The Lunar Surface Electromagnetics Experiment

Stuart D. Bale

Physics Department and Space Sciences Lab

University of California, Berkeley

…for the entire LuSEE team

- LuSEE was **selected** in June 2019 by NASA in the Lunar Surface Instrument and Technology Payloads (**LSITP**) for the Commercial Lunar Payload Services (**CLPS**) program – *originally based on PSP/FIELDS flight spare hardware*

- Under contract by MSFC/PMPO and **in development**

- LuSEE is a program **split into 2 payloads on 2 separate landers**

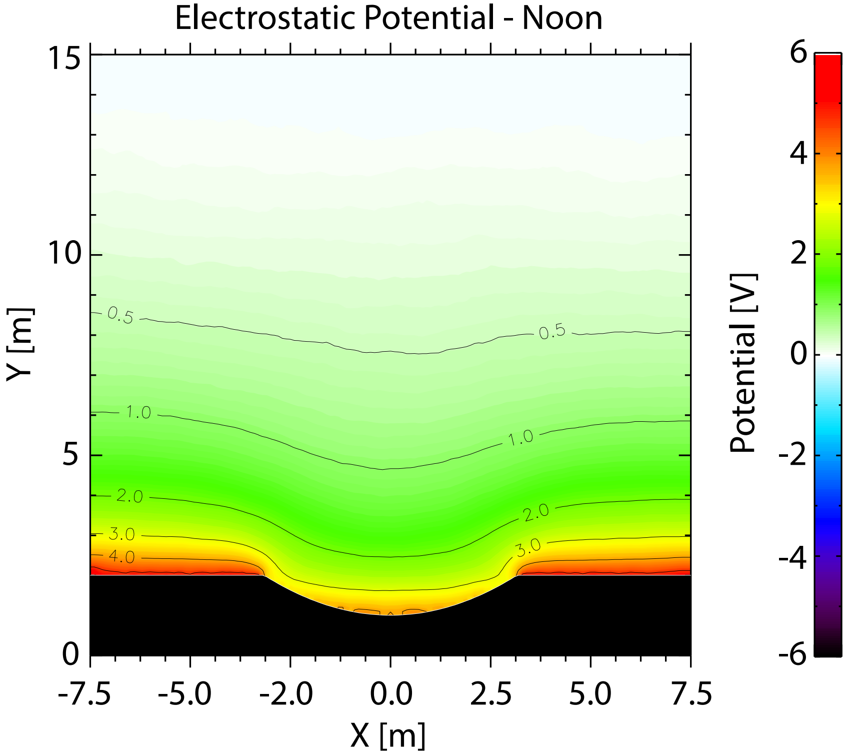
  - **LuSEE 'Lite'** to the Schrödinger Basin (south pole farside) in late 2024 on the CP-12 mission
    - Surface plasma physics and waves, DC electrostatic potentials, dust impacts, and coordination with LITMS/LMS (magnetotellurics)

  - **LuSEE 'Night'** to the farside mid-latitudes in 2025? on the CS-3 mission in a major collaboration with the US Department of Energy (**DOE**) – BNL and LBL
    - Low frequency radio astronomy (< ~50 MHz) with **standalone** operations through the lunar night
    - Lunar farside landing side, mid-latitudes
    - Operations through the lunar night, full EMI control

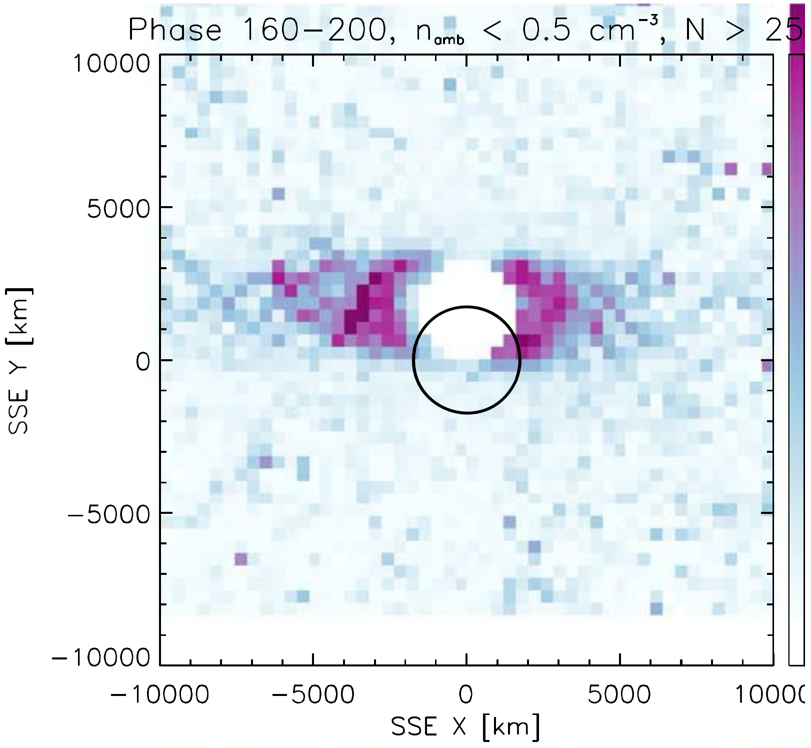
LuSEE ‘Lite’ Objectives and Measurements

- Lunar ionosphere - plasma waves
- Surface-geospace interactions - plasma waves
- Lunar surface electrostatic potential/sheath

- Dust/electrostatic field interactions
- Support for LMS/LITMS electromagnetic sounding
  - Electrical structure of the upper-mantle



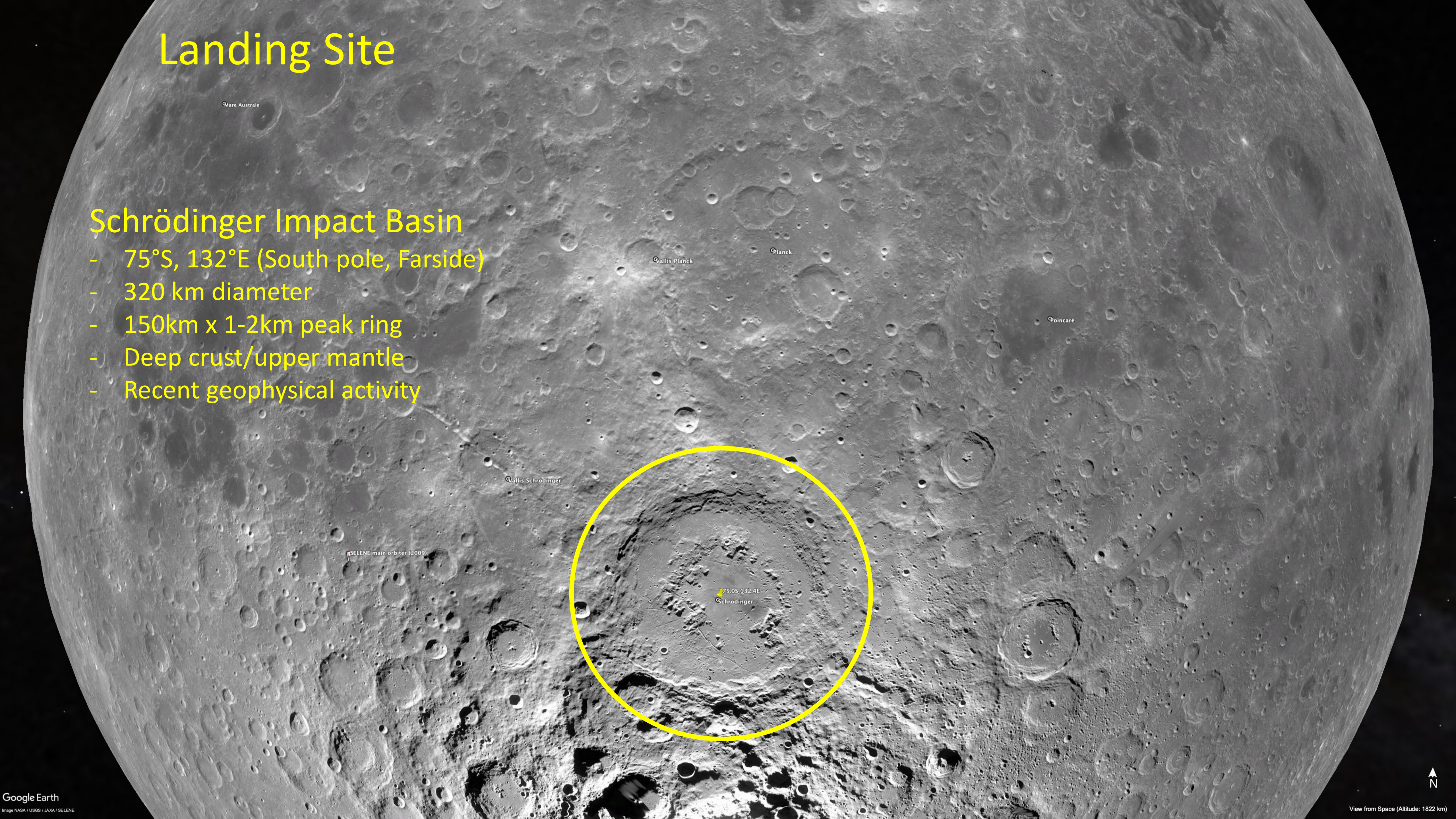
(Poppe)



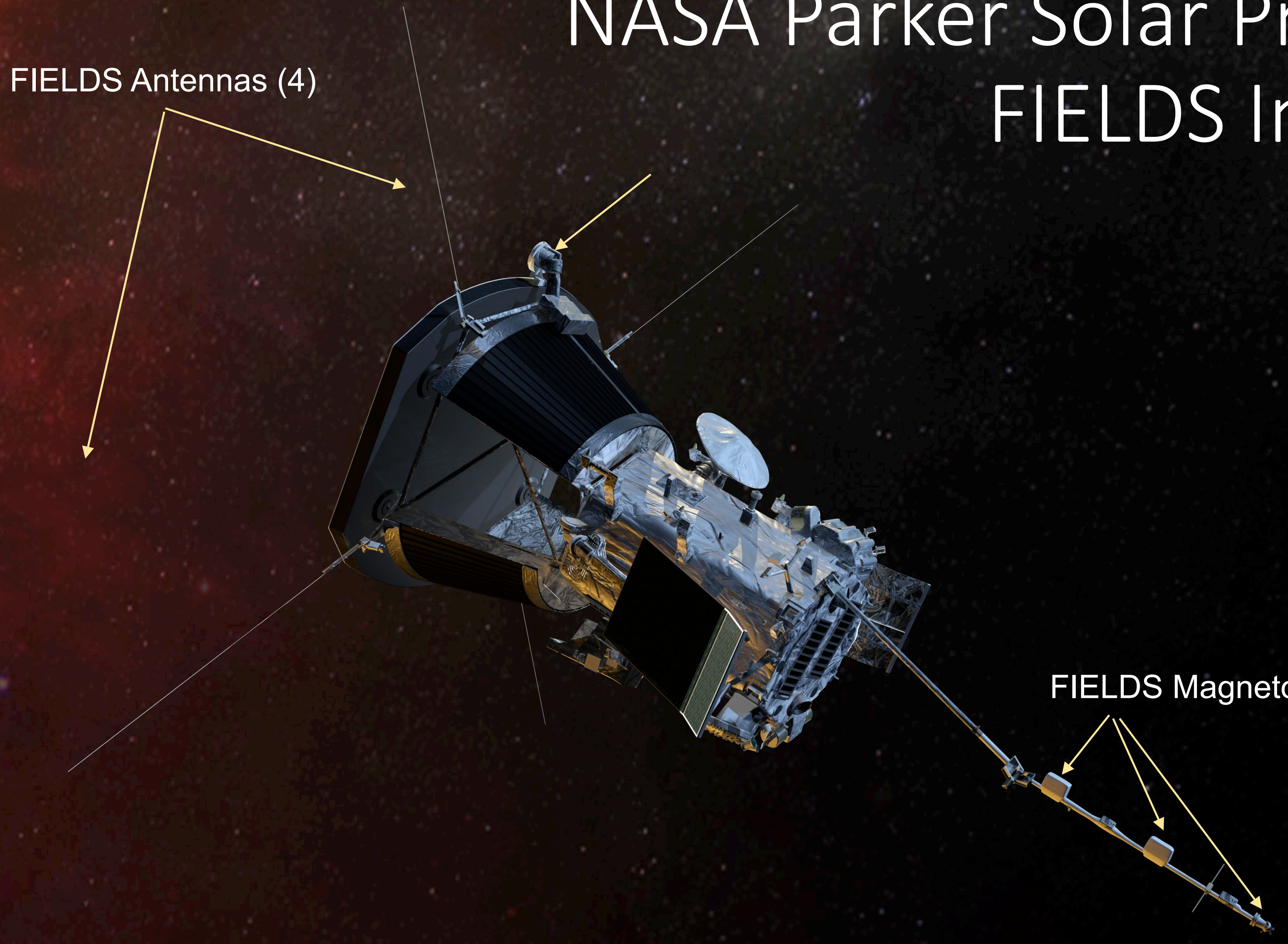
Landing Site

Schrödinger Impact Basin

- 75°S, 132°E (South pole, Farside)
- 320 km diameter
- 150km x 1-2km peak ring
- Deep crust/upper mantle
- Recent geophysical activity



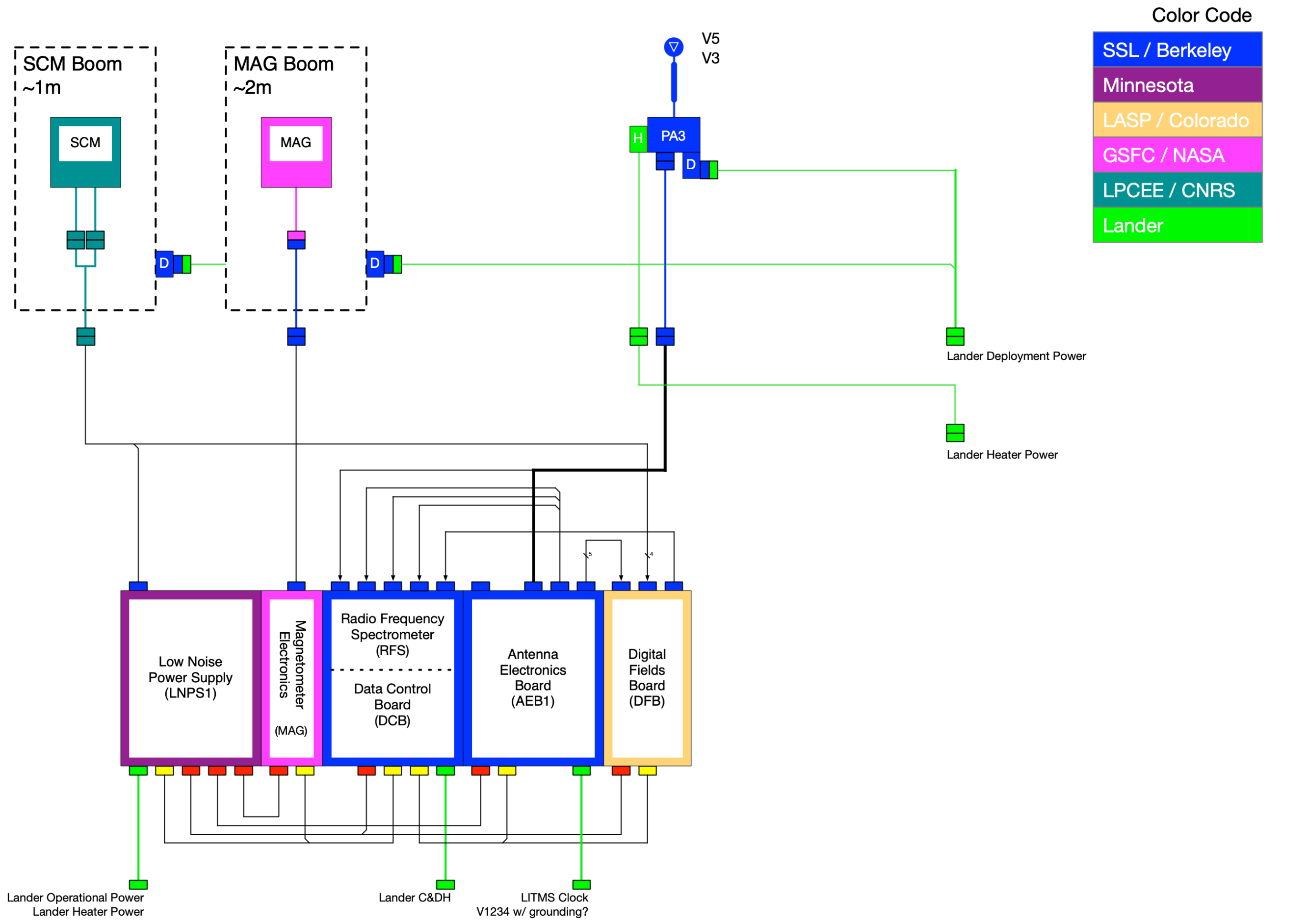
NASA Parker Solar Probe (PSP) FIELDS Instrument



LuSEE instrument hardware is FS/EM or derived from PSP/FIELDS (Bale et al., 2016; Pulupa et al., 2017)

LuSEE ‘Lite’ Block Diagram

- Vector 'DC’ magnetic field (fluxgate magnetometer)
  - 293 Sa/sec (146 Hz Nyquist)
- 3-d vector AC magnetic field (search coil magnetometer)
  - 293 Sa/sec (146 Hz Nyquist)
  - Burst mode to 150,000 Sa/sec
  - Spectra and cross spectra to 75 kHz
- 1-d AC magnetic field (search coil magnetometer)
  - Spectra and cross-spectra to 1 MHz
- 1 single-ended voltage with current-biasing & floating ground – from V3
- 4 single-ended voltages – from LITMS instrument electrodes
  - 293 Sa/sec (146 Hz Nyquist)
  - Burst mode to 150,000 Sa/sec
  - Spectra and cross-spectra to 75 kHz
- Quasi-thermal noise measurements to 1 MHz
- Radio emission spectra and cross-spectra to ~20 MHz



LuSEE-Lite Instrument Block Diagram

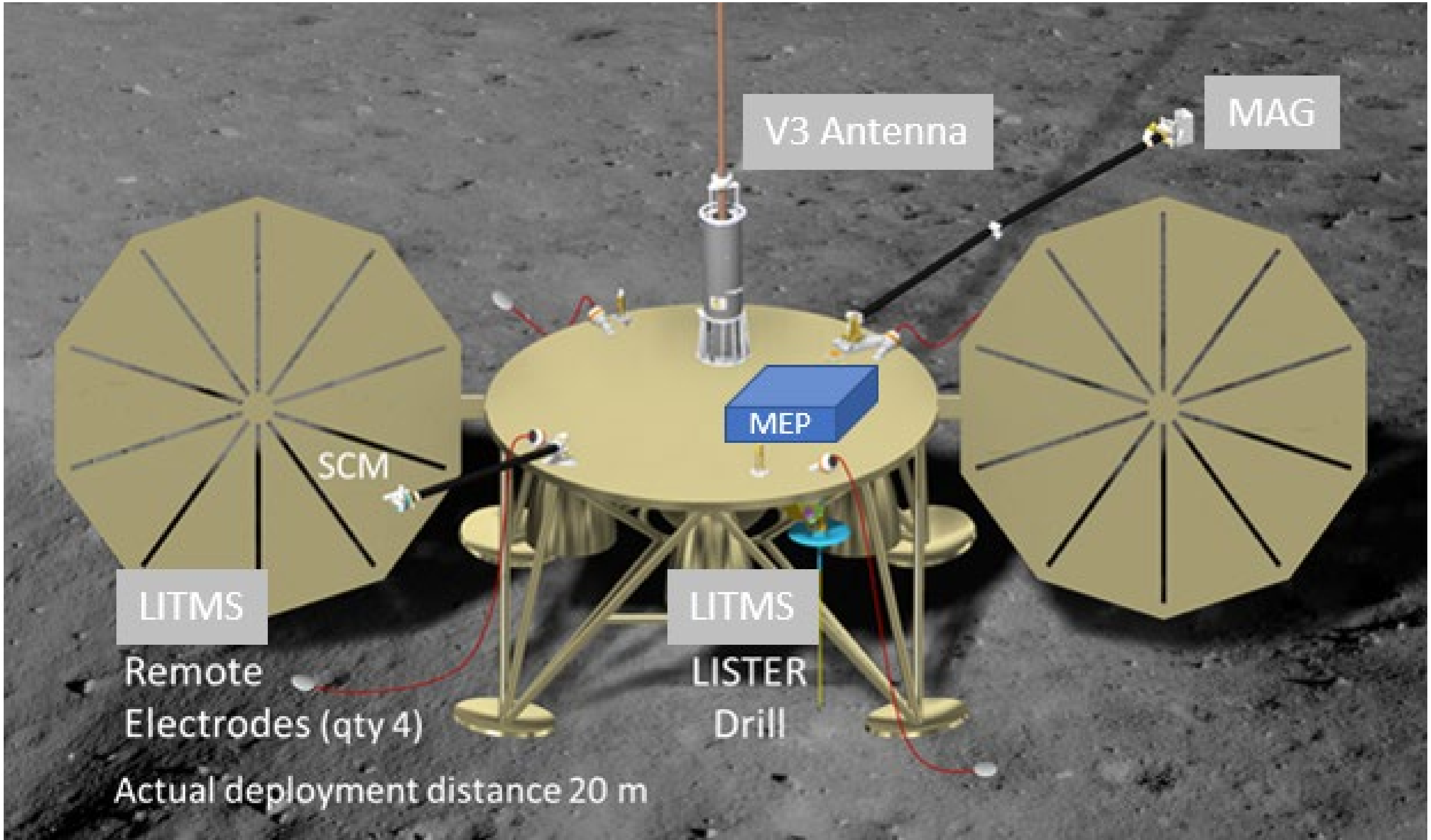
9 January 2022

LuSEE ‘Lite’ will be integrated in Berkeley *this summer*

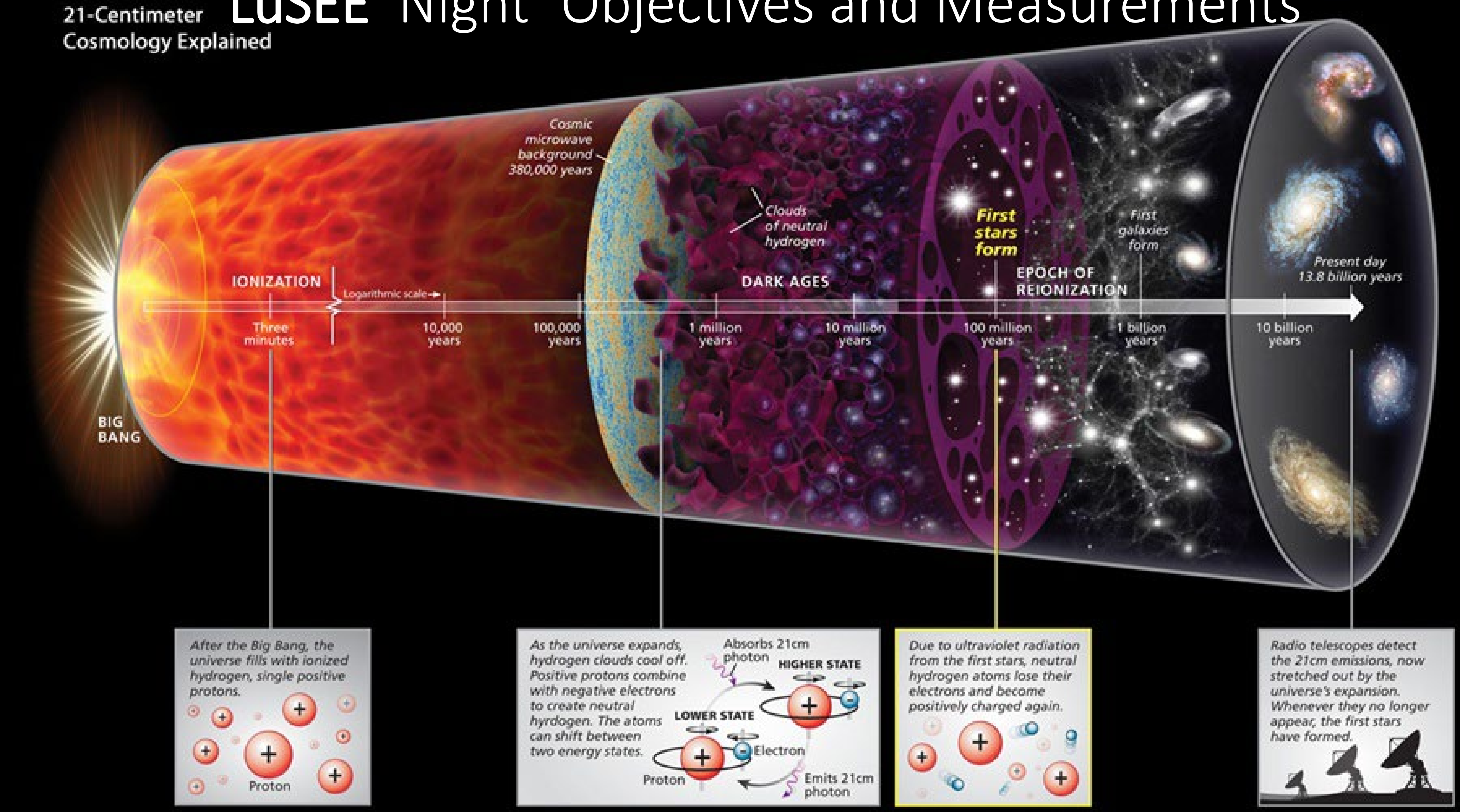
Direct heritage from NASA Parker Solar Probe and ESA Solar Orbiter

LuSEE 'Lite' Deployed

(notional lander)

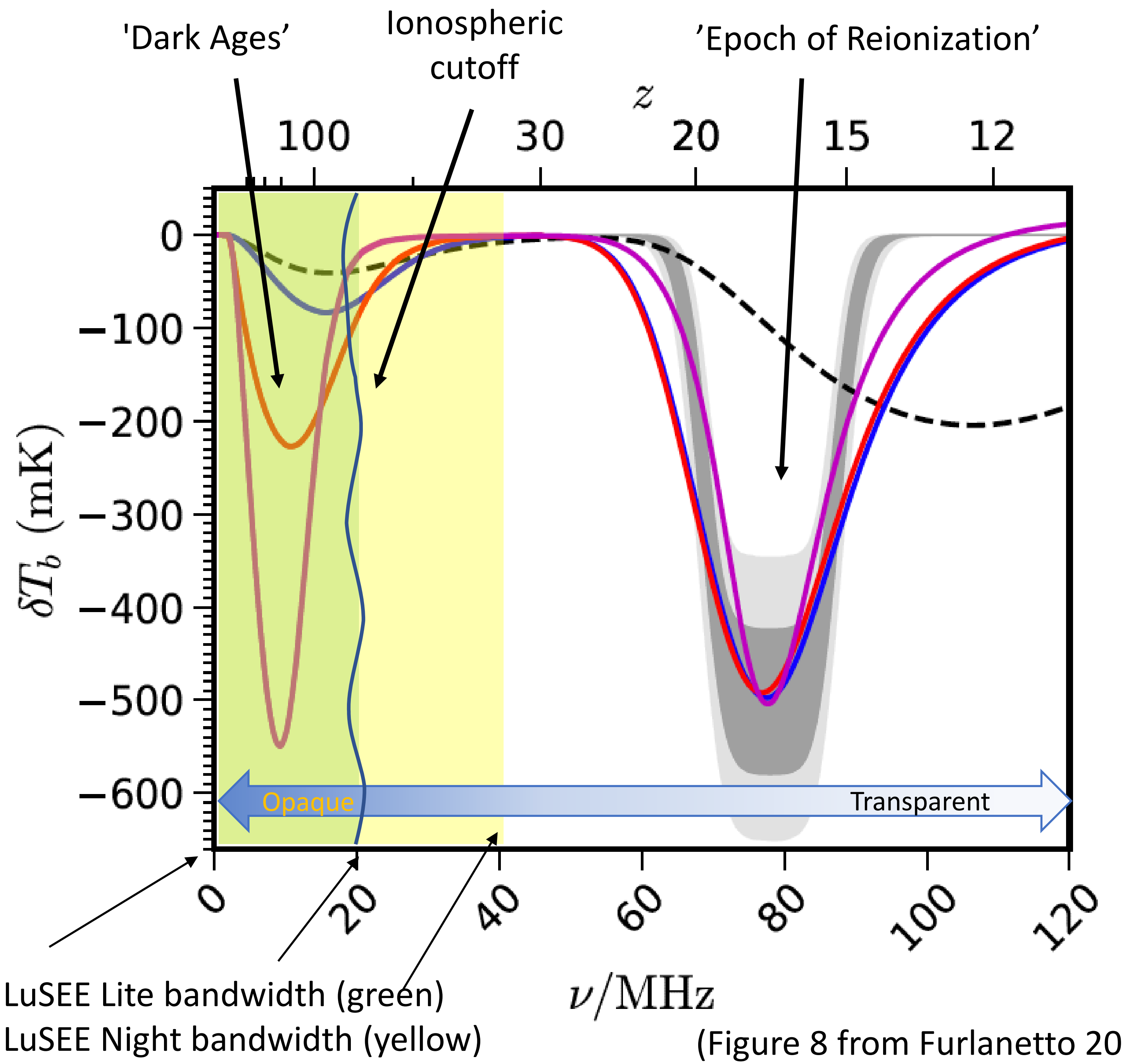


LuSEE 'Night' Objectives and Measurements



Why go to space?

- Cosmology predicts two 21cm absorption features in the highly-redshifted CMB spectrum.
  - Recombination at z ~ 100-200 (ν ~ 20-10 MHz)
  - Dark Ages
  - The Epoch of Reionization (or 'Cosmic Dawn') at z ~ 15-20 (ν ~ 80-70 MHz)
- Exoplanet radio emission? Discrete sources? The quiet corona?
- The Earth's ionosphere starts to become opaque below ~20 MHz. Measurements of the z~100 absorption spectrum *must* be made in space.
- An initial measurement of the EoR feature has been made from Earth and several facilities are currently attempting to verify.



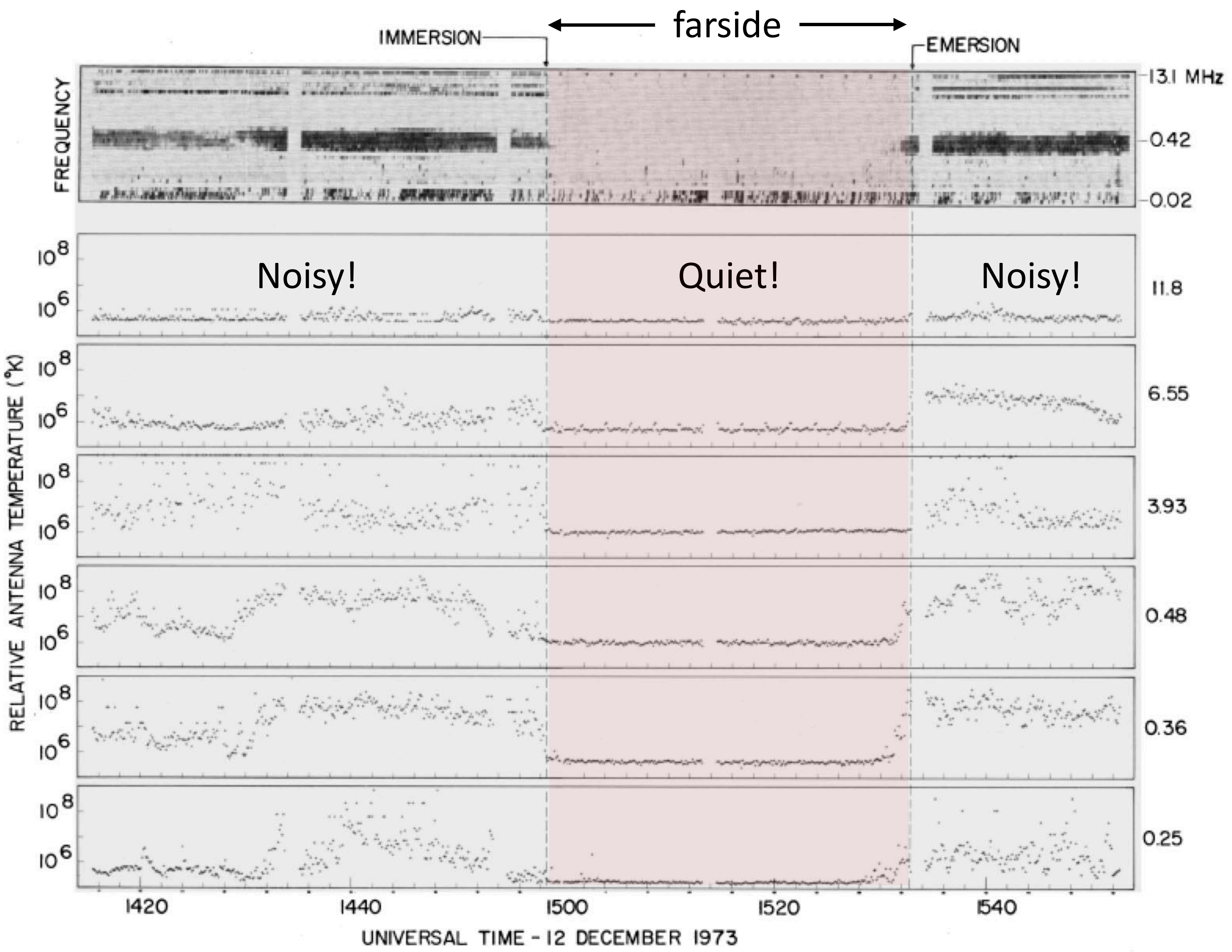
(Figure 8 from Furlanetto 2019)

Why the Moon?

- The Earth is noisy and the ionosphere is opaque < ~20 MHz
  - AKR at < 1 MHz
  - Shortwave radio stations, all across the band
- The Sun is noisy
  - Solar radio bursts from flares, CME shocks, etc. This is our solar science
  - Solar blackbody radiation
- The outer planets are noisy
  - Jovian decametric emission
  - Saturnian emissions

The lunar farside (*still*) offers radio-quiet intervals shielded from Earth (always) and the Sun (monthly) and outer planets (regularly).

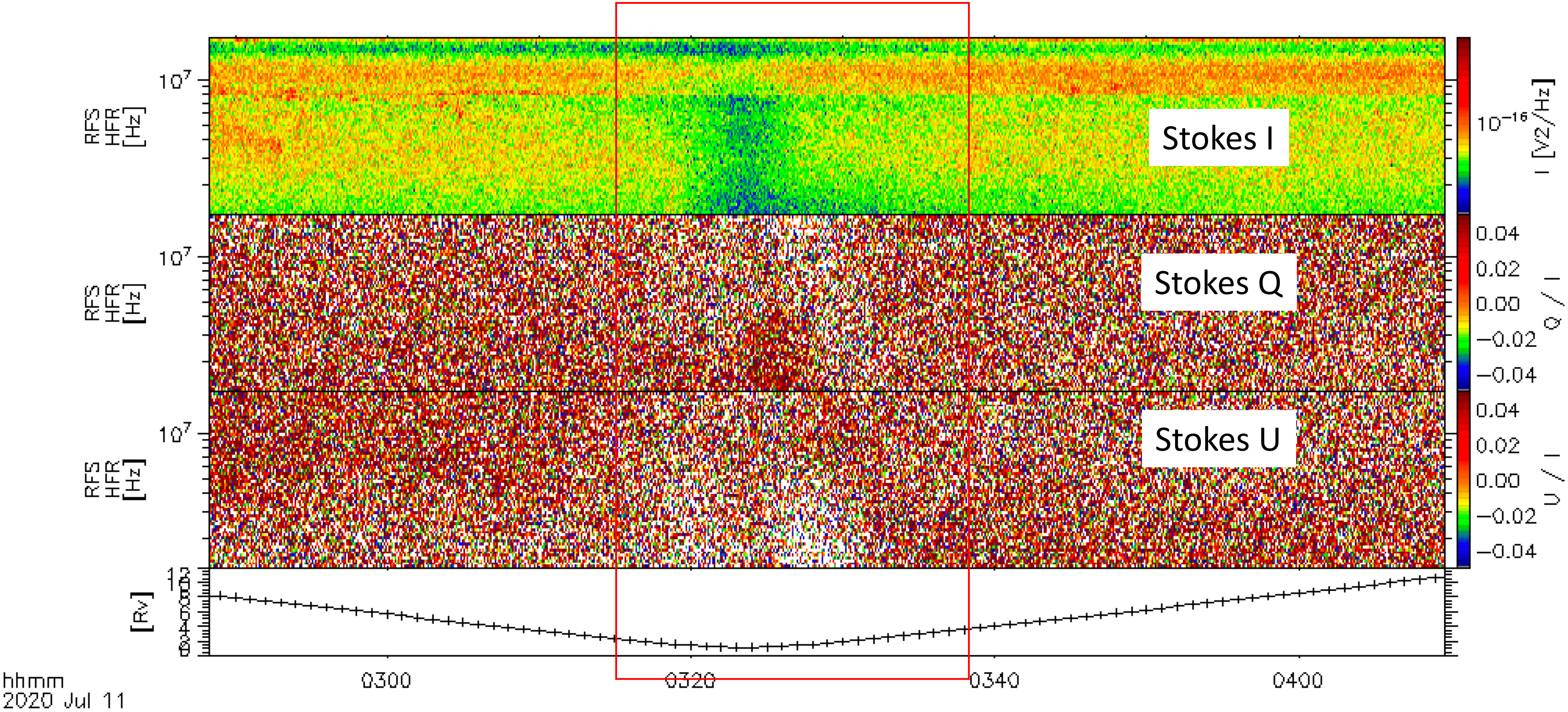
- A long history of concepts.
- The Chinese Chang'e 4 Instrument



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

Why the Moon?

Galactic foreground intensity and polarization are modified



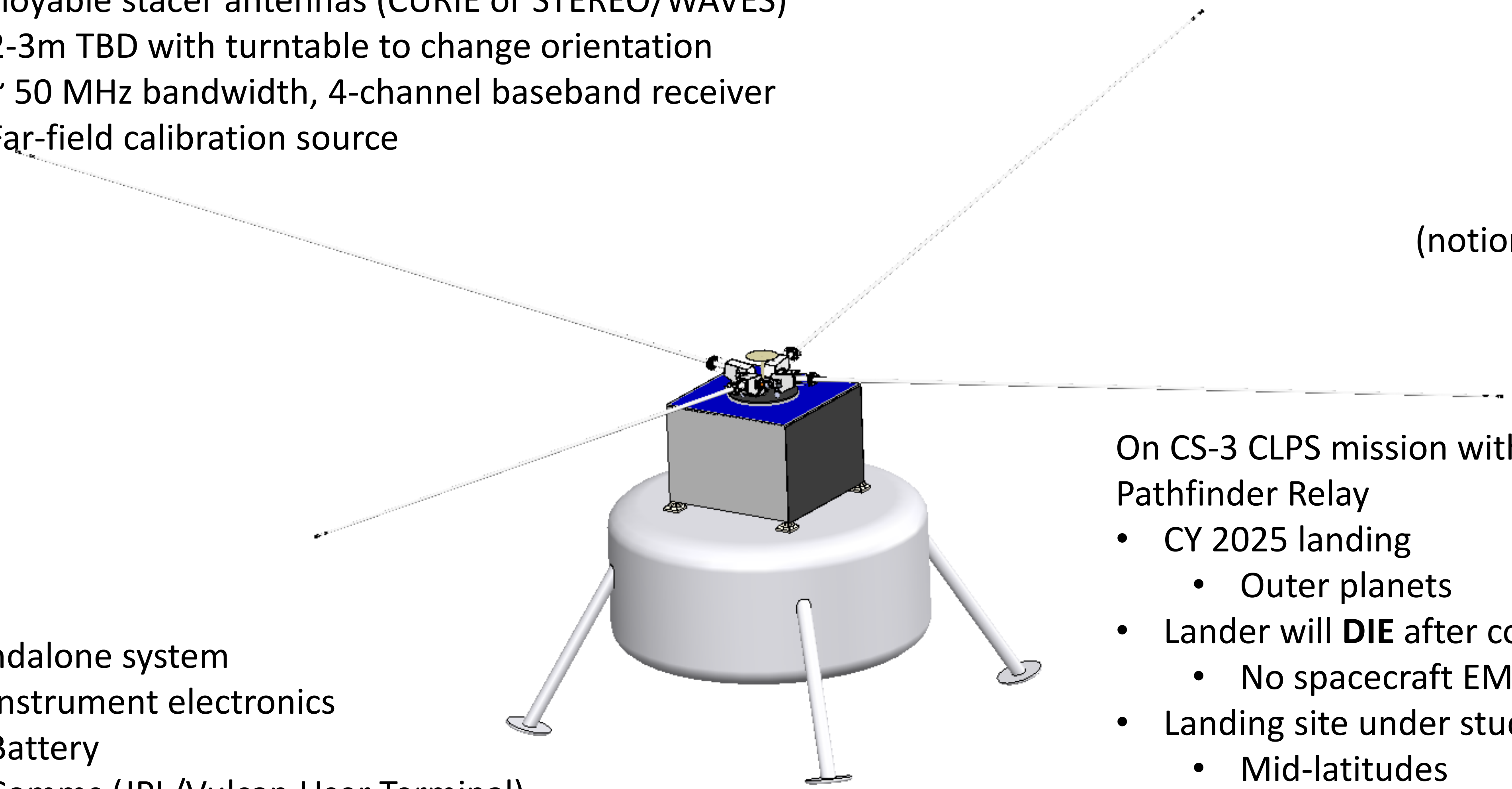
Parker Solar Probe flyby of Venus – planet acts as an occulting disk

LuSEE ‘Night’ Concept

Major involvement from US **DOE** (BNL and LBL)

Deployable stacer antennas (CURIE or STEREO/WAVES)
- 2-3m TBD with turntable to change orientation
- ~ 50 MHz bandwidth, 4-channel baseband receiver
- Far-field calibration source

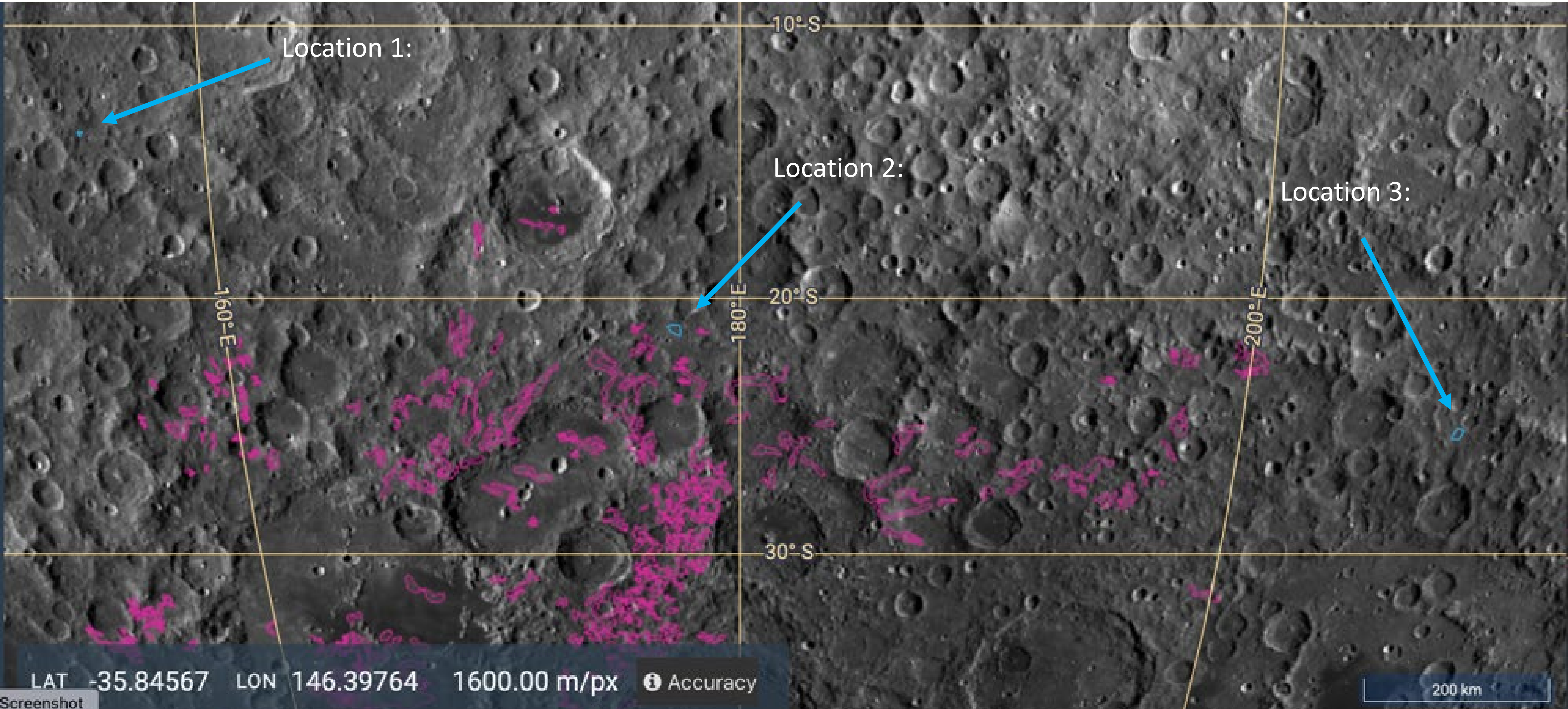
(notional lander)



On CS-3 CLPS mission with ESA Lunar Pathfinder Relay
- CY 2025 landing
  - Outer planets
- Lander will **DIE** after commissioning
  - No spacecraft EMI!
- Landing site under study
  - Mid-latitudes
  - Farside
  - Slightly south?

Standalone system
- Instrument electronics
- Battery
- Comms (JPL/Vulcan User Terminal)
- PRISM FSS-like (JPL PALETTE) thermal design

Landing site candidates driven by terrestrial EMI, thermal constraints, and relay downlink



Conclusions

- **LuSEE Lite is ready to be integrated at SSL/Berkeley**
  - Delivery 'in place' this year and to a CP-12 lander once selected
  - Delivery to Schroedinger Basin (South pole) in CY 2024.
  - Lunar surface plasma physics, ionosphere, dust, and support for E/M subsurface sounding

- **LuSEE Night is in active development in partnership with DOE**
  - Brookhaven National Lab and Lawrence Berkeley Lab under DOE MIE
  - CS-3 lander to the lunar farside, mid-latitudes in 2025 – manifested with ESA Lunar Pathfinder
  - Radio astrophysics/cosmology pathfinder
    - Quiet corona, galactic foreground, discrete sources and outer planets, cosmology
    - 50 MHz bandwidth Stokes polarization measurements
    - Antenna modeling work in progress
    - Thermal design (w/ JPL) in progress

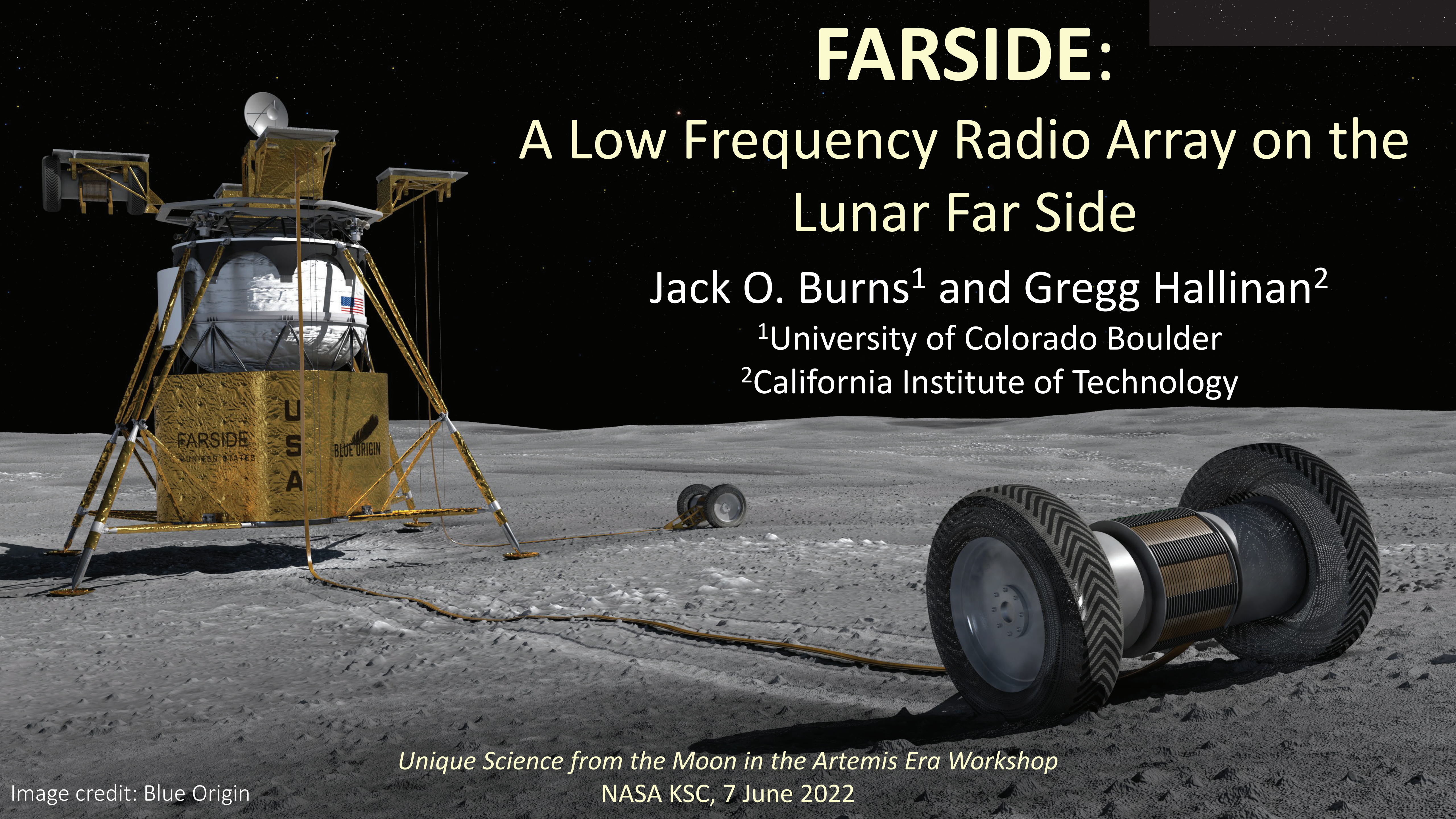
FARSIDE:

A Low Frequency Radio Array on the Lunar Far Side

Jack O. Burns[1] and Gregg Hallinan[2]

[1]University of Colorado Boulder

[2]California Institute of Technology



Unique Science from the Moon in the Artemis Era Workshop

NASA KSC, 7 June 2022

Image credit: Blue Origin

Collaborations

PI: Jack Burns (University of Colorado Boulder); Deputy-PI: Gregg Hallinan (Caltech); Robert MacDowall (NASA Goddard); Judd Bowman (ASU); Justin Kasper (BWX Technologies); Richard Bradley (NRAO); David Rapetti (NASA ARC/USRA); Alex Hegedus (U. of Michigan); Jonathon Kocz, Jonathan Varghese, Zhongwen Zhan, Wenbo Wu (Caltech), James T. Keane (JPL/Caltech), Jonathan Pober (Brown University), Steven Furlanetto (UCLA)

Lawrence Teitelbaum, Jim Lux, Andres Romero-Wolf, Tzu-Ching Chang, Marin Anderson, Issa Nesnas, Mark Panning, Andrew Klesh, Alex Austin, Patrick McGarey, Adarsh Rajguru, Matthew Bezkrovny, Varhaz Jamnejad , Eric Sunada, Jeff Booth

Steve Squyres, Alex Miller and the Blue Origin Team

Radio Astronomy from the Moon & the Unique Opportunity of the Lunar Far Side

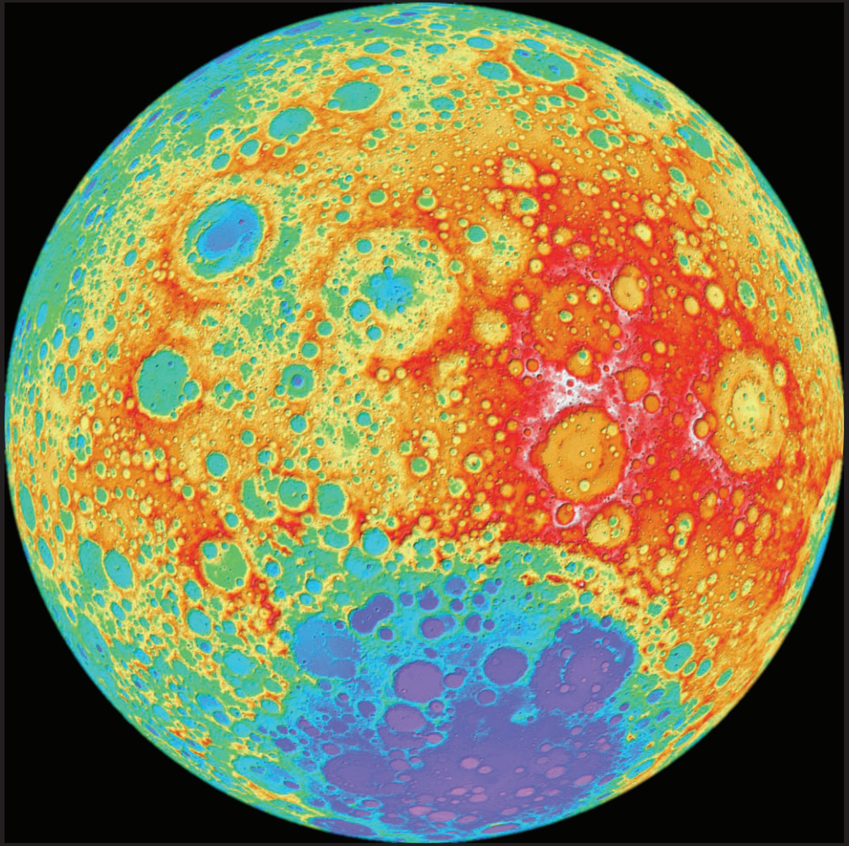
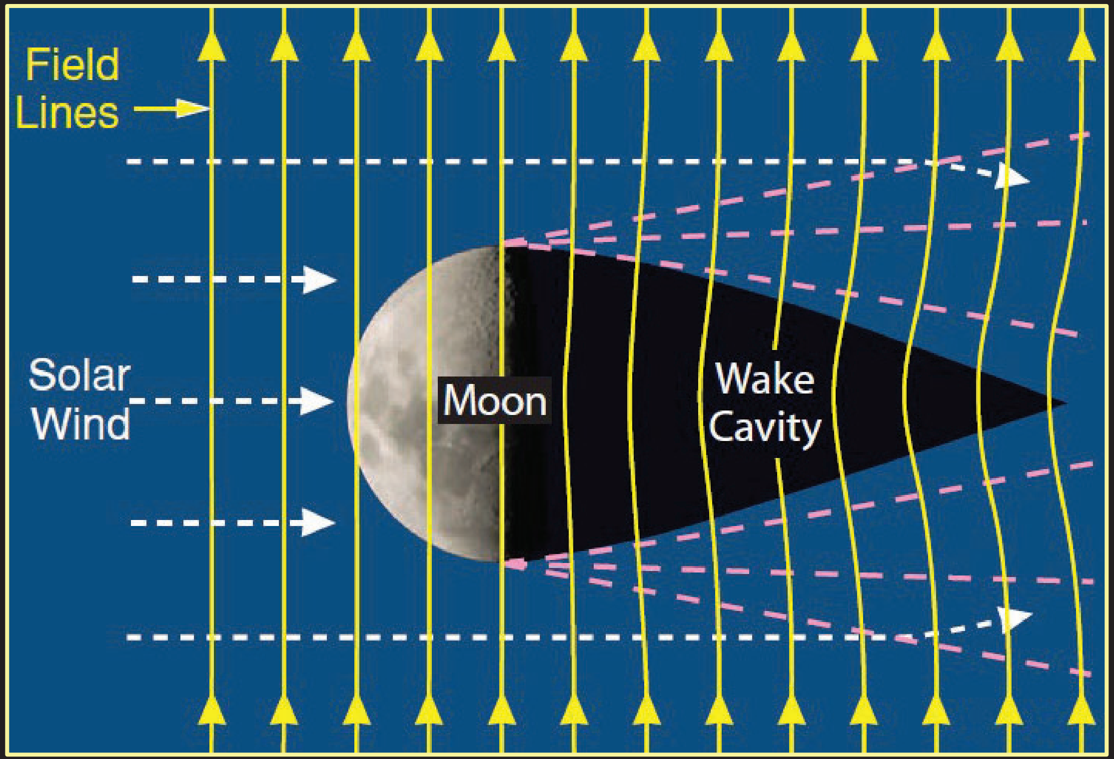


Image courtesy of Blue Origin

The Lunar Far Side

Shielded at night from shot noise produced by solar wind below ~1 MHz



Credit: Steve Bartlett

- Lunar farside highlands regolith is thick, has low conductivity, and varies slowly with depth
- No ground screen required

FARSIDE* Probe Study

- Nov 2018: Directed probe study commenced – JPL selected as NASA Center
- Mar 2019: Overall architecture selected [JPL Team X]
- Apr 2019: Follow up Rover, Base Station and Instrument studies [Team X]
- July 2019: Astro2020 APC White paper [https://arxiv.org/abs/1907.05407]
- Nov 2019: Final Probe Study Report submitted [https://arxiv.org/abs/1911.08649]
- April 2020: Commencement of JPL / Blue Origin Partnership
- Aug 2020: Planetary Science Decadal Review White Paper
- Nov 2021: Release of Astro2020 Decadal Survey - Dark Ages as The Discovery Area for Cosmology
- April 2022: Release of Planetary Science Decadal Survey – identifies importance of monitoring stellar variability and detecting auroral radio emission for exoplanet habitability.

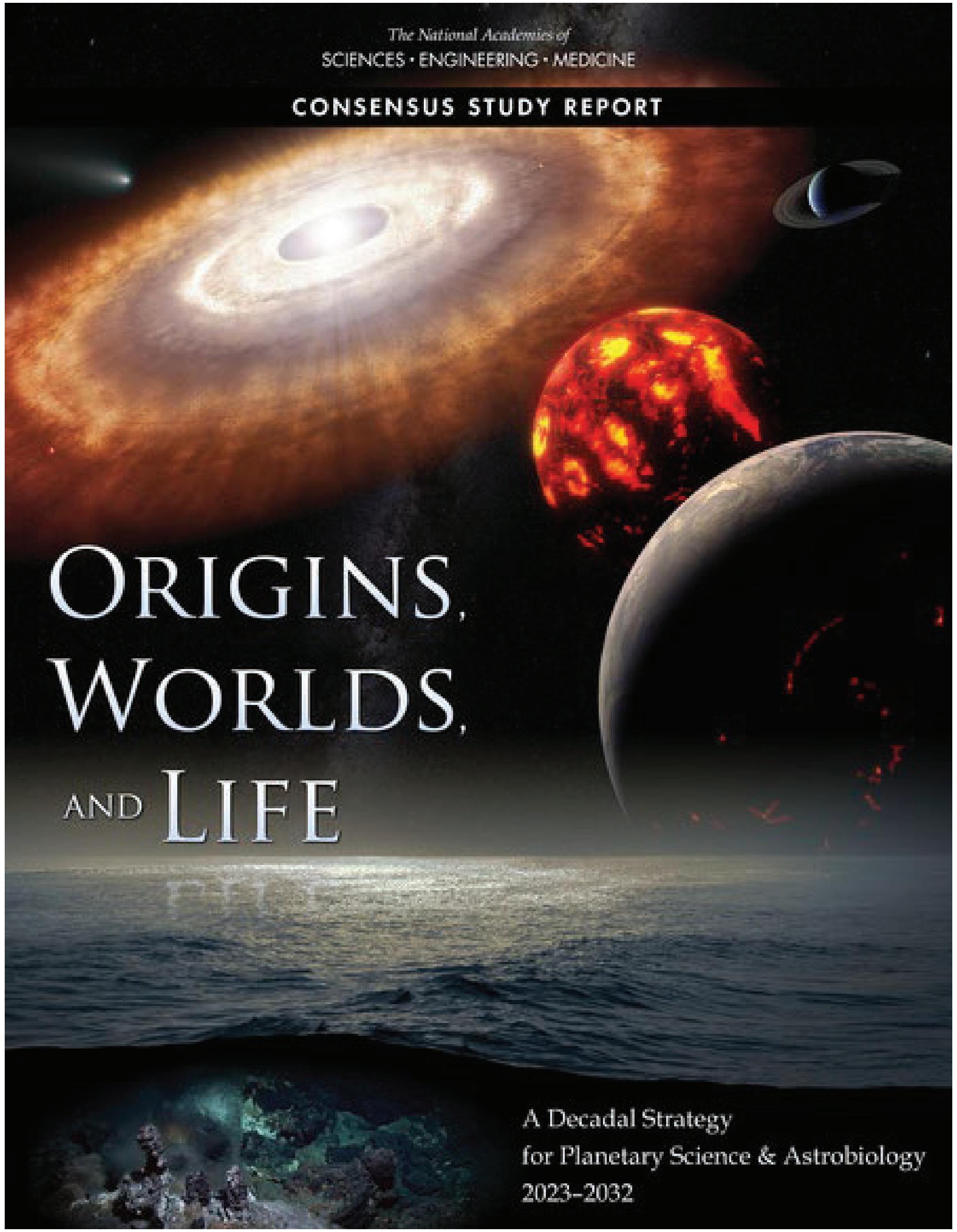
- **Heritage from SunRISE and OVRO-LWA**

*FARSIDE = Far side Array for Radio Science Investigations of the Dark ages and Exoplanets

FARSIDE Science Cases

Magnetospheres and
Space Environments of
Habitable Planets

The Dark Ages &
Cosmic Dawn

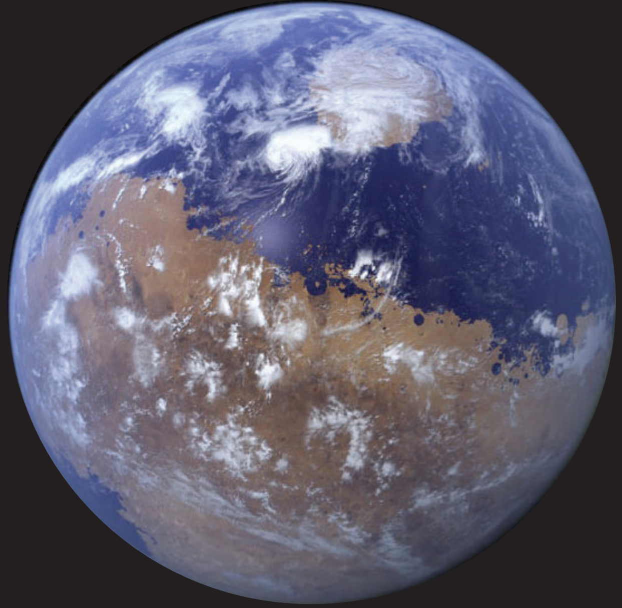


The excited aurorae in the waveband spanning radio to X-ray spectrum are both a window into the workings of these magnetospheres and one of the main loss processes of the energy of the confined plasma. A combination of in situ plasma and magnetic field observations with simultaneous or near simultaneous remote observations of the aurora would help to determine the nature of magnetospheric energy transport and quantify the competing processes governing magnetospheric dynamics and structure in the outer solar system.

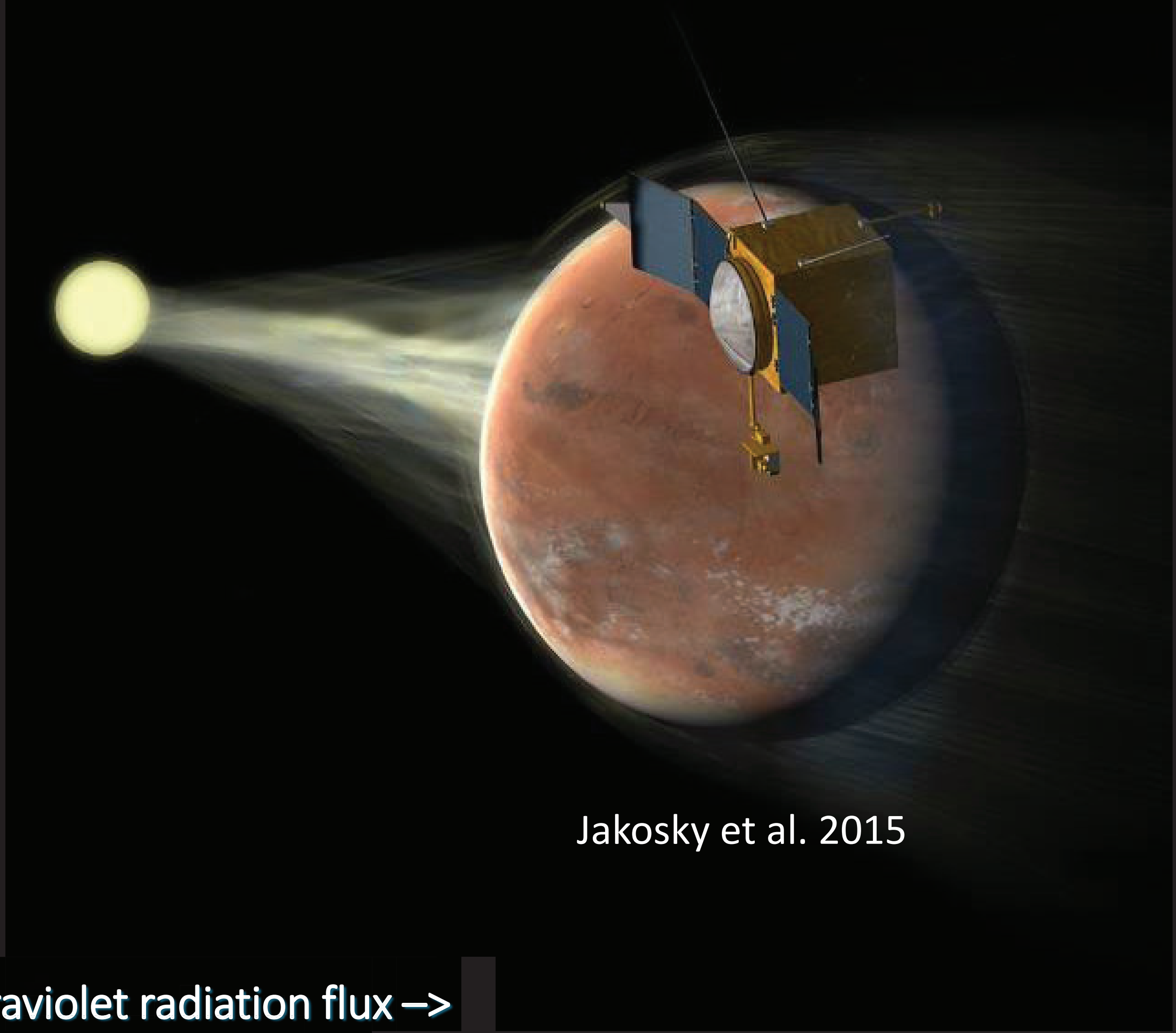
Strategic Research for Q12.5. Search for magnetospheric activity at exoplanets with remote sensing of phenomena associated with magnetic fields, potentially including radio emission.

Q12.11b Are Biosignatures Observable on Exoplanets in the Near Future?

These stars often exhibit extreme levels of stellar activity, which may adversely impact the habitability of orbiting planets. However, M dwarfs comprise 75 percent of all stars in the galaxy, so understanding whether life can persist around them is critical to understanding the distribution of possible life in the galaxy, and they provide examples of planets with significantly different star-planet evolutionary histories compared to the worlds of the solar system.



Young Mars was warmer and wetter



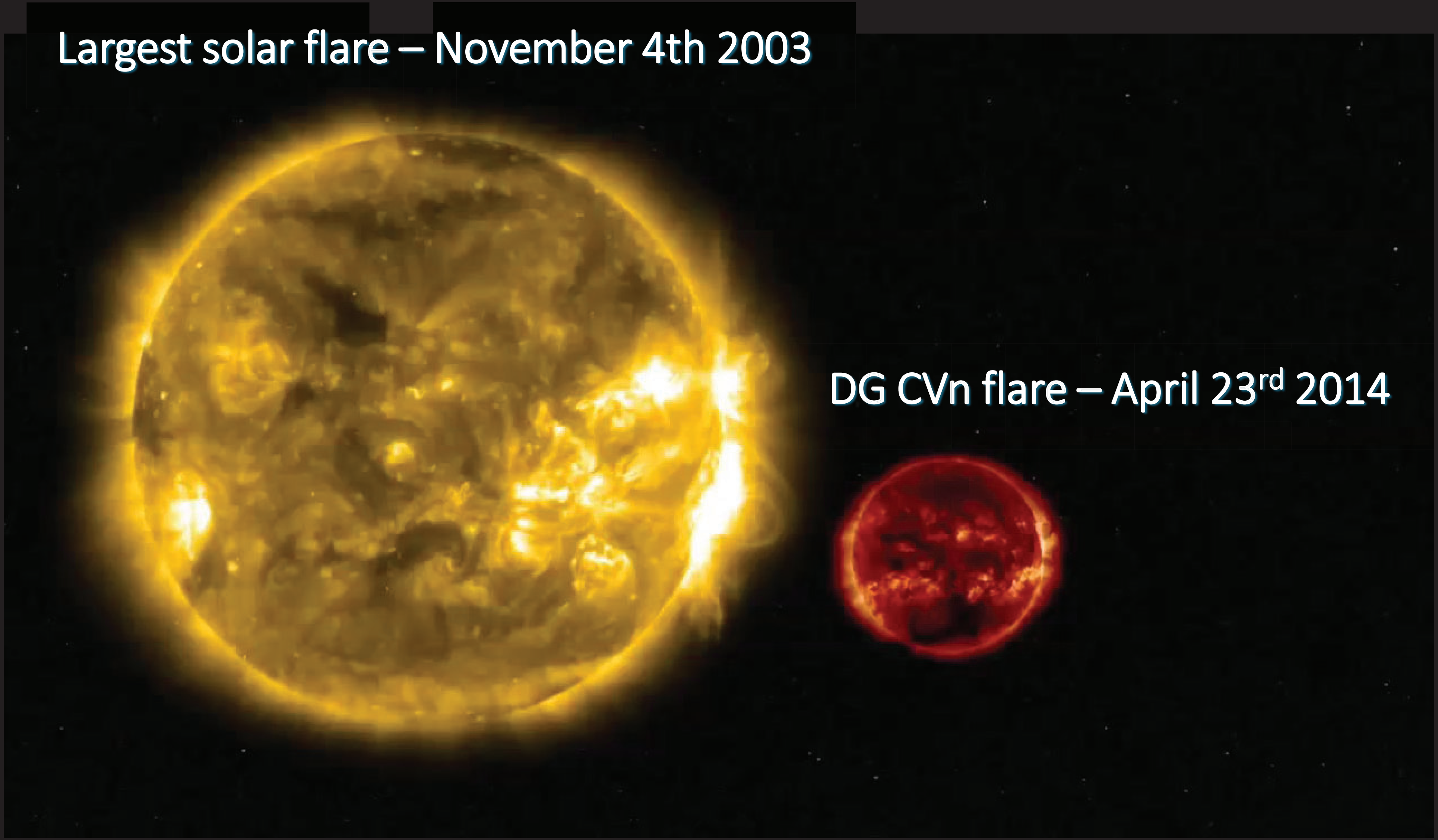
Jakosky et al. 2015

- Flares – higher X-ray and ultraviolet radiation flux –> drives photochemistry and thermal escape
- Particle flux - CMEs and SEPs –> can erode atmosphere – eg. ion pick-up erosion (Kulikov 2007)

Credit: Chuck Carter and Caltech/KISS

Can we directly detect CMEs and planetary magnetic fields?

Yes – with radio telescopes

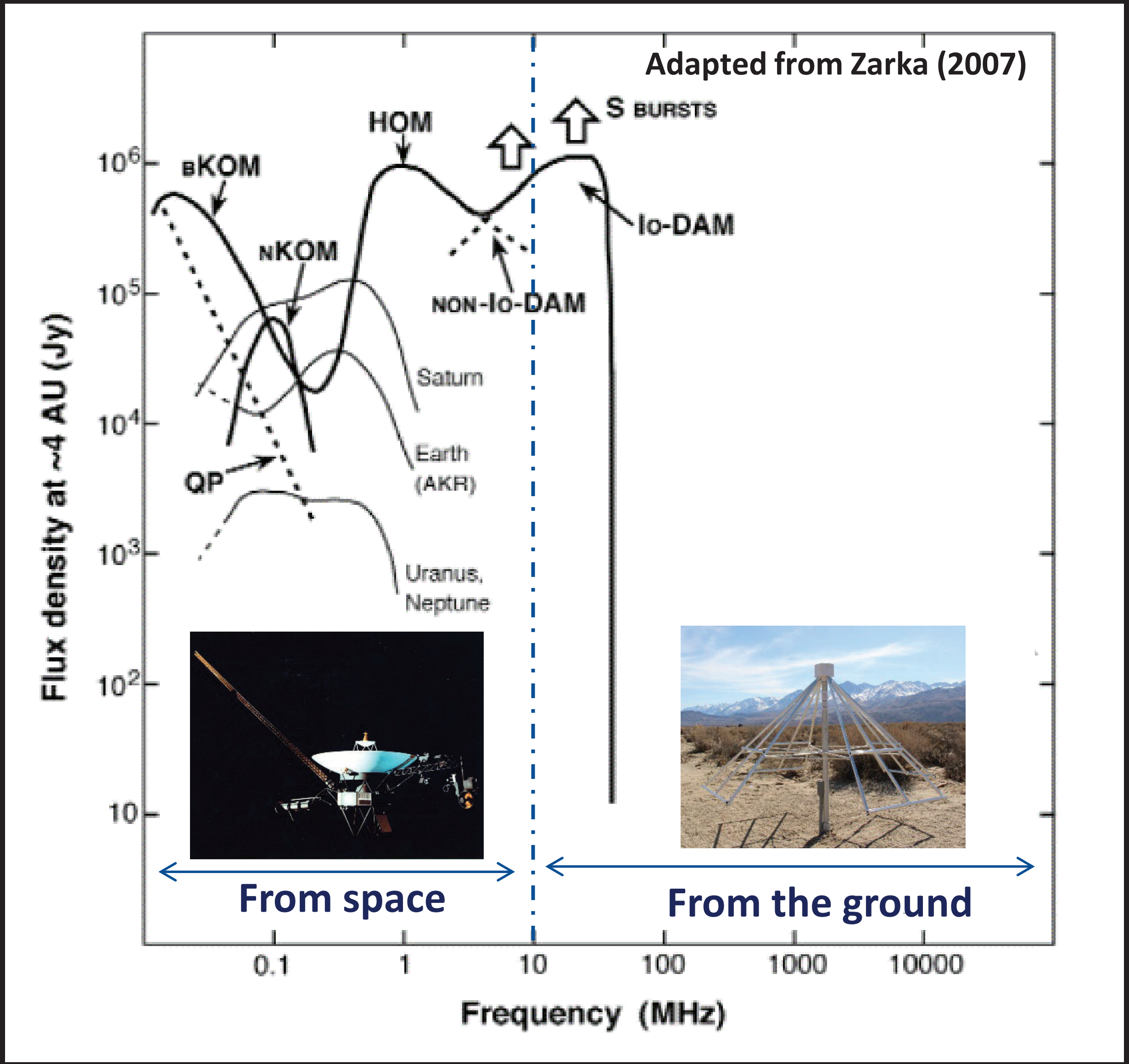

Largest solar flare – November 4th 2003
DG CVn flare – April 23rd 2014

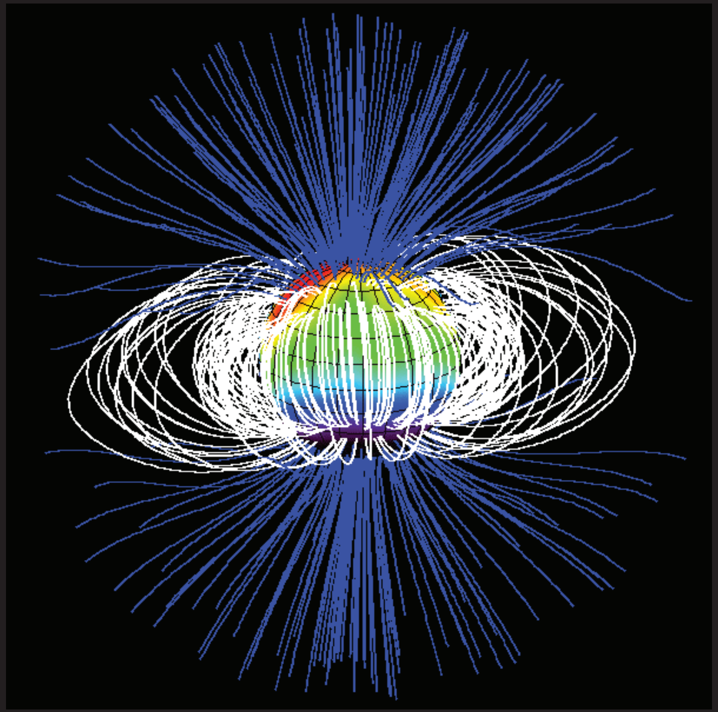
Type II Radio Burst

Why Low Frequencies?

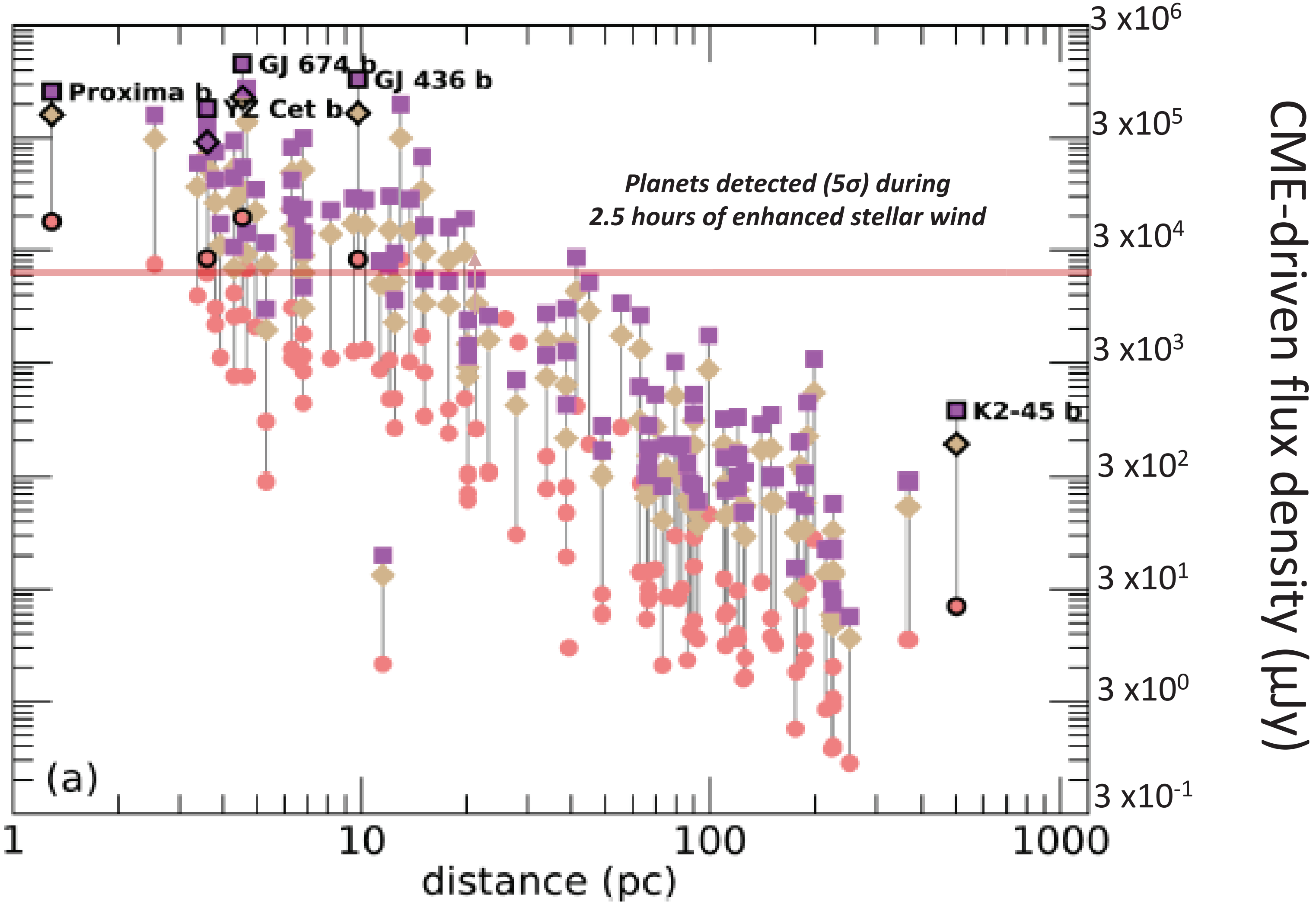
Electron cyclotron maser emission

Frequency (MHz) = B_{Gauss} x 2.8



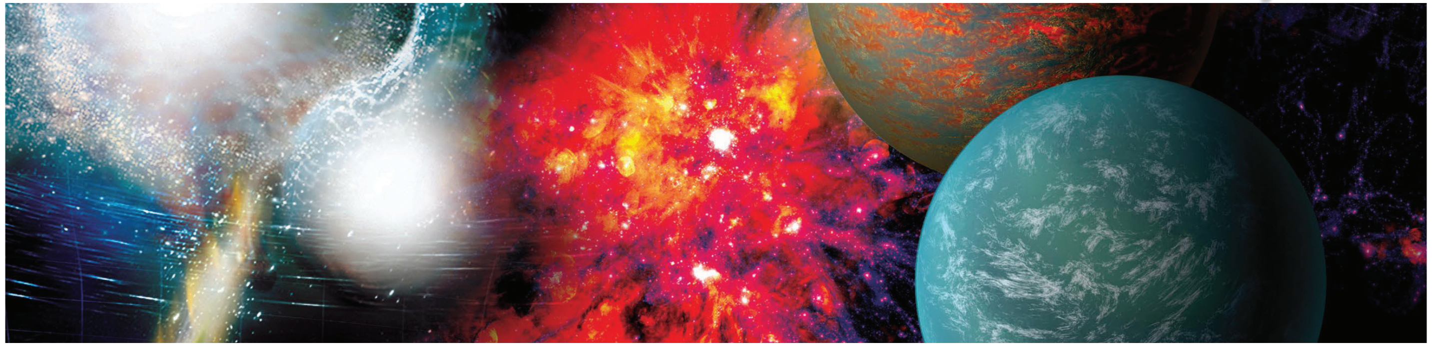


Donati et al. 2006

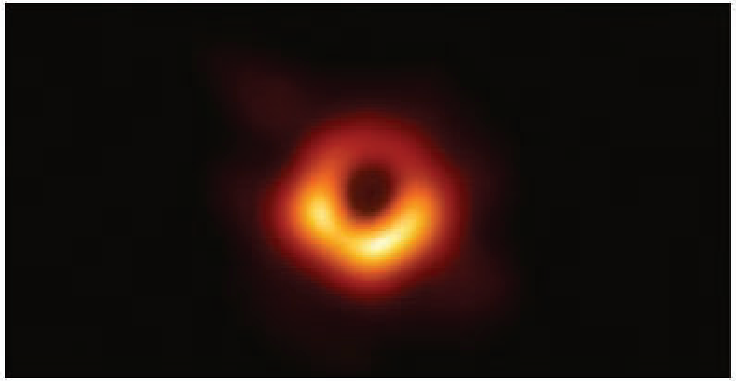


Adapted from Vidotto et al. 2019

Astro2020 Decadal Survey



Worlds and Suns in Context



New Messengers and New Physics

Cosmic Ecosystems

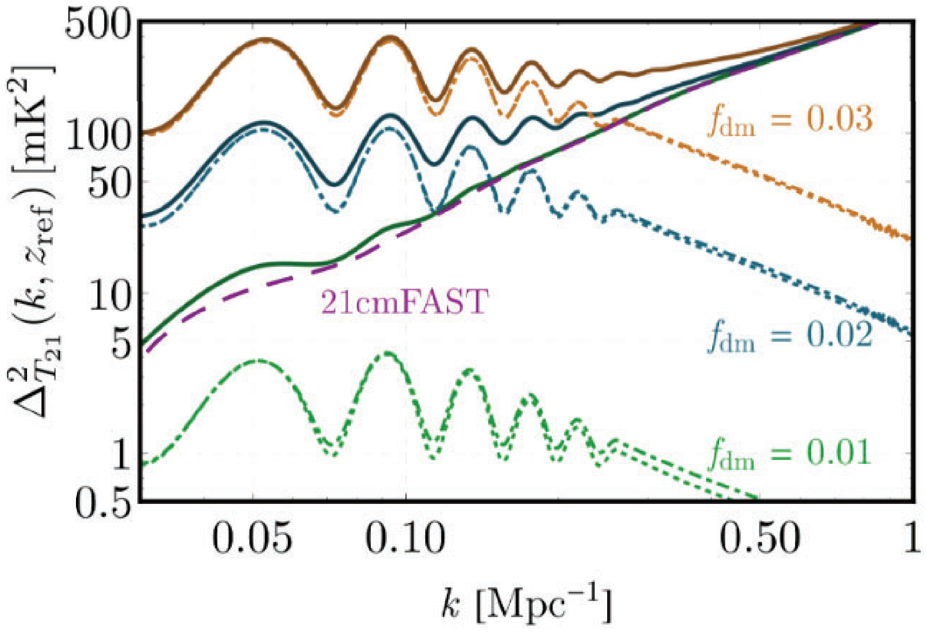
Dark Ages Cosmology

"The transition from a smooth universe to one with stars and galaxies occurred less than 500 million years after the Big Bang. Finding innovative ways to probe cosmology in the "dark ages" prior to any significant star formation is one of the discovery areas identified here."

Evolution of Hydrogen in the Early Universe

Credit: Marcelo Alvarez

21-cm Power Spectrum



- Lack of luminous sources makes the Dark Ages signal a clean and powerful cosmological probe and also renders the 21-cm line the *only* observable signal from this era.
- Because 21-cm measurements can probe these small scales inaccessible by other means, they enable stringent constraints on key probes of inflation and non-Gaussianity, as well as constraints on the curvature of the Universe and the mass of the neutrino.
- Many exotic processes (e.g., dark matter) imprint distinct signatures in the Dark Ages power spectrum.

See Furlanetto, Bowman, Mirocha, Pober, Burns et al. 2019, Astro2020: Decadal Survey on Astronomy and Astrophysics, science white papers, no. 144; Bulletin of the American Astronomical Society, Vol. 51, Issue 3.

1.1 Science Traceability Matrix

Investigation	Goals	Objectives	Scientific Measurement Requirements: Physical Parameters	Scientific Measurement Requirements: Observables	Instrument Functional Requirements	Instrument Predicted Performance	Mission Functional Requirements Common to all Investigations	Mission Functional Requirements Specific to Each Investigation
Exoplanets and Space Weather	NASA Science Plan 2014 • Discover and study planets around other stars, and explore whether they could harbor life. New Worlds, New Horizons (2010 Decadal Survey) • Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet? • Discovery area: Identification and characterization of nearby habitable exoplanets. Exoplanet Science Strategy (National Academies of Sciences 2018) Goal 2: to learn enough about the properties of exoplanets to identify potentially habitable environments and their frequency, and connect these environments to the planetary systems in which they reside. • The presence and strength of a global-scale magnetic field is a key ingredient for planetary habitability.	E1: Determine the prevalence and strength of large-scale magnetic fields on rocky planets orbiting M dwarfs and assess the role of planetary magnetospheres in the retention and composition of planetary atmospheres and planetary habitability.	Planetary magnetic field strength (proportional to frequency). Local stellar wind velocity. Planetary rotation period and assessment of the presence of a convective interior for a sample of rocky planets orbiting M dwarfs out to 10 pc.	Planetary radio flux: < 250 μJy (in the 150 kHz–250 kHz band). Frequency range: 150 kHz–1 MHz band. Polarization (IQUV stokes parameters)	**Noise Equivalent Flux** (for 60 second integration): 40 mJy @ 200 kHz \ 0.5 Jy @ 10 MHz **Pointing Resolution (FWHM):** 10 deg @ 200 kHz \ 10 arcmin @ 10 MHz **Spectral Resolution:** < 25 kHz **Temporal Resolution:** < 60 seconds **Minimum Frequency:** < 150 kHz **Maxmimum Frequency:** > 20 MHz **Number of Frequency Channels in band:** > 1000 **Polarization:** Full Stokes radio telescope or array on lunar farside with < 5% uncertainty **Sky Coverage:** > 5,000 sq. degrees Any other driving requirements with sidelobes? UV coverage? Confusion?	**Noise Equivalent Flux:** 40 mJy @ 200 kHz \ 0.5 Jy @ 10 MHz **Pointing Resolution (FWHM):** 10 deg @ 200 kHz \ 10 arcmin @ 10 MHz **Spectral Resolution:** 25 kHz **Temporal Resolution:** 60 seconds **Minimum Frequency:** 100 kHz **Maxmimum Frequency:** 40 MHz **Number of Frequency Channels in band:** 1400 **Polarization:** Full Stokes radio telescope or array on lunar farside (to avoid ionosphere and RFI), operational from 300 kHz to 10 MHz. [5% uncertainty] **Sky Coverage:** 10,000 sq. degrees	**Location:** Latitude and longitudes within 65 degrees of the anti-Earth point (required to suppress RFI from Earth by −80dB).	**Observation time:** > 1000 hours
		E2: Determine whether the largest stellar flares are accompanied by comparably large CMEs that can escape the corona of the star to impact the space environment of orbiting exoplanets. E3: Determine the space weather environment of rocky planets orbiting M dwarfs during extreme space weather events and assess whether such events play a decisive role in atmospheric retention and planetary habitability. E4: Determine the impact of extreme space weather events on exoplanets orbiting Solar type (FGK) stars and assess whether such events play a decisive role in atmospheric retention and planetary habitability.	Stellar radio bursts from particles accelerated in magnetic fields that vary with frequency due to their local plasma environment.	Radio burst dynamic spectrum: sensitivity 40 mJy @ 200 kHz \ 0.5 Jy @ 10 MHz over 60 seconds. Frequency range: 150 kHz–35 MHz band.	**Noise Equivalent Flux** (for 60 second integration): 40 mJy @ 200 kHz \ 0.5 Jy @ 10 MHz **Pointing Resolution (FWHM):** 10 deg @ 200 kHz \ 10 arcmin @ 10 MHz **Spectral Resolution:** < 25 kHz **Temporal Resolution:** < 60 seconds **Minimum Frequency:** <= 100 kHz **Maxmimum Frequency:** > 35 MHz **Number of Frequency Channels in band:** > 1000 **Sky Coverage:** > 5,000 sq. degrees			
Cosmology	"Explore how (the Universe) began and evolved" NASA Science Plan (2014) "What is the nature of dark matter?" Astro2010 "Resolve the structure present during the dark ages and the reionization epoch" NASA Astrophysics Roadmap	C1: Determine if excess cooling beyond adiabatic expansion in standard cosmology and exotic physics (e.g., baryon-dark matter interactions) are present in the Dark Ages with > 5σ confidence.	Redshift-dependent *mean* brightness temperature variation of the cosmic radio background at the level of −100 mK due to the spin-flip transition of neutral hydrogen. Redshift range approx. (50 < z < 130)	Brightness temperature: a −40 mK absorption feature between 11–28 MHz against the cosmic radio background, globally averaged over > 10 deg^2. Frequency range approx. 11–28 MHz (corresponding to 50 < z < 130). Frequency resolution of 50 kHz to resolve the absorption feature and allow foreground & RFI mitigation and systematic checks. Astrophysical foreground mitigation to better than 10^5 level in spectral domain.	**Noise Equivalent Brightness Temperature Sensitivity:** < 20 mK **Antenna Beam Size:** field-of-view > 10 deg^2 (non-driving) **Antenna Beam Pattern Knowledge:** To a level of < 50 dB.	**Noise Equivalent Brightness Temperature Sensitivity:** 15 mK **Antenna Beam Size:** field-of-view > 10,000 deg^2 **Antenna Beam Pattern Knowledge:** 50 dB		**Observation time:** > 5000 hours

From the Probe Study Report: https://arxiv.org/abs/1911.08649

Instrument Requirements

Quantity	Value
Antennas	256 × 100 m length dipoles (100 kHz – 40 MHz)
Frequency Coverage	100 kHz – 40 MHz (1400 × 28.5 kHz channels)
Field of View (FWHM)	>10,000 deg^2
Spatial Resolution	10 degrees @ 200 kHz / 10 arcminutes @ 15 MHz
Antenna efficiency	6.8×10^{-6} @ 200 kHz / 9.5×10^{-5} @ 15 MHz
System Temperature[a,b]	1.0×10^{6} K @ 200 kHz / 2.7×10^{4} K @ 15 MHz
Effective Collecting Area[c]	~ 12.6 km^2 @ 200 kHz / 2,240 m^2 @ 15 MHz
System Equivalent Flux Density (SEFD)	230 Jy @ 200 kHz / 2.8×10^{4} Jy @ 15 MHz
1σ Sensitivity[b] (60 seconds; bandwidth = **ν**/2)	93 mJy @ 200 kHz[d] / 1.3 Jy (1.2 K) @ 15 MHz
1σ Sensitivity[b] (1 hour; bandwidth = **ν**/2)	12 mJy @ 200 kHz[d] / 170 mJy (160 mK) @ 15 MHz
1σ Sensitivity[b] (1000 hours; bandwidth = **ν**/2)	230 μJy[e] @ 200 kHz[d] / 3.8 mJy (5.2 mK) @ 15 MHz

[a] *System temperature includes contribution from the sky and ground due to the absence of a ground screen.*
[b] *These values have been updated from the Astro 2020 report due increased fidelity in the front-end design (see §3.5).*
[c] *Effective area is impacted by loss of gain into the ground due to absence of a ground screen. Antenna efficiency not included.*
[d] *Sensitivity calculations at 200 kHz assume night time conditions.*
[e] *Deep confusion-free integrations are possible < 3 MHz due to the absence of extragalactic sources.*

Going to space does not solve all your problems…

Advantages

No ionosphere

Less RFI

Thermal stability for extended periods of time

Disadvantages

No tinkering?

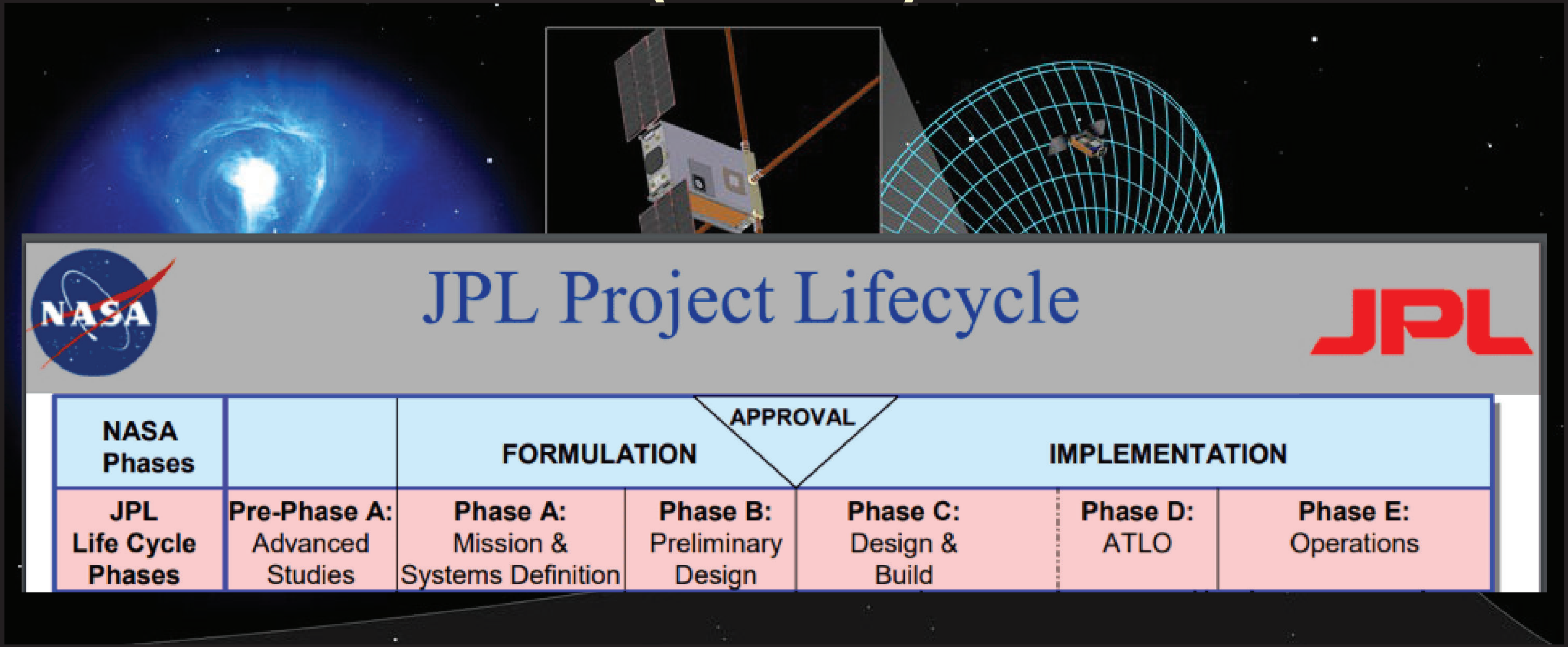
A large collecting area is expensive

Common

Know thy beam

Know the sky

Heritage: Sun Radio Interferometer Space Experiment (SunRISE)



Loose formation of six 6U form factor smallsats in 10 km sphere

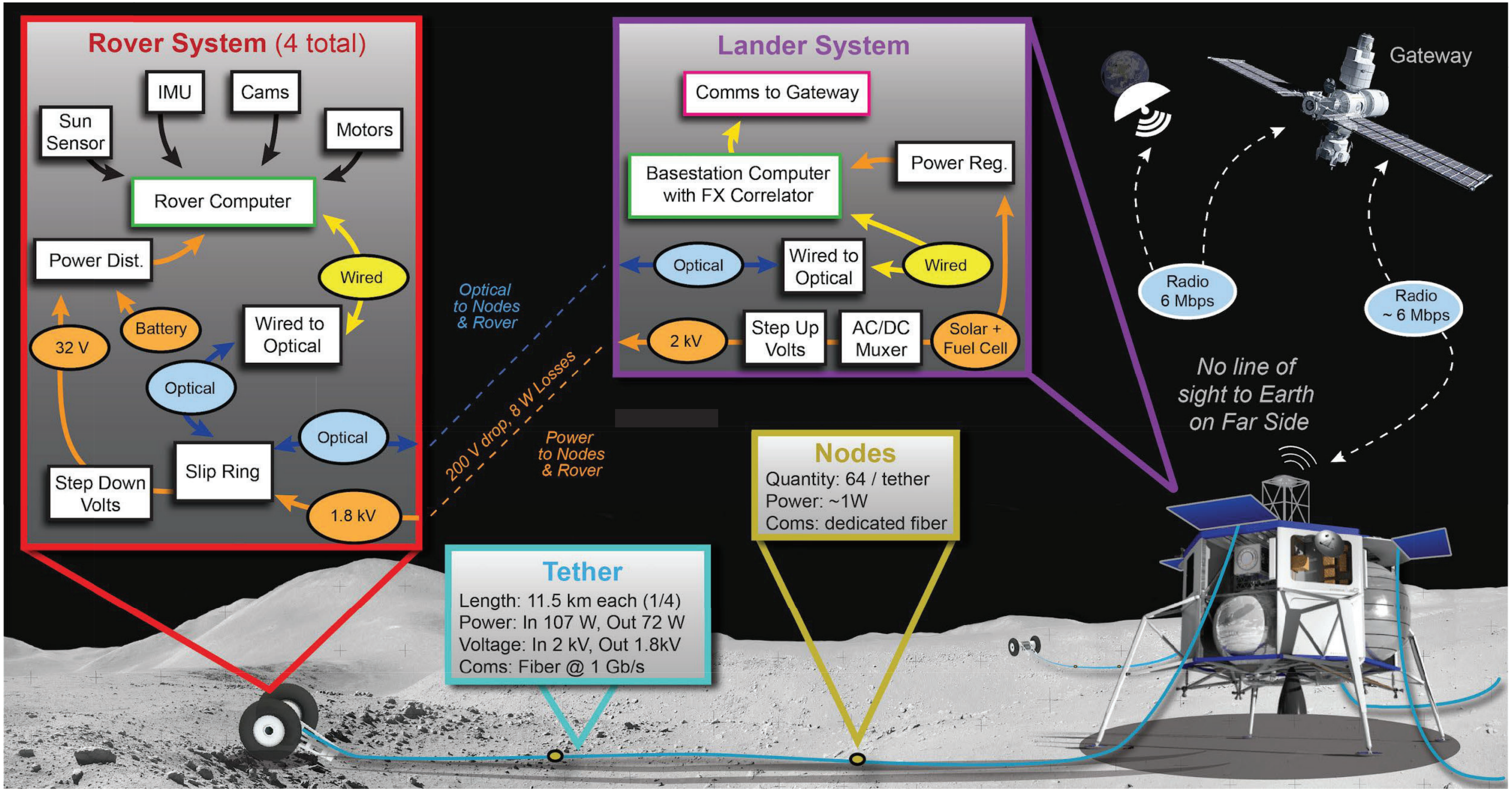
Radio receiver (0.1 – 20 MHz) with crossed 5 m dipole antennas

Targeting April 2024 - September 2025 launch date

Courtesy of Justin Kasper & Joe Lazio

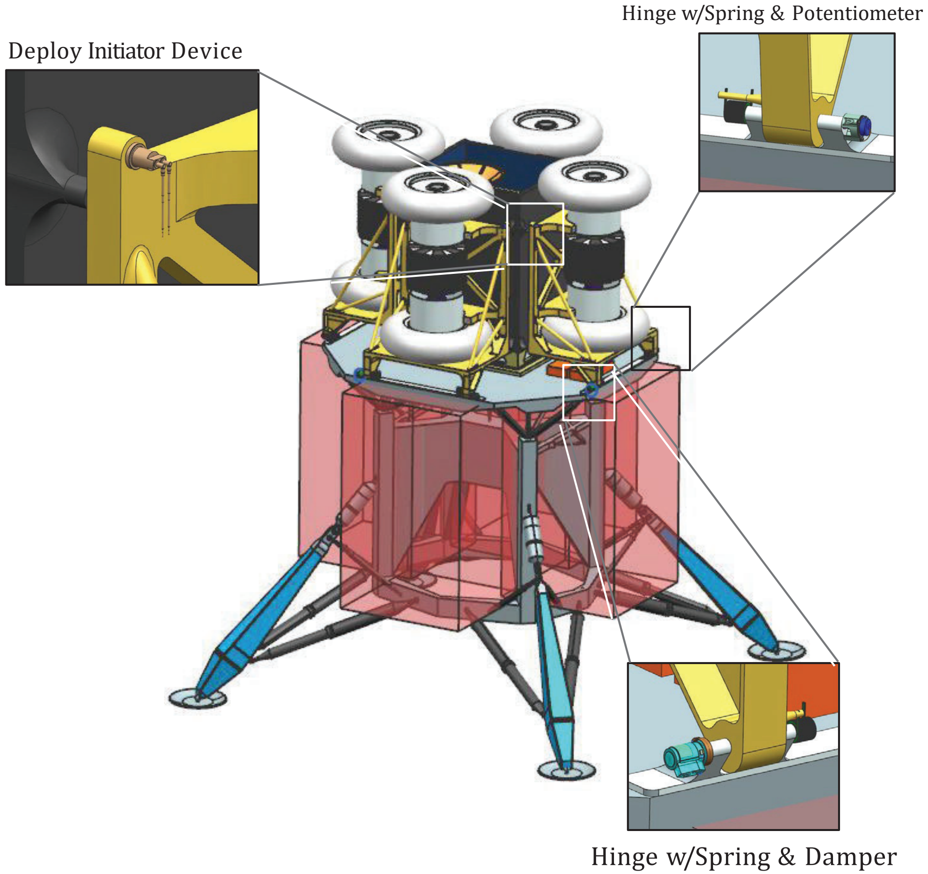
FARSIDE Mission Architecture

Frequencies: 100 kHz to 40 MHz

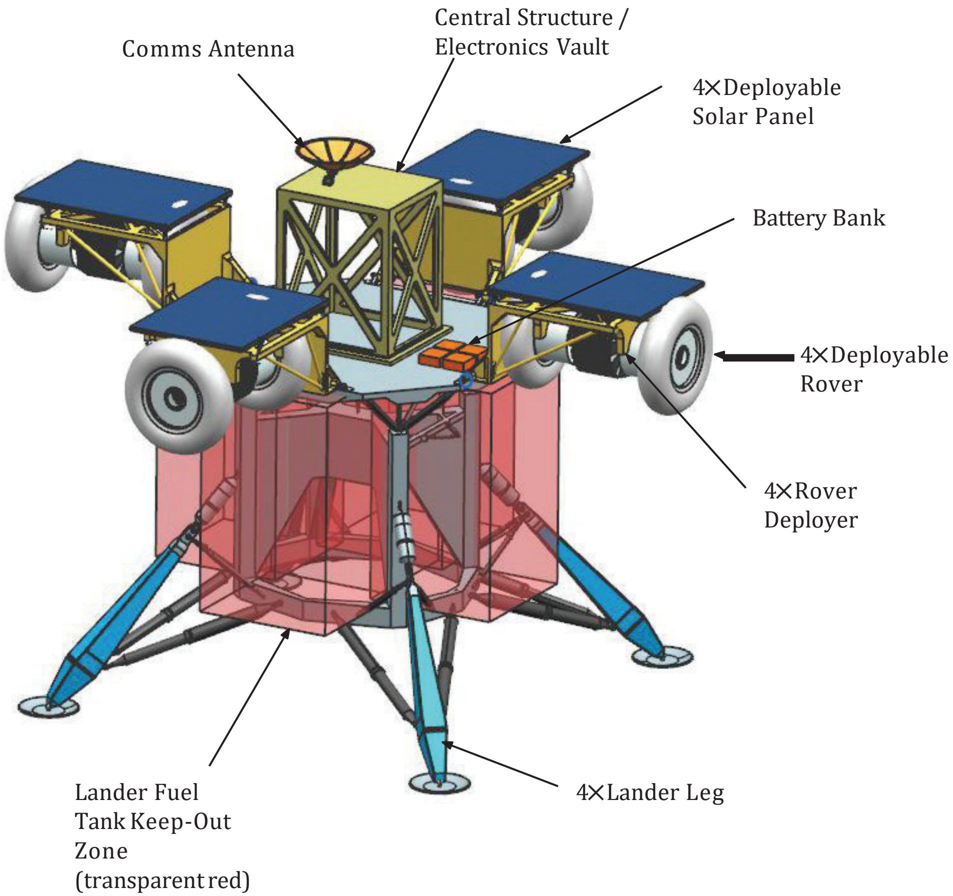


Lander/Rover Configuration Overview

Stowed/Landing Configuration



Mid-Deploy Configuration



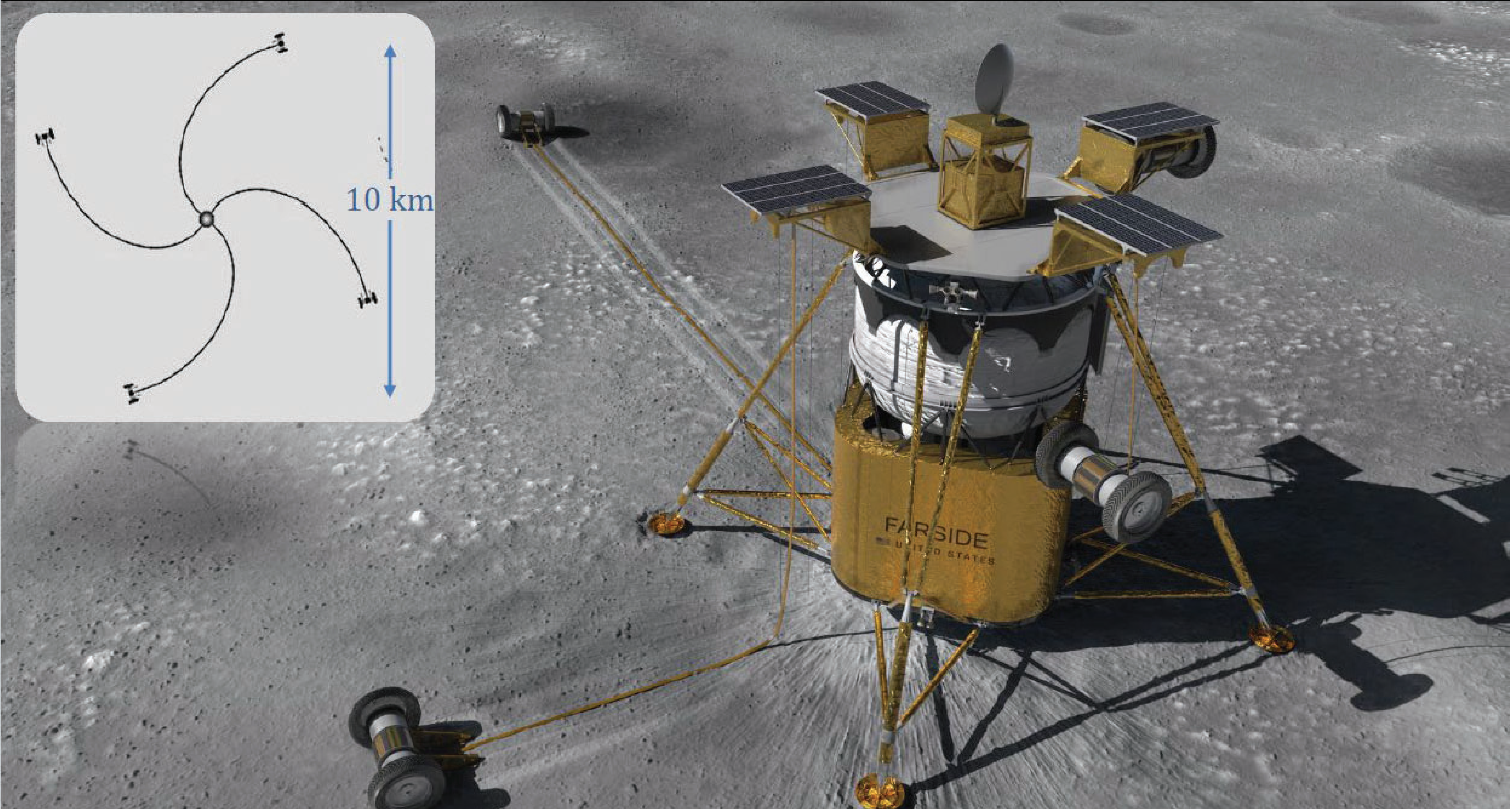
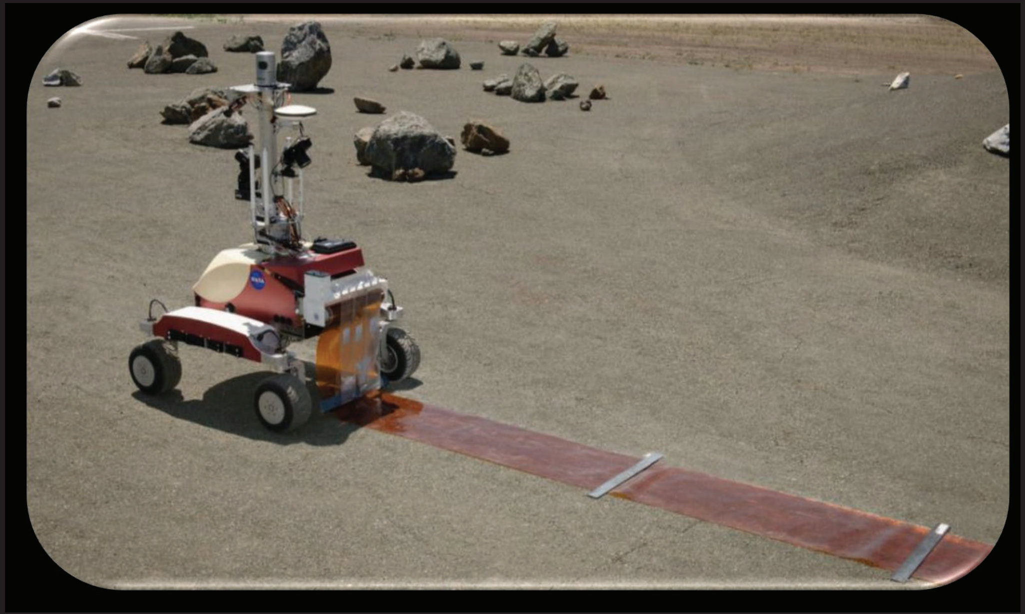


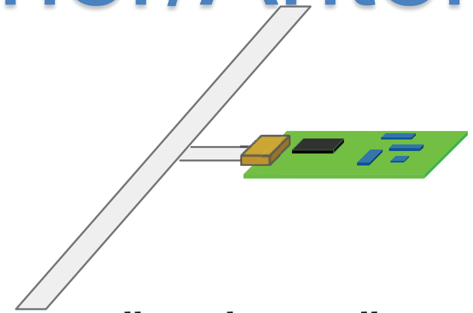
Image credit: Blue Origin

Astronaut Luca Parmitano (Italy) orbiting Earth on the ISS teleoperates the K10 rover at NASA Ames to simulate deploying a lunar farside radio telescope.

Fong, Burns+



Tether/Antenna Length



Key Drivers

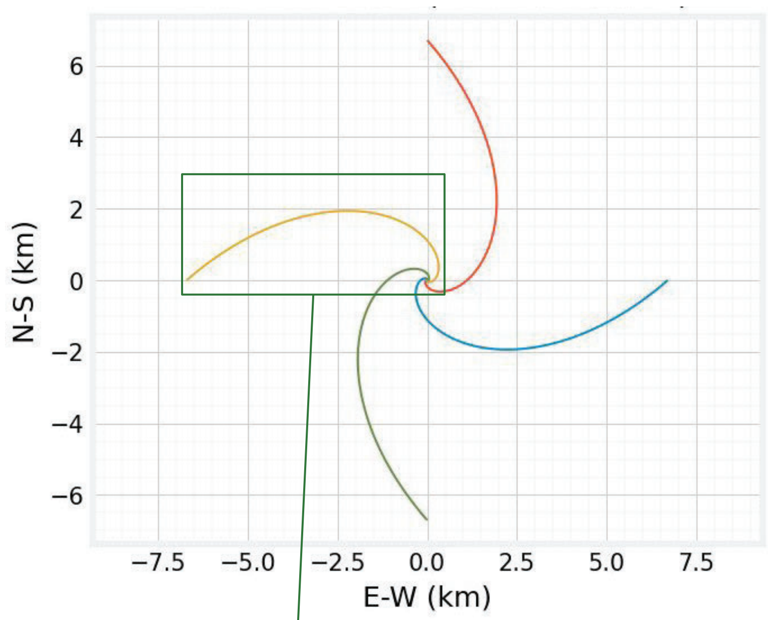
- Spiral-arm length
- Aligning the dipole horizontally and vertically (zig-zag in spiral pattern)

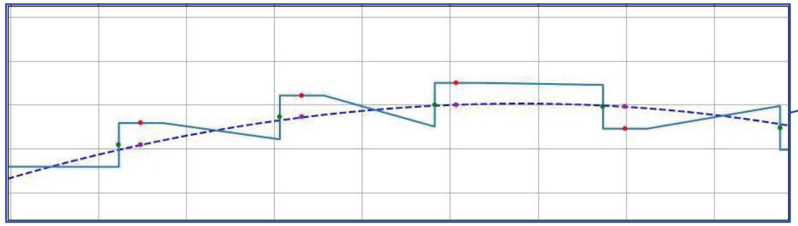
Arm Length = 8.9 km (basic curve without dipole)

Arm Length = 11.5 km (with dipole zig-zag)

Total tether length = **46 km**

Pattern could be further optimized





Design Strategy

Node Sizing

↓

Node / Tether Integration

↓

Spool Deployment Strategy

↓

Spool Sizing

↓

Rover Design

↓

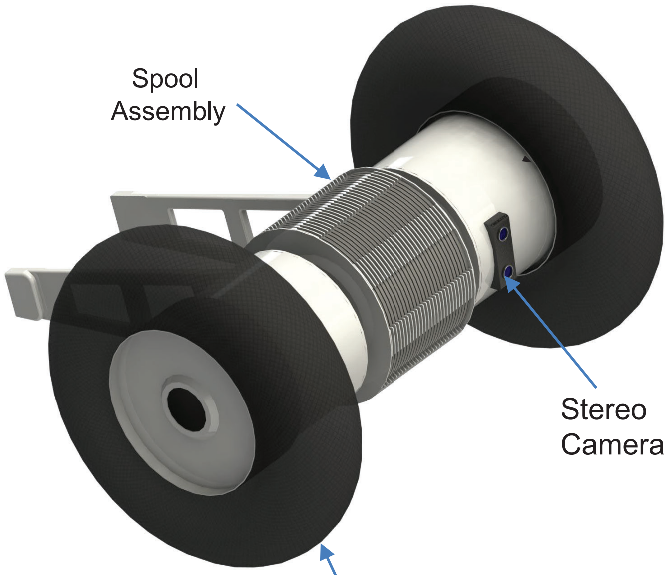
Egress Strategy

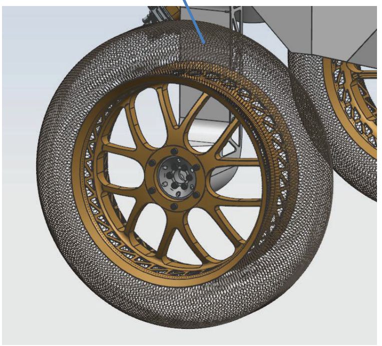
↓

Lander Accommodations

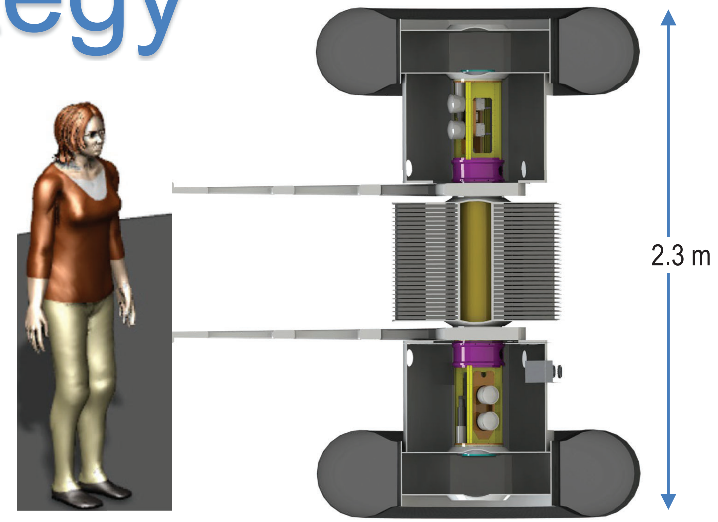
↓

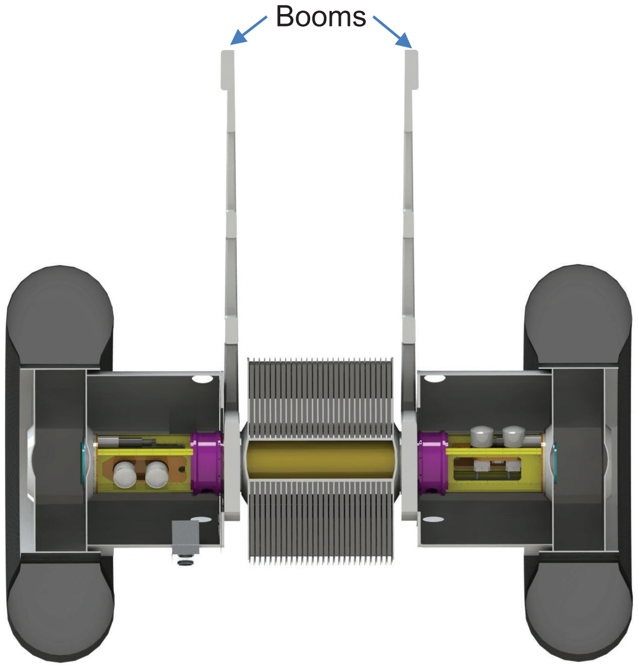
Lander Configuration





Apollo-style compliant mesh wheel





FARSIDE Science Cases

Imaging Type II/III Solar Radio Bursts

Auroral Radio Emissions from Saturn, Uranus, Neptune; lightning; Planet 9?

Magnetospheres & Space Weather Environments of Habitable Exoplanets

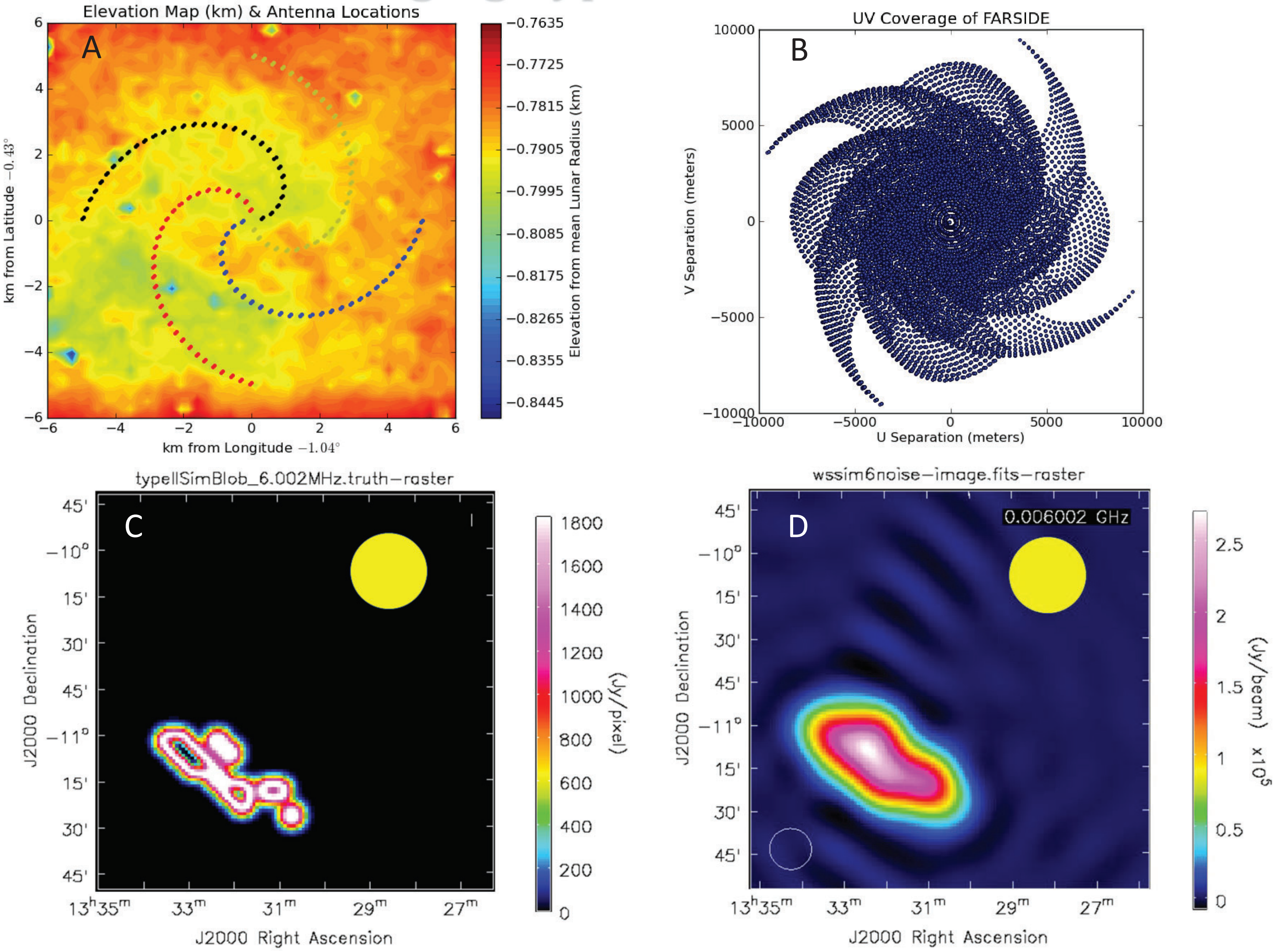
Sounding of the Lunar Subsurface

Measuring farside lunar quakes with Distributed Acoustic Sensing.

Tomography of the ISM

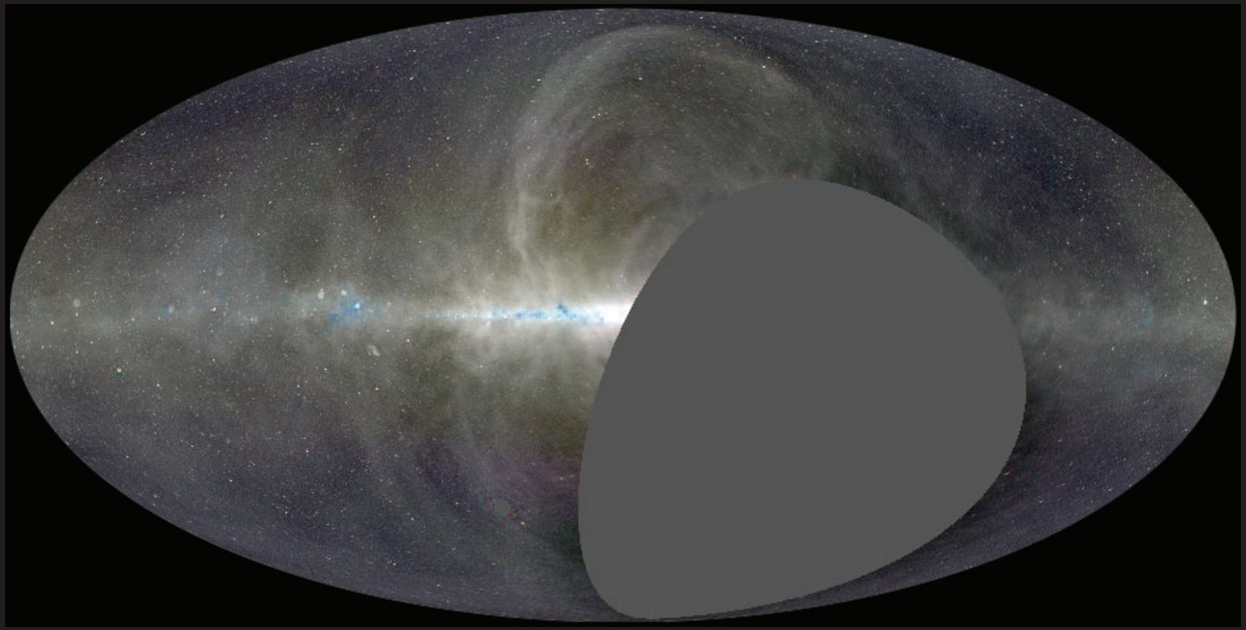
Dark Ages Hydrogen Cosmology

Imaging Type II Radio Bursts



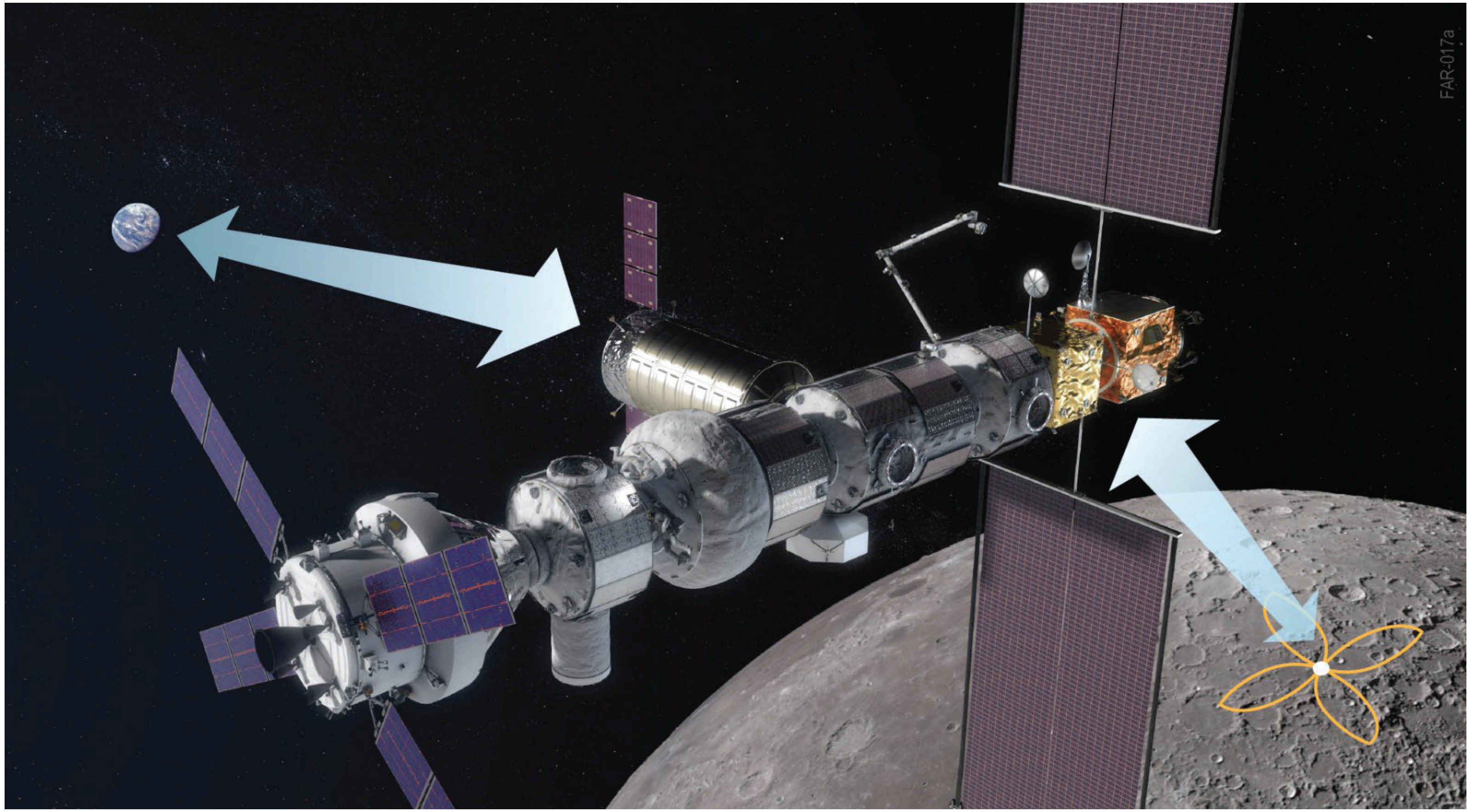
Burns, MacDowall, Bale, Hallinan, Bassett, Hegedus, 2021, *Planetary Science Journal,* 2:44.

Data Products

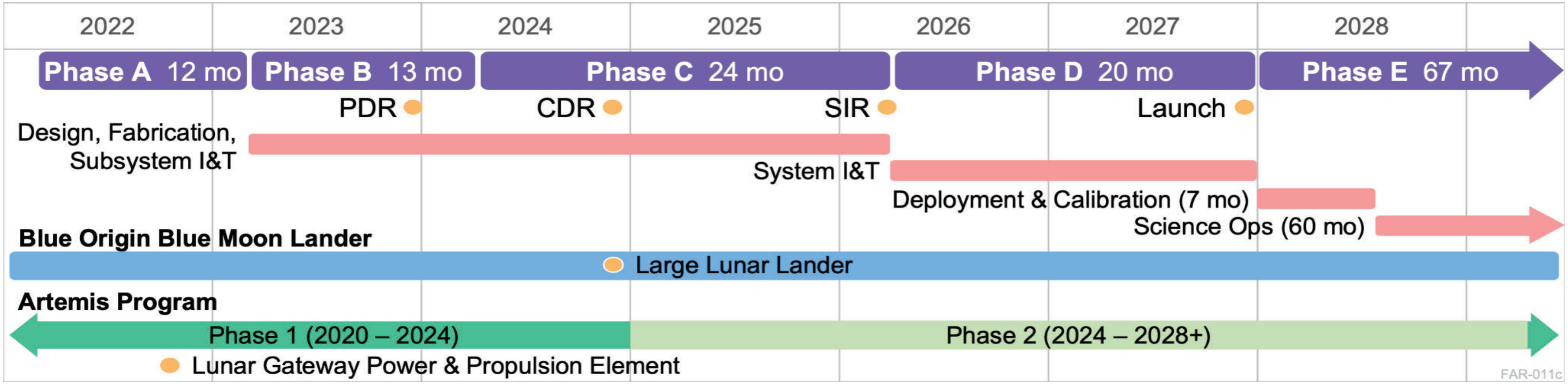


Data products are identical to OVRO-LWA, but 100x lower in frequency

Frequency range: 0 – 40 MHz (1400 channels)
Integration time: 60 s
All visibilities: 65 GB/day
All-sky imaging every 60 seconds (Stokes I and V)
Deep all-sky imaging every lunar day (no confusion noise!)



Assumed Lunar Gateway Communications Support	
Rover forward link (Ku-band)	16 kb/s
Rover return link (Ka-band)	5 MB/s
Lander forward link (Ku-band)	16 kb/s
Lander return link (Ka-band)	10 Mb/s



Cost Summary (FY2019$M)		Team X Estimate	
	CBE	Res.	Cost + Reserve
Total Cost	$1080M	27%	$1330M
MMRTG + RHU	$70M	0%	$70M
Launch Vehicle	$150M	0%	$150M
Development & Ops Cost	$865M	29%	
Development Cost	$800M	30%	$1040M
Phase A	$8M	30%	$10M
Phase B	$70M	30%	$90M
Phase C/D	$720M	30%	$940M
Operations Cost (Phase E/F)	$65M	15%	$75M

Final Thoughts

- The lunar far side has unique characteristics that are ideal for low frequency radio astronomy:
    - Radio-quiet (>80 dB below that of near side)
    - Free from ionospheric effects (refraction & absorption)
    - Stable surface & subsurface
    - Wake cavity at night shields antennas from solar wind-induced shot noise at <1 MHz.
- Going to the Moon solves many but not all problems.
- Compelling science cases including Exoplanetary Magnetospheres & Space Weather; Dark Ages & Cosmic Dawn
- FARSIDE requires no technology breakthroughs & is within cost bounds for a Probe mission.
- Access to the Moon via CLPS and Artemis makes FARSIDE feasible for this decade.