LuSEE-Night:
The Dark Ages from the Far Side of the Moon

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On behalf of the LuSEE-Night Team

RPM – Oct 24, 2024

BERKELEY LAB

Brookhaven National Laboratory

Space Sciences Laboratory UC Berkeley ssl.berkeley.edu SSL

University of Minnesota

Outline

Science Introduction

- Dark Ages
- Global 21-cm spectrum
- Lunar far side

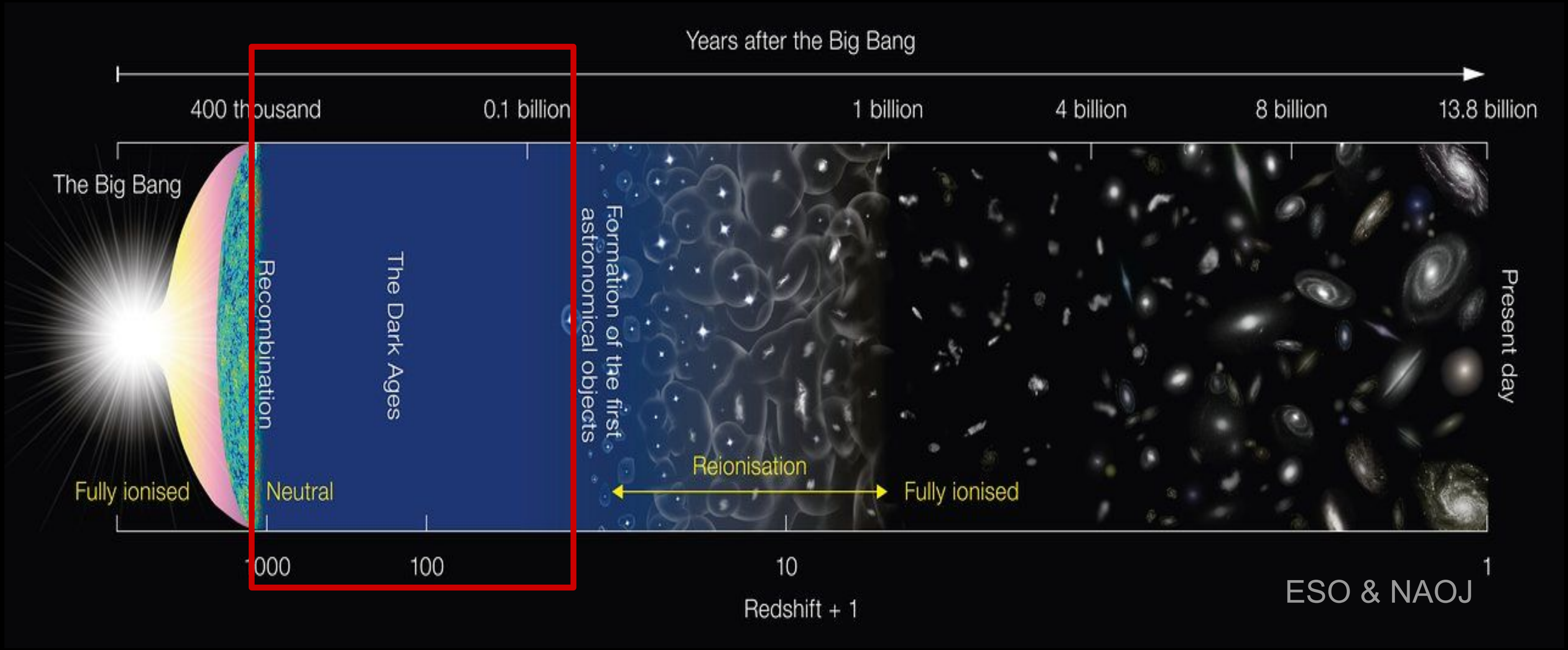
LuSEE-Night

- Project overview
- LuSEE-Night payload
- Antennas – design & testing

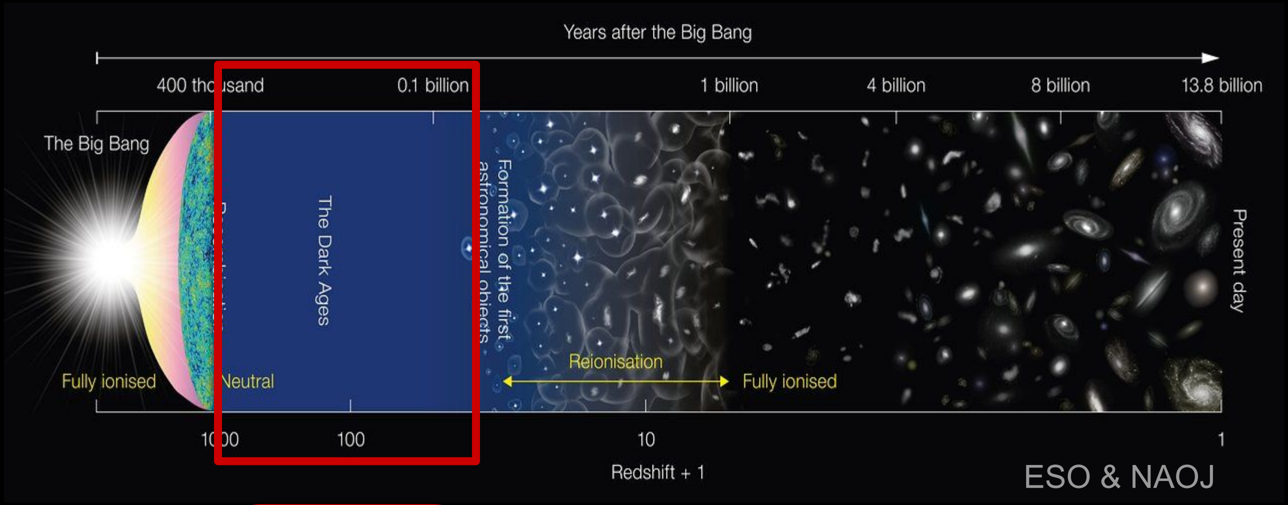
Science Introduction

The Dark Ages

Period between CMB and Cosmic Dawn



One of the least constrained frontiers of modern cosmology!



Space and ground based mm-wave (Planck, CMB-S4)

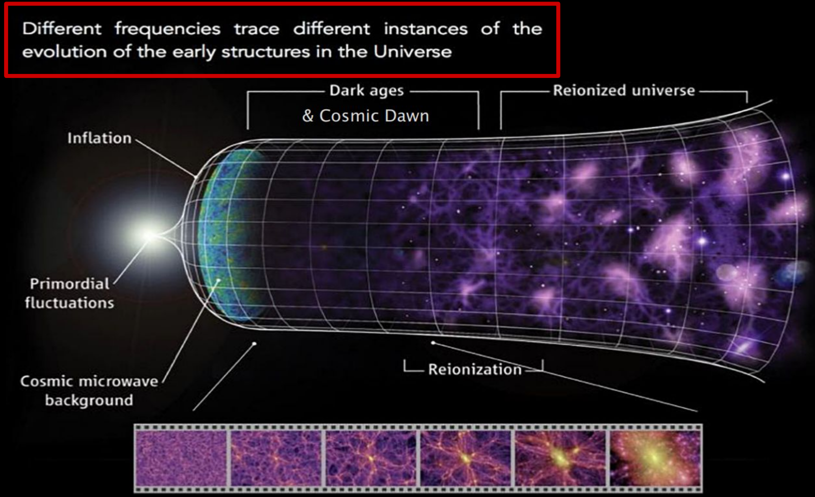
Ground based radio surveys (Edges, LWA)

Space and ground based optical, infrared, and radio surveys (JWST, DESI, SCP)

LuSEE-Night

Why observe the Dark Ages?

- Precision cosmology
  - Free of astrophysical complexity
  - More constraining than CMB
- Beyond the standard model
  - Gravitational waves
  - Neutrino decay lifetime
  - Dark matter annihilation or decay

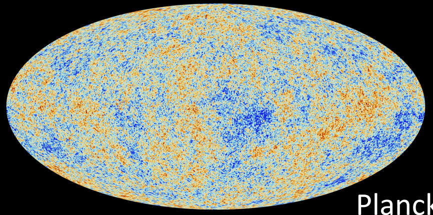


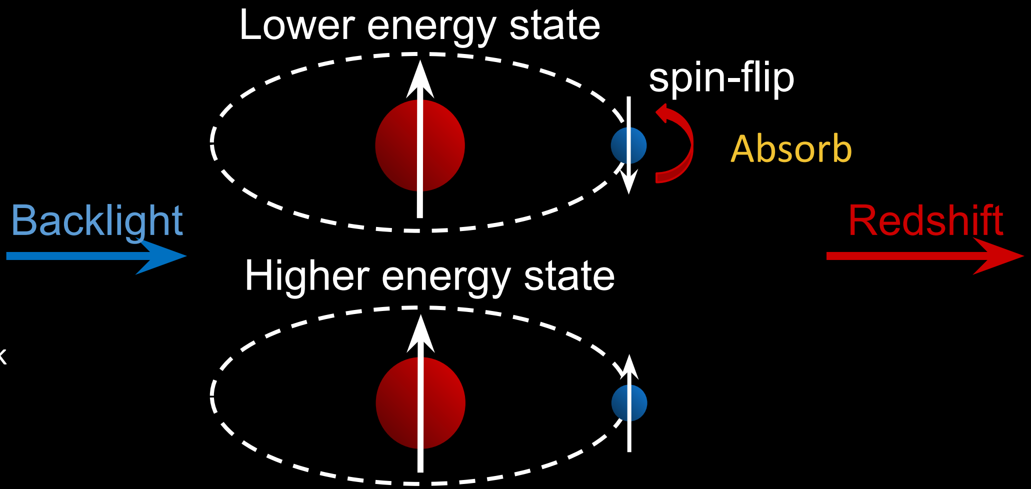
Koopmans et al. (2021)

Test our knowledge of fundamental physics & further constrain ΛCDM models

Any measured deviation from ΛCDM → profound implications on fundamental physics

What can we observe?





Recombination forms hydrogen and releases CMB

Absorption of CMB by neutral hydrogen's hyperfine transition
21 cm = 1420 MHz

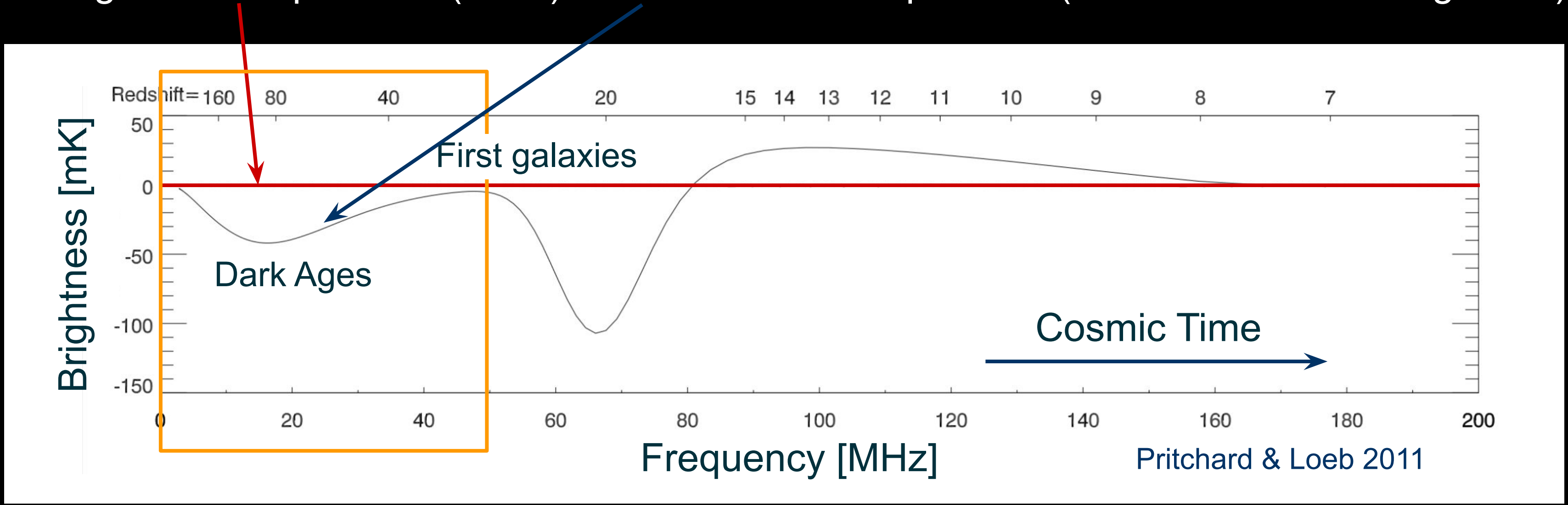
Observe redshifted absorption line
0.5 MHz ~ 50 MHz

What can we observe?

21-cm hyperfine transition → ***single known method to observe the Dark Ages***

Background temperature (CMB)

Global 21 cm spectrum (distortion to the background)



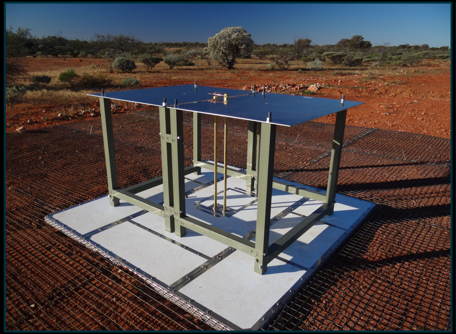
“Line intensity mapping (LIM) observations of that era could enable tests of the theory of inflation by providing a precise map of tracers of structure formation, such as emission from primordial hydrogen gas or other atomic or molecular lines. […] DOE has already partnered with NASA to construct one pathfinder LIM experiment, LuSEE-Night”

P5 Report - 2024

"The panel sees 21 cm and molecular line intensity mapping of the Dark Ages and reionization era as both the discovery area for the next decade and as the likely future technique for measuring the initial conditions of the universe in the decades to follow."

Astronomy & Astrophysics Decadal Survey - 2020s

Deployed single-element 21 cm experiments



EDGES
(ASU & MIT)
Western Australia

50 – 200 MHz

SCI-HI
(CMU-Mexico)
Mexico

40 – 130 MHz

SARAS-2
(India)
Timbaktu Collective

40 − 200 MHz

PRI^{Z}M
(Berkeley-South Africa)
Marion Island

30 − 200 MHz

*not a complete list

**many planned experiments

Deployed multi-element 21 cm experiments

LOFAR
(Netherland and European countries)
Netherlands

70 – 200 MHz

LEDA
(Harvard-Berkeley)
Owens Valley Radio Observatory

30 – 85 MHz

HERA
(US-South Africa)
Karoo Desert of South Africa

50 – 225 MHz

*not a complete list

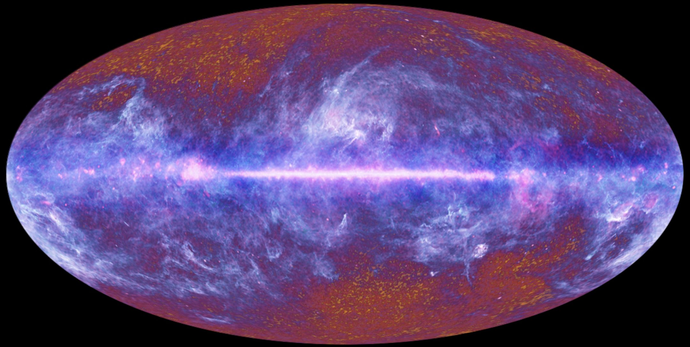
**many planned experiments

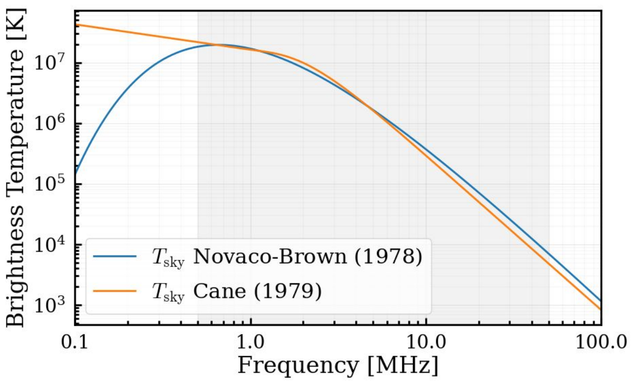
Challenges of observing the Dark Ages signal

Galactic emission: ~10^6 brighter than 21 cm spectrum

- Foregrounds not well described by power-laws due to free-free absorption
- But… foregrounds have strong spatial structure & are polarized

Interesting science by itself!





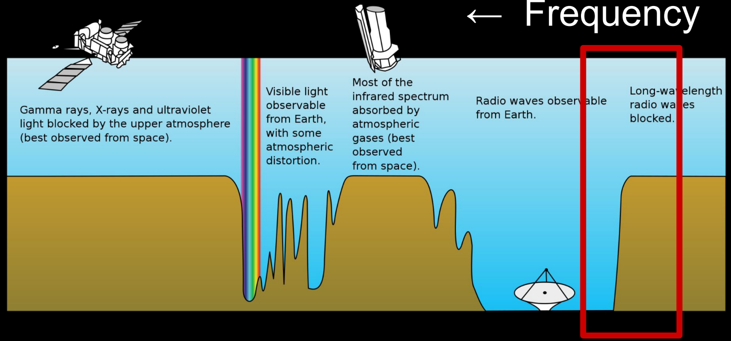
From *where* can we observe the Dark Ages signal?

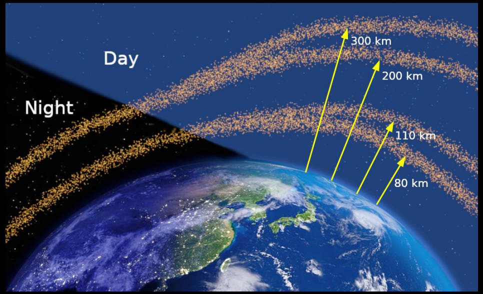
Ionosphere is opaque at low frequencies

Strong RFI

← Frequency

Atmospheric opacity





Wavelength →

NASA (originally); wikimedia

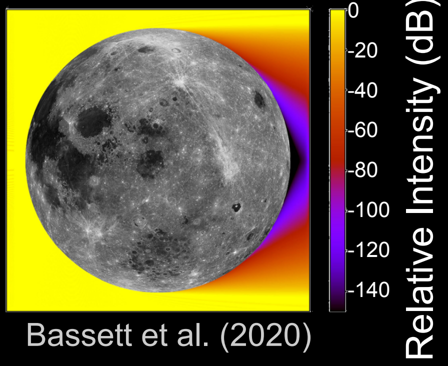
The Dark Ages are challenging to observe from Earth

The lunar far-side

No (significant) ionosphere

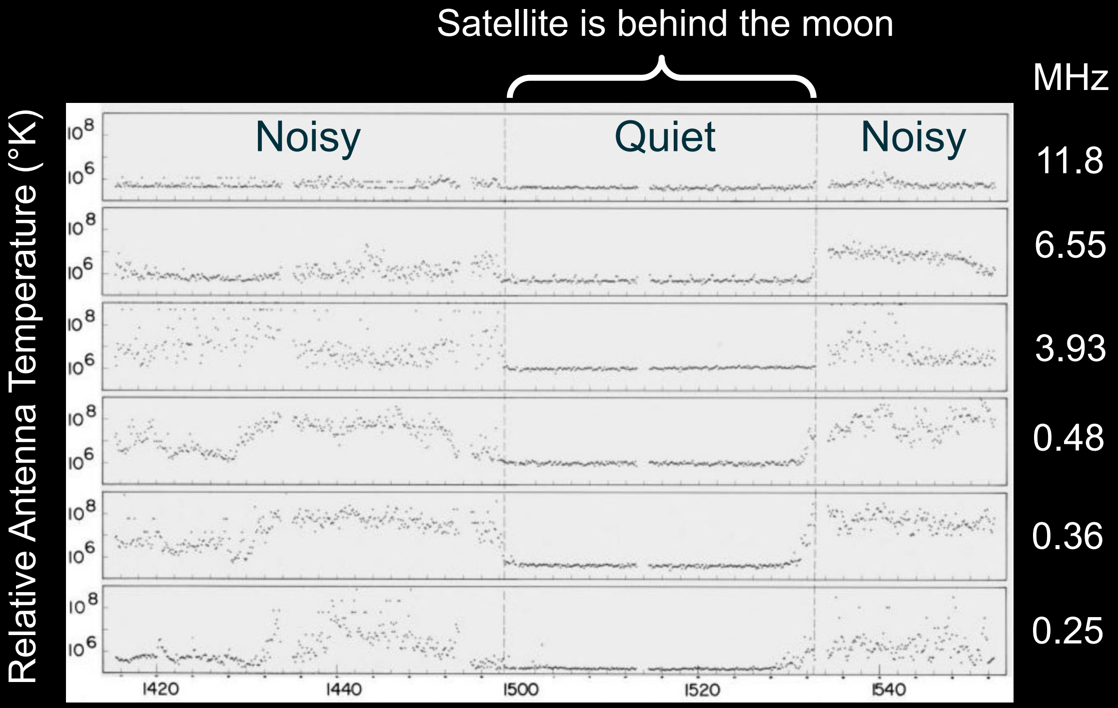
Radio quiet far-side

RF attenuation at 30 kHz



Bassett et al. (2020)

Radio Astronomy Explorer-2 Satellite Data



Universal Time - 12 December 1973

Alexander et al. (1975)

Other missions to the lunar surface

Chang’e 4 (China)
Landed Jan. 3, 2019 on the far side

Observed their own radio emission

JAXA's SLIM (Japan)
Landed Jan. 19, 2024 south of the equator

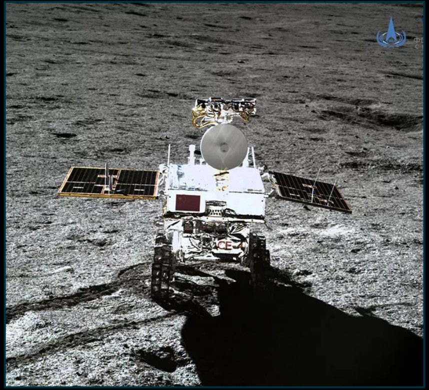
Landed in its nose, solar panels could not generate power

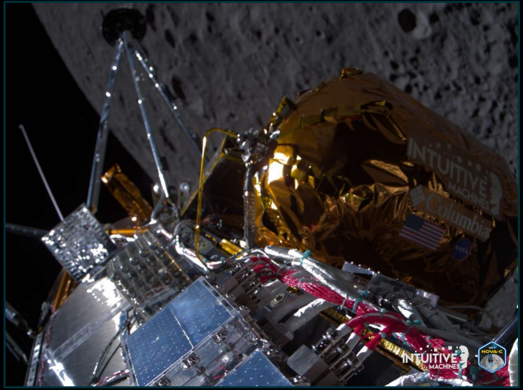
IM Odysseus - ROLSES (USA)
Landed Feb 22, 2024 near the South Pole

Pre-deployment of boom
Lander tipped onto its side during landing

Chandrayaan-3, (India)
Landed Aug 23, 2024 in the South Pole region

Successful landing





CLPS mission

Lunar Surface Electromagnetic Explorer at Night

LuSEE-Night

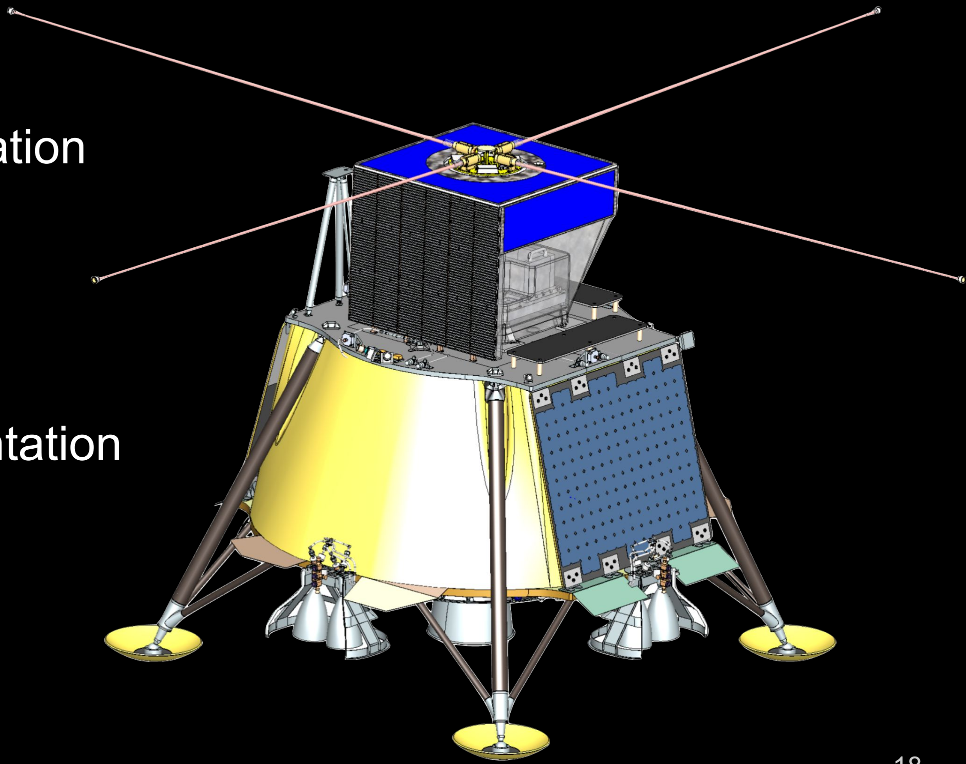
Origins of LuSEE-Night

Proposed to NASA by UC Berkeley’s Space Science Lab (SSL)

Up-Scope opportunity with DOE augmentation

- ➢ Lunar night survival
- ➢ Improved spectrometer
- ➢ 4 monopoles

BNL selected as lead lab for DOE augmentation



LuSEE-Night Goals

- Establish the lunar surface as a viable site for low-frequency radio astronomy
- Perform the most sensitive observations of the radio sky at 0.5 – 50 MHz
- Characterize foregrounds at low frequencies
- Place the most stringent constraints on the Dark Ages trough to date

Further science LuSEE-Night can access

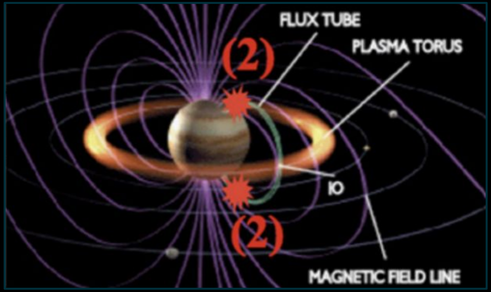
Cosmology – constrain WIMP annihilation signal

Bright radio sources – leverage characteristic diffraction pattern of sources near the horizon

Heliophysics – solar radio type II & III bursts

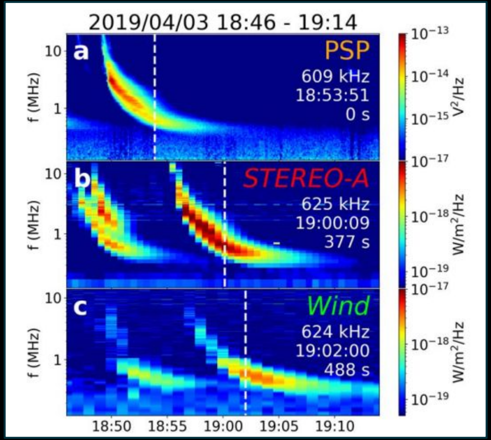
Lunar electromagnetic environment

Jovian emission



Zarka et al. 2013

Type III radio burst



Krupar et al. 2020

LuSEE-Night Payload

The LuSEE-Night hardware team

BNL

- Spectrometer
- Integrated electronics assembly
- Power distribution
- Telemetry

LBNL

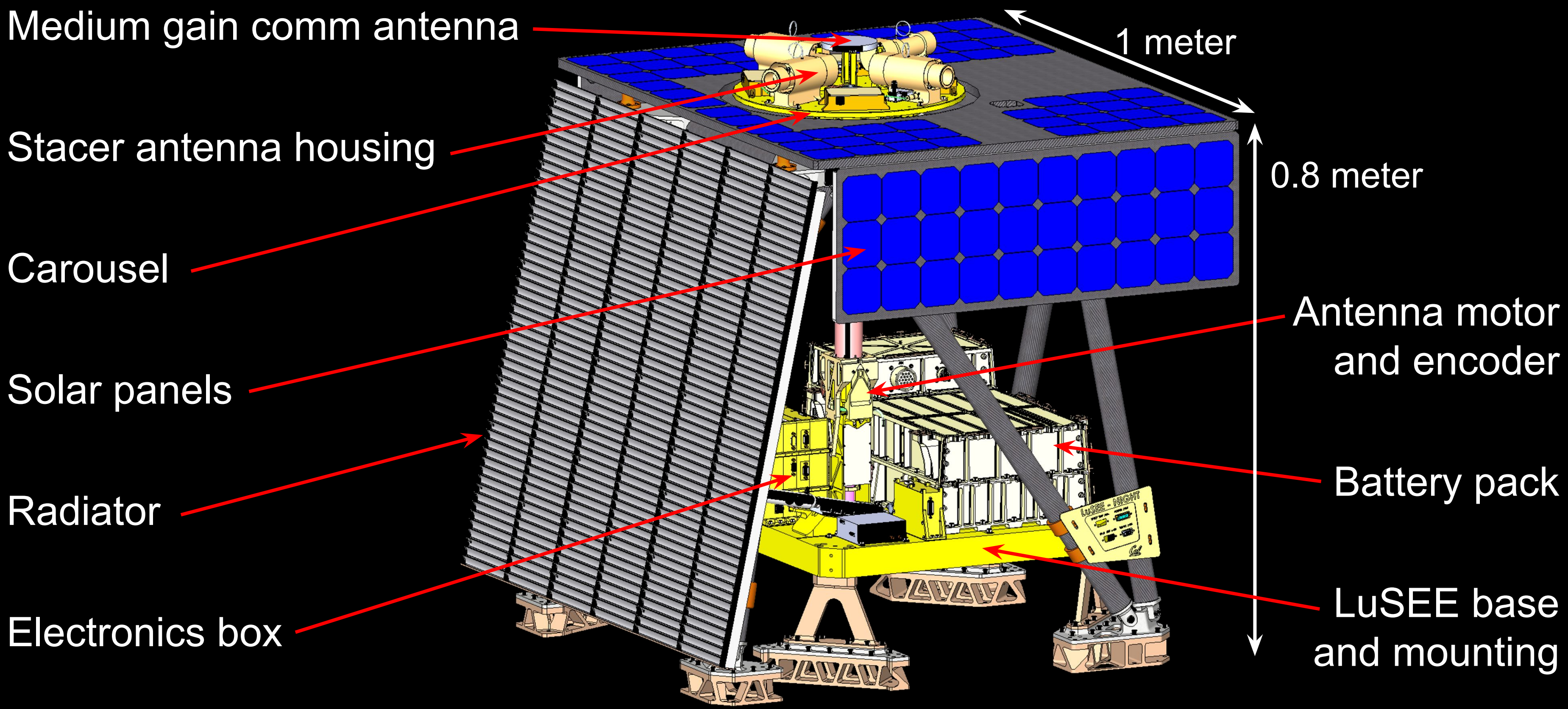
- **Antenna**

SSL

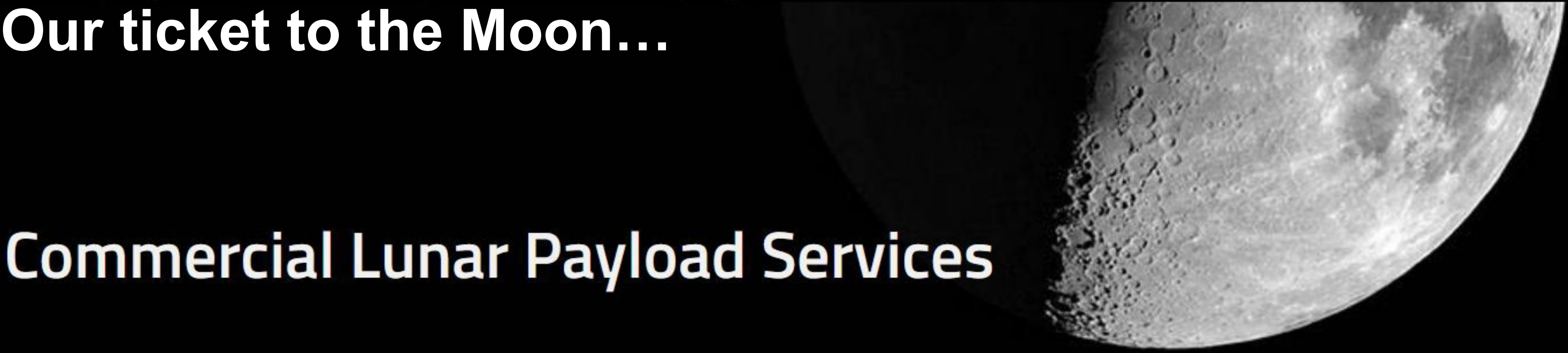
- Payload module
- Thermal control
- System integration

University of Minnesota

- System engineering
- Low EMI power supply


Medium gain comm antenna
Stacer antenna housing
Carousel
Solar panels
Radiator
Electronics box
1 meter
0.8 meter
Antenna motor
and encoder
Battery pack
LuSEE base
and mounting

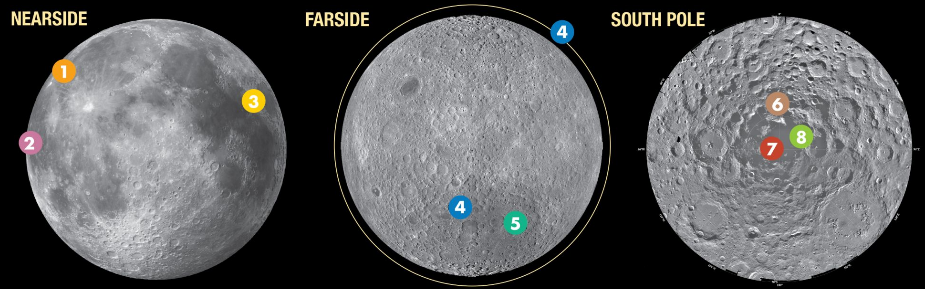
Our ticket to the Moon…



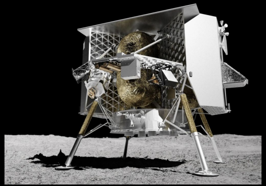
A NASA initiative – rapid delivery of payloads to the lunar surface by American companies

COMMERCIAL LUNAR PAYLOAD SERVICES LANDING SITES

National Aeronautics and Space Administration



1 – Astrobotic Peregrine Mission-1



Launch:
January 8, 2024
Did not land

4 – Firefly Blue Ghost Mission 2

Future

LuSEE-Night

7 – Intuitive Machines IM-2

Launch:
February 15, 2024
Landed:
February 22, 2024

2 – Intuitive Machines IM-3

Future

5 – Team Draper

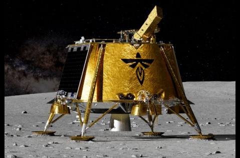
Future

LuSEE-Lite

6 – Intuitive Machines IM-1

Future

3 – Firefly Blue Ghost Mission 1



Future

1 – Astrobotic Griffin Mission-1

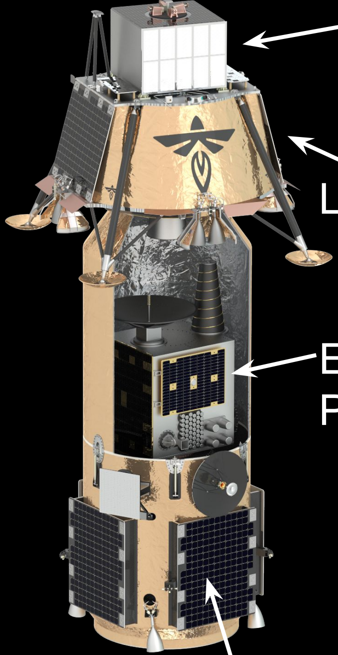
Future

Launch:

SpaceX Falcon 9

Journey to the Moon:

Blue Ghost Transfer Vehicle

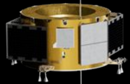


LuSEE

Lunar Lander

ESA's Lunar Pathfinder

Heliospace calibration sources



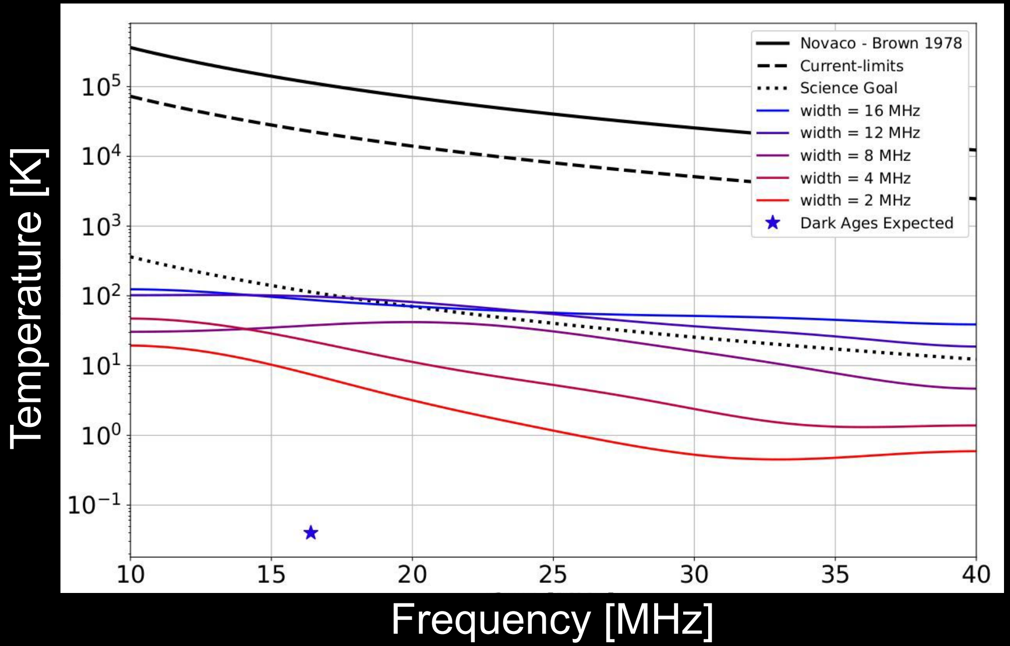
Landing on the Moon:

Blue Ghost Lunar Lander

FIREFLY AEROSPACE

Performance forecast

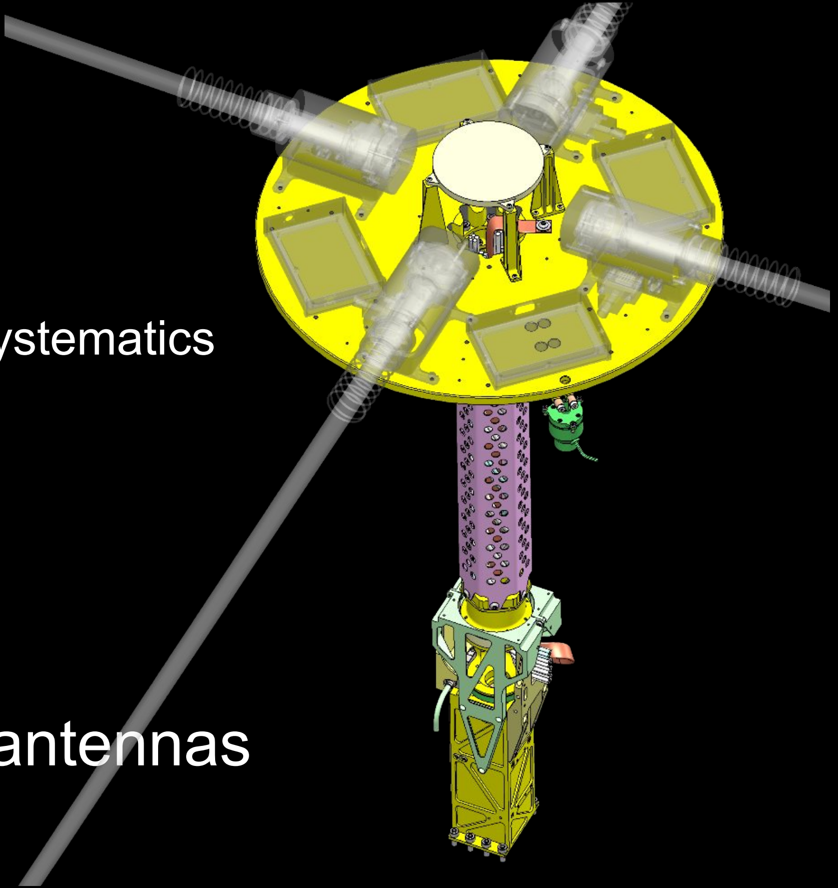
Science Goal: constrain foregrounds to the 10^{-3} level



Antenna Subsystem

LBNL & SSL

Antennas: science requirement



1. Smooth spectral response
2. Sensitivity
3. Polarization-sensitive
4. Manage effect of lunar regolith & mitigate systematics

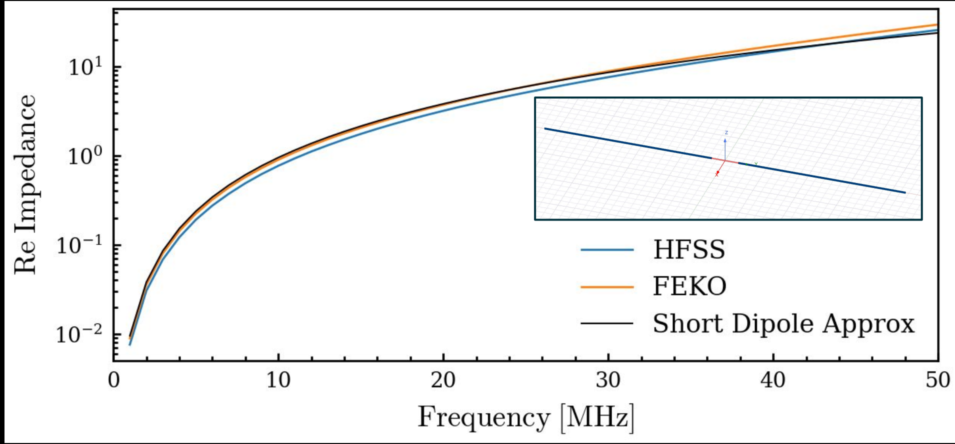
Mission requirements:

- High TRL
- Light, compact, robust
- Survive temperature extremes

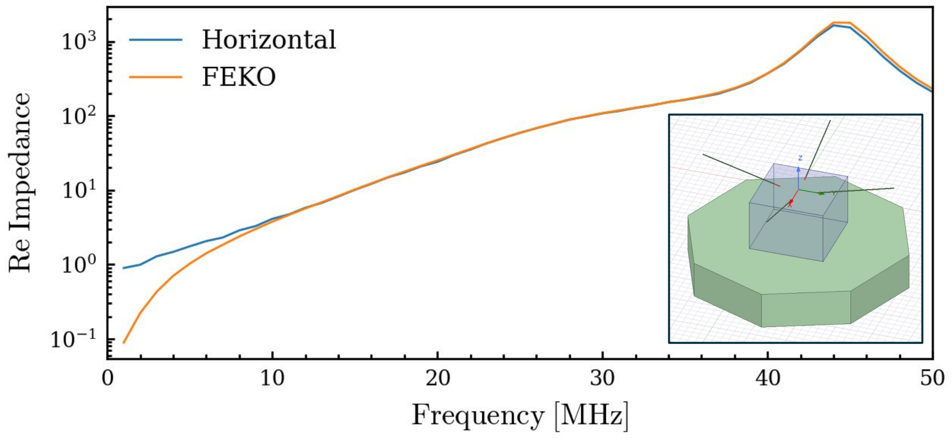
Four orthogonal 3-meter monopole antennas

Simulator comparison – HFSS vs FEKO

Dipole in vacuum



LuSEE on Moon



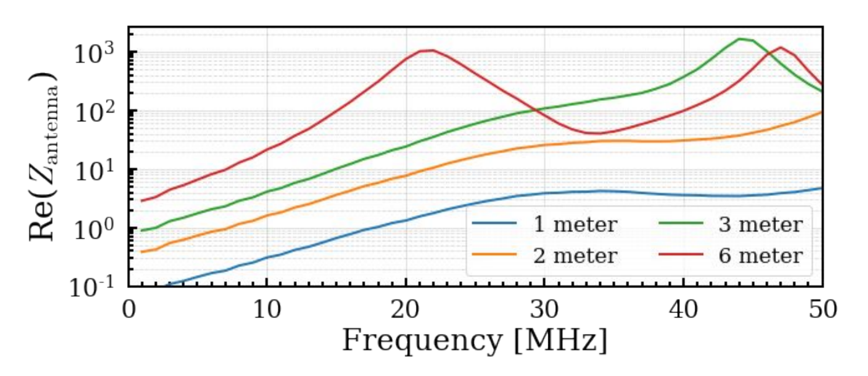
Good agreement between simulators

*except at frequencies <10 MHz with lunar soil

Design choice: 3 meter monopoles

Impedance

- Sensitivity ↔ resonances



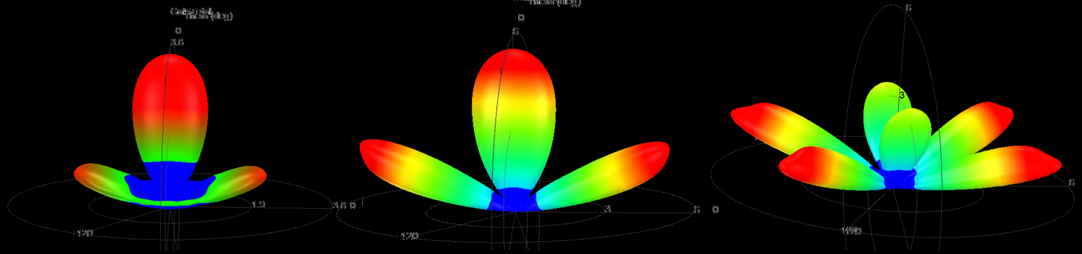
Beam shape

- Gain ↔ beam complexity

1 meter

3 meter

6 meter



50 MHz

Design choice: antenna height

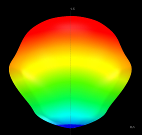
Interaction with the lunar regolith

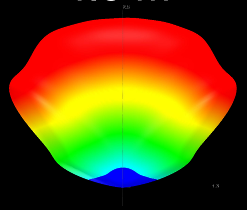
➢ Ground coupling ↔ interferences

Closer to the ground → stronger coupling

2 m | 4.5 m

10 MHz

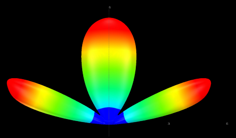


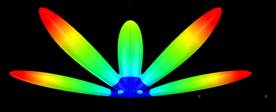


Higher above the ground → standing waves between antenna and ground

2 m | 4.5 m

50 MHz





Design choice: rotation capabilities

Carousel mount

- Ability to cover the stokes parameters

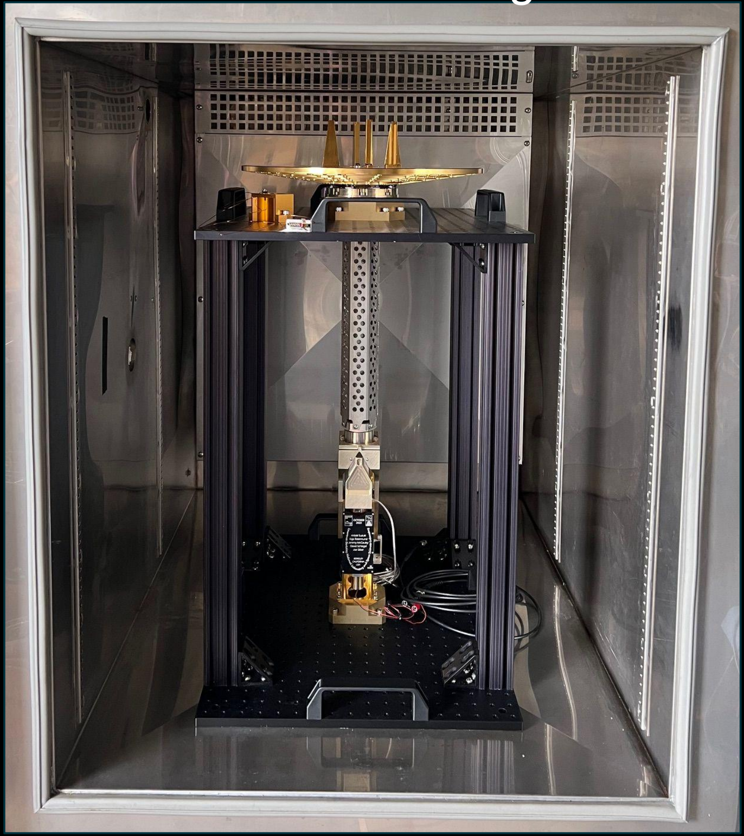
Sensitively separate

➢ Sky signal / analog chain / regolith / lander

Survive and operate in Lunar environmental extremes

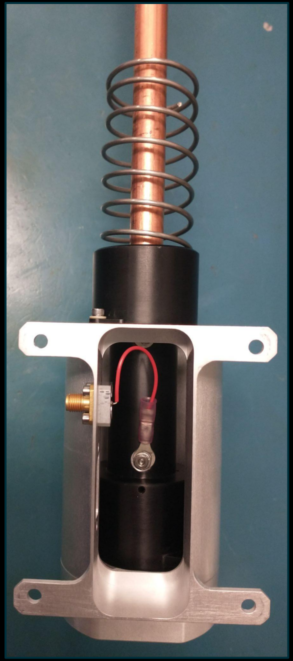
Design and modelling done by Joe Silber

Thermal testing



Stacer antennas

Rolled BeCu sheet   Flat spring   Stowed during launch   Deployed 4° above horizontal

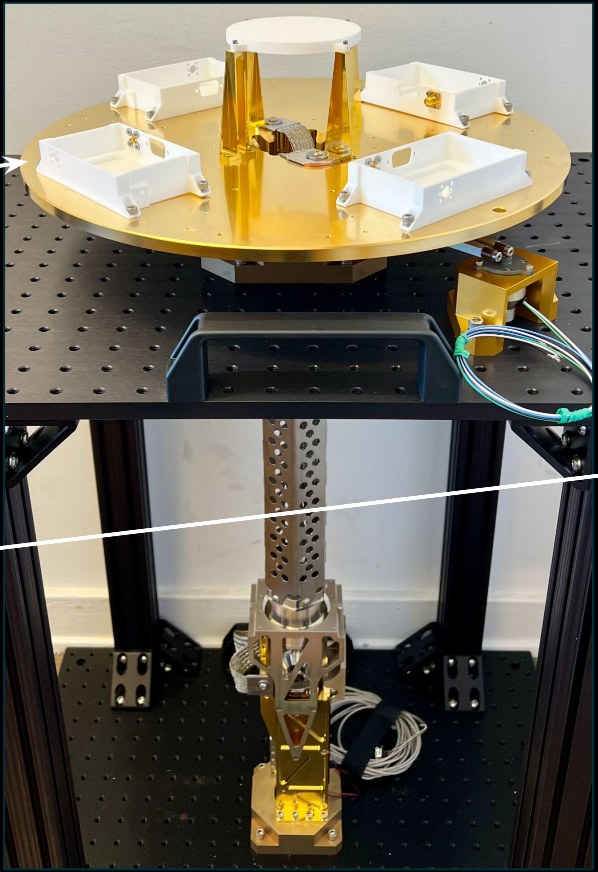


Youtube credit: Kyle Gilroy

Flight model assembly & integration

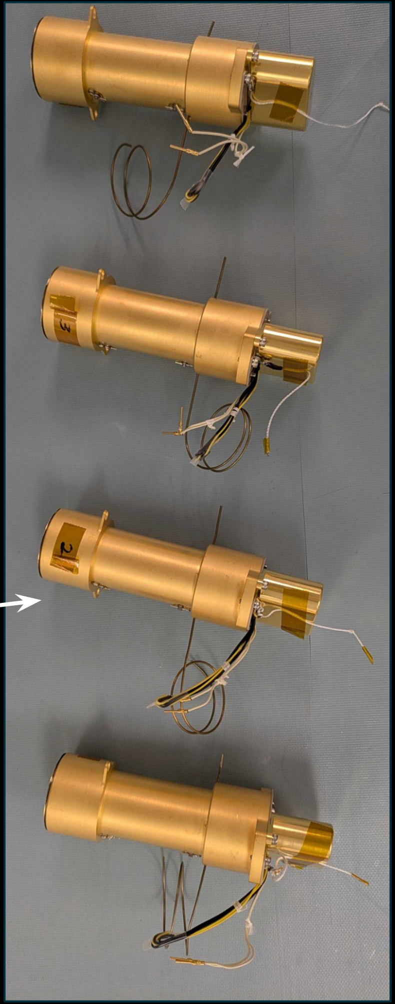
Successful delivery of FM carousel to SSL

Assembly done by
Kaja Rotermund, Joe Silber, Aritoki Suzuki



Ongoing assembly of stacers ~~and~~ their housing

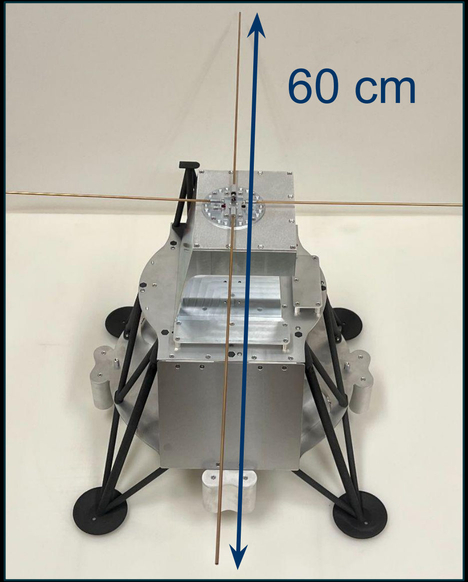
Assembly done by Jeremy McCauley (SSL)

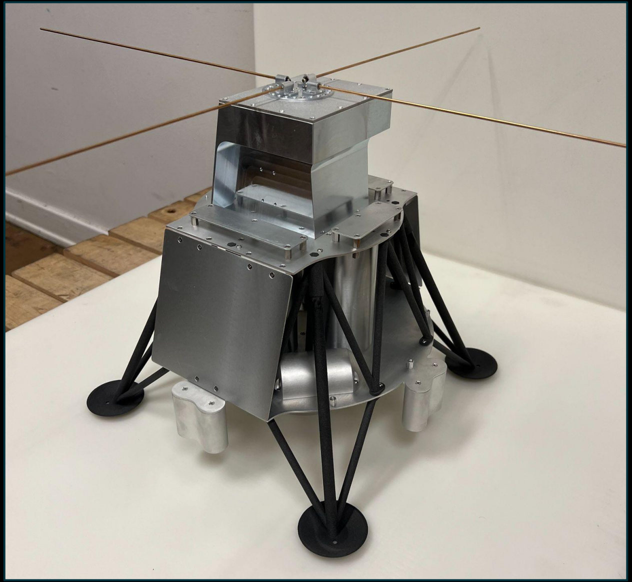


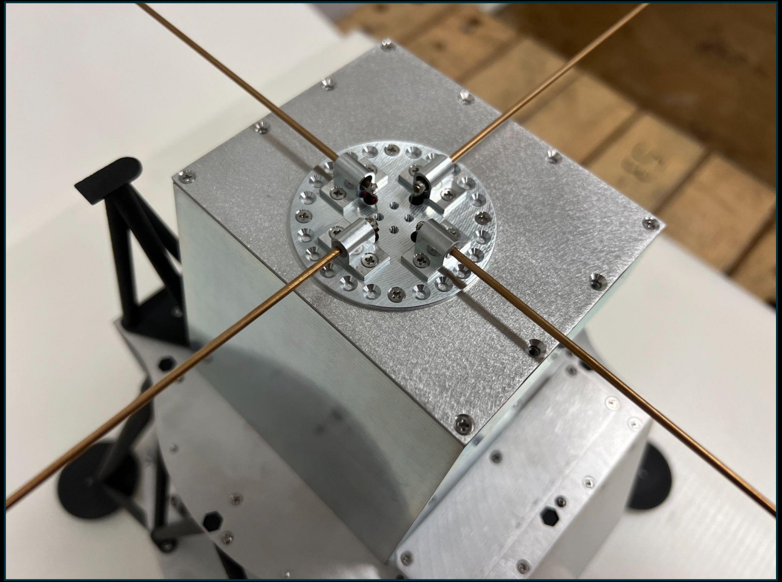
Antenna characterization

LBNL

1:10 scale model tests







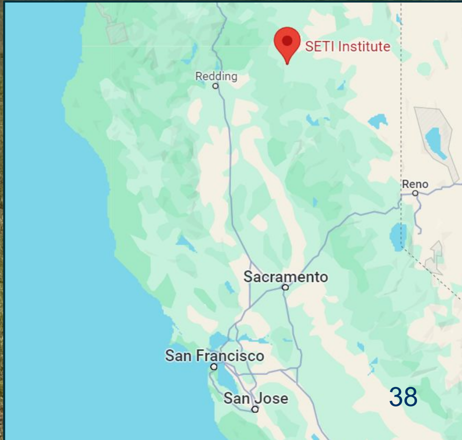
Build confidence in our simulations

Baseline calibration

Hat Creek Observatory – SETI Institute

Thank you:
Alex Pollak, David DeBoer
(UC Berkeley)

Park Fire

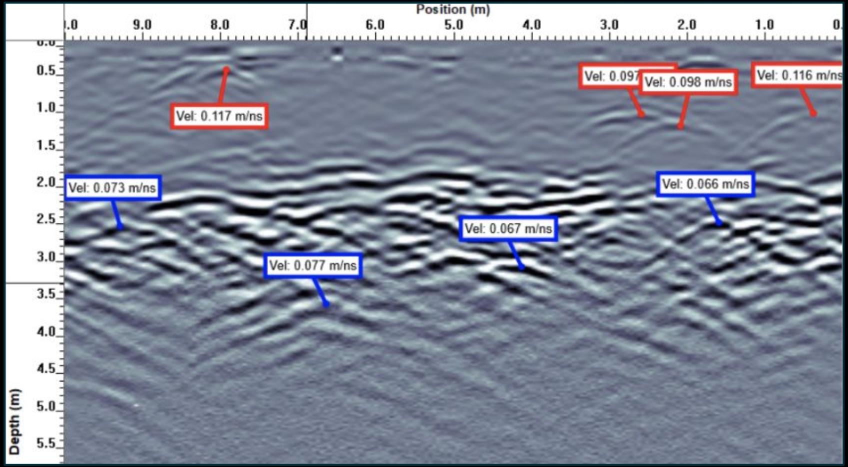


Ground Penetrating Radar

Dielectric constant measurements

- ➢ Frequency- and depth-dependent

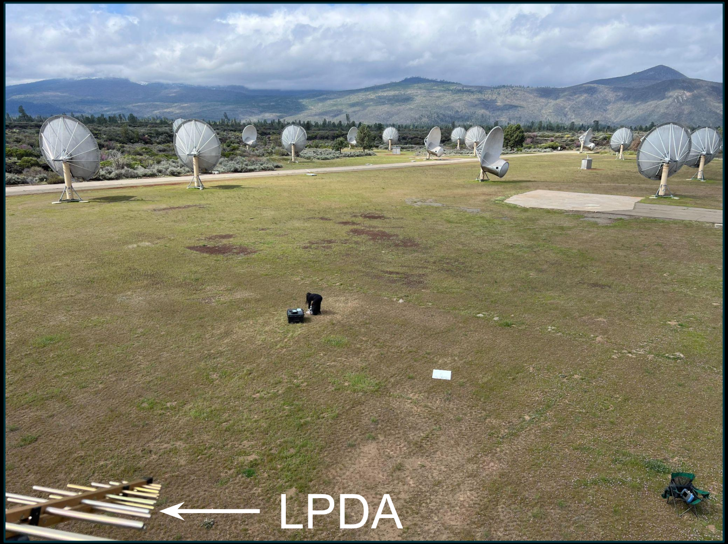
Fatima Yousuf (grad) & Suvan Ravi (undergrad) (UC Berkeley)

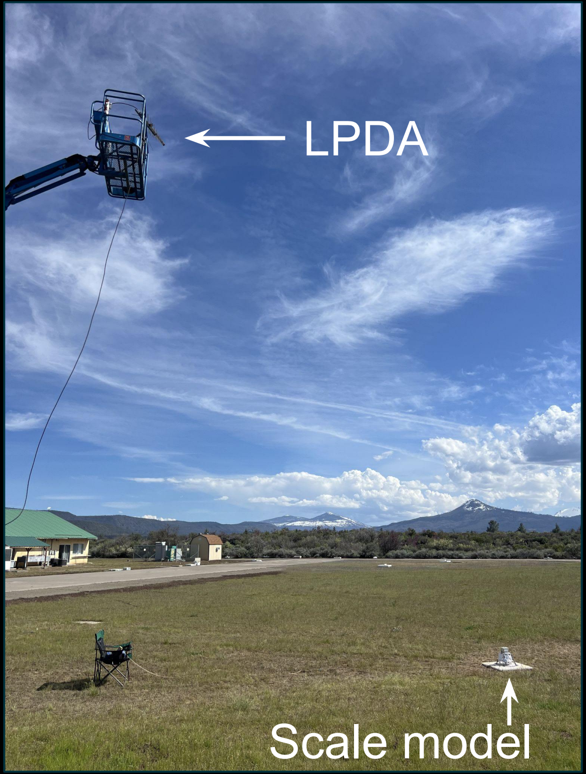


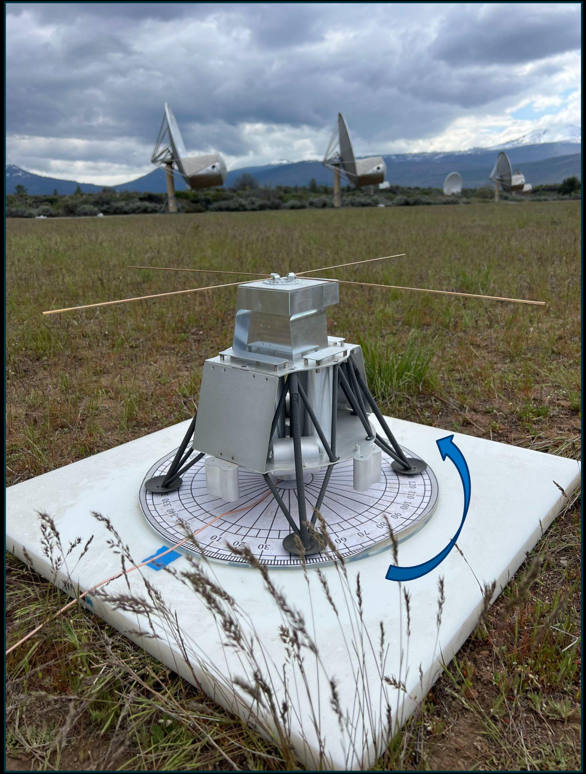
Top soil:
0-1.5 m
$\epsilon_r = 5.3$

Bedrock:
1.5-4.5 m
$\epsilon_r = 12.2$

Beam pattern measurements – 1:10 scale model





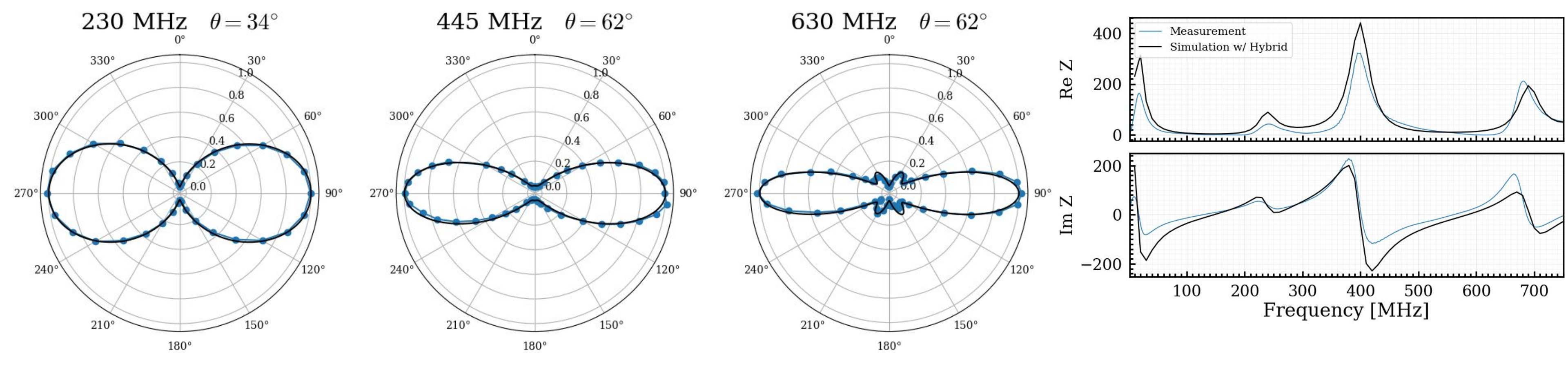


Hat Creek measurements

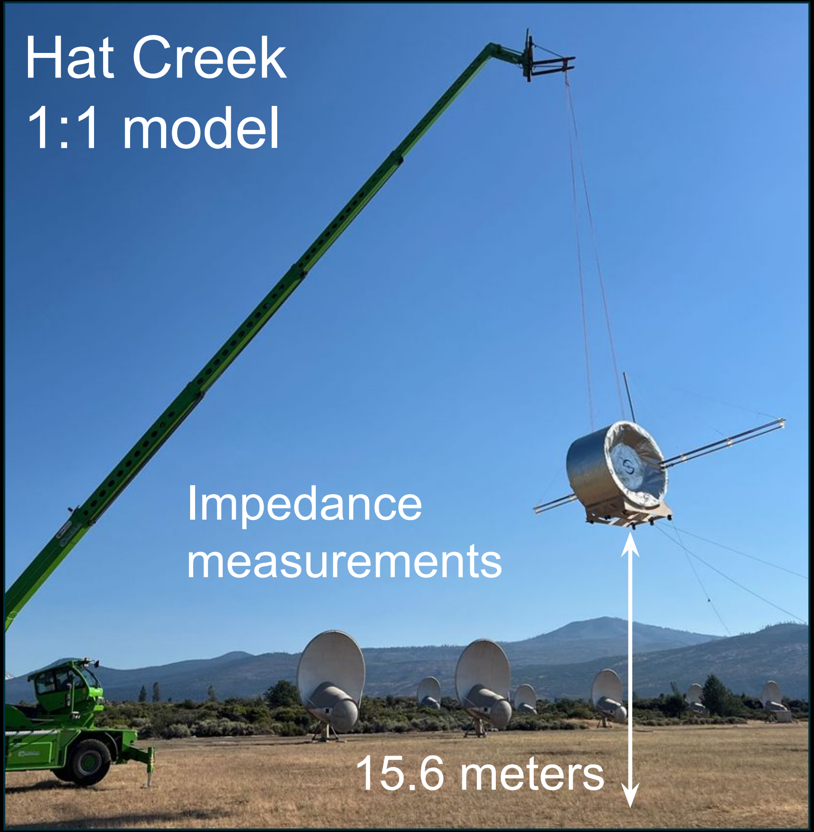
Measurements and simulations agree in shape

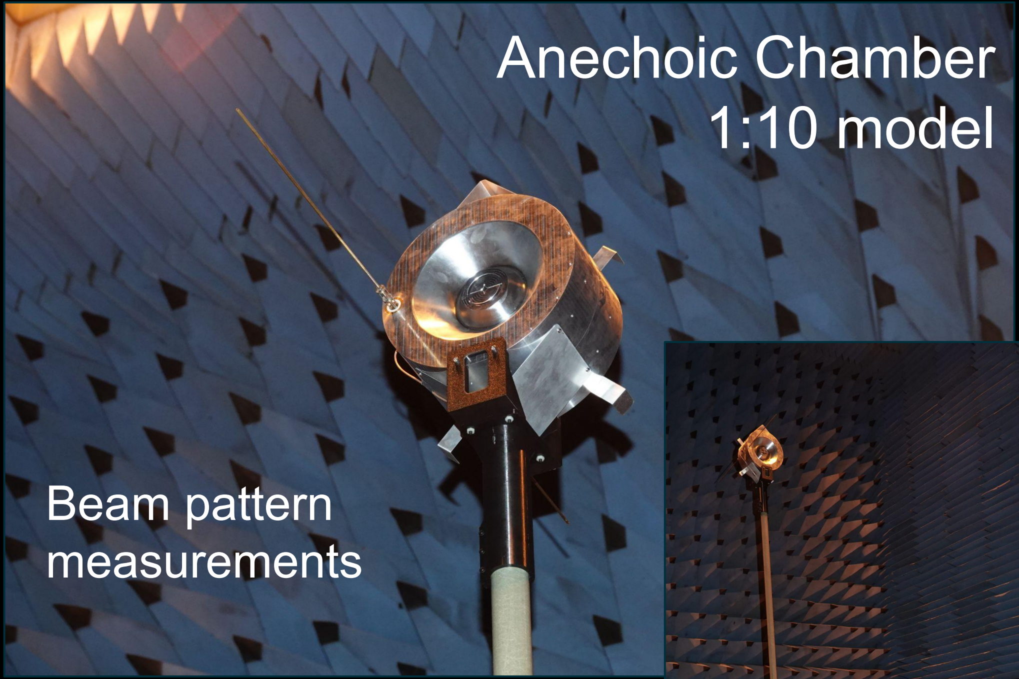
Ongoing efforts: ensuring the amplitude of measurements and simulations converge

Measurements (blue dots) Simulation (black)

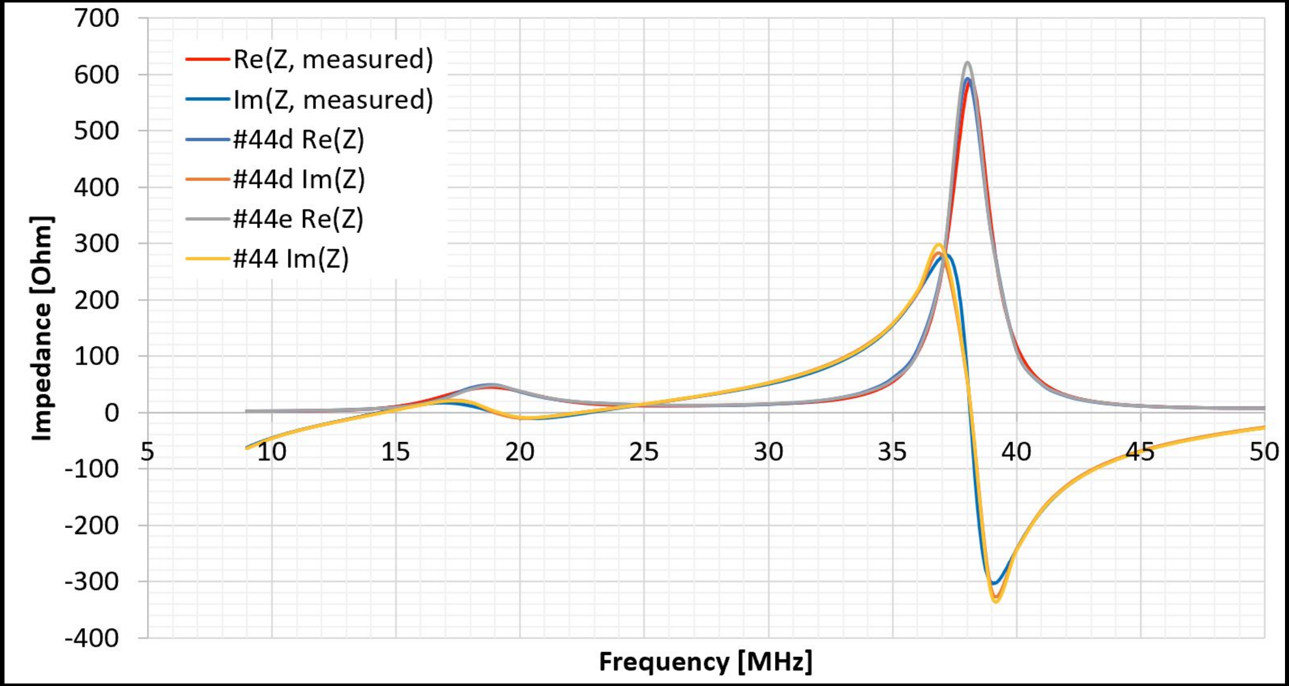


Heliospace: orbiting calibration source

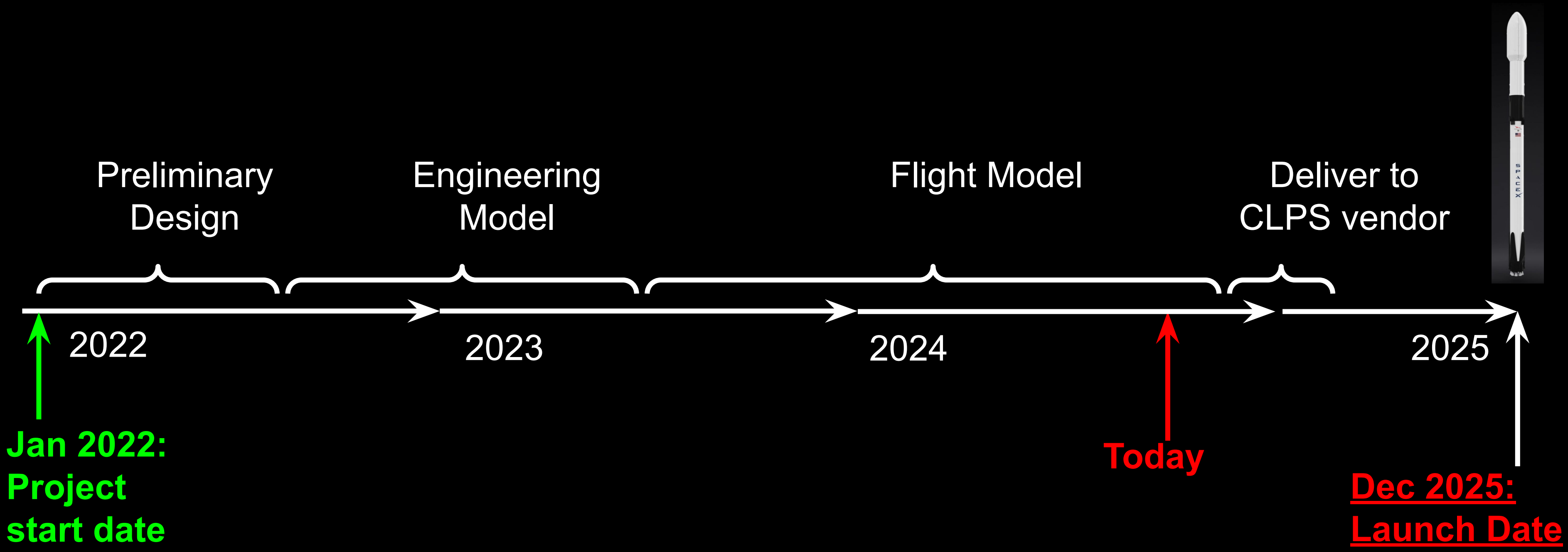




Heliospace: impedance of 1:1 model



Timeline



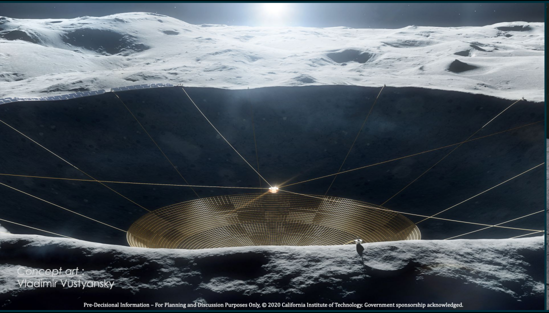
Preliminary Design
Engineering Model
Flight Model
Deliver to CLPS vendor
2022
2023
2024
2025
Jan 2022: Project start date
Today
Dec 2025: Launch Date

LuSEE-Night is a pathfinder…

… both in location, foregrounds and science goals!

Other lunar pathfinder experiments targeting the Dark Ages:

Lunar Crater Radio Telescope (LCRT)

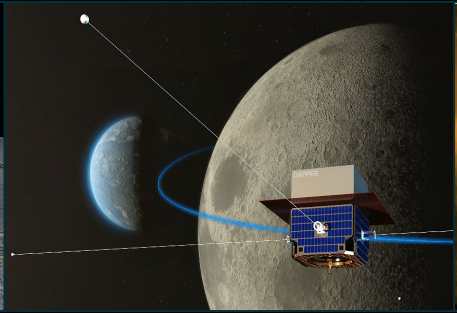


Caltech

FarSide

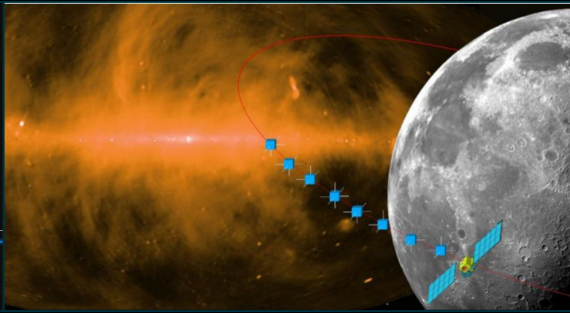
CU Boulder

Dark Ages Polarimetry PathfindER (DAPPER)



CU Boulder

Discovering the Sky at the Longest Wavelengths (DSL)



Chinese Academy of Science
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Thank You.