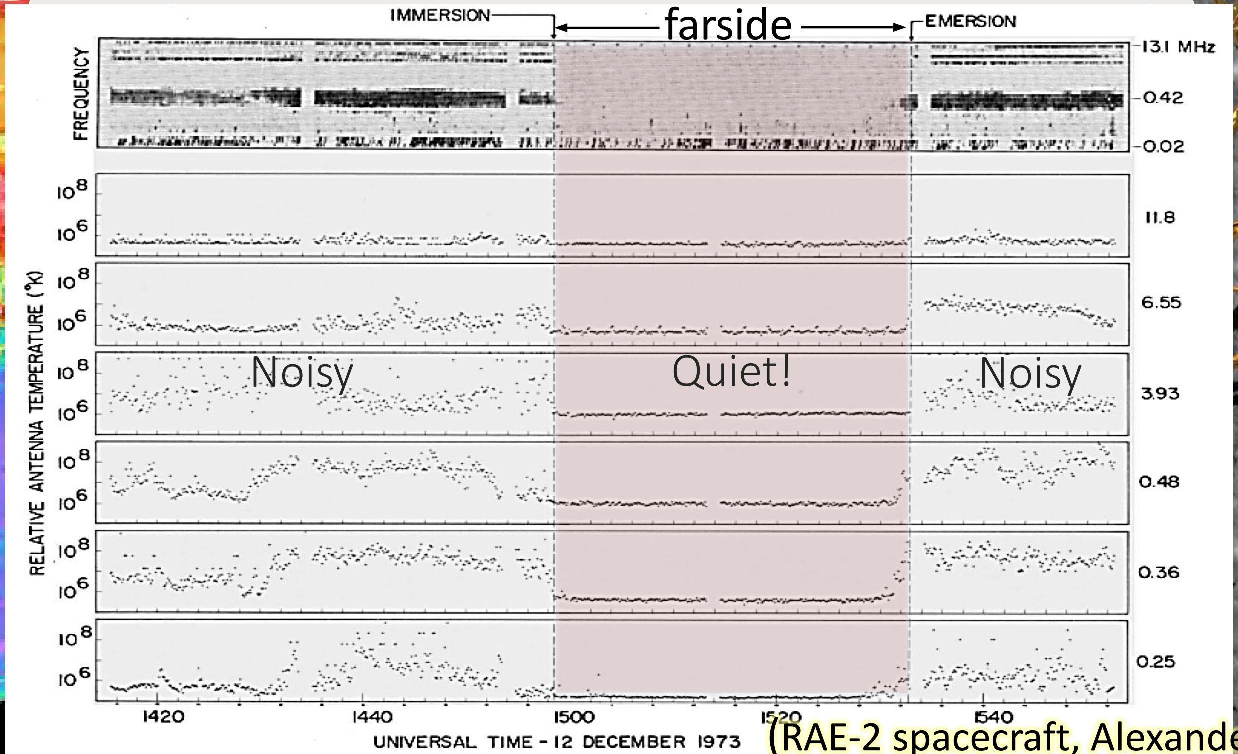
Planetary Science Decadal Recommendations on Magnetospheres & Exoplanets

- Excited aurorae in the waveband spanning **radio** to X-ray spectrum are a window into the workings of these magnetospheres.
- *Strategic Research* - search[es] for magnetospheric activity at exoplanets with remote sensing of phenomena associated with magnetic fields, potentially including radio emission.
- M-dwarf stars which house exoplanets often exhibit extreme levels of stellar activity, which may adversely impact the habitability of orbiting planets.

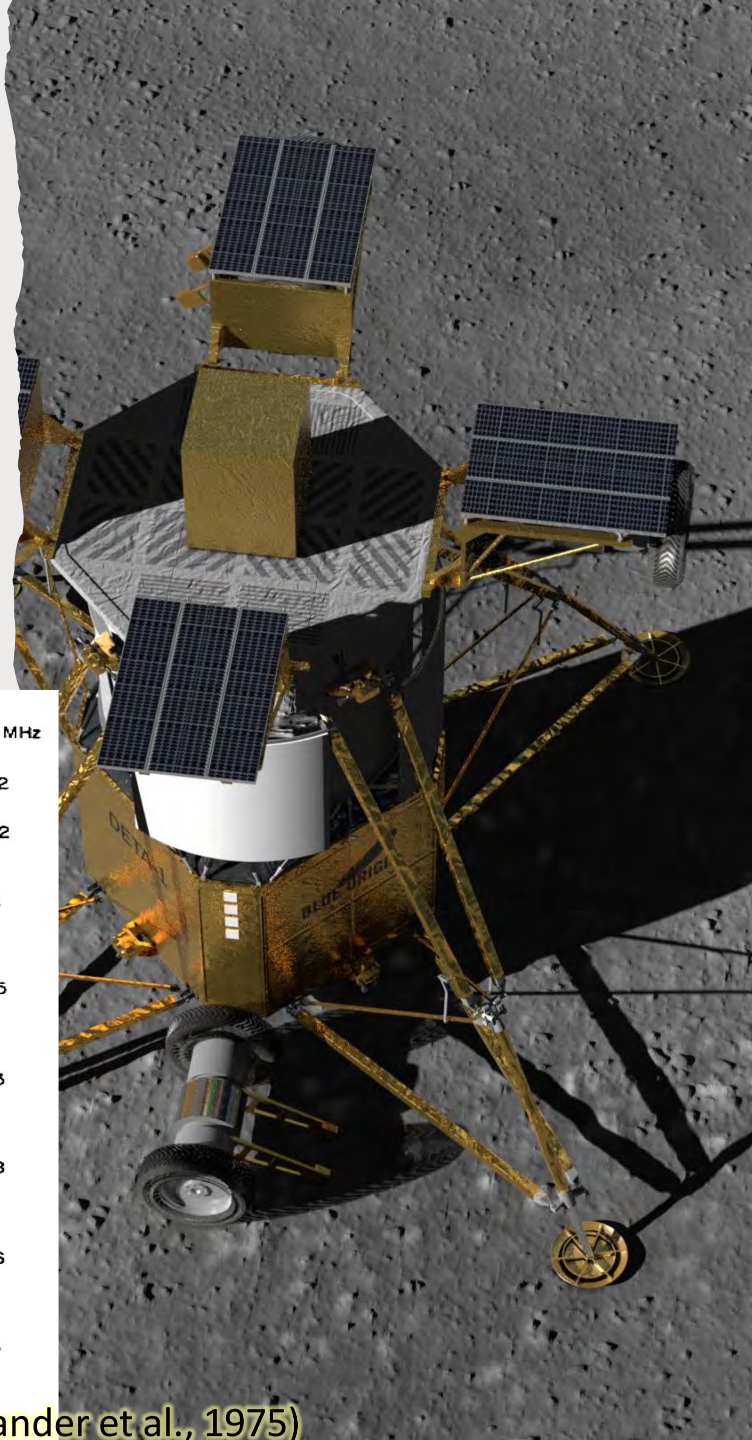


The lunar far side is enabling for Low Frequency Radio Astrophysics & Cosmology:

- uniquely radio-quiet,
- lacks a significant ionosphere,
- dry, stable environment.

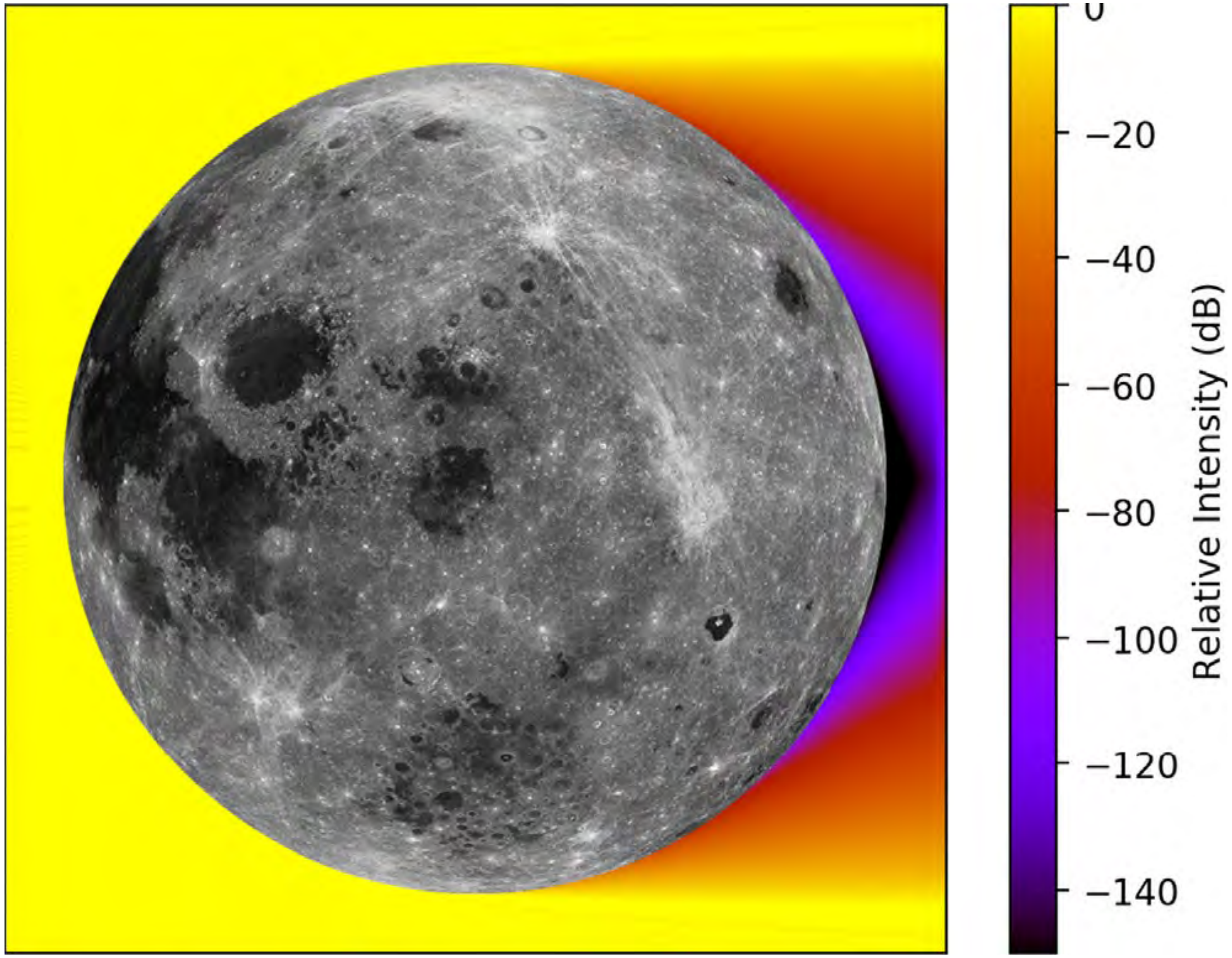


(RAE-2 spacecraft, Alexander et al., 1975)



Numerical Modelling of the Radio-Quiet Zone on the Lunar Far Side

Results of a 4000 x 4000 km FDTD simulation at 30 kHz. RFI incident from the left is attenuated behind the Moon on the right. An image of the Moon from the NASA LROC. Bassett, Rapetti, Burns et al. 2020, *Ad. Space Research*, 66, 1265.



NASA's Artemis & CLPS Program

SLS

Commercial Lunar Payload Services (CLPS)

The Gateway in Lunar Orbit

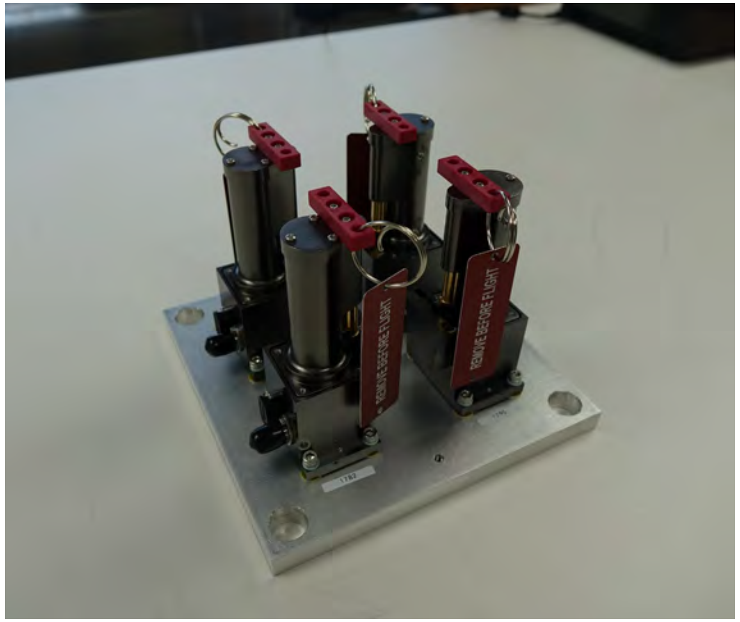
Orion

First astronauts
on the Moon in the 21st century

Artemis Base Camp

Courtesy of NASA

IM-1 with ROLSES antennas deployed

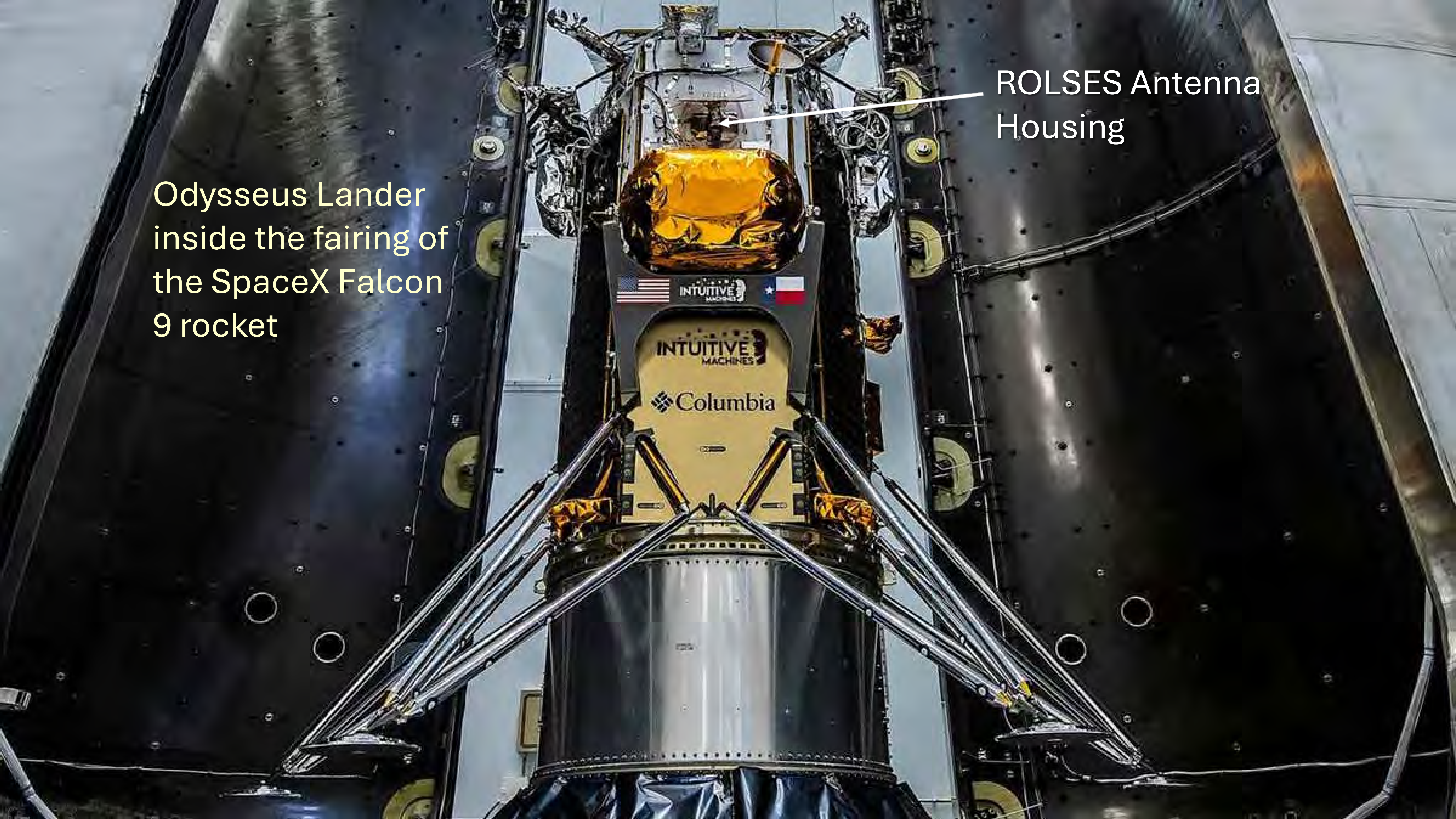


Stowed STACER antennas

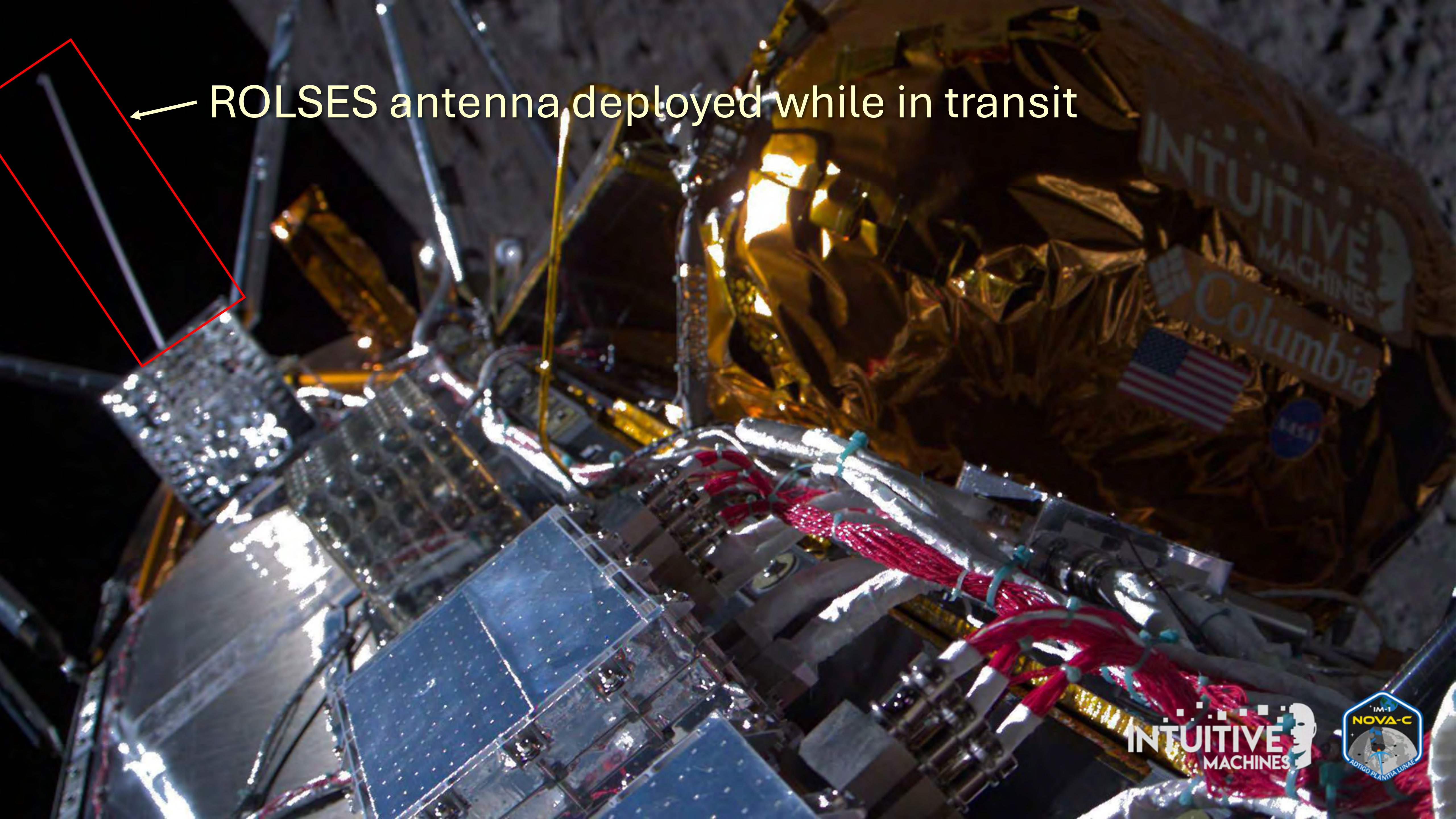
ROLSES spectrometer board

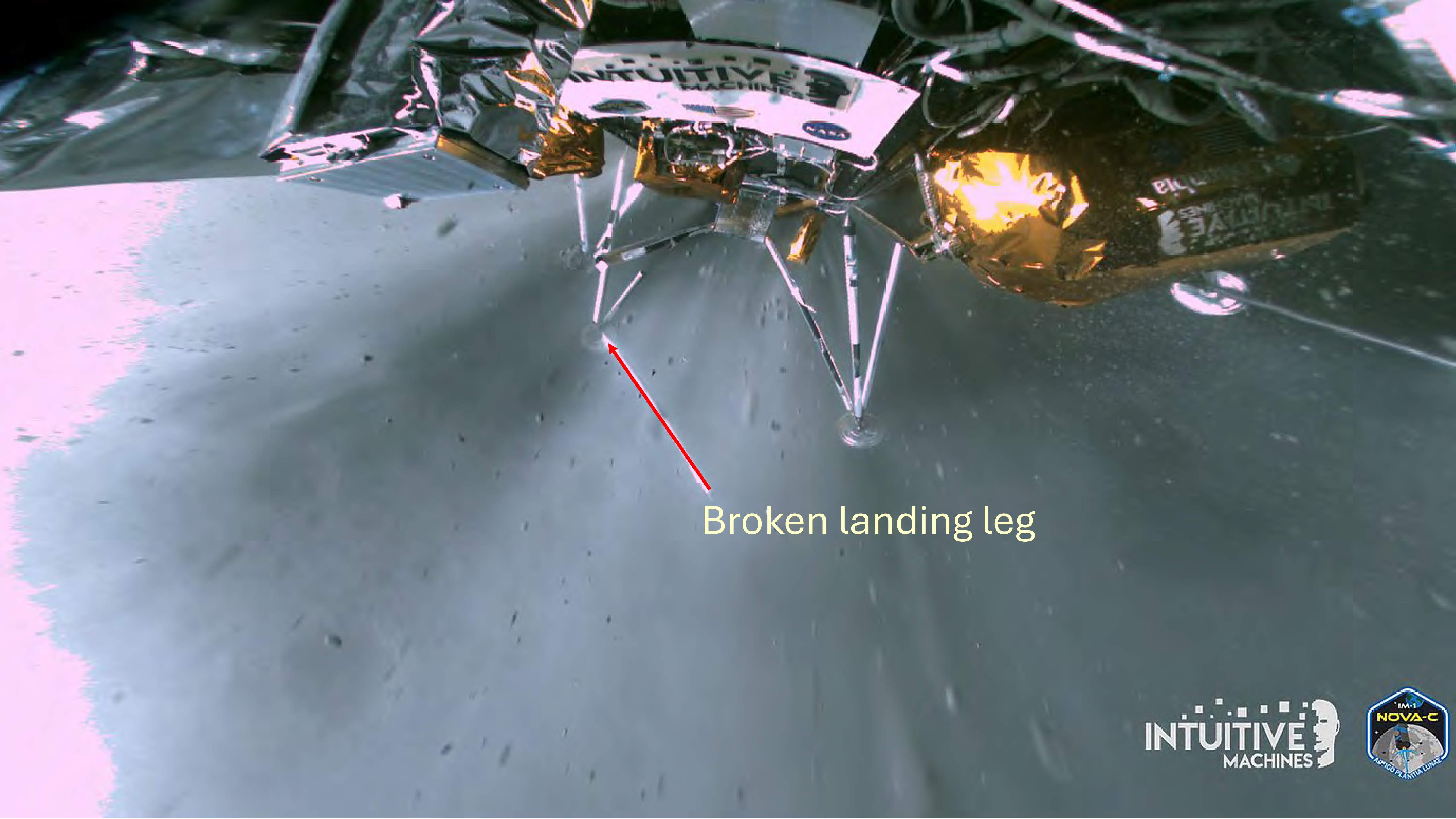
Radio wave Observations at the Lunar Surface of the Electron Sheath (ROLSES)

- ROLSES Team: N. Gopalswamy (PI), J. Burns, R. MacDowall, W. Farrell, D. Bradley, M. Reiner, D. McGlone, M. Choi, S. Murphy, R. Katz, I. Kleyner, D. Rapetti, J. Hibbard, J. Dorigo Jones.
- ROLSES instrument is a new build with heritage from NASA SMAP Earth Remote Sensing satellite:
  - Four 2.5-m monopole antennas.
  - Radio spectrometer with 2 bands: 10 kHz – 1 MHz and 10 300 kHz – 30 MHz.
- Landed near-side, South Pole region.


ROLSES Antenna Housing
Odysseus Lander inside the fairing of the SpaceX Falcon 9 rocket
INTUITIVE MACHINES
INTUITIVE MACHINES
Columbia

Launch 15 February 2024
Landing 22 February 2024


ROLSES antenna deployed while in transit
INTUITIVE MACHINES
Columbia
INTUITIVE MACHINES
IM-1
NOVA-C


Broken landing leg
INTUITIVE MACHINES
IM-1
NOVA-C

Results from NASA's First Radio Telescope on the Moon: Terrestrial Technosignatures and the Low-Frequency Galactic Background Observed by ROLSES-1 Onboard the Odysseus Lander

Joshua J. Hibbard,[1] Jack O. Burns,[1] Robert MacDowall,[2] Natchimuthuk Gopalswamy,[2] Scott A. Boardsen,[2] William Farrell,[3] Damon Bradley,[3] Thomas M. Schulszas,[2] Johnny Dorigo Jones,[1] David Rapetti,[4,5,1] and Jake D. Turner[6]

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[4]*NASA Ames Research Center, Moffett Field, CA 94035, USA*

[5]*Research Institute for Advanced Computer Science, Universities Space Research Association, Washington, DC 20024, USA*

[6]*Department of Astronomy and Carl Sagan Institute, Cornell University, Ithaca, New York 14853, USA*

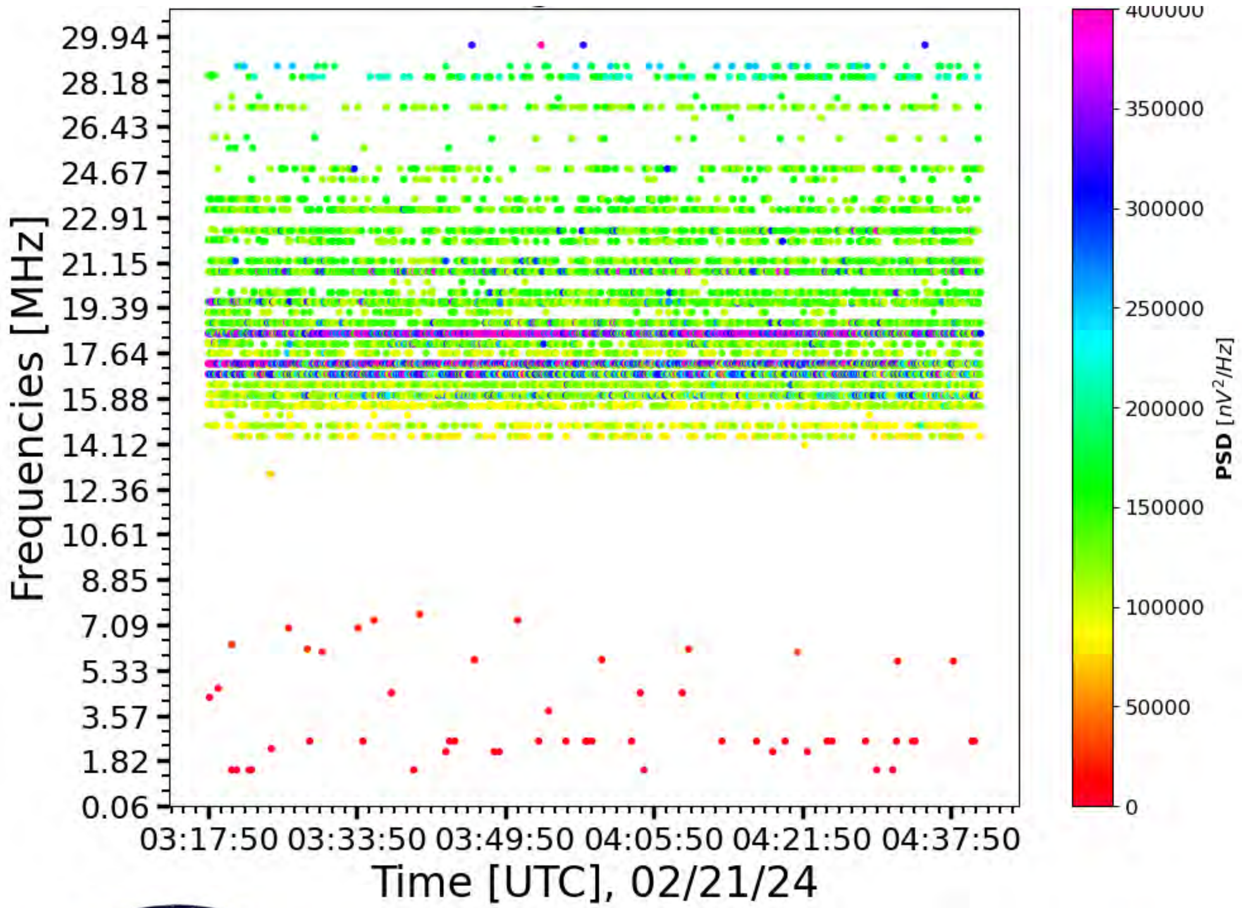
ABSTRACT

Radiowave Observations on the Lunar Surface of the photo-Electron Sheath instrument (ROLSES-1) onboard the Intuitive Machines' *Odysseus* lunar lander represents NASA's first radio telescope on the Moon, and the first United States spacecraft landing on the lunar surface in five decades. Despite a host of challenges, ROLSES-1 managed to collect a small amount of data over fractions of one day during cruise phase and two days on the lunar surface with four monopole stacer antennas that were in a non-ideal deployment. All antennas recorded shortwave radio transmissions breaking through the Earth's ionosphere—or terrestrial technosignatures—from spectral and raw waveform data. These technosignatures appear to be modulated by density fluctuations in the Earth's ionosphere and could be used as markers when searching for extraterrestrial intelligence from habitable exoplanets. After data reduction and marshaling a host of statistical and sampling techniques, five minutes of raw waveforms from the least noisy antenna were used to generate covariances constraining both the antenna parameters and the amplitude of the low-frequency isotropic galactic spectrum. ROLSES-2 and LuSEE-Night, both lunar radio telescopes launching later in the decade, will have significant upgrades from ROLSES-1 and will be set to take unprecedented measurements of the low-frequency sky, lunar surface, and constrain the cosmological 21-cm signal. ROLSES-1 represents a trailblazer for lunar radio telescopes, and many of the statistical tools and data reduction techniques presented in this work will be invaluable for upcoming lunar radio telescope missions.

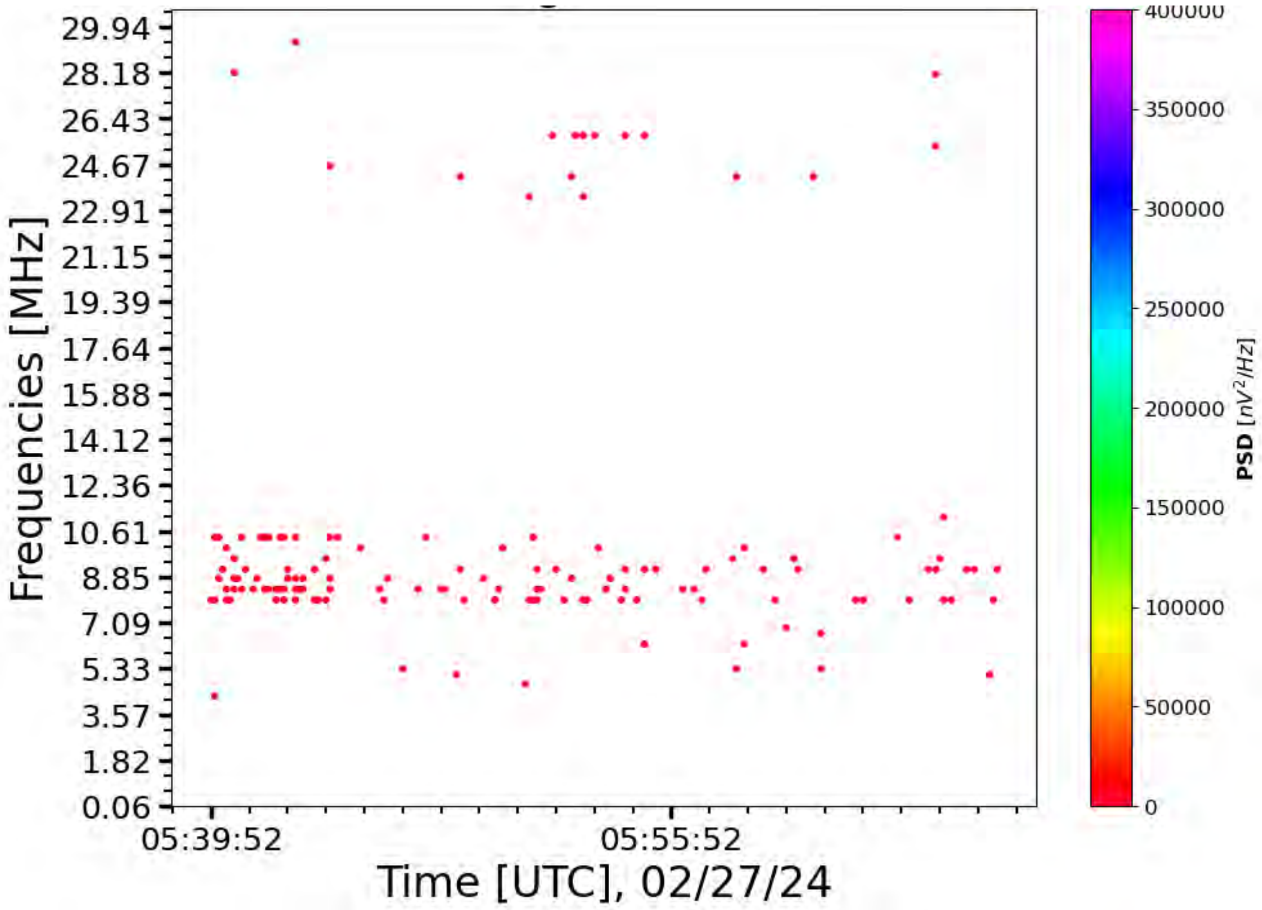
Hibbard, Burns et al. 2025, ApJ, submitted, arXiv:2503.09842

Techno-signatures

In-Transit, Calibrated, Cleaned



Lunar Surface, Calibrated, Cleaned



Clear, good S/N measurements of Human-made Earth Transmissions

- Instrument frequency bandwidth corrections applied
- Flagged channels with internal EM interference
- Corrected for instrumental shelf noise

Hibbard, Burns, MacDowell, Gopalswamy et al. 2025, submitted to ApJ

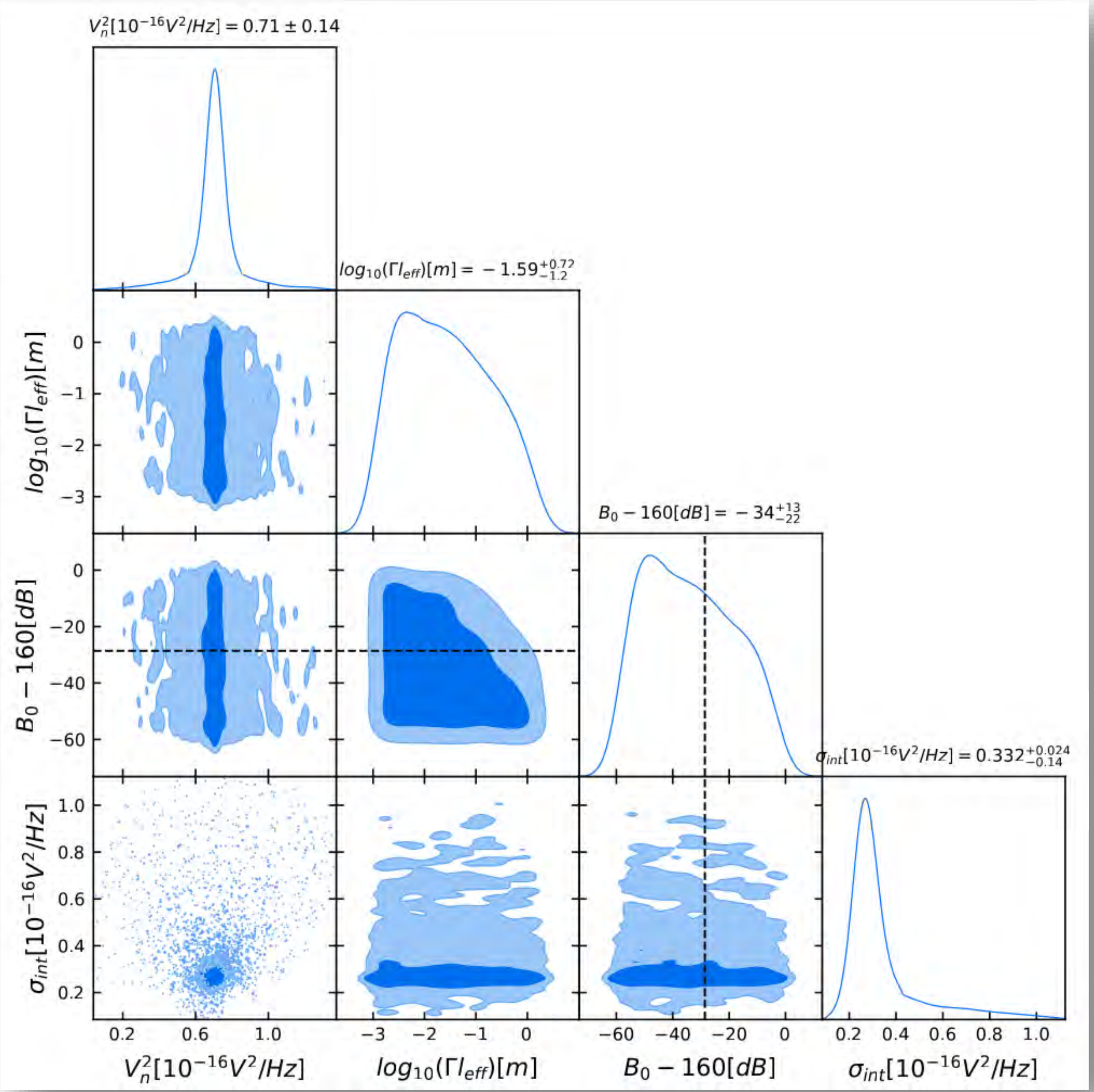
First Detection of the Galaxy from the Moon

Parameter Constraints

$$V_r^2 = V_{\rm noise}^2 + \frac{2\pi}{3} Z_0 \Gamma^2 l_{\rm eff}^2 B_\nu(\nu)$$

where Z_0 is the impedance, Γ is antenna efficiency, l_{eff} is the effective length of the antenna, and B is the Galaxy brightness

- At different levels of frequency averaging, there is a *slight* preference for a model with the Galactic spectrum over one without (comparing KS-test p-values).
- Black dashed line shows the expected value of the Galactic amplitude from the Novaco and Brown 1978 spectrum.



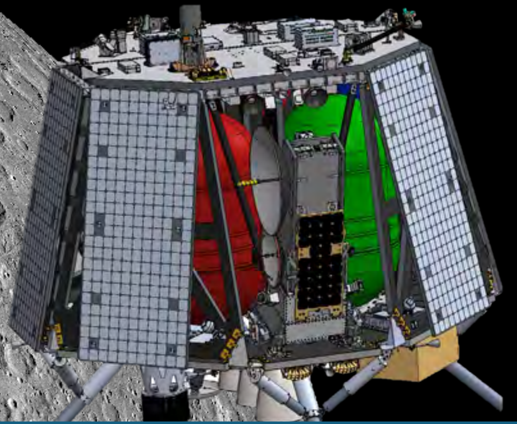
Hibbard, Burns et al. 2025, submitted to ApJ

Radio Astronomy Payloads on NASA CLPS Missions

see Burns+ 2021, *Planetary Science Journal*, 2, 44B

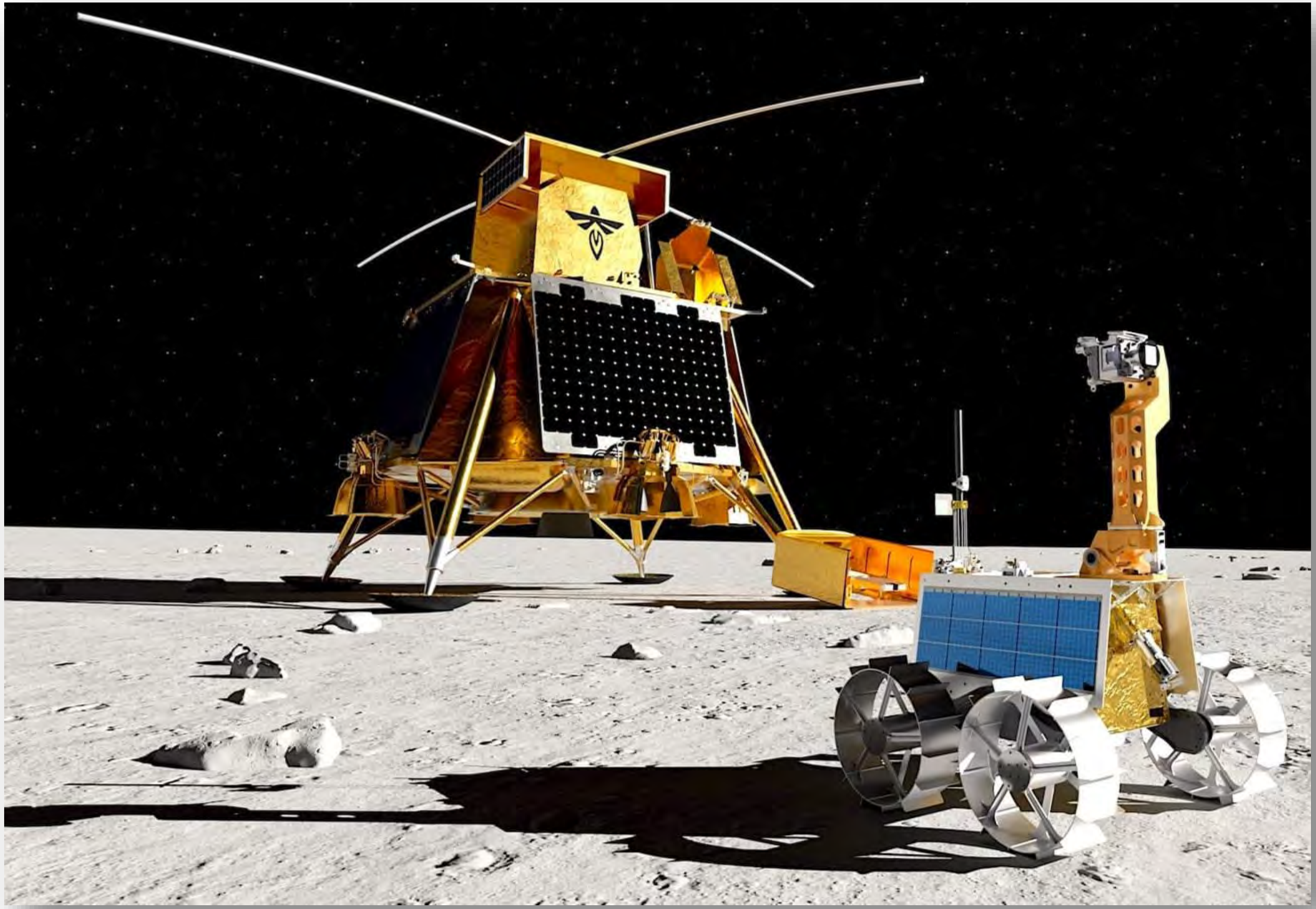
Intuitive Machines delivered ROLSES (Radio wave Observations at the Lunar Surface of the Electron Sheath) to the lunar South Pole in February 2024.

Firefly Aerospace will land LuSEE-Night on far side in 2026. It probes the Dark Ages of early Universe.



iSpace/Draper Apex lander will bring LuSEE – Lite to the Schrödinger Impact Basin on far side in 2027. Science includes measuring plasma waves & surface-geospace interactions.

ROLSES-2 will be delivered to near-side Gruithuisen domes in ~2028 on Firefly Blue Ghost 3 lander.



Courtesy of Firefly Aerospace

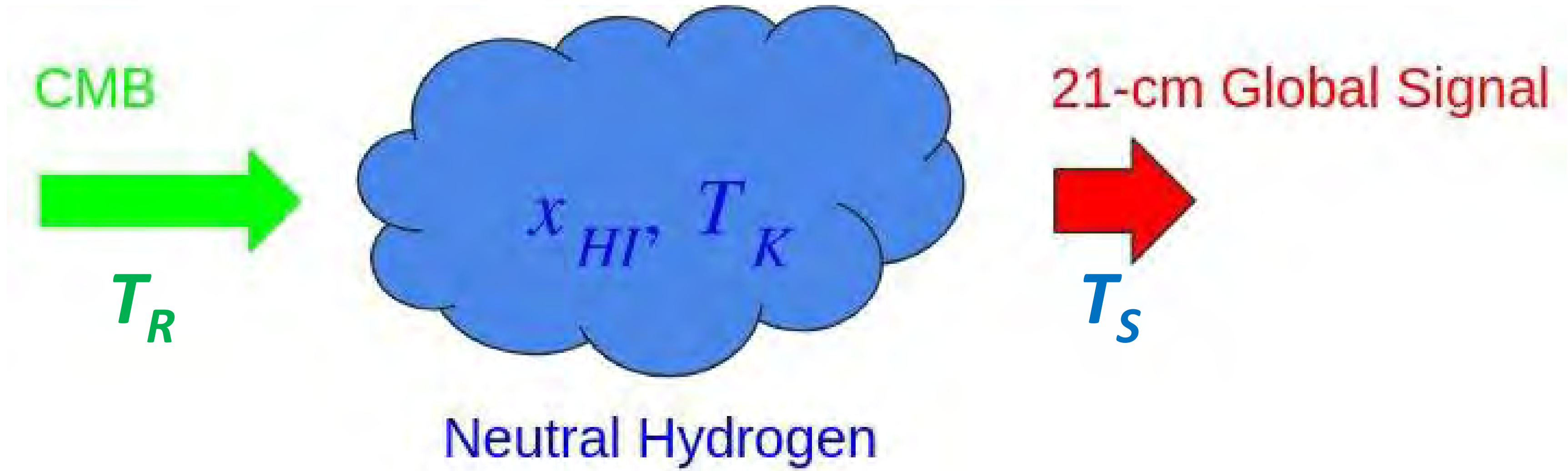
Lunar Surface Electromagnetics Experiment (LuSEE-Night)

The first 21-cm cosmology observations from the lunar far side at night

Stuart D. Bale (PI), Jack Burns, Johnny Dorigo Jones, Keith Goetz, Christian Hellum-Bye, Sven Herrmann, Joshua Hibbard, Milan Maksimovic, Ryan McLean, Raul Monsalve, Paul O'Connor, Aaron Parsons, Marc Pulupa, Rugved Pund, David Rapetti, Kaja Rotermund, Ben Saliwanchik, Anže Slosar, David Sundkvist, and Aritoki Suzuki

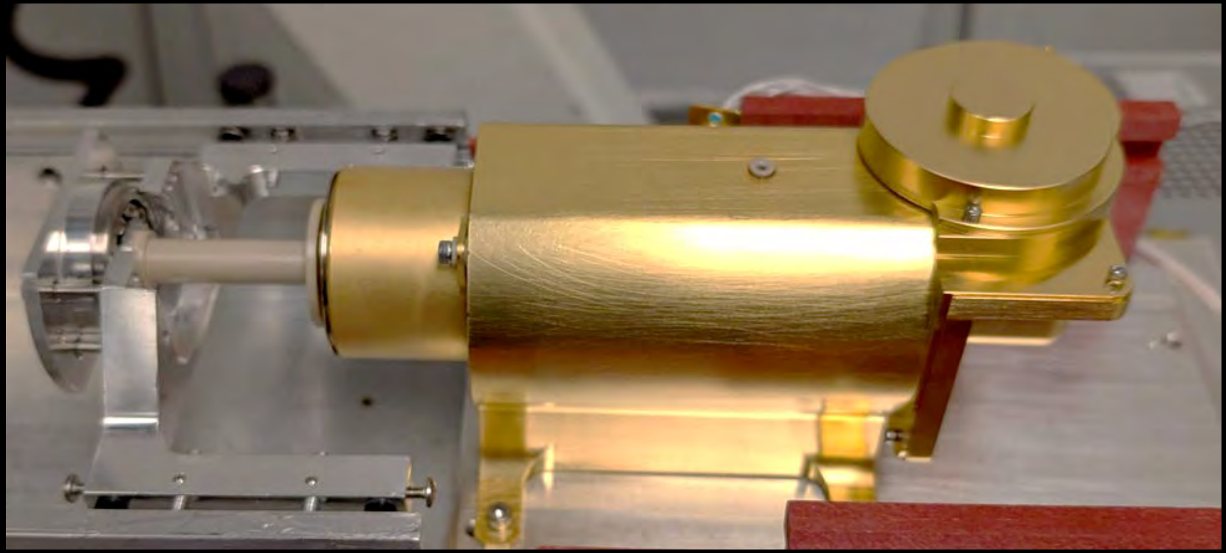
Bale+, 2023, https://arxiv.org/abs/2301.10345.

Differential Brightness Temperature



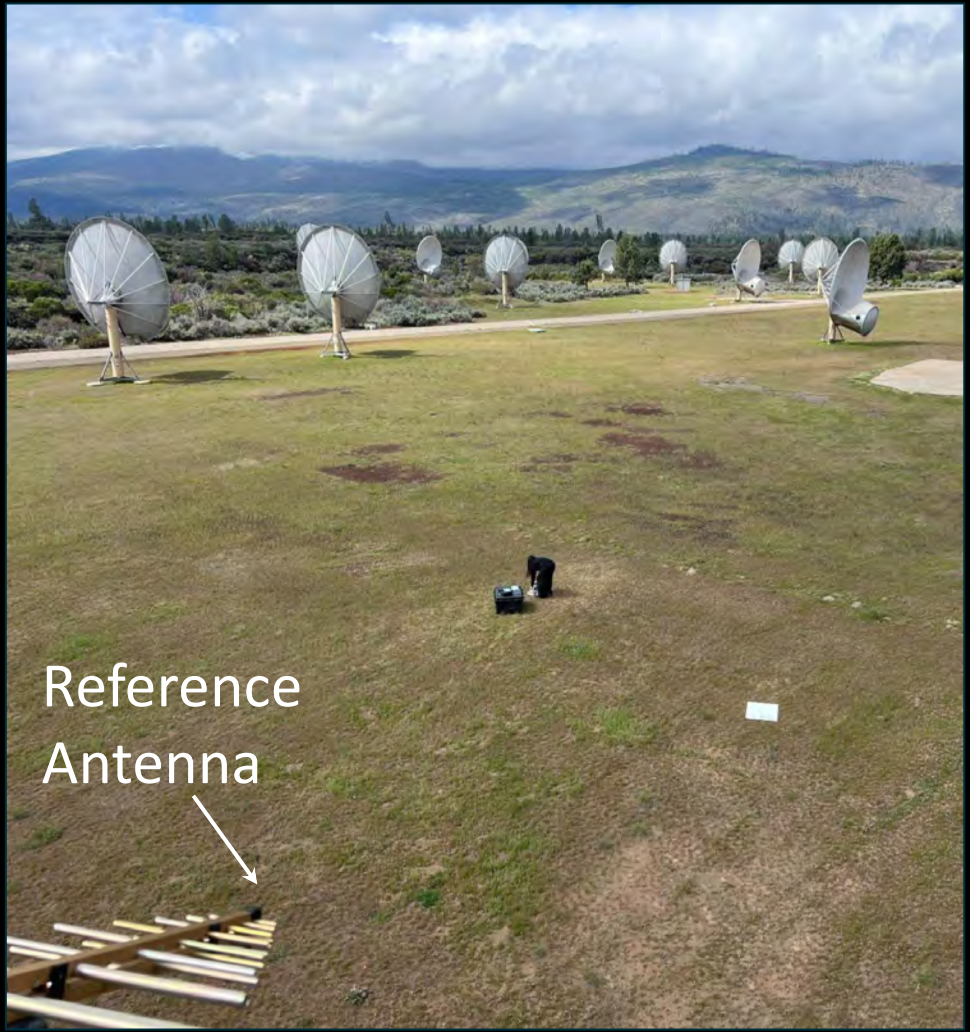
$$\delta T_b(\nu) \propto x_{HI}\left(1 - \frac{T_R}{T_S}\right)$$

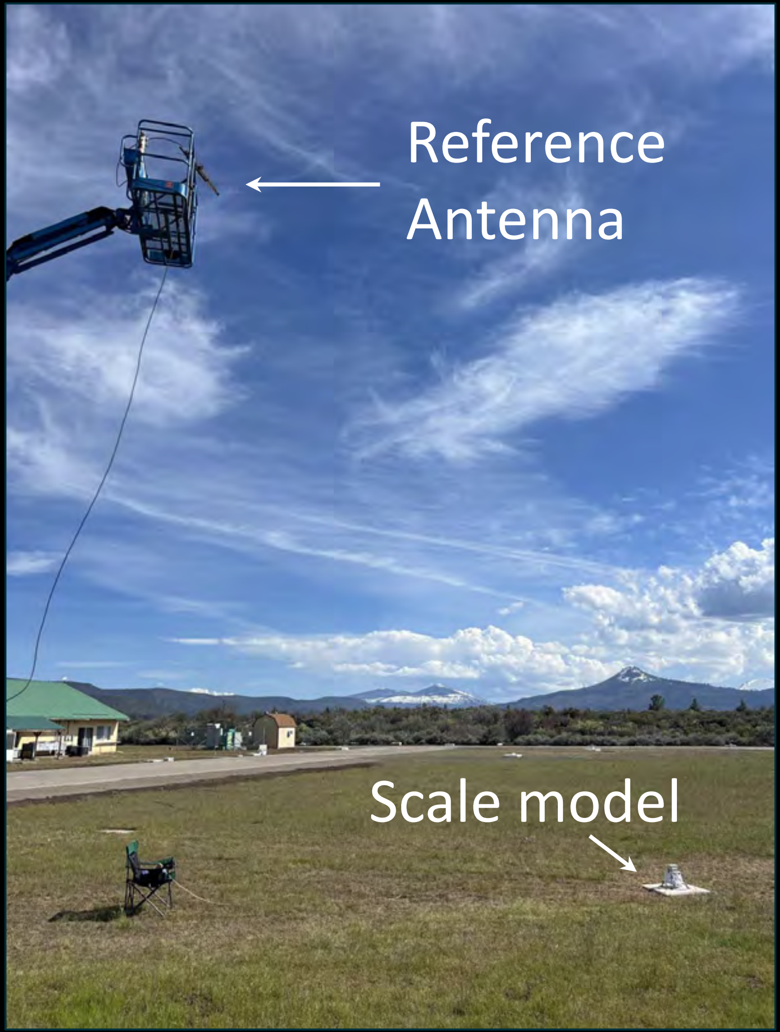
Stacer antennas



Rolled BeCu sheet, Stowed during launch, deploy as rolled flat spring

Beam pattern measurements

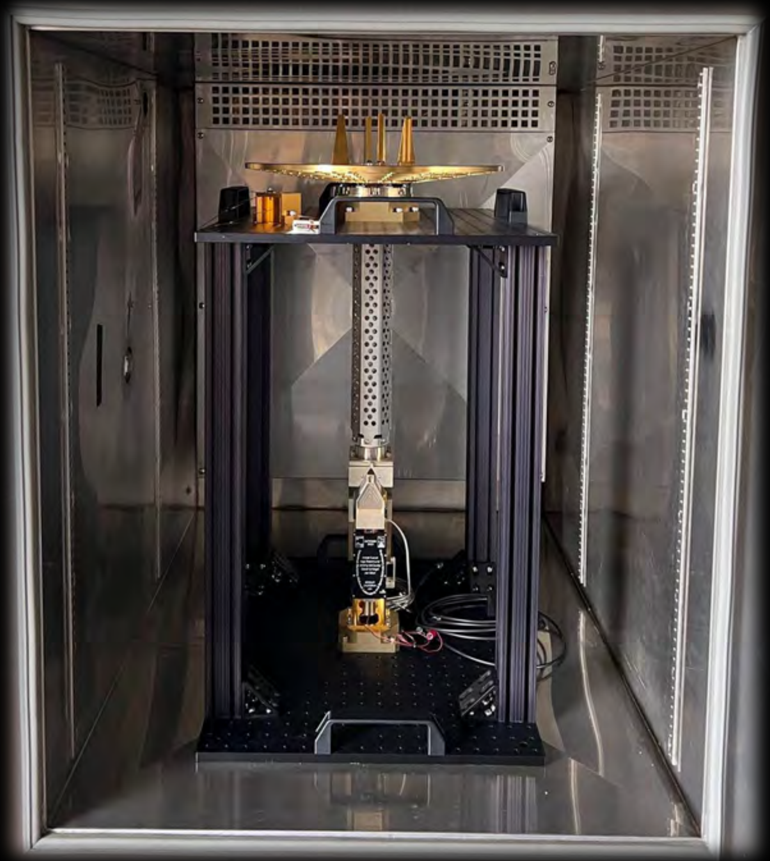




- Fixed reference antenna, rotated the LuSEE-Night scale model
- Measure slices of beam and compare against simulation

Flight model Assembly, Integration & Test

Assembly



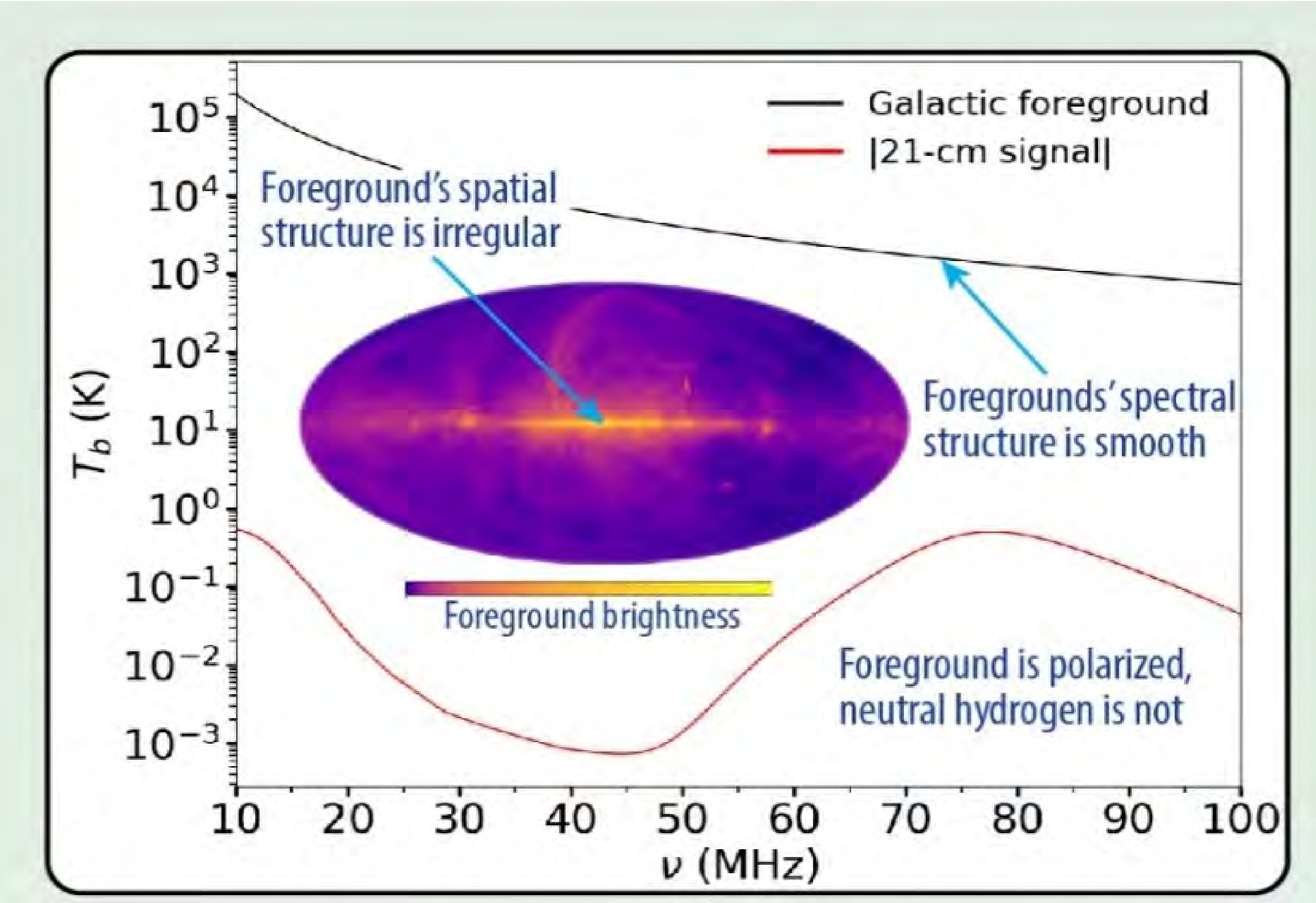
Thermal test

Integration

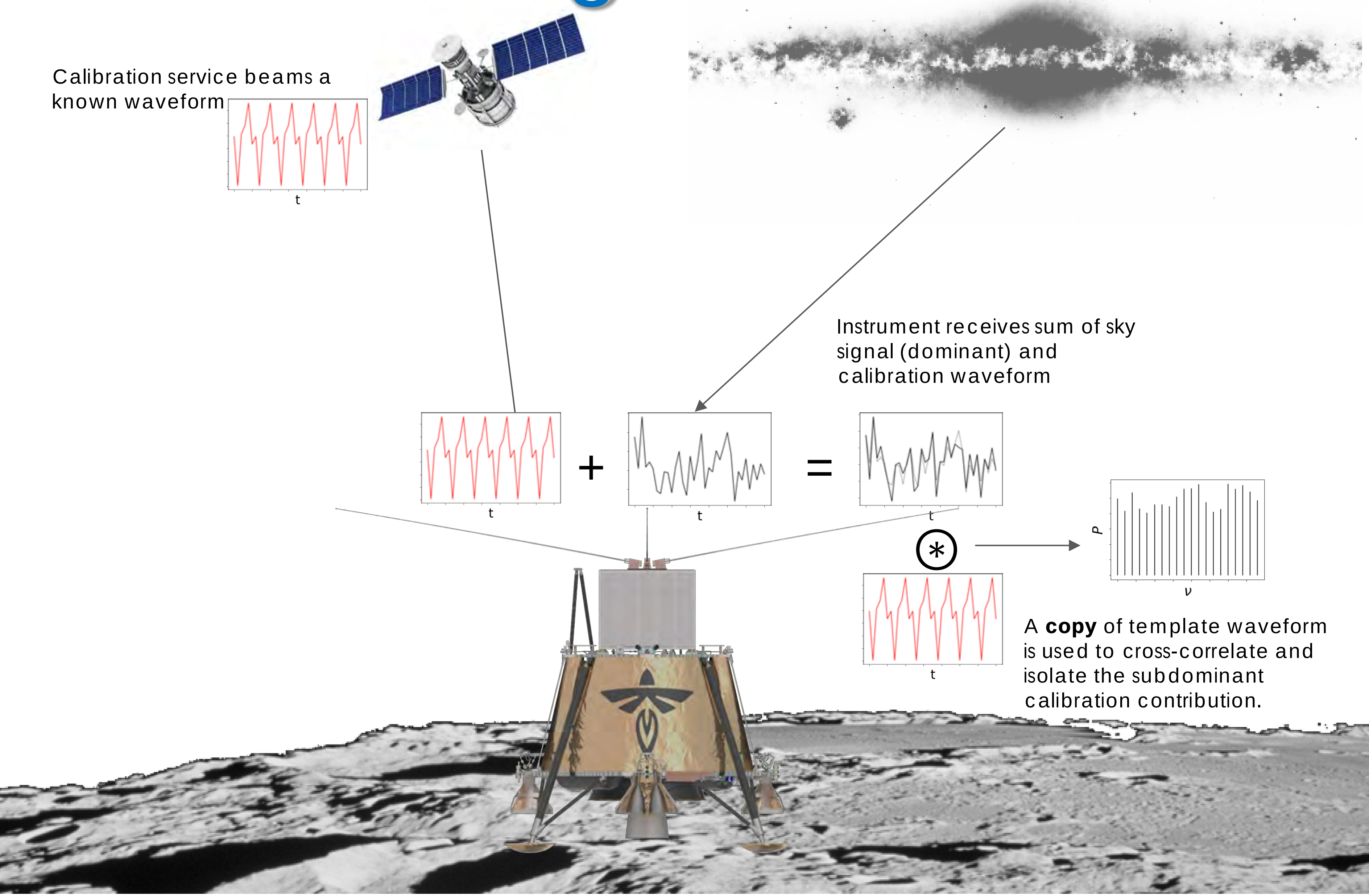
- Flight model parts assembled, torqued, tested
- We ended up gold plating almost every metal part

Even from the Moon, a Global 21-cm Cosmology Experiment is Challenging because of Bright Foreground

Digital Control Board for LuSEE-Night



LuSEE-Night Far-Field Calibration



Advantages of cross-correlation technique:

- sky background does not cross-correlate
- only one copy of template attenuated by the distance (1/r scaling), allowing high SNR recovery
- See arXiv:2201.11806 for similar approach on the ground

Current status:

- Firefly selected to build radio beacon.

FARVIEW

LUNAR RESOURCES

FarView

Phase II Concept Study funded by NASA Innovative Advanced Concept (NIAC) program

An in-situ manufactured lunar far side, 100,000 dipole radio array concept for 21-cm Dark Ages cosmology

Jack Burns for the Science Team

University of Colorado Boulder

Alexander Hegedus, SRI International

Jonathan Pober, Brown University

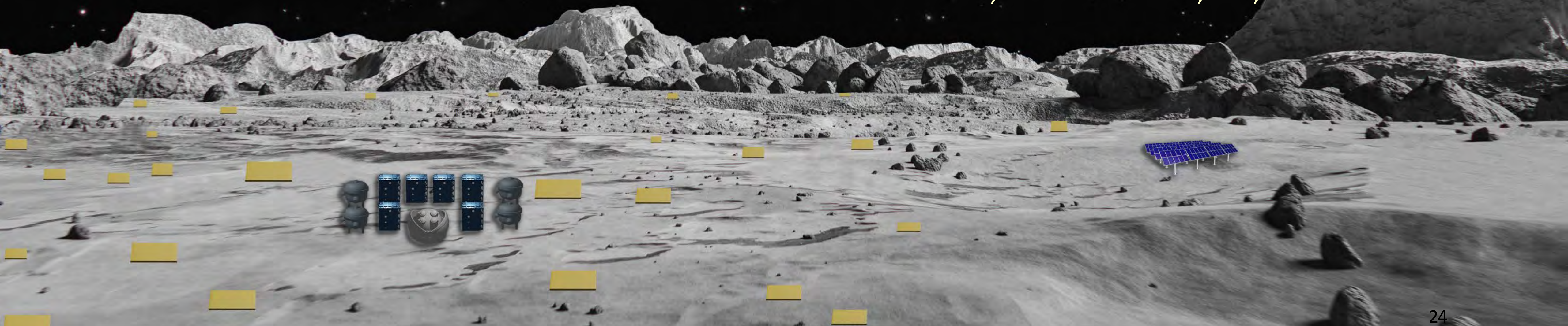
Gregg Hallinan, Caltech

Nivedita Mahesh, Caltech

Tzu-Ching Chang, Caltech/JPL

Judd Bowman, Arizona State University

Ron Polidan, Lunar Resources, Inc., PI

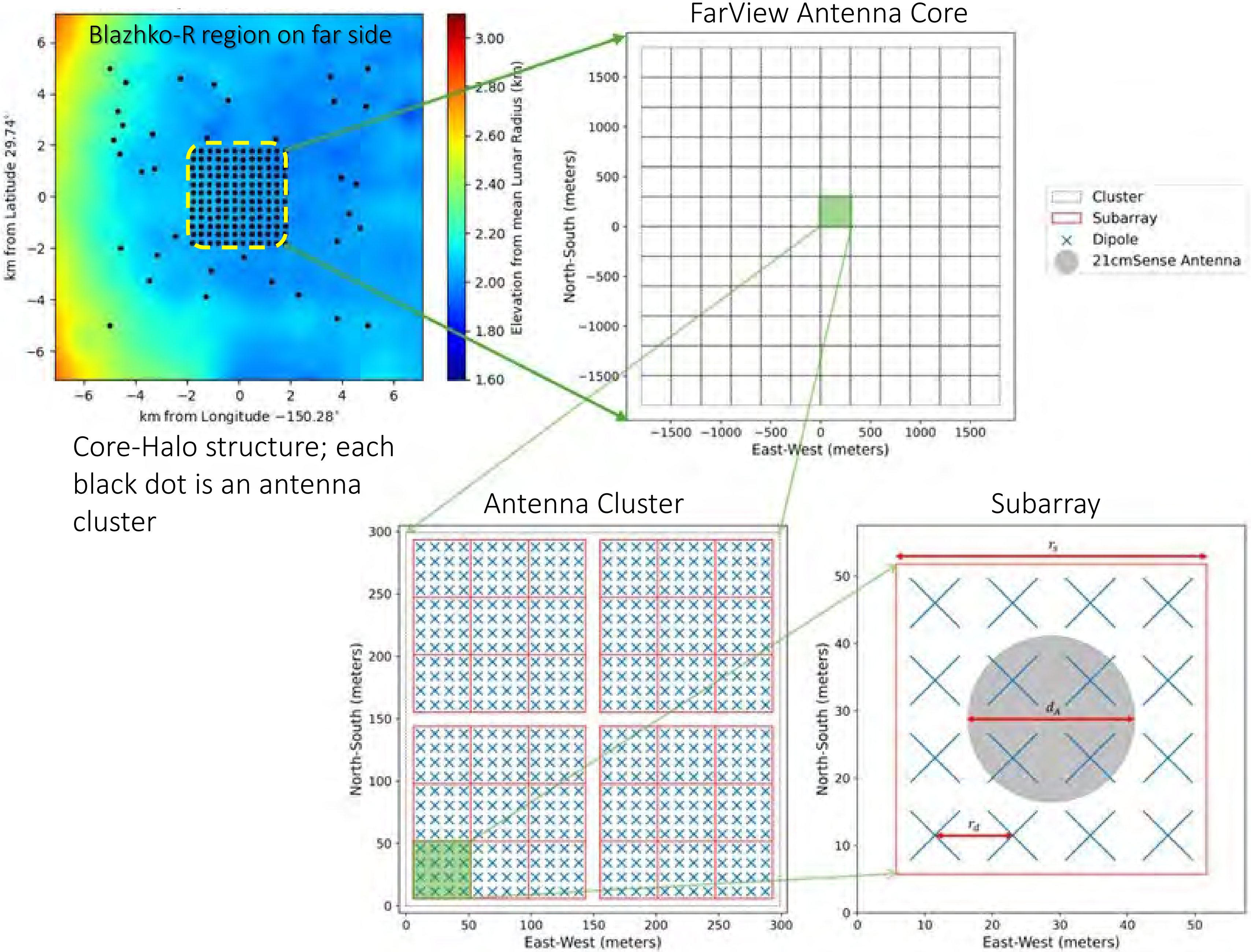


See Polidan, Burns, et al. 2024, *Advances in Space Research*, 74, 578.

FarView Architecture

FarView architecture is hierarchical with top level in a core-halo (83,000-20,000 antennas).

- Halo is 14×14 km to measure Foreground.
- Core is 4×4 km. Antennas gathered into
    - Subarrays with 16 cross-dipoles.
    - Clusters with 36 subarrays.
- For the fiducial array r_d = 11.5-m, r_s = 46-m, and d_A = 24.7-m.

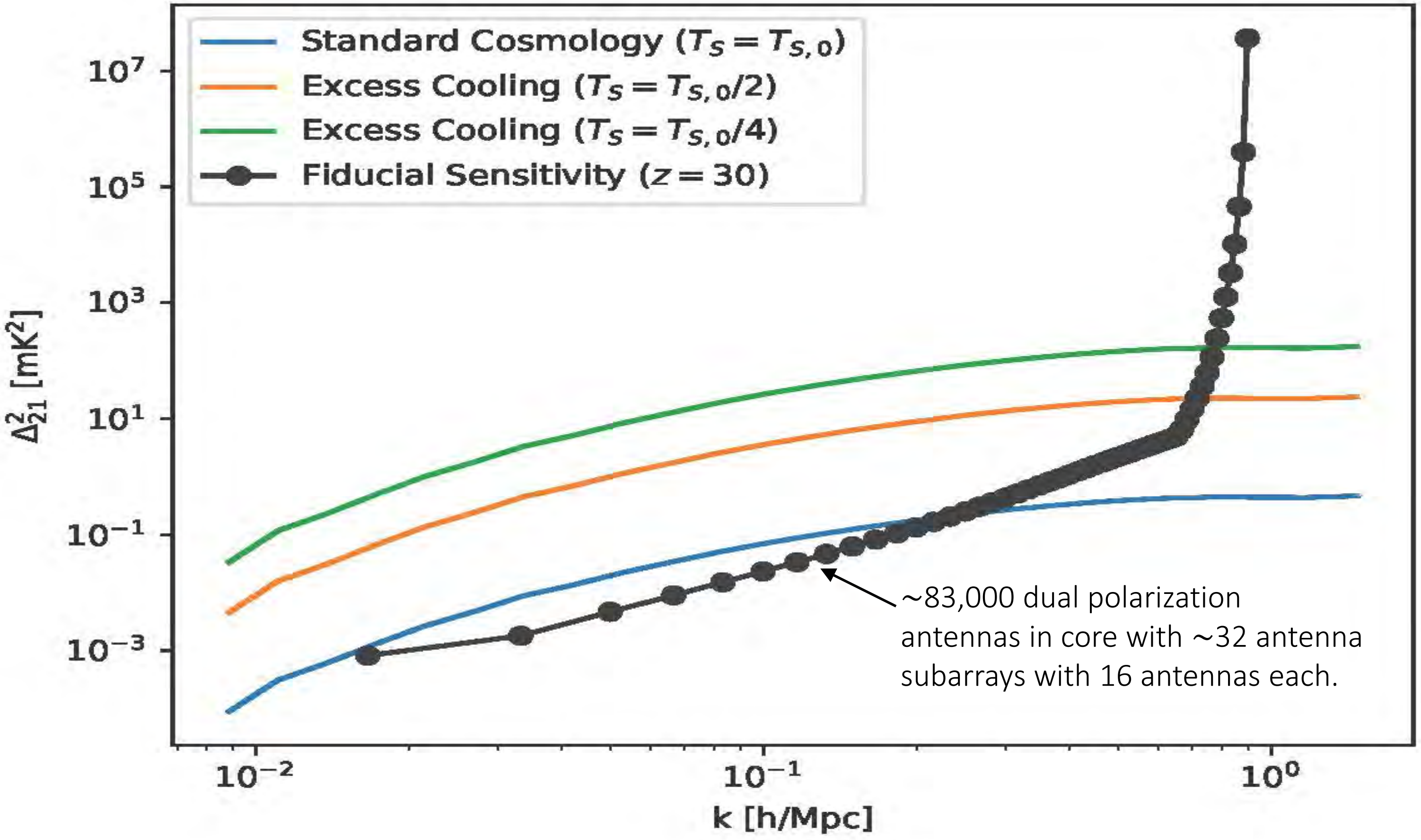


Core-Halo structure; each black dot is an antenna cluster

Smith & Pober, 2025, ApJ, 984, 116.

New Simulations of Sensitivities with Beamforming

LUNAR RESOURCES



New numerical simulations using *21cmSense* code suggests that to achieve required sensitivity for Dark Ages, we need

- Smaller subarrays with closer spacing between antennas.
- More subarrays and more antennas devoted to core.

Smith & Pober, 2025

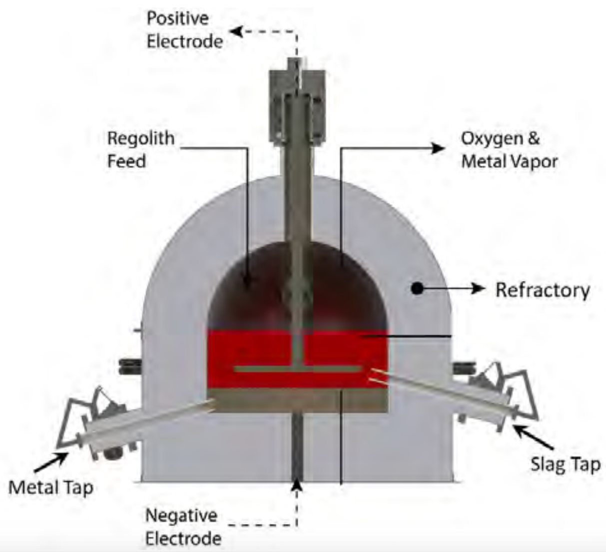
FarView Lunar Manufacturing: Molten Regolith Electrolysis

- Metal Extraction Electrolysis Process
  - o Extract: Iron, Silicon, Aluminum, Magnesium
- Utilize Aluminum for antennas and Silicon and Aluminum for thin film silicon solar cells
  - o Also use Magnesium for antennas
  - o Collect and hold Iron for future use
- *FarView* Metals Requirement
  - Approx 45,000 kg

∴ Require 6 MRE Units Operating for ~6 yrs

- ~6 tonnes of launch mass to gain 45 tonnes of metals

- We also developed a Wire Fabrication Process for the dipole antennas on the Moon



MRE undergoing testing in a vacuum chamber at NASA KSC

FARVIEW

LUNAR RESOURCES

A Single *Blue Moon* Lander Can Deploy a 400 Antenna Cluster & LTV on the Moon

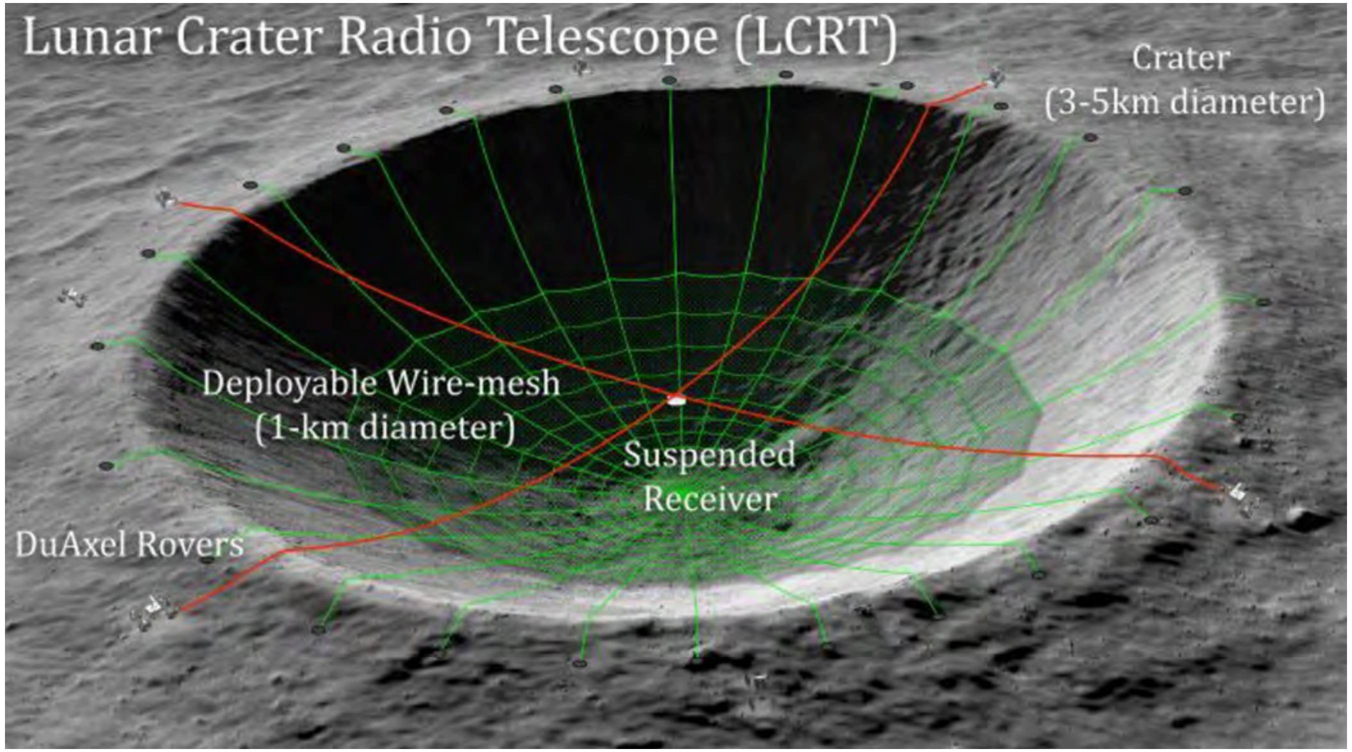
FarView and Astronauts – Early Stages

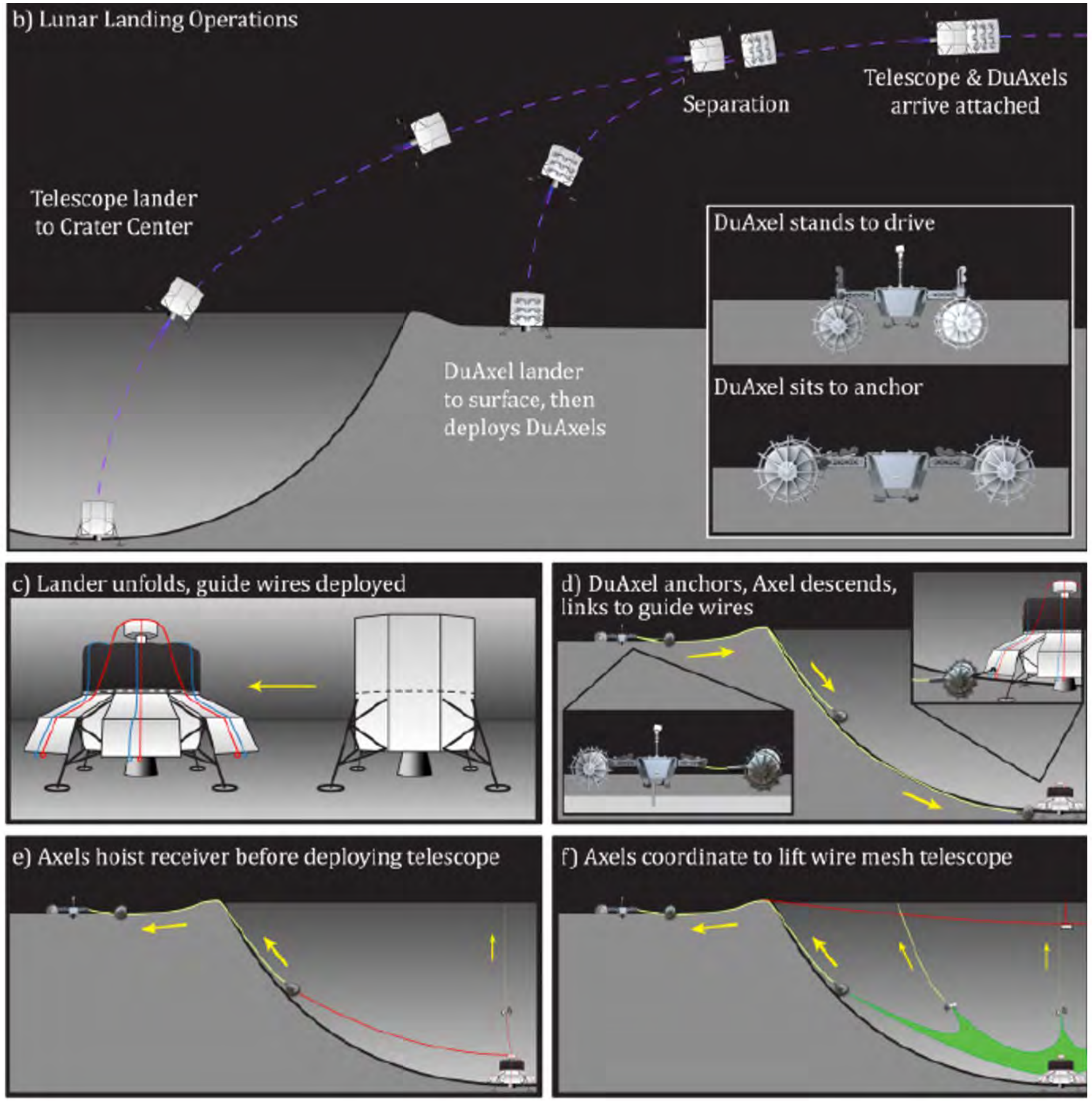
- In-situ assessment/survey of the surface and subsurface conditions to safeguard that the *FarView* site meets all the suitability criteria.
  - Ensure no small scale (~1-3 m) hazards (rocks, craters) that could not be removed with surface processing.
  - Assessment of the subsurface structure with a ground penetrating radar.
  - Deliver a small prototype array (5-20 antennas) to surface to fully evaluate the site.

- Astronaut support for *FarView* for initial landing & setup of hardware.
  - Initial landing could deliver all the hardware for *FarView* using a large lunar lander such as Blue Origin's Blue Moon landers. Pre-deploy these assets with the astronauts.
  - Checkout of extraction & manufacturing hardware may require combined astronaut/robotic support to deploy and assemble hardware and bring into operation.

Lunar Crater Radio Telescope

Saptarshi Bandyopadhyay, JPL

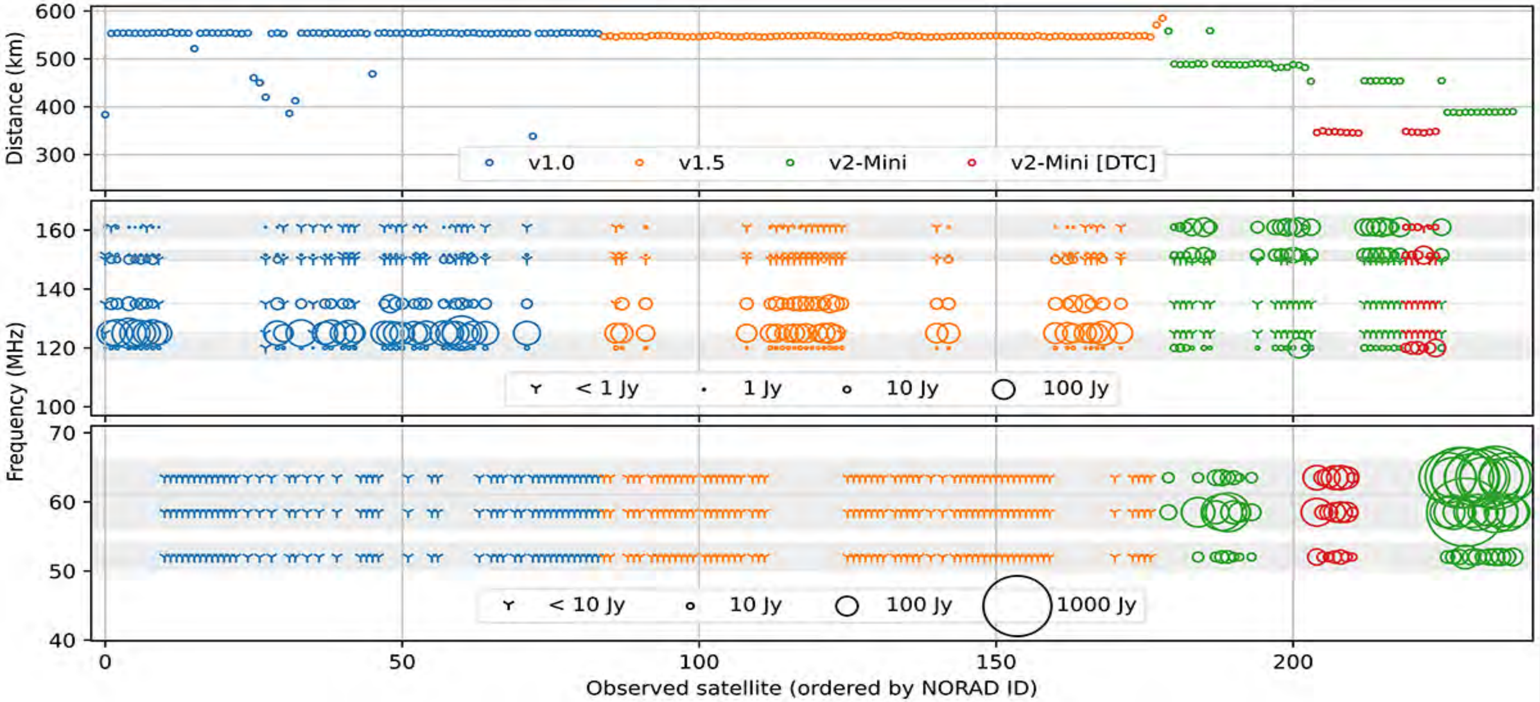




Radio Leakage from Starlink Satellites – Implications for the Moon

"Observations with the LOFAR radio telescope between 10 to 88 MHz and 110 to 188 MHz show broadband emission [from Starlink satellites]…The spectral power flux density of this broadband UEMR varies from satellite to satellite, with values ranging from 15 to 1300 Jy, between 56 and 66 MHz,", Bassa et al. 2024, *A&A*, 689, L10.

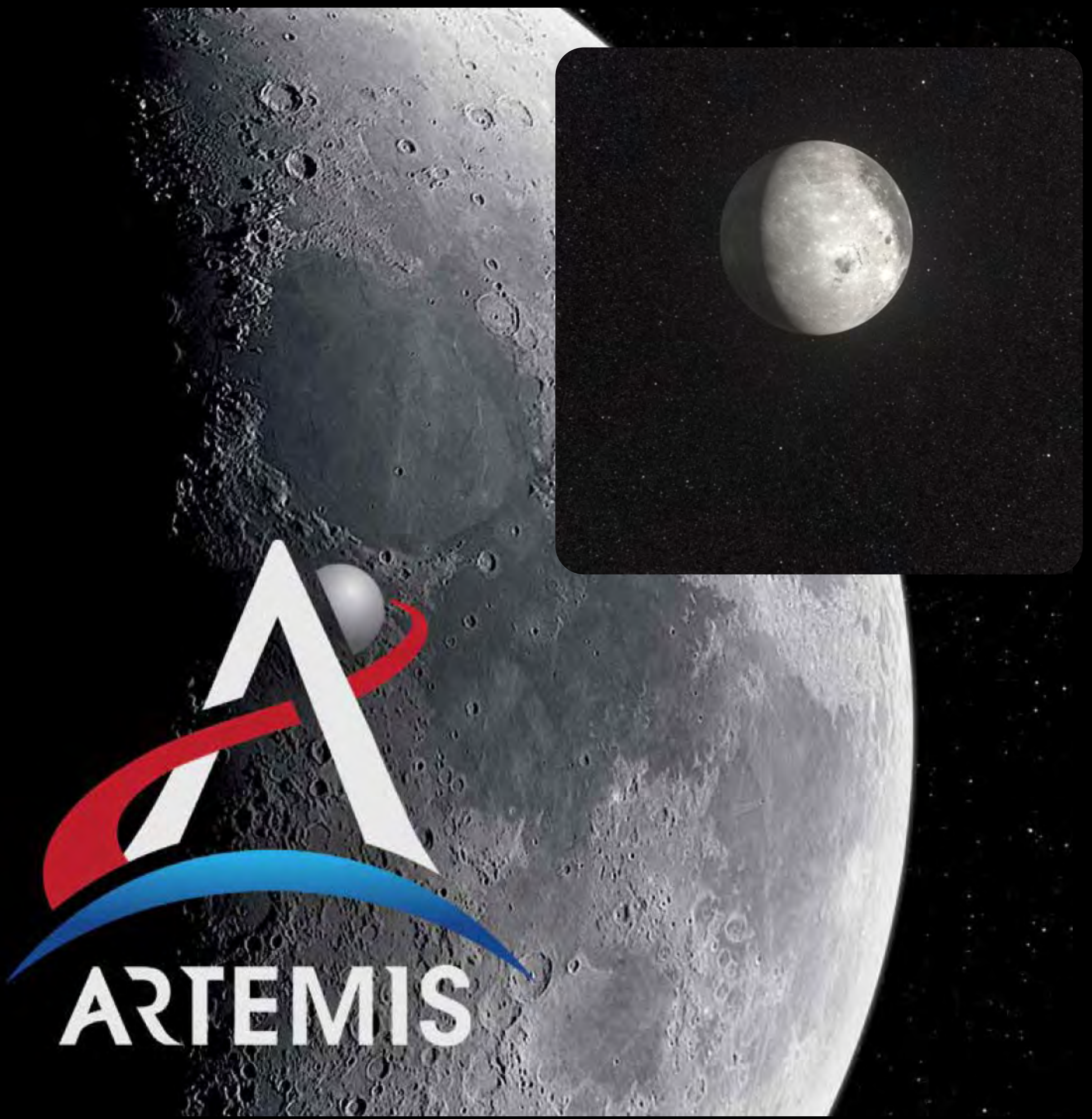
See also Krolikowski & Elvis, 2024, *Phil. Trans. Roy. Soc.*, in press.



Distances and power flux density measurements of Starlink satellites that passed through the beam pattern of the two 1 h LOFAR observations.

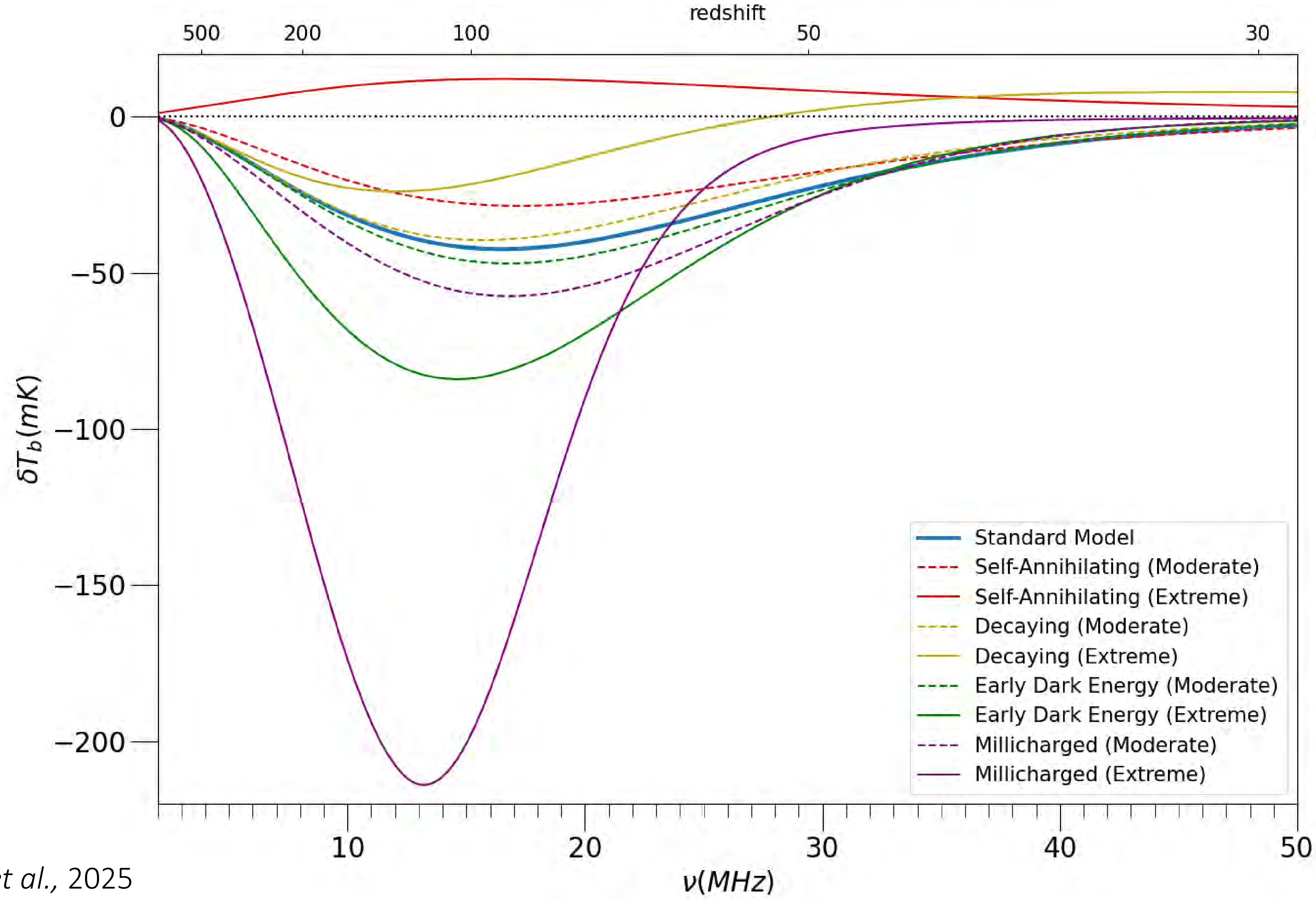
Summary & Conclusions

- NASA CLPS delivered the first radio telescope to the surface of the Moon in February 2024.
- *ROLSES-2* & *LuSEE-Night* will further investigate lunar plasma environment & cosmic Dark Ages in next few years.
- *FarView* will measure 3-D spatial/spectral fluctuations to explore new physics potentially including dark matter, neutrinos, & inflation.



Extra Slides

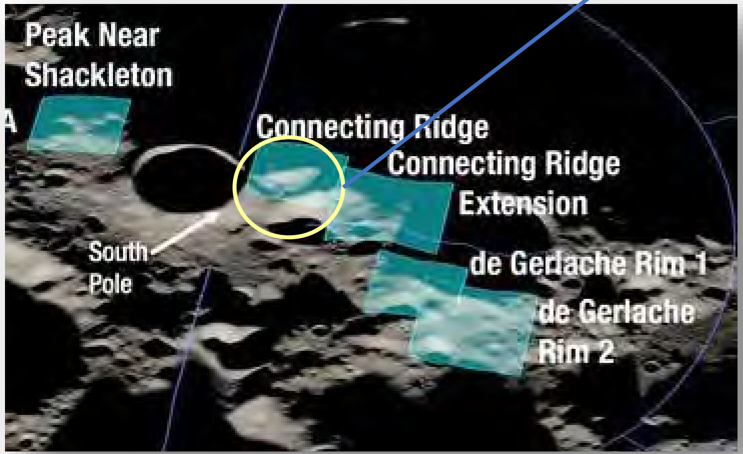
Effects from Exotic Physics on Dark Ages Signal: Alternative Dark Matter & Dark Energy Models

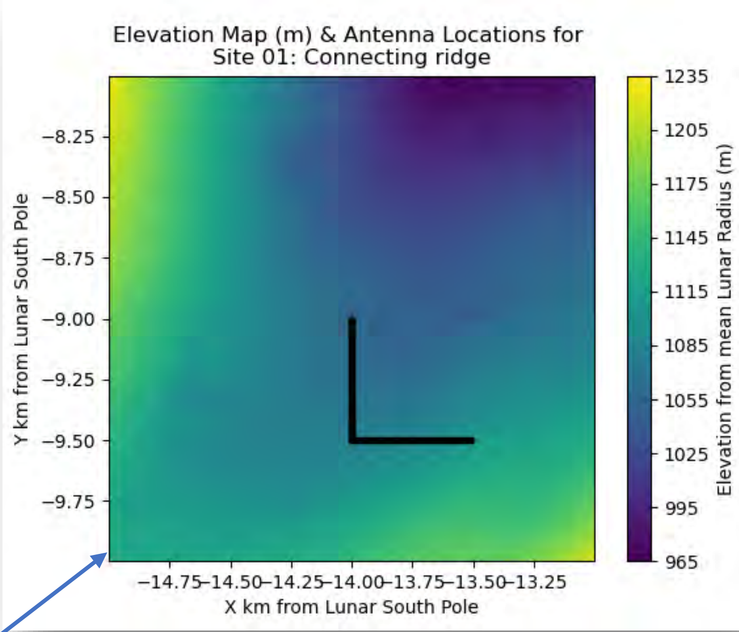


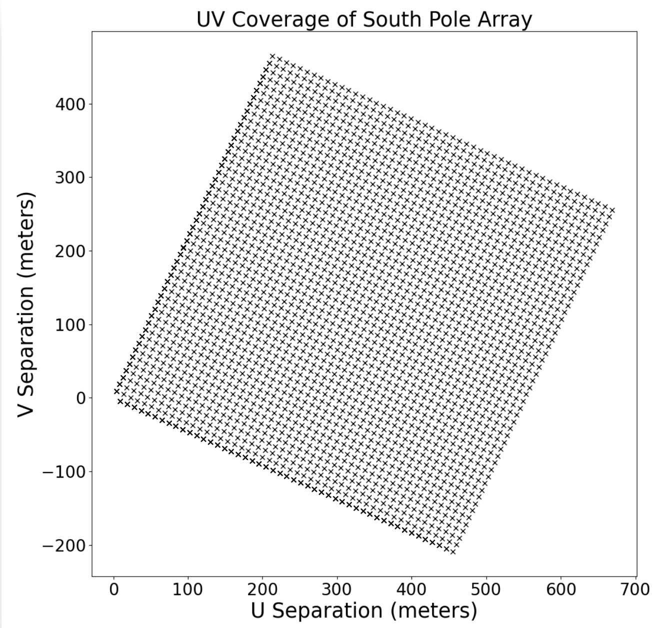
D. Barker *et al.*, 2025

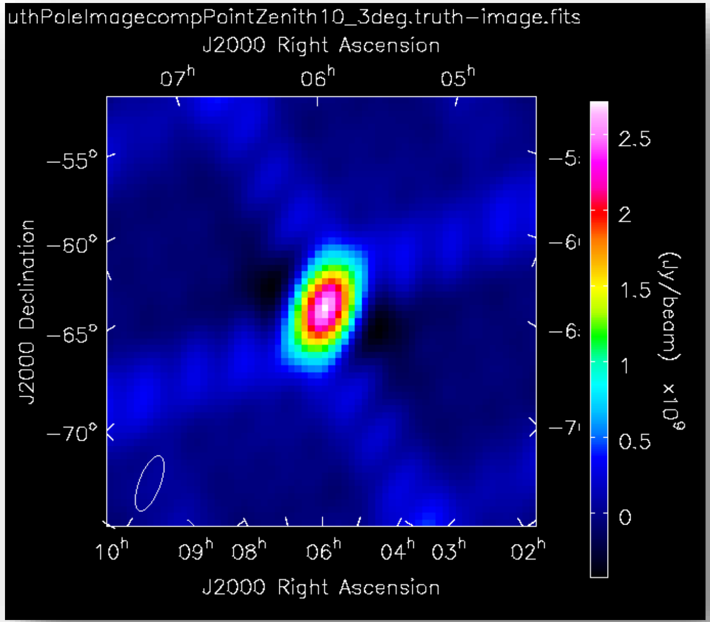
Low Frequency Radio Interferometric Array at Artemis Landing Site

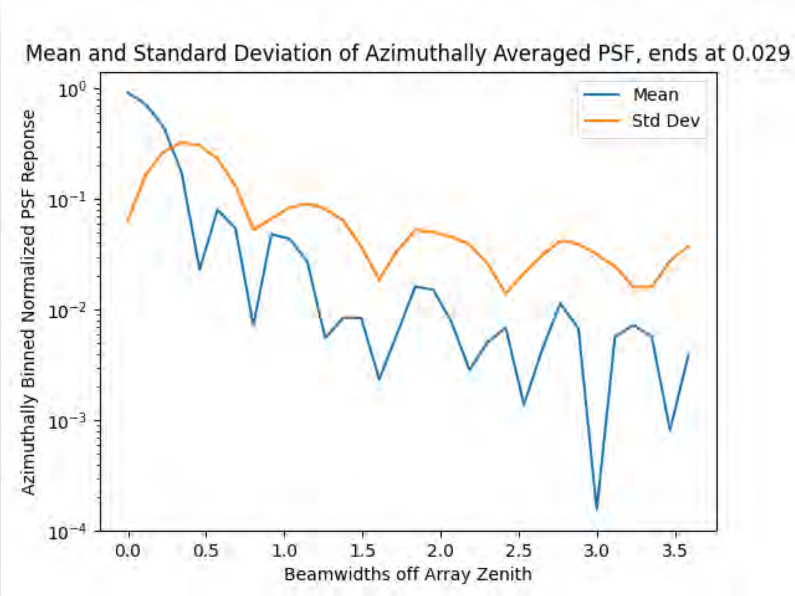
- A ~1-km tether can house up to 100 radio dipoles, each 10-m tip-to-tip, to create a unique, sensitive synthetic aperture radio interferometer (Hegedus+ 2023).











Point response function for Tethered Array, 1-min integration, at 10 MHz

Trade Study for Beamforming

LUNAR RESOURCES

Criteria	Weight	Sub-array	Score	Individual dipoles (no sub-arrays)	Score
Computational requirement	25%	Reduces the computations required by reducing the u-v points/number of visibilities.	5	N^2 computational steps with N = 100,000 is large. Best case with EPIC is still N*log(N).	3
Deployment	10%	Easy rover operations	4	More distance & time travelled by rover due to larger number of cables	3
	10%	Fewer cables (less mass and volume)	5	Cables from each dipole to the central node	2
	10%	Fewer correlators on the surface (6400 correlators)	3	100,000 correlators	2
Technology Progression	5%	Building correlators for ~6400 elements is doable in the coming decade. We are already expanding to 10^7 in this decade	4	Expanding to 10^{10} correlations is more difficult in the foreseeable future	3
Field of View (FOV)	5%	Reduces the instantaneous FOV from all-sky to $\lambda/[(N_{sub})^{0.5} *17m] \sim 25°$ at 10 MHz	4	All-sky field of view	5
Cadence of coverage	5%	Reduced	4	Maximum possible	5
Blind transient detection rate	5%	Decreased	4	Best possible	5
Sample/Cosmic variance	5%	Higher	4	Lower	5
Foreground contamination	5%	Lower contamination	5	More contamination due to larger FoV	4
Chromaticity	10%	Higher	3	Lower	5
Operational Complexity	5%	Steerable beams	3	Drift scan	5
Totals	**100%**		**4.15**		**3.3**

Analysis suggests a preference for beamforming although it might result in a loss of some science.

FarView Mission Design Parameters Derived from the Science Analyses

Parameter		Value		Rationale
Location		Radio-quiet zone on the lunar far side		The radio quiet zone is a ~65° radius circular area centered on 0° latitude, 180° longitude) on the lunar far side where the natural and anthropogenic low frequency radio signals from the Earth (a major noise source for FarView) are almost totally blocked. This very low noise environment is required to detect the Cosmic Dark Ages signal.
Frequency Band		5 - 50 MHz		For detection of highly redshifted 21-cm radiation from the Cosmic Dark Ages.
Total Number of Dipoles		100,000		Minimum necessary to achieve cosmology sensitivity requirement.
Antenna Distribution		Core/Halo distribution		Core should have ~80% of total number of antennas. This distribution is required to supply sensitivity in the core to detect the Dark Ages signal and enough sensitivity in the halo to adequately remove the foreground.
Antenna Length		~10 meters		Optimal length to produced required sensitivity.
Antenna Separation		11.5 meters		Optimized separation that maximizes sensitivity and is viable given the antenna length and rover maneuverability.
Antenna Distribution		Zig-Zag Pattern		Cross-dipole antennas are required to measure polarization. Non-cospatial cross dipoles can be achieved by deploying dipoles with one orthogonal to the next in a zig-zag pattern.
Positional Tolerance for Placement of Individual Antennas		~2 meters in all three axes		Tolerance needs to be $<0.1\lambda$ at 15 MHz and flexibility to avoid small boulders & craters.
Orientation Tolerance for Placement of Individual Antennas		≈10 degrees		Maintain coherence for polarization with post-processing corrections.
Polarization Measurement		Equal number of antennas for both orientations		Allows calculation for full Stokes parameters enabling polarization measurements.
Lunar Surface		Relatively smooth and flat with undulations of <2 m in height		Tolerance needs to be $<0.1\lambda$ at 15 MHz over the area spanned by 3 dipole antennas.
Lunar Subsurface		High crustal thickness (≥ 25 km)		Minimize subsurface reflections of the incoming radio signal that will distort the radio beam.
Visible Horizon		Avoid sites with nearby mountains		A jagged horizon, one with lots of mountains, will compromise the data analysis. Map of horizon will be needed for data analysis to remove horizon effects.

Estimated Data Rates for FarView

FarView will generate prodigious amounts of data. To estimate the data rates, we assume:

- 100,000 cross-dipoles within subarrays with bandwidth of 5-50 MHz.
- 5 kHz spectral resolution with ~9,000 spectral channels over 45 MHz bandwidth.
- Core is 4 km & halo is 14 km in diameter. Resolutions at 45 MHz for core is ~5.7' and for halo is 1.7'.
- Beamforming of subarrays reduces down correlations from 10^{10} to $N^2_{stations}$.
  - $N_{stations}$ for core = 144 * 36 = 5184
  - $N_{stations}$ for halo = 35 * 36 =1260
- Integrate for ~1 min & 2.4 mins for longest and shortest baselines, leading to 1440 and 600 integrations every 24 hrs.
- Assume 64 bits to store complex visibilities.

With all these parameters, the data rate per day to be downlinked to Earth is:

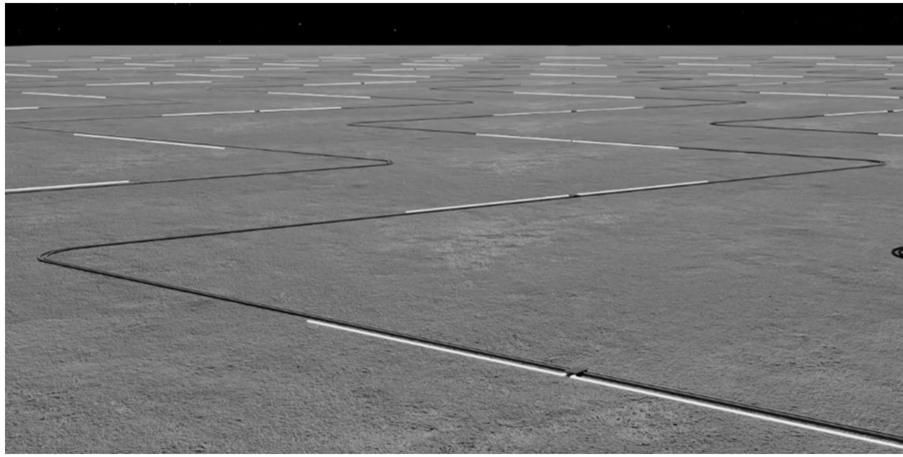
- Data-rate/24^h (halo) = $N_{stations}(N_{stations}-1)/2 * N_{channels} * N_{bits} * N_{pol} * N_{integrations}$
  = 793,170 * 9000 * 64 * 4 * 1440
  = 329 TB/day
- Data-rate/24^h (core) = 1,342,433* 9,000 * 64 * 4 * 600
  = 232 TB/day

We are exploring methods to reduce data rate including:

- Aggressive baseline-dependent averaging / fringe-rate filtering.
- Real-time averaging of redundant visibilities.
- **EPIC** (E-Field Parallel Imaging Correlator). Reduces # of computations from N^2 to N*log(N).

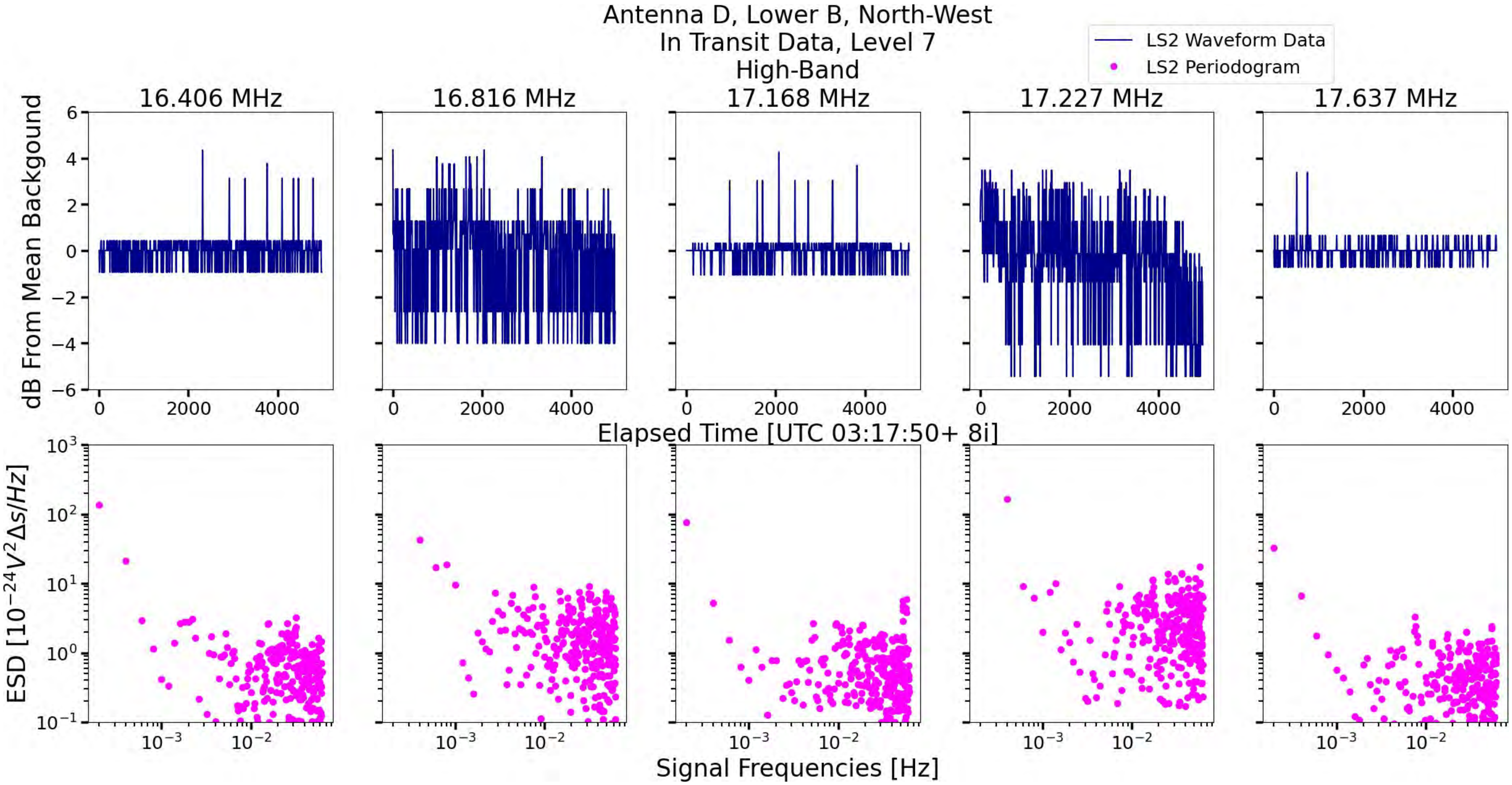
FarView Lunar Manufacturing

- *FarView* Observatory Incorporates 100,000 dipole antennas
  - In addition, Power Cables, PreAmps, Data & Comm, Power System…..
- Metallic Components: antennas and power cable wires
  - 1,000,000 m 'wire' for antennas
  - 3,200,000 m wire for power cables
  - Wire mass ~ 0.01 kg/m
  - Total Observatory 'wire' mass ~42 tonnes



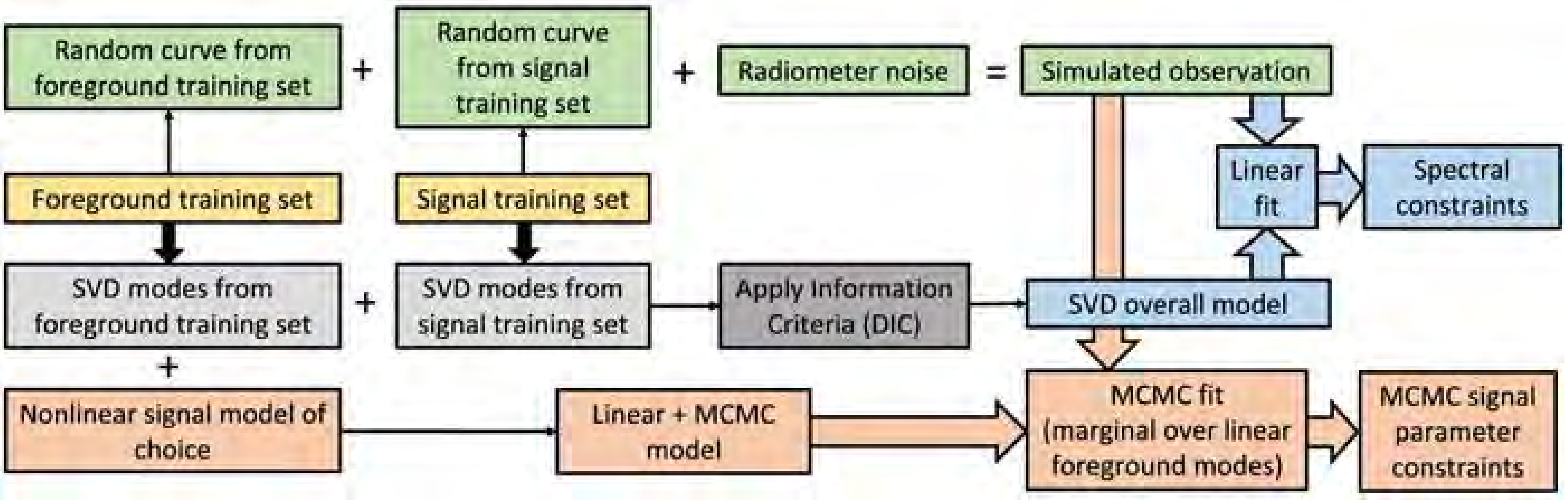
- Why bring metallic wire to the Moon?
  - Lunar regolith contains aluminum (aluminum oxide)
  - Reduce oxide and extract aluminum metal on the Moon
  - Use extracted aluminum metal for manufacturing 'wire' for FarView on the Moon
  - Make Observatory more Cost Effective/less Cost Prohibitive

Viewing Earth in the Radio: Technosignatures



Hibbard et al. 2025, *submitted to ApJ*

Signal Extraction Pipeline – The forward-model approach



Rapetti et al. 2020, ApJ, 897, 174

Publicly available pipeline codes for global 21-cm experiments: component separation & parameter constraints, pylinex https://github.com/CU-NESS/pylinex: beam-weighted foregrounds, perses https://github.com/CU-NESS/perses: global 21-cm models, ares https://github.com/mirochaj/ares.

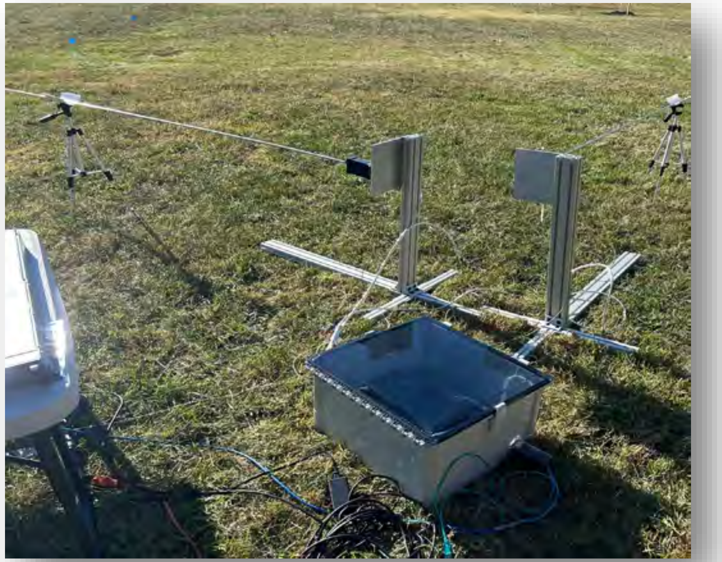
Lessons Learned & Upgrades for ROLSES-2

ROLSES-2 assigned to the CP-21 CLPS manifest, Gruithuisen Domes on lunar near side, in ~2028.

- Upgrade antenna actuator for higher temperatures.
- Internal Cal source to monitor gain variations.
- Improved shielding from internal interference.
- 4 antennas operate as cross dipoles to measure polarization.

Stacer antennas deployed in the Lab.

Spectrometer board with FPGA



Recent field test of Stacer antennas