Review of 21cm from the MOON

Anže Slosar, Brookhaven National Laboratory

6th Global Signal Workshop + 21cm Cosmology Meeting

Trieste, 15 September 2023

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

@BrookhavenLab

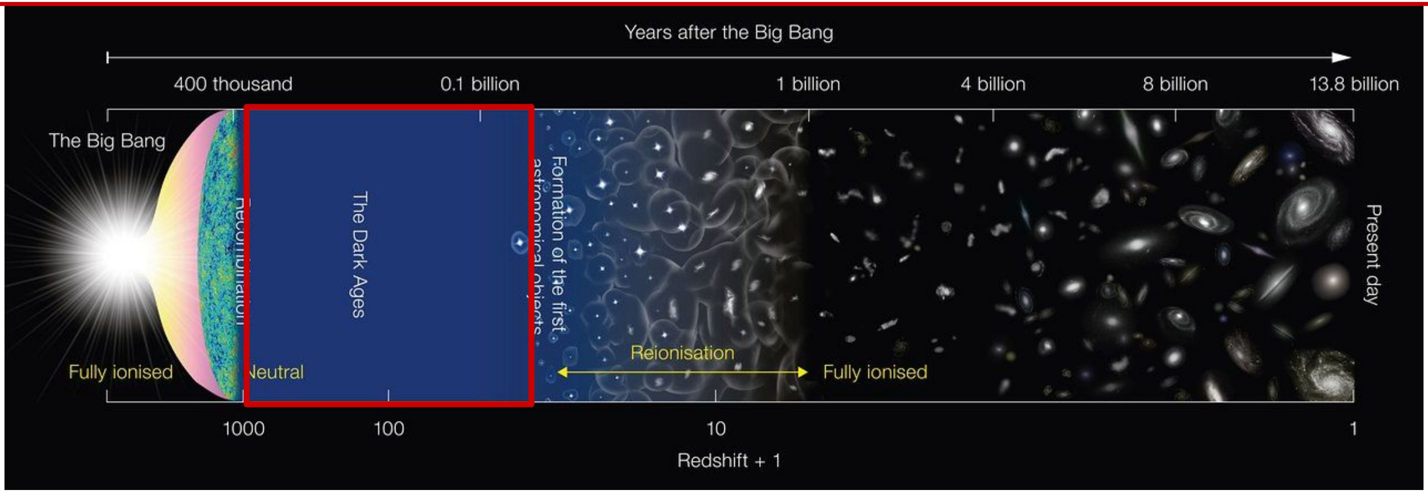
Part 1:
The big picture

Context: The Dark Ages

- Period between:
  - Surface of last scattering where Cosmic Microwave Background is Emitted; and
  - Cosmic Dawn when the first stars run on
- No compact radiation sources → linear physics
- No compact radiation sources → no optical radiation to observe
- The only known way to observe is to rely on 21-cm hydrogen line redshifted into 1-50MHz
- As with Cosmic Microwave Background, there is the monopole signal and fluctuations around it

The final frontier of modern cosmology

Can model it exactly using only GR, atomic physics, thermodynamics – no gastrophysics!

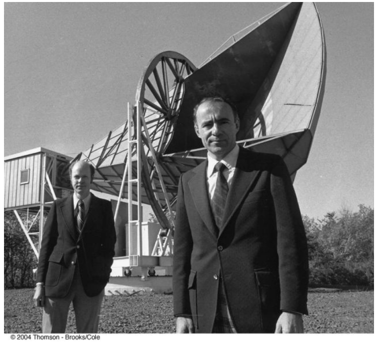


ESO & NAOJ

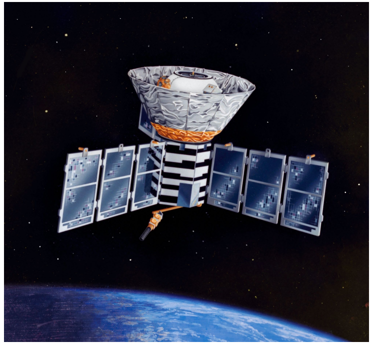
You eat the elephant in small pieces

Cosmic Microwave Background

- Monopole discovered 1965 by Penzias and Wilson (Nobel Prize in 1978)



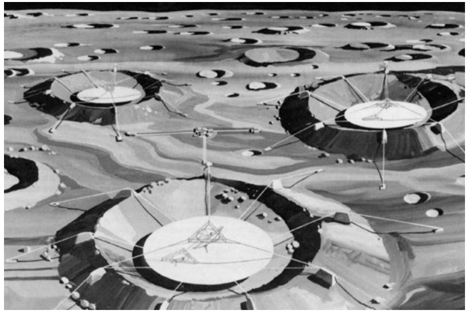
- Fluctuations discovered 1990 by COBE satellite (Smoot's Nobel Prize in 2006)



Dark Ages

- Monopole detected 2030s (?)

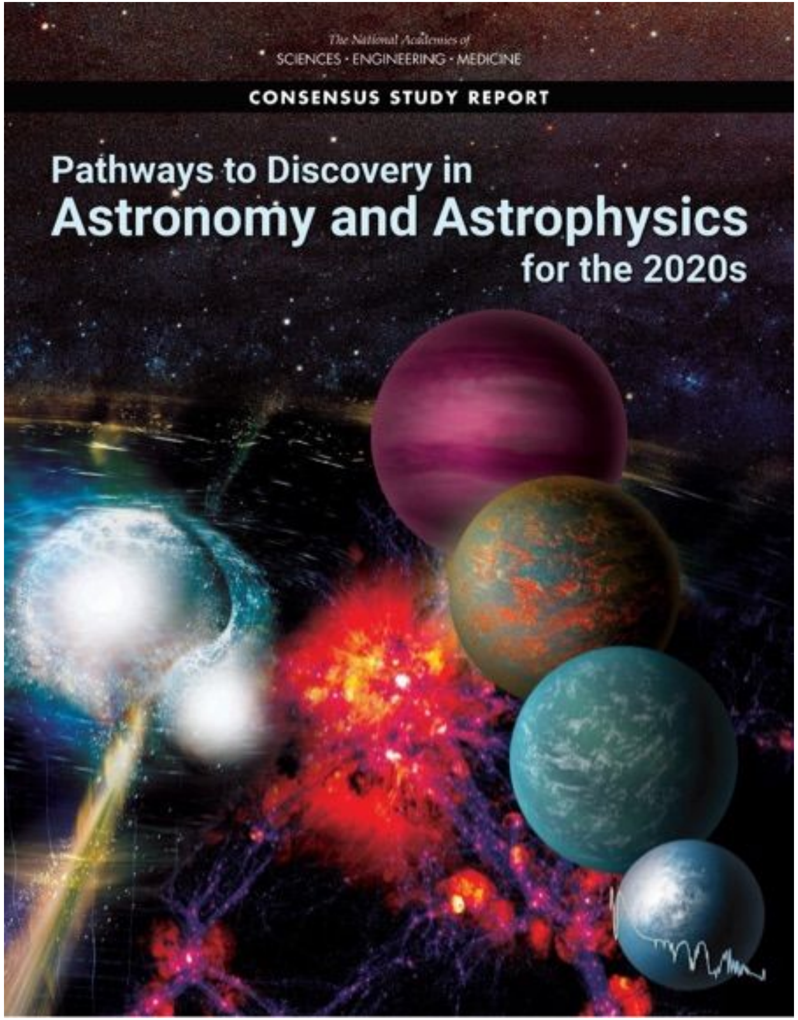
- Fluctuations detected 2060(?)



Decadal Survey on Astronomy & Astrophysics,
Panel on Cosmology p.258

DISCOVERY AREA: THE DARK AGES AS A COSMOLOGICAL PROBE

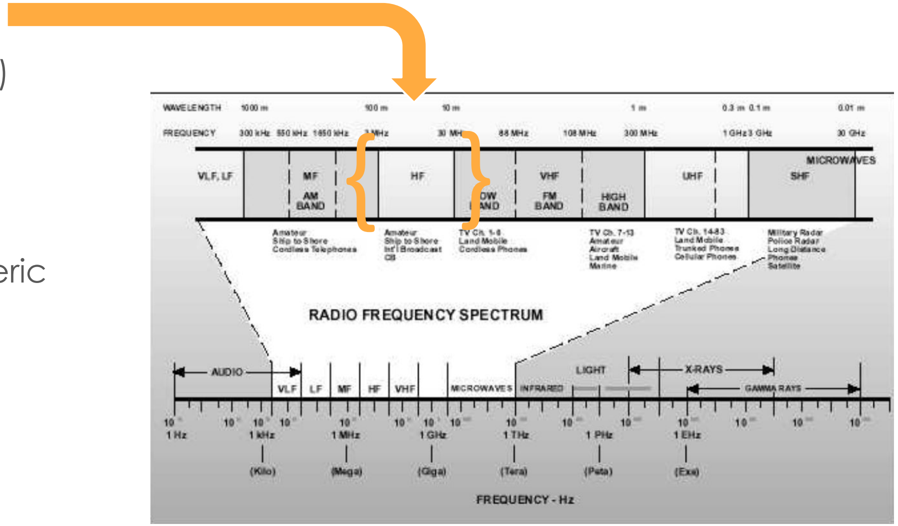
"The panel sees 21 cm and molecular line intensity mapping of the Dark Ages and reionization era as both the discovery area for the next decade and as the likely future technique for measuring the initial conditions of the universe in the decades to follow.



What do we need to measure this?

Objective:

- observe the sky at low radio frequencies (0.5 – 50MHz) where the Dark Ages signal lives



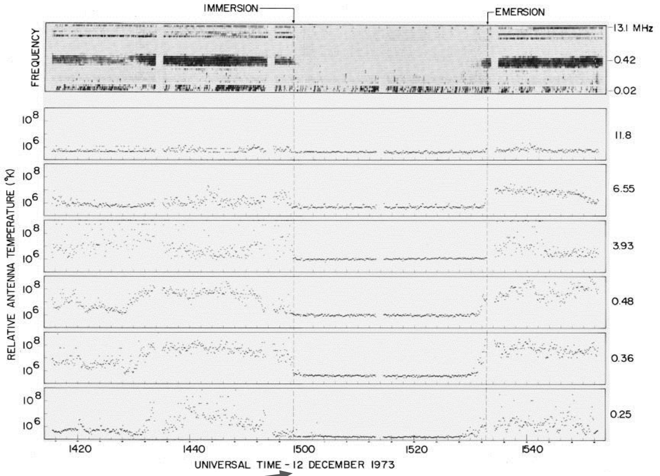
Impossible from Earth:

- RF contamination from anthropogenic and atmospheric sources
- Ionosphere absorbs, emits, and refracts at these frequencies

Solution:

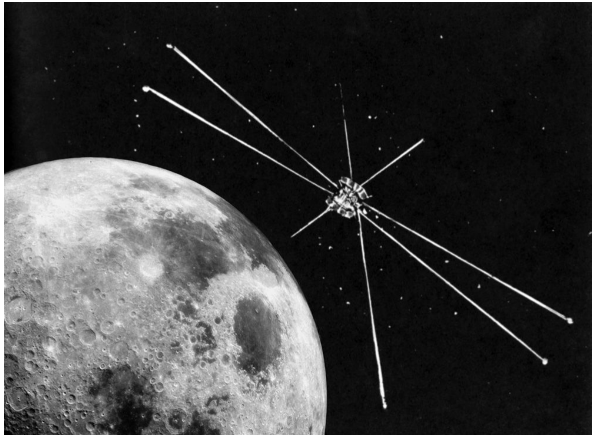
- Telescope on the Moon's far side is protected from terrestrial RFI
- The Moon has no atmosphere → no ionospheric distortions
- During the lunar night, solar RFI is also blocked
- On the Moon surface, environment also extremely stable and repeatable

What do we know about low-frequency sky



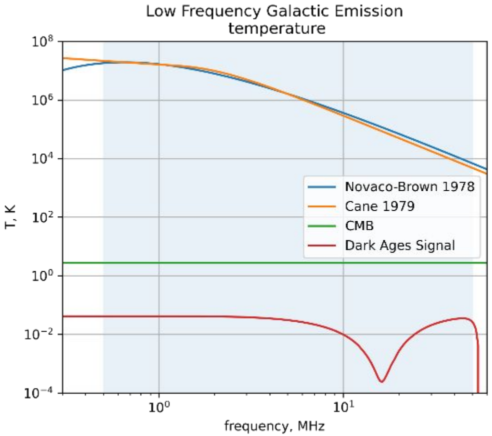
The Dark Side of the Moon by Pink Floyd released in March 1973

- We have empirical evidence that the far side of the moon is radio-quiet
- Caveat: in orbit, not on the surface



Radio-Astronomy-Explorer-2 was the largest spacecraft ever built with four 230m antennas

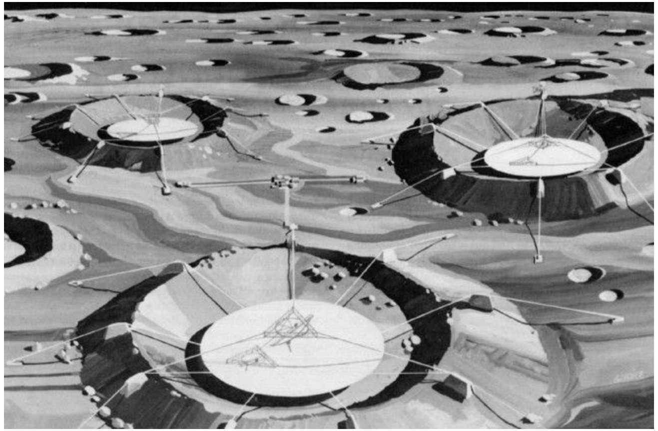
- Last real data on the low-frequency sky from the late 1970s
- Still state-of-the-art dataset to be superseeded



- Dark Ages signal is dominated by orders of magnitude brighter synchrotron emission from Galaxy

How to build a telescope on the Moon?

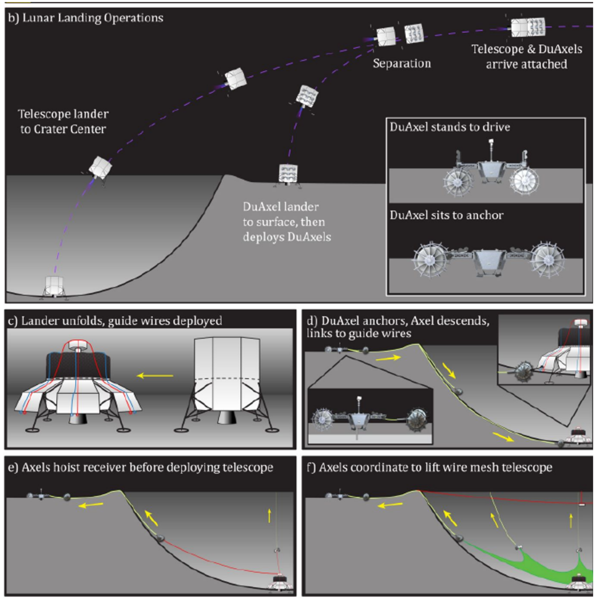
- People were day-dreaming about putting a telescope of the far side of the Moon since 1950s
- Richard Vondrak working at Apollo Science Operations Center proposed using lunar craters to build radio telescopes like the Arecibo Observatory in Puerto Rico.

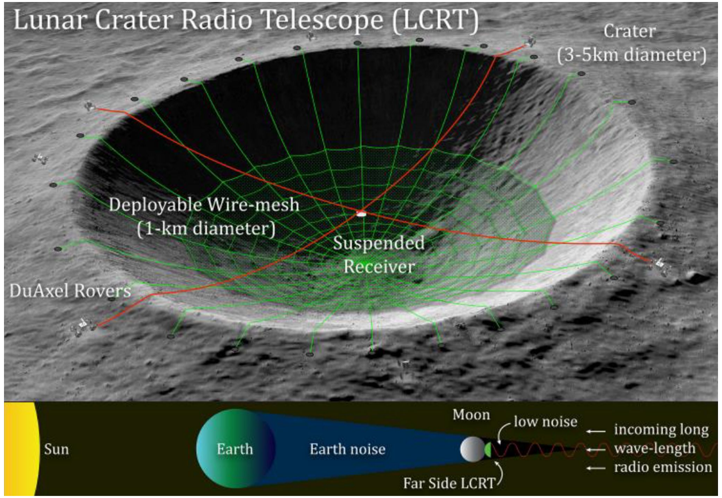


1950s concept from Apollo times: Arecibos in Lunar Crater

Arecibo (now decommissioned)

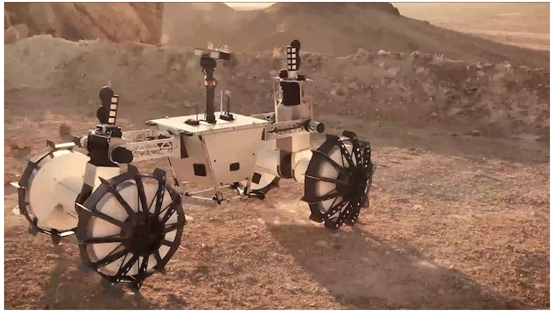
Lunar Crater Radio Telescope



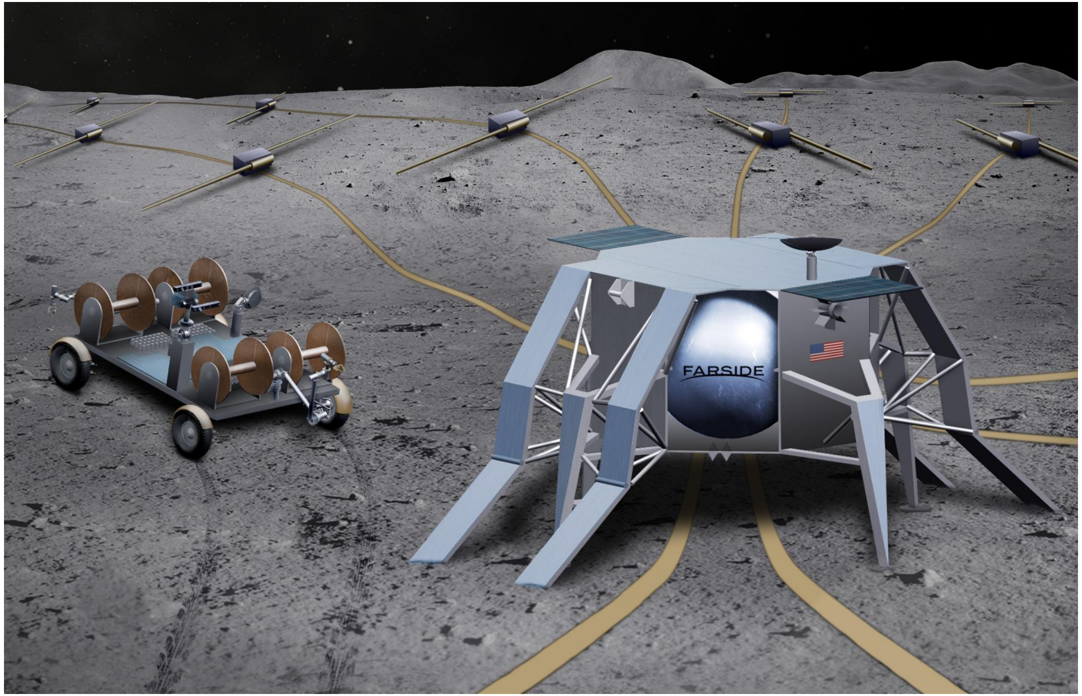


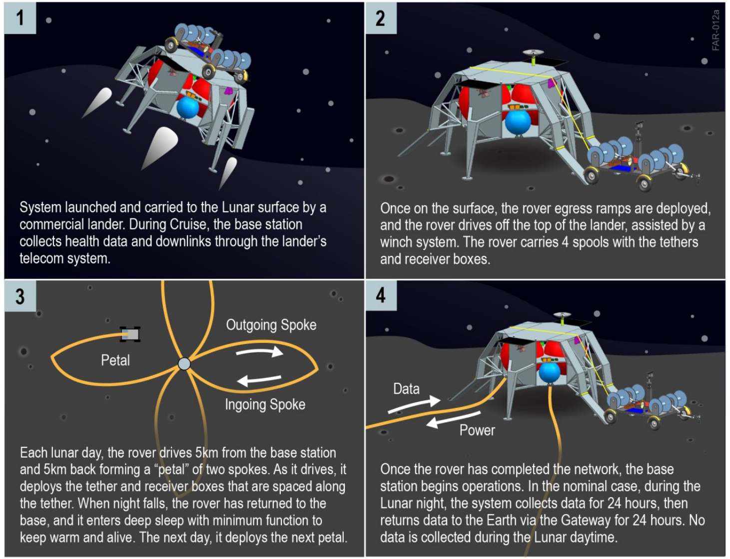
LCRT: modern incarnation of the crater concept
PI: Saptarshi Bandyopadhyay

DuAxels actually exist



FARSIDE:



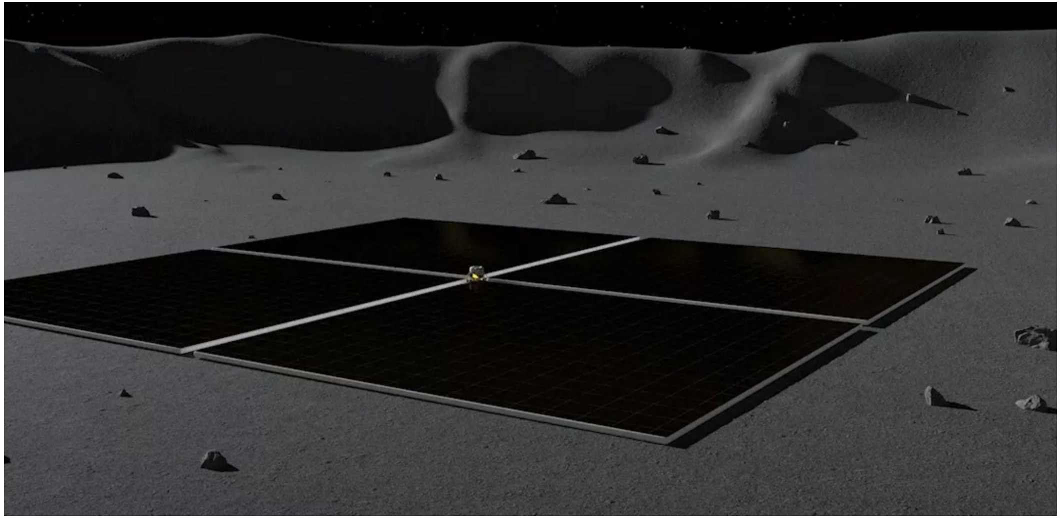


Lands and installs a 128-node interferometric array of dipole antennas

PI Jack Burns

ALO: Astronomical Lunar Observatory

- Inflatable 32x32 array
- 1-80 MHz, total cargo ~1500kg
- launch ~2027-2029
- PI: Marc Klein Wolt
- ESA funded conceptual design level, designed by ASTRON in Netherlands
- See Koopmans' talk



Motivated by the hierarchy problem….

New Journal of Physics
The open access journal at the forefront of physics

Deutsche Physikalische Gesellschaft DPG
IOP Institute of Physics

Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

OPEN ACCESS

RECEIVED
1 July 2021

REVISED
25 October 2021

ACCEPTED FOR PUBLICATION
7 January 2022

PUBLISHED
22 February 2022

PAPER

A very high energy hadron collider on the Moon

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Keywords: high-energy physics, future colliders, beyond the standard model, high-temperature superconductors, lunar science, space travel, megastructures

Abstract

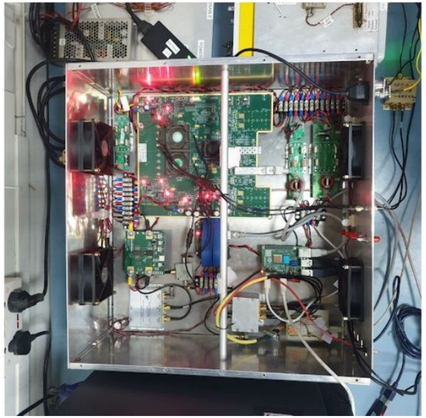
The long-term prospect of building a hadron collider around the circumference of a great circle of the Moon is sketched. A circular collider on the Moon (CCM) of ~11 000 km in circumference could reach a proton–proton center-of-mass collision energy of 14 PeV—a thousand times higher than the Large Hadron Collider at CERN—optimistically assuming a dipole magnetic field of 20 T. Several aspects of such a project are presented, including siting, construction, availability of necessary materials on the Moon, and powering, as well as a discussion of future studies and further information needed to determine the more concrete feasibility of each. Machine parameters and vacuum requirements are explored, and an injection scheme is delineated. Other unknowns are set down. Due to the strong interest from multiple organizations in establishing a permanent Moon presence, a CCM could be the (next-to-) next-to-next-generation discovery machine for high-energy particle physics and a natural successor to next-generation machines, such as the proposed future circular collider at CERN or a super proton–proton collider in China, and other future machines, such as a collider in the Sea, in the Gulf of Mexico. A CCM would serve as an important stepping stone toward a Planck-scale collider sited in our Solar System.

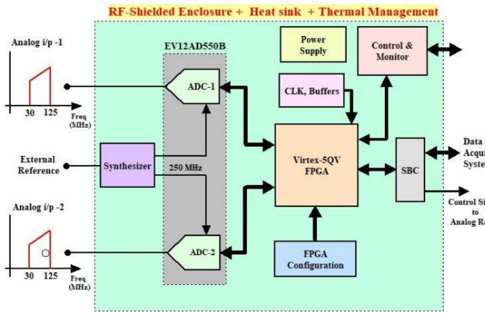

Bayt.com Blog:
Back to Reality: How to Ease into Work After a Relaxing Vacation

PRATUSH

- 40 - 200 MHz (55 - 110MHz baseline design)
- PI Mayuri S Rao
- Currently in design phase with ISRO
- PRATUSH antenna sits right on top of the spacecraft
- All electronics (PRATUSH + satellite) enclosed beneath the antenna
- Observations are made when in the shadow region on the lunar farside
- data is downlinked when in view of the Earth on the nearside.
- All subsystems are individually designed to be maximally smooth

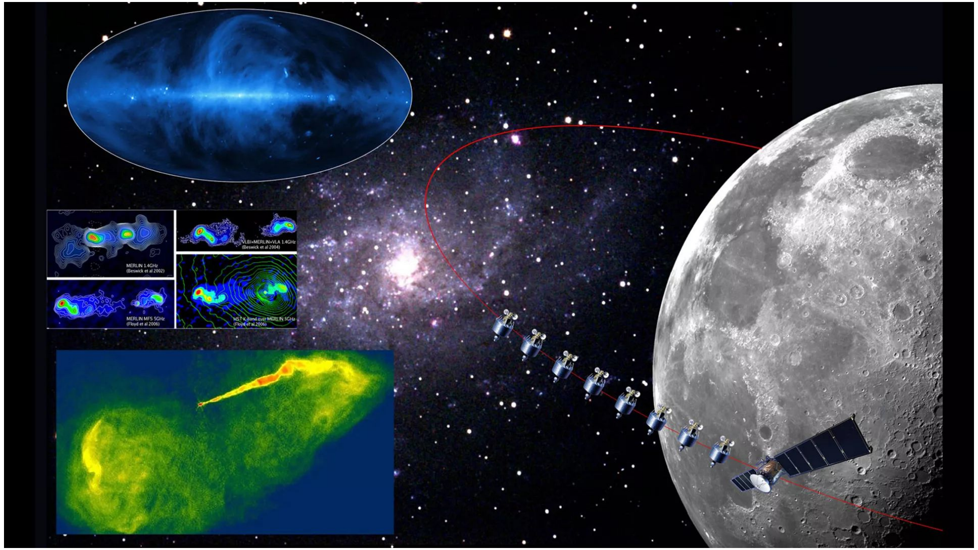
Monocone antenna design on shaped reflector (55 -110 MHz)





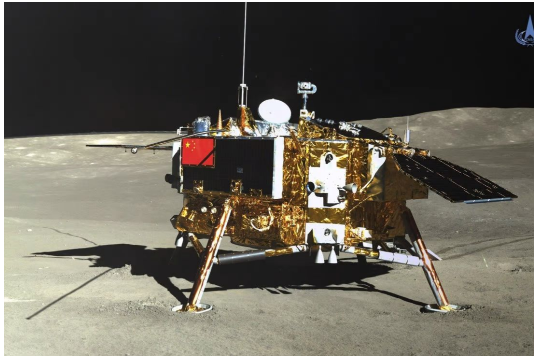
Hongmeng Project: Discovering Sky at the Longest Wavelength

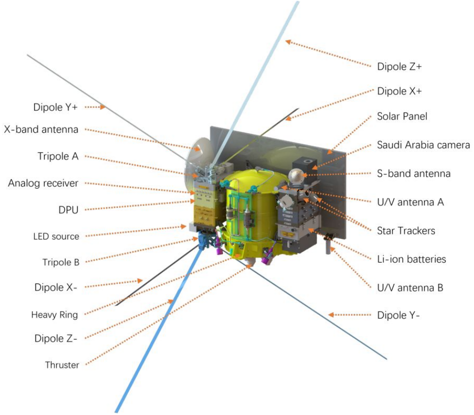
- Chinese proposed effort
- PI Xuelei Chen
- Mother + 8 daughter satellites
- tunable receiver below 30MHz
- A two satellite pathfinder did not manage to get fringes last year due to failure of one of the satellites
- See Wu’s talk

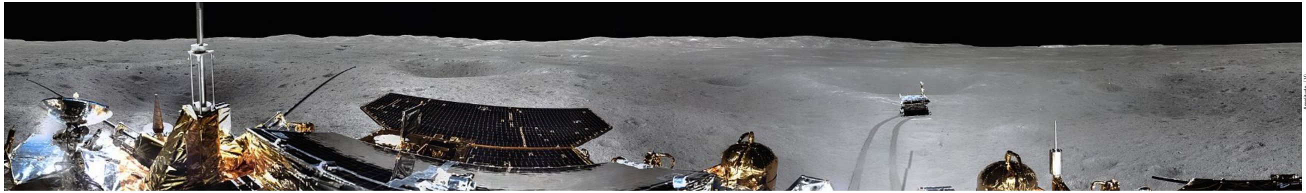


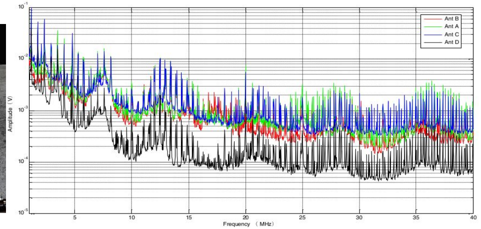
Chang’e-4

- Chinese Lander to the Far Side of the Moon
- Achieved first soft landing on the far side of the Moon, on 3 January 2019
- Carried Low. Frequency Radio Spectrometer (LFRS) on lander
- Carried NCLE (Netherlands-China Low-Frequency Explorer) on relay satellite
- Both instruments believed to be dominated by switching noise
- carried extra antenna to detect that, but no cigar





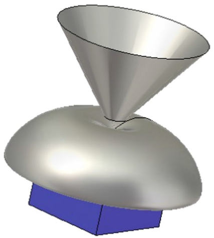




Do you want to be on the Moon or in orbit?

Advantages of orbit:

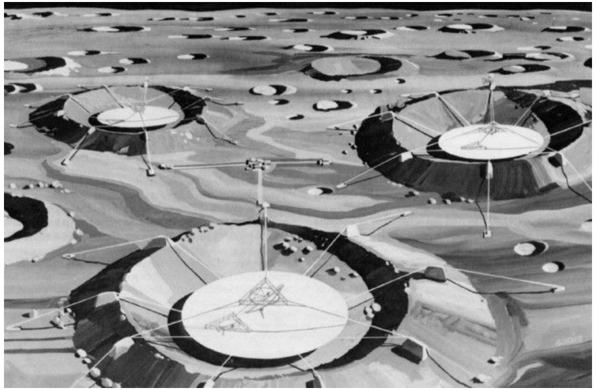
- system to simulate is compact and considerably smaller than wavelength
  - The entire system can be made geometrically simple and symmetric
- power management is easier: can re-charge every few hours
- orbit is cheaper than landing
- easy to implement rotation modulation (e.g. through tumble)



PRATUSH concept

Advantages of lunar surface:

- Long, stable nights
- Stabler baselines for interferometers
- Potentially quieter environment with less dense plasma



Meanwhile, in the US: Confluence of a few factors...

Department of Energy

Department of Energy and NASA Sign Memorandum of Understanding

OCTOBER 20, 2020

Energy.gov » Department of Energy and NASA Sign Memorandum of Understanding

WASHINGTON, D.C. – Today, U.S. Secretary of Energy Dan Brouillette and NASA Administrator Jim Bridenstine signed a new memorandum of understanding (MOU) furthering the longstanding partnership between the Department of Energy (DOE) and NASA that has enabled 50 years of notable space exploration.

The agreement – discussed during the October 2020 Secretary of Energy Advisory Board meeting – supports President Trump's Space Policy Directive-1 and other U.S. national space policies. Under the directive and NASA's Artemis program, America will land the first woman and the next man on the Moon by 2024 and establish sustainable lunar exploration by the end of the decade to prepare for the first human mission to Mars.

"From achieving a better understanding of the Moon, to providing the nuclear fuels to propel Voyager 1 and 2 into space, DOE and NASA have been strong collaborators in our Nation's space mission for decades," said Secretary Brouillette. "This new MOU will continue our esteemed work together as this Administration strives to reach the next generation of space innovations and exploration."

"Artemis depends on a coalition of partners across U.S. government, industry, and the world," said NASA Administrator Jim Bridenstine. "The DOE's energy, science, and technology expertise remains crucial to the success of NASA missions. Together, we will mature and ready systems for exploring more of the Moon and venturing humans farther into space, all for humanity's benefit on Earth."

Request for Information Related to High Energy Physics and Space-Based Astrophysics

JANUARY 22, 2021

Office of Science » Request for Information Related to High Energy Physics and Space-Based Astrophysics

On behalf of the Department of Energy's (DOE) Office of Science and the National Aeronautics and Space Administration's (NASA) Science Mission Directorate, we invite interested parties to respond to this Request for Information (RFI) on collaborative activities that further scientific advances in high energy physics and space-based astrophysics, in support of our shared scientific goals.

NASA - DOE MOU

- a top down effort to encourage agencies to collaborate
- followed by a request for information asking for short white-papers:
  - potential lunar surface missions on the far side of the Moon;
  - space-based probes of fundamental physics on the International Space Station;
  - synergies in the use of data from the Vera C. Rubin Observatory, the Nancy Grace Roman Space Telescope, and the Euclid mission.
- Anecdotally, lunar missions and dark energy synergies attracted most attention

CLPS - Commercial Lunar Payload Services

- advent of SpaceX taught NASA that a lot of money can be saved with commercial providers
- a similar program is developed to support Artemis program:
- Now at ~11 eligible vendors that bid on contracts
  - Number of vendors is expected to settle around ~a few.
- awarding 1-4 missions every year
- actively looking for payloads through PRISM (Payloads and Research Investigations on the Surface of the Moon) calls and otherwise
- they view payloads as essentially an exercise in how to run the contracting process
- first launches expected in ~~June~~ November 23 (from awards in 2019)

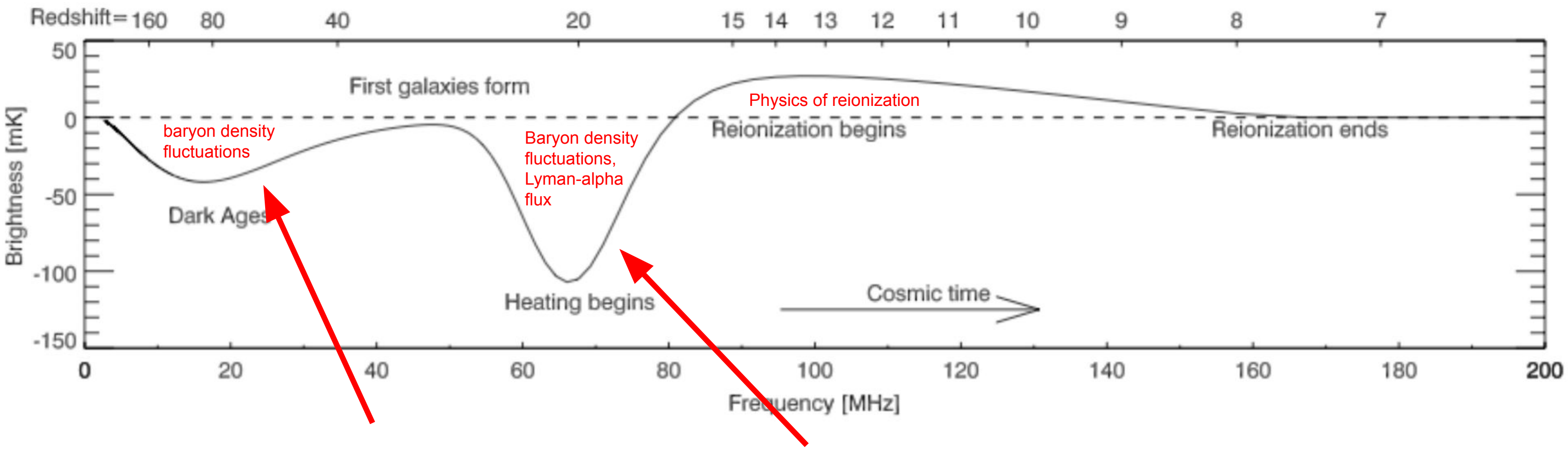
Landers selected in the first round: Peregrine (Astrobotic Technology), Nova-C (Intuitive Machines), Z-01 (OrbitBeyond)

21cm relevant CLPS missions

- ROLSES:
  - Radiowave Observations at the Lunar Surface of the photoElectron Sheath
  - Launching on Intuitive Machines 1 Mission
  - See next talk by Jack Burns
- LuSEE-Night:
  - part 3 of this talk

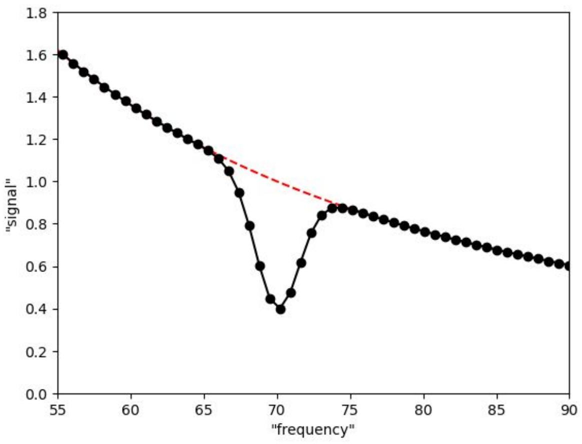
Part 2 (intermezzo):
Dark Ages Foreground Isolation

How do we extract signal and how does this affect the instrument design?



- We are trying to identify the shape of the throughs
- The propaganda is: foregrounds are smooth, signal is not

Smoothness separation



- We want to identify a presence of a sharp feature on the smooth background
- The process:
  - fit a smooth “foreground” away from the expected peak position
  - subtract the smooth component
  - what remains is is the signal of interest
- For this to work, **the uncertainty in background determination should be subdominant:**
  - i.e. it shouldn’t matter what functional form I use for fitting the background
- For smooth, e.g. power-law like foregrounds

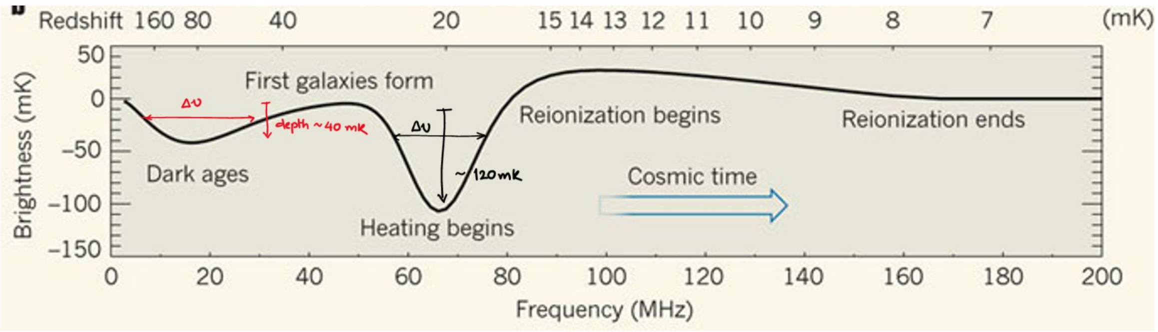
$$\frac{\Delta F}{F} \sim \frac{\Delta \nu}{\nu}$$

- And foreground fit uncertainty over the feature width will scale the same
- Therefore, the “smoothness separation” paradigm only works when

$$\frac{S}{F} \gtrsim \frac{\Delta \nu}{\nu}$$

- Feature should be either very localized, or fractionally large
- Otherwise, the answer will depend on the foreground functional form

Will the smoothness separation work for the monopole?

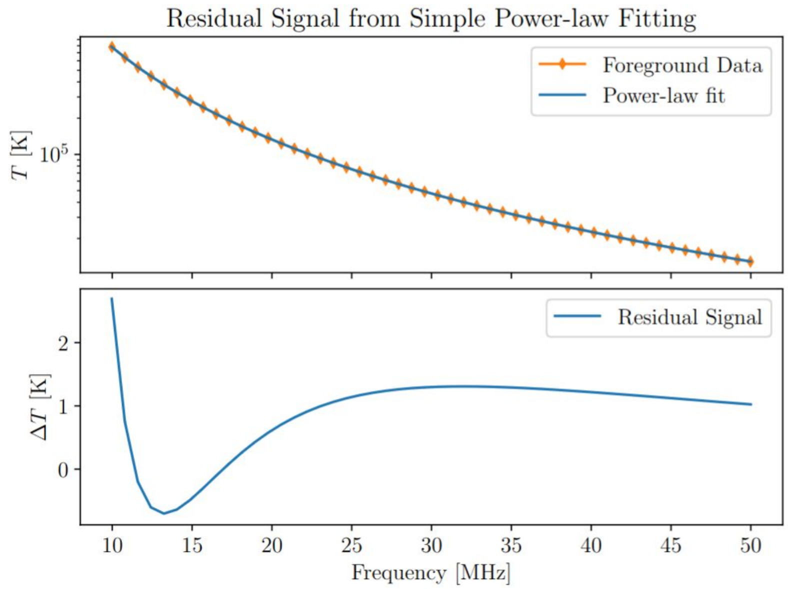


Signal	S/F	$\Delta\nu/\nu$	Does it work?
BAO	~0.3	~0.2	Yes, barely (but we have no-wiggle theory)
Cosmic Dawn	~10^{-3}	~0.1	No.
Dark Ages	~10^{-5}	~1	Fuck no!

Ergo the incessant EDGES fights

To drive the point home...

- Take a sum of two power-law with indices -2.54, -2.56
- Fit with a single power law (get spectral index -2.55)
- Look at the residuals
    - residual feature is no broader than the Dark Ages signal
    - Yes, you can absorb it, but then so you will absorb the Dark Ages signal...



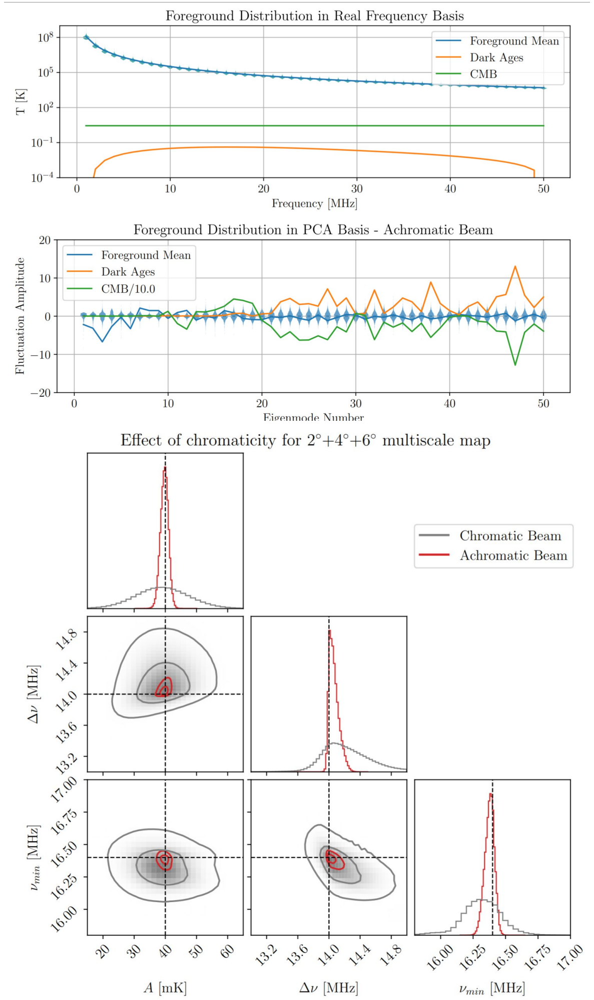
What is the way out?

- You need to add more information:
  - more actual data – spatially resolved spectra
  - priors (theoretical or otherwise)
- Approach 1:
  - write down a complete Bayesian model for your data, your instrument and any additional information
  - perform an optimal Bayesian analysis
  - you need to describe data at 10^{-5} level:
    - will likely need many thousands, potentially a million parameters
    - need to go beyond's
  - see Rapetti's talk
- Approach 2:
  - use foreground fluctuations to build a data-driven model of foregrounds
  - very different set of assumptions

Pund and Slosar, in prep

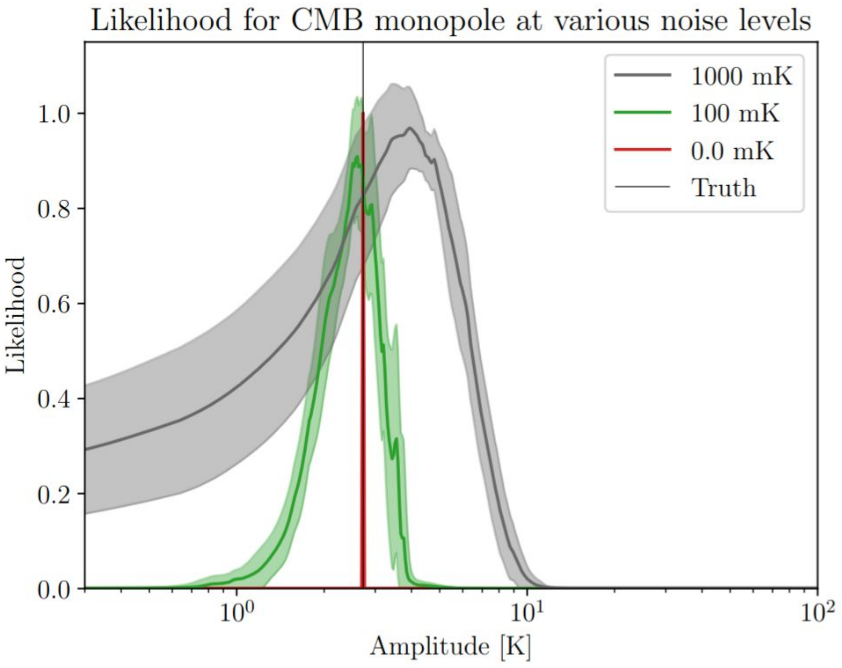
- Replace "signal is smoother than foregrounds" with "foreground fluctuations around the mean are generated by the same process as the foreground mean"
- Defensible assumption, but it is a physical one
    - if foregrounds are generated by some local process, the beam will modulate them
- Chromaticity still hurts:
    - spreads foregrounds over larger number of "shape" space
- Transfer function:
    - hurts less: need to know beam to percent rather than ppm
- Gain fluctuations:
    - hurt more: they make signal appear as a foreground
    - percent level control is sufficient

- Simulation using a Cong et al ULSA maps
- 2 degree resolution instrument with galactic cut
- Fit 3 parameter model; dark ages signal scaled by:
  - amplitude
  - central frequency
  - width
- First 20 SVD modes lost to foregrounds, but some information remains

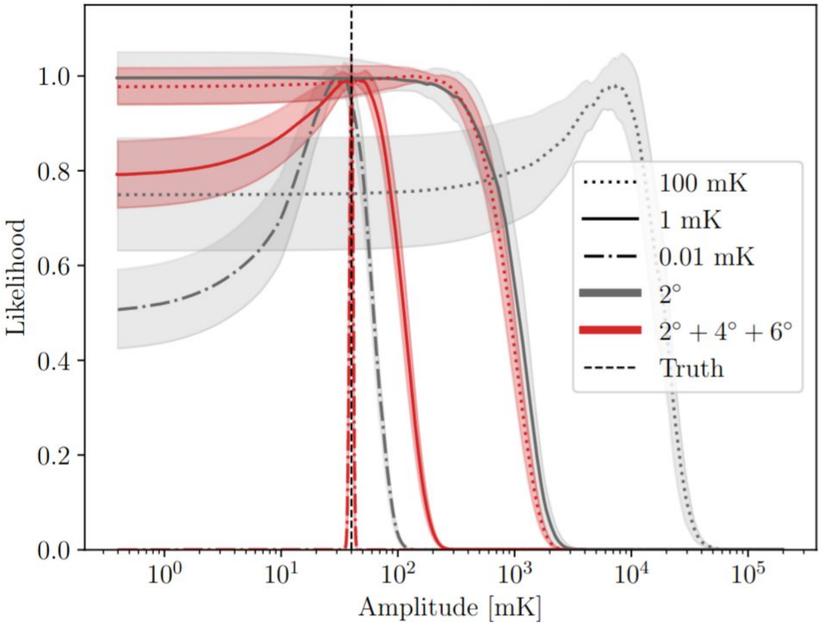


Chromaticity hurts – automatically

Some results



We can recover CMB!



Multiscale maps help a lot.

Part 3
LuSEE-Night

NASA-DOE LuSEE partnership

- UC Berkeley’s Space Sciences laboratory (SSL) was chosen to provide a payload for a 2024 CLPS mission.
- Original LuSEE (Lunar Surface Electromagnetics Experiment) targeted plasma science, but incorporated a 20MHz RF spectrometer:
  - concept heavily relied on reusing existing spare parts from Parker Solar Probe
- A synergy with DOE’s 21cm cosmology program was realized, and the mission was extended to include a dedicated, multi-night instrument dedicated to Dark Ages science
- Original concept split into 2+1 parts:
  - LuSEE-Lite - focus on day time solar science on CP-12
  - LuSEE-Night - focus on night-time radio science on CS-3
  - Far field calibration “service provision” on CS-4
- Will follow NASA CLPS schedule: launch date 25/9 - 26/1
- This is now a fully funded effort

Parker Solar Probe

Overarching Science Goals

LuSEE-Night is a pathfinder for the Dark Ages Science from the far-side of the Moon:

Goal 1: ***Establish the Lunar surface as a viable observatory for low-frequency radio astronomy;***

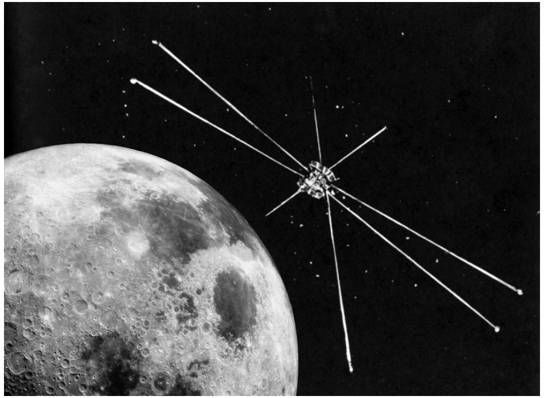
Goal 2: ***Perform the most sensitive observations of the radio sky at 1-50MHz with 20% absolute calibration;***

Goal 3: ***Quantify the systematic effects affecting global spectrum measurement accuracy, and investigate methods to mitigate them;***

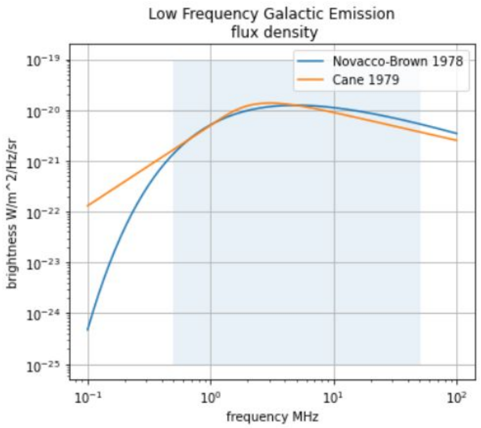
Goal 4: ***Constrain the presence of a non-smooth monopole component at the 10^{-3} level compared to foregrounds.***

LuSEE-Night: A Dark Ages Pathfinder

- The main problem is that the Dark Ages signal is buried under order of magnitude brighter emission from foregrounds
- Currently the most informative data on low-frequency radio sky are from 1970s
- Our main goals are to update knowledge with modern instrumentation and pave the way for subsequent instrumentation
- We need to understand the limiting systematics on the Moon's surface:
  - how stable it really is?
  - how important are the effects of the regolith?
  - how important are transients, micrometeorites and similar?
  - etc



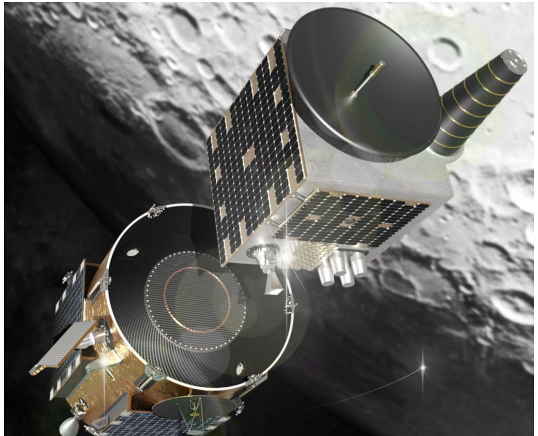
Radio-Astronomy-Explorer-2 was the largest spacecraft ever built with four 230m antennas



Data from 1970s:
still state of the art

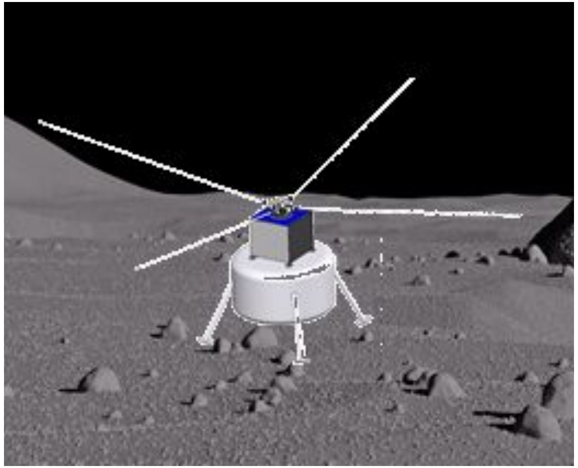
CLPS provider has been selected!

- Firefly Aerospace will take LuSEE-Night on the Moon on the Blue-Ghost 2 mission
- Launch 12/25, lading 1/26
- Lunar-Pathfinder and LuSEE-Night are main payloads



LuSEE-Night instrument

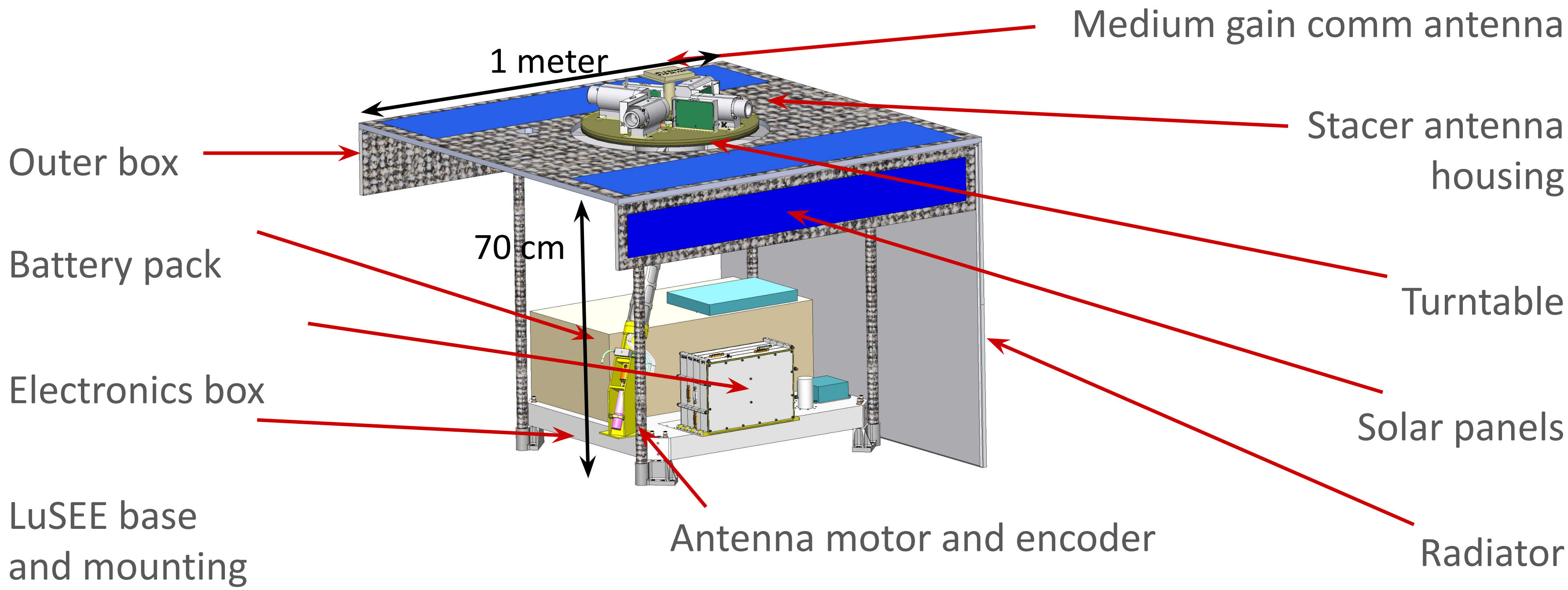
- Instrument design largely driven by the project timeline
- We need to optimize within the limits of:
  - max heritage technology
  - realistic improvements given budget
  - budget includes $, power, time-to-develop
- Basic design includes:
  - 4 STACER antennas
  - ability to actuate in azimuth
  - independently amplified
  - all possible cross-correlations measured and integrated with full bandwidth spectrometer
  - 4 real auto-correlations
  - 6 complex cross-correlation quantities, including two pseudo-dipoles



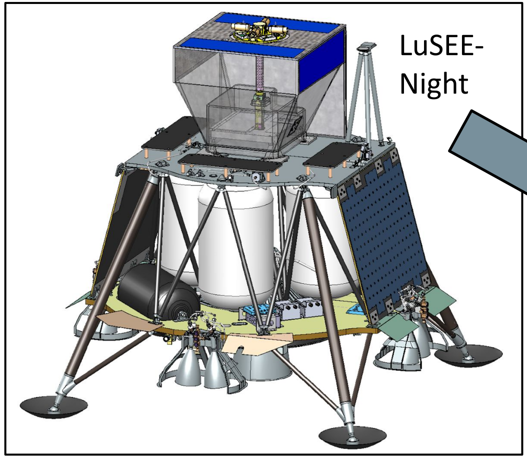
scientists' render

CLPS provider's render

LuSEE-Night payload



LuSEE-Night

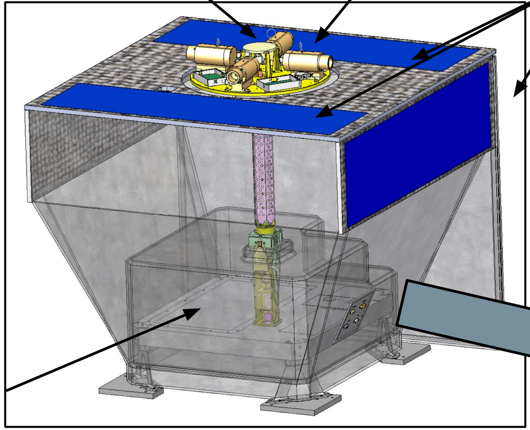


Firefly Blue Ghost Lander

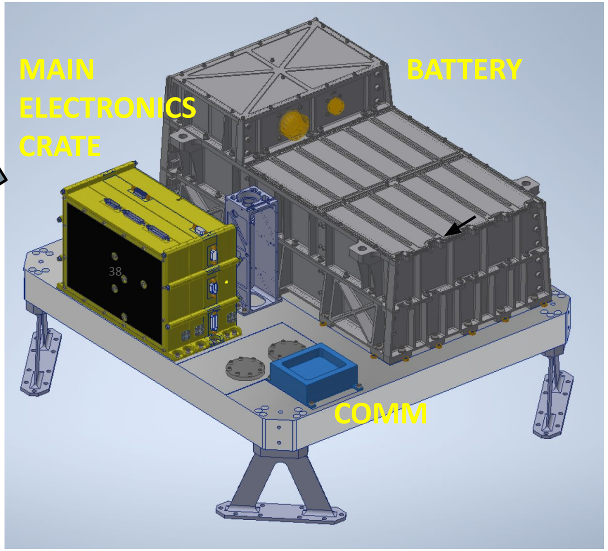
S-band communication antenna

Science Antenna carousel

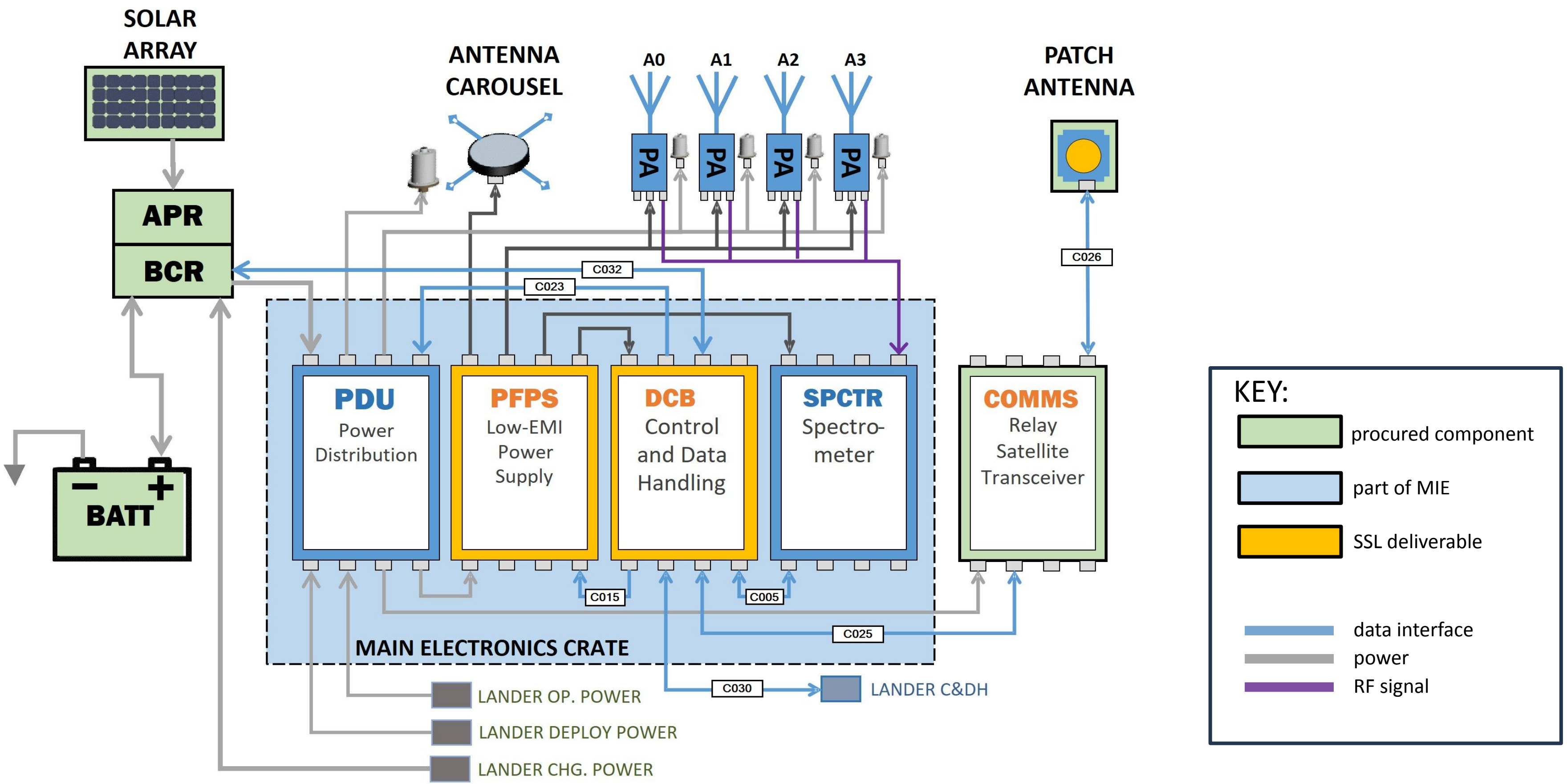
Solar Panels



INNER EQUIPMENT ASSEMBLY



Instrument Block Diagram (Aug 2023)

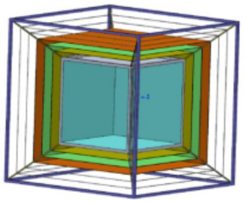


Challenges of a radio telescope on the Lunar far-side

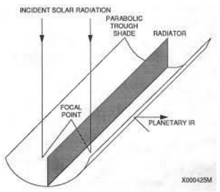
- Thermal management:
  - how to keep cool during the day
  - how to keep warm during the night
- Power management
- Data transfer
- Antenna performance
  - modulation
  - calibration

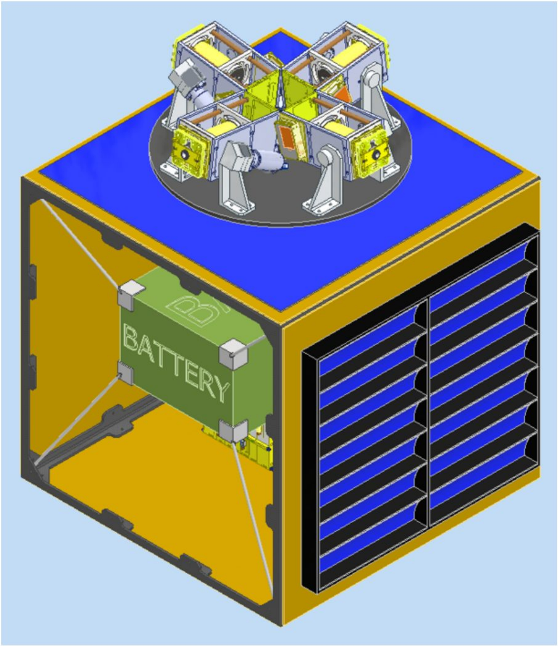
Thermal management

- A major consideration of the design
- Without atmosphere, everything is radiativelly coupled
- We copied Farside Seismic Suite concept
- During the night:
  - Sky at 3K, lunar surface at 100K
  - box-in-a-box concept with sufficient thermal insulation:
    - spacerless mylar insulation
  - ~20W battery dissipation keeps ut sufficiently warm passively



- During the day:
  - a variable conductance heatpipe
  - a parabolic radiator facing 3K





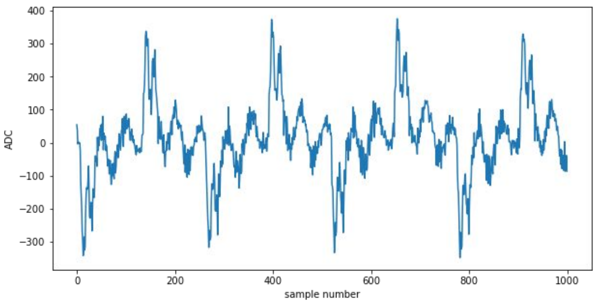
Power and Battery subsystem

Battery

- Our battery use is very atypical for space use:
  - We will recharge at most 20 times
- 50% of payload weight (~40kg) in battery
- 6500Wh with margin

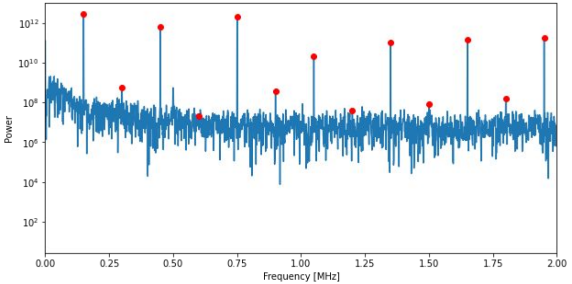
Picket-fence power supply

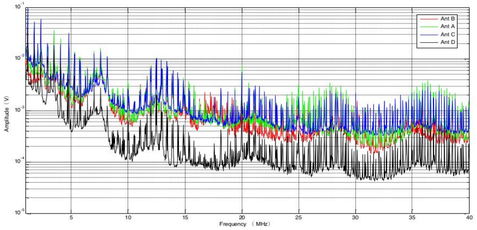
- picket-fence RFI management: all switching power supplies synched to the same master clock that also drive ADC
- All RFI confined to a base frequency + harmonics
- very strong requirement on lander complete death after first sunset
- Spikes can be removed very efficiently with DSP in spectrometer with negligible signal loss
- Self-RFI plagued the Chang’e-4



raw-signal from the parker solar probe

Cannot resolve width of these lines (<1Hz)

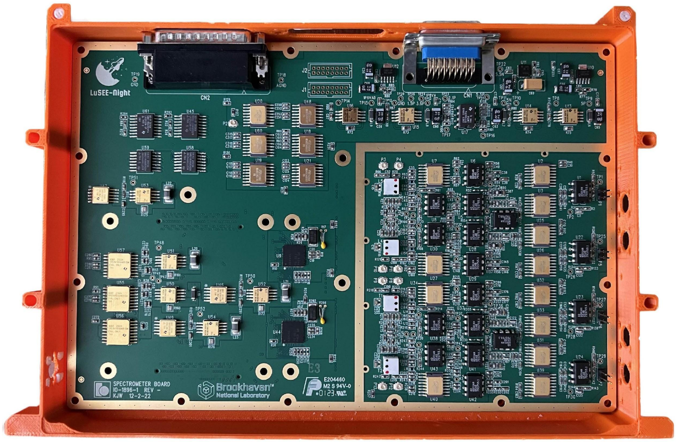




Chang’e-4 data dominated by platform RFI

Spectrometer design

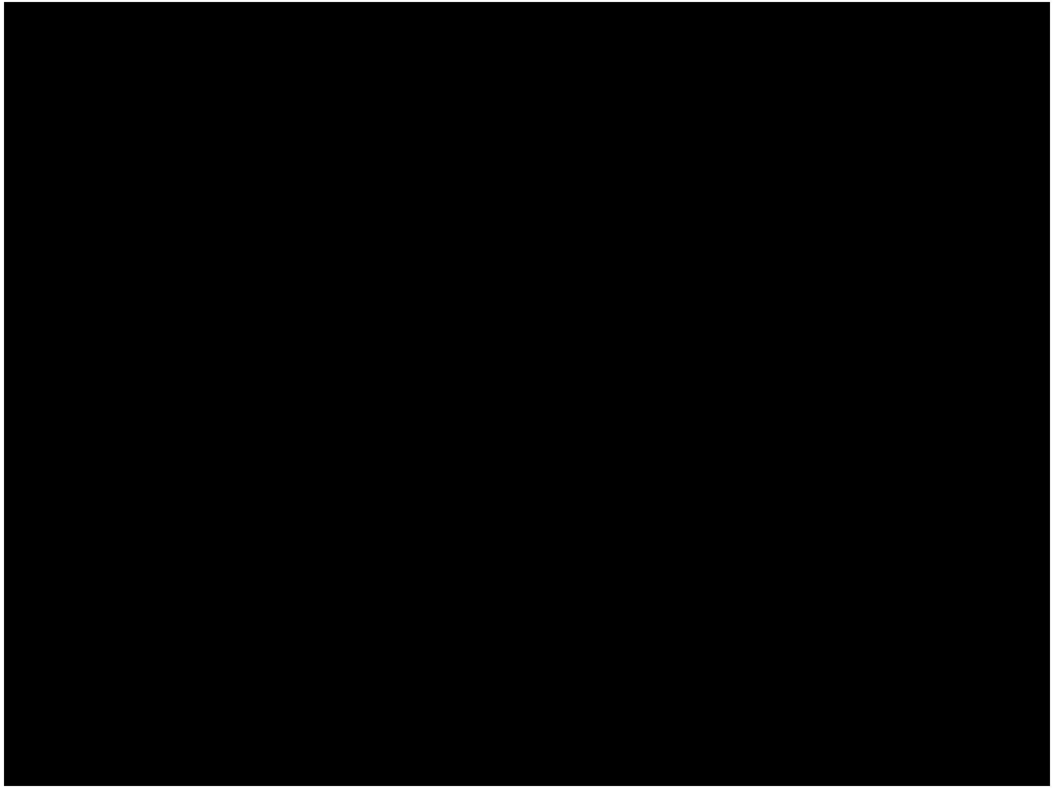
- Our design strongly based on the Parker Solar Probe Radio Frequency Spectrometer
- Updated FPGA, bandwidth, number of channels
- Nominally 2048 channel polyphase filter-bank
- But fancy:
  - notch filter
  - x64 single bin selectable zoom:
    - 400 Hz resolution, can resolve Faraday rotation
  - calibrator support



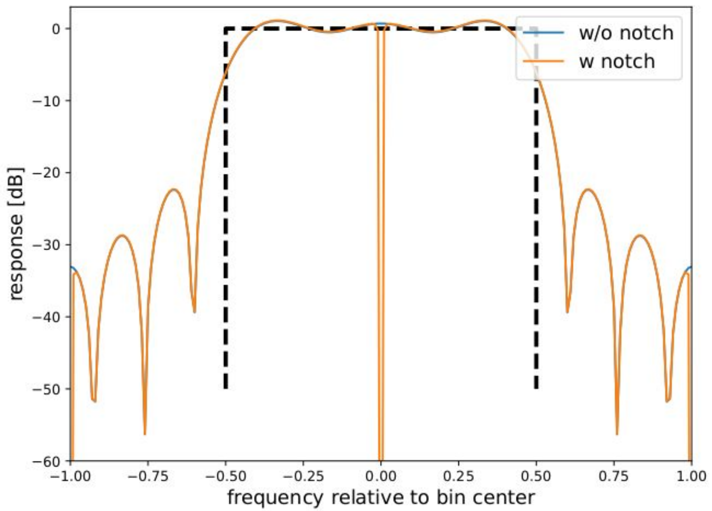
Spectrometer parameter	Experiment	
	Parker RFS (HF channel)	LuSEE-Night
Frequency range	0.01 – 19.2 MHz	0.5 – 50.0 MHz
Digitizer channels	2	4
Sampling clock	39 MSPS	100 MSPS
Duty factor	~1%	~100%
FPGA	RTAX4000	RTG4
Correlation products	2	6
Transient capture	No	Yes

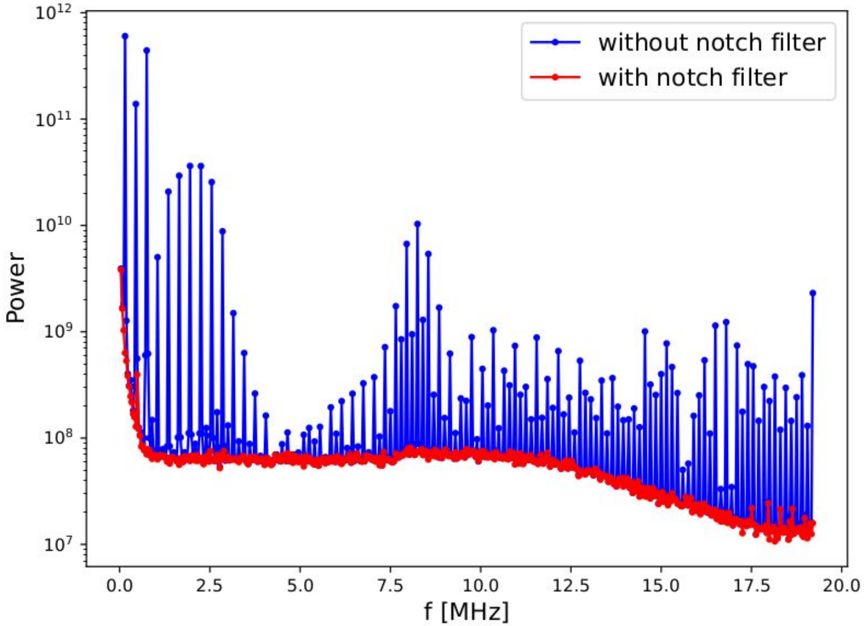
Current devel version runs full 51.2MHz bandwidth, 2-input, 2048 channel spectrometer on <0.6W.

Spectrometer movie



Notch filter to remove picket-fence





Actual PSP waveforms through our firmware

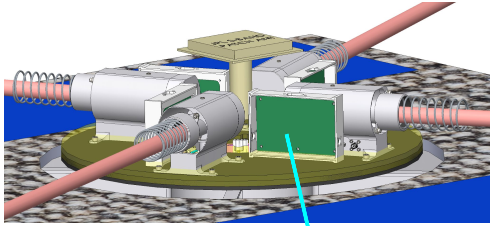
Antennas: science requirements

1. Smooth spectral response
2. Sensitivity
3. Polarization-sensitive
   - To separate polarized foregrounds from unpolarized Dark Ages
4. Manage effect of lunar regolith
5. Mitigate systematics

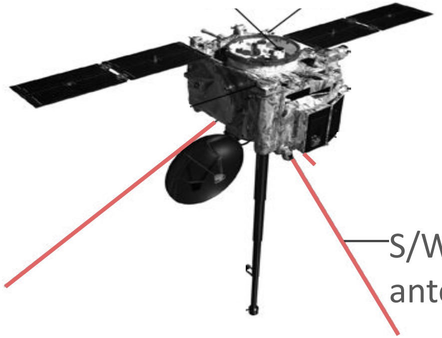
Mission requirements:

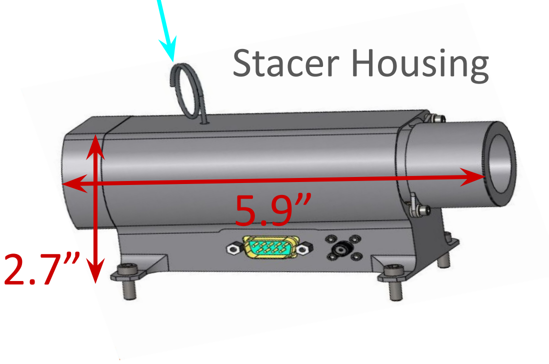
- High TRL
- Light, compact, robust
  - Antenna subsystem < 7.8kg

Four 3-meter monopole antennas



STEREO/WAVES

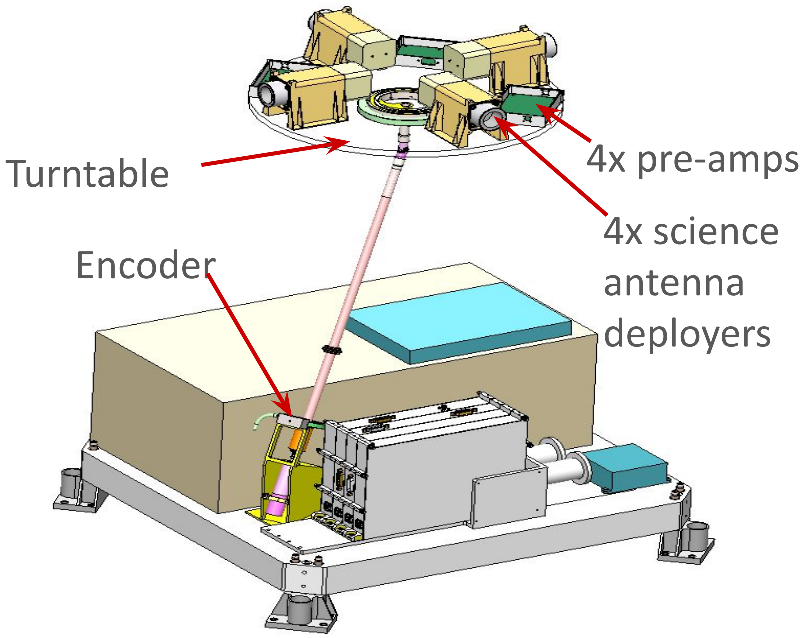




Covering stokes parameter, mitigation of systematics

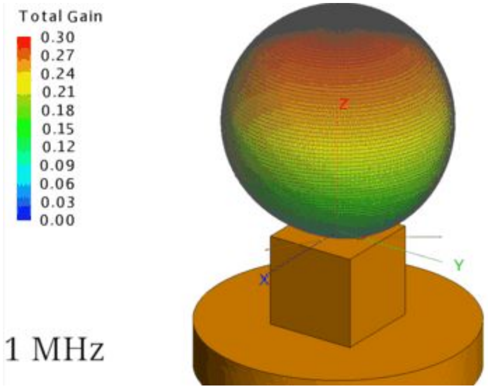
- Φ rotation ✔
  - Machined Al turntable
    - Diameter ~ 400 mm
    - Thickness ~ 10 mm
  - Rotation monitored by encoder
    - ± 95°, < 0.1° precision

Sensitively separate
➢ Sky signal / analog chain / regolith

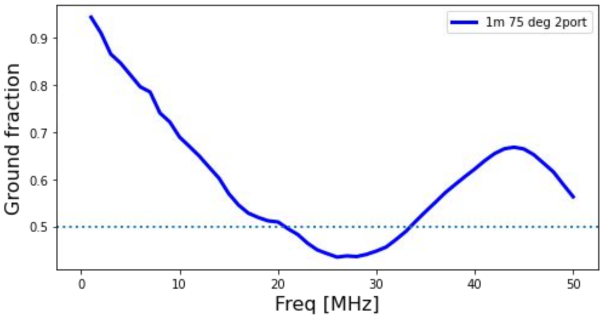


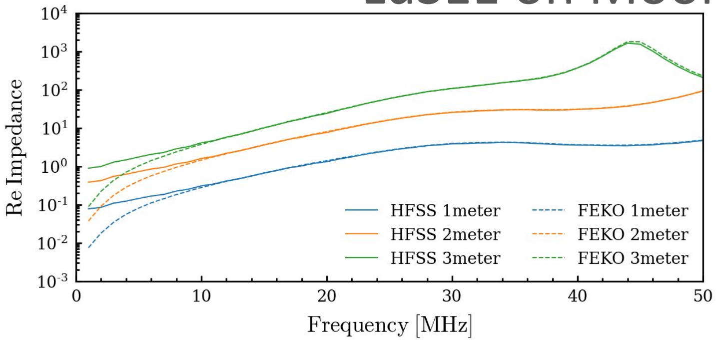
Modeling LuSEE on the lunar far-side

- Optimizing antenna design within mechanical constraints is challenging
- Chromaticity unavoidable
- Beams affected by lander and regolith.
- Fraction of power absorbed by (dielectric) regolith significant
- Have done significant work comparing results with three simulation packages (CST, HFSS, FEKO)

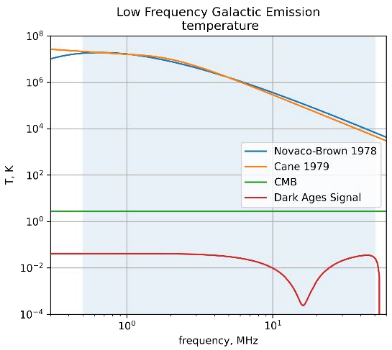


LuSEE on Moon





Signal to noise considerations



- Signal to noise is governed by the radiometer equation:

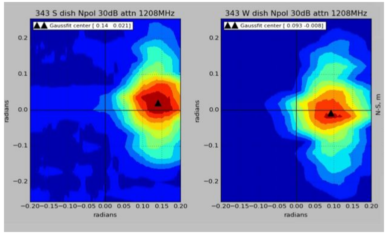
$$\Delta T = \frac{T_{\rm sky} + T_{\rm noise}}{\sqrt{Bt}}$$

- LuSEE-Night is a 4 element interferometer, so O(1) factors better
- Square root factor is a experimenter's greatest foe

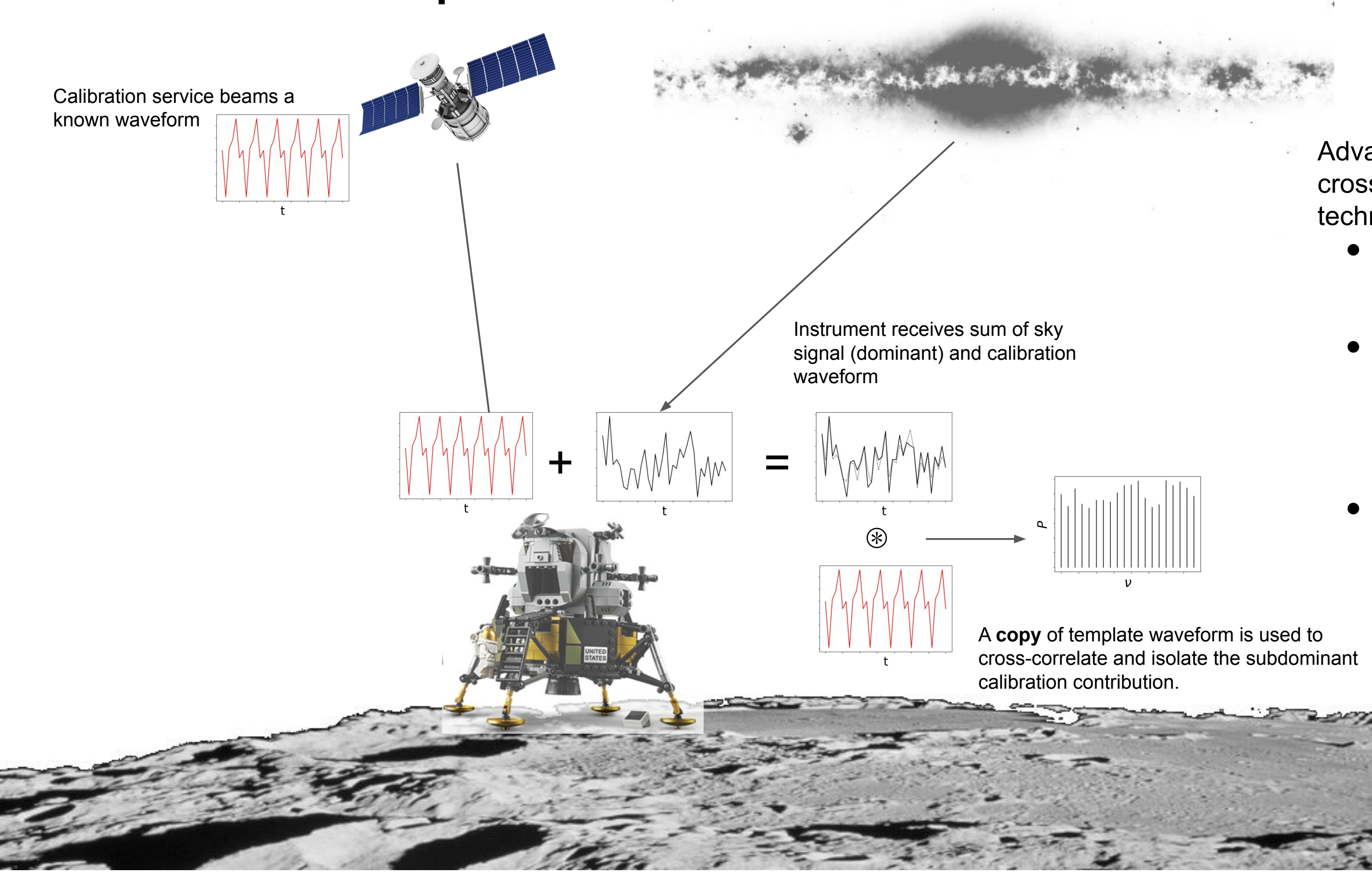
T_{noise} / T_{sky}	0	**0.5 (~design)**	1	2	10
Time to integrate to CMB **(mins)**	8	**20**	30	70	1000
Time to integrate to Dark Ages **(lunar cycles)**	2	**4**	7	17	225

Far-field Calibrator

- Field of 21cm is a study of calibration methods
    - Foregrounds many times brighter
- Precision calibration of radio telescope beams at sub-percent precision remains to be demonstrated
- Many attempts with drones, but nobody has reached required precision
- **A true far-field, power stabilized calibrator is almost certainly necessary for dark ages work:**

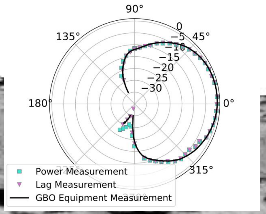


Basic Concept



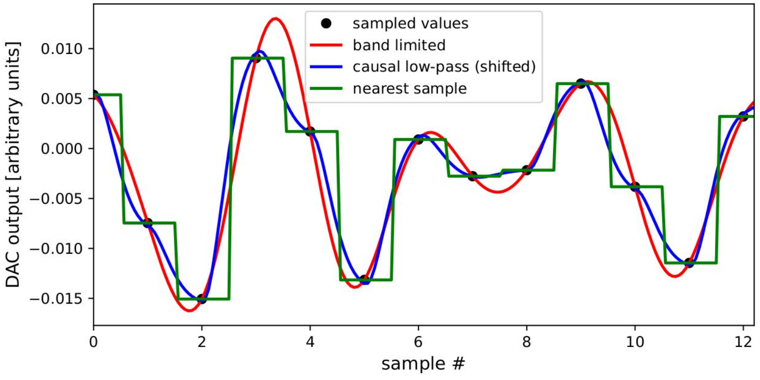
Advantages of cross-correlation technique:

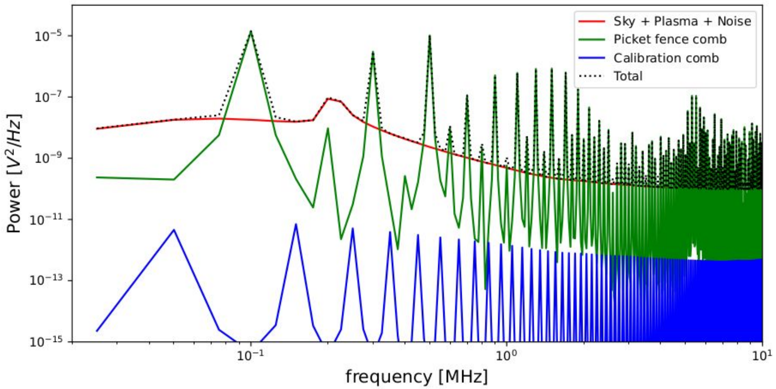
- sky background does not cross-correlate
- only one copy of template attenuated by the distance (1/r scaling), allowing high SNR recovery
- See arXiv:2201.11806 for similar approach on the ground



Calibration scheme

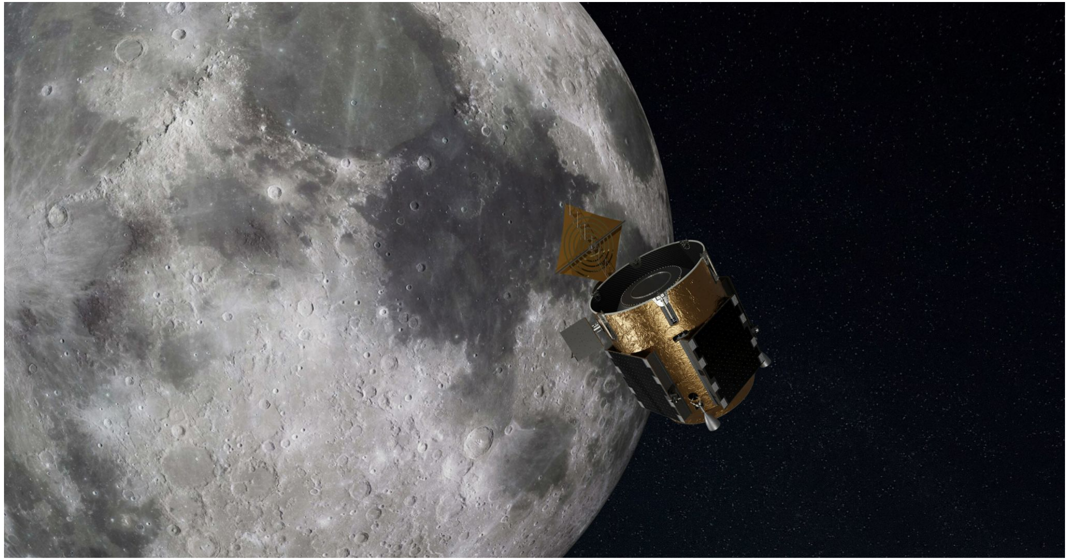
- A pseudo-random waveform of length N is generated so that its Fourier components have random phase and unit argument
- If this waveform is repeated, it generates a frequency comb
- We are detecting this comb, designed to be slotted between our picket-fence comb
- Main issues:
  - relative clock drifts
  - DAC/ADC frequency aliasing





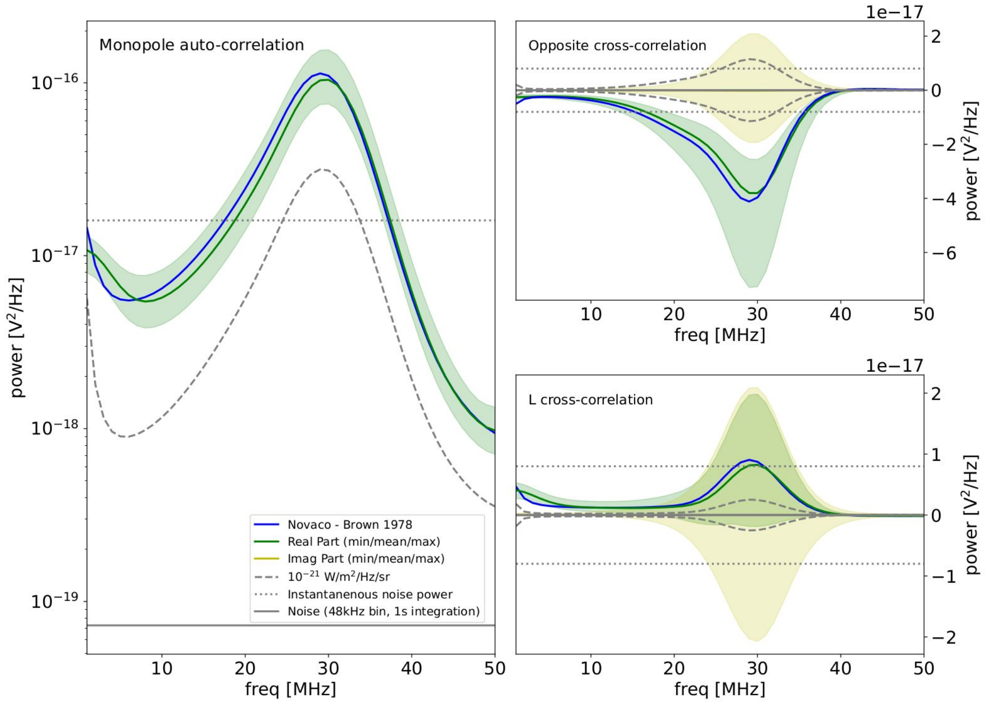
Calibrator status

- Recentl approved CLPS CS-4 mission is for *provision of calibration service*
- Firefly has been selected also as a provider of the calibration service
- Kick-off meeting in October

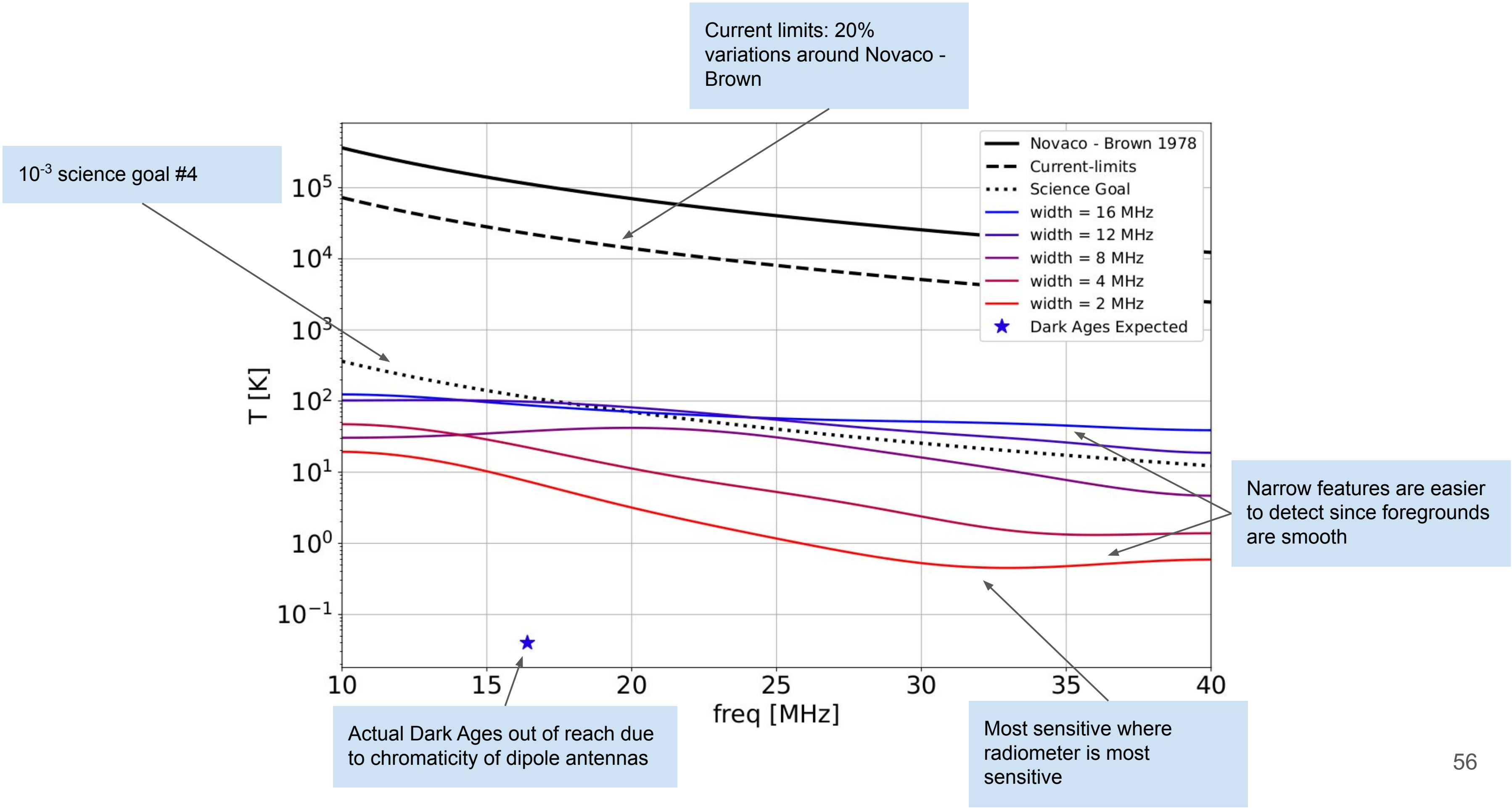


What do we expect to see?

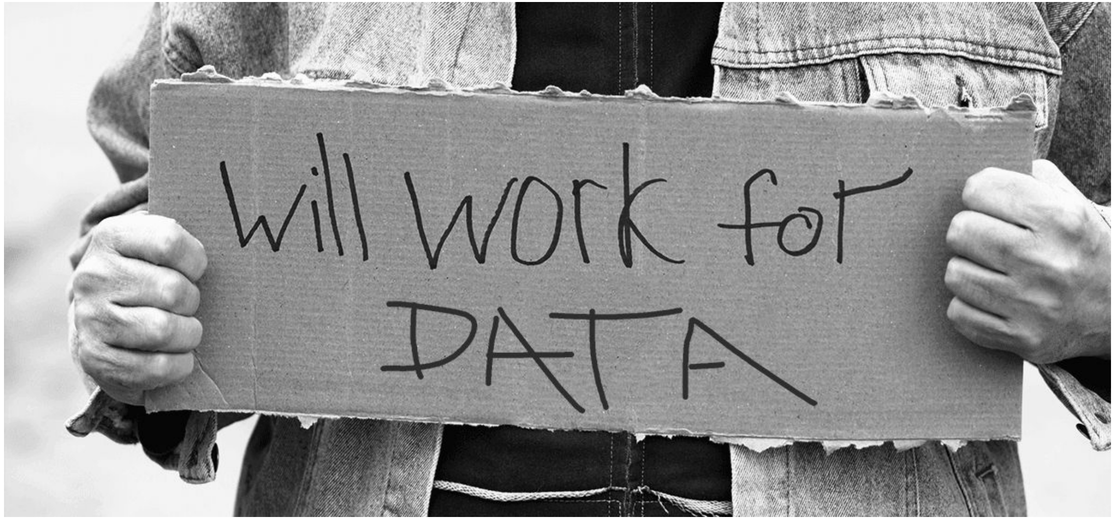
- Mostly galaxy and mostly at around dipole resonance
- Lunar surface plasma:
  - Day:10-20/cm^3 - plasma peak at ~30kHz, might just about see it
  - Night: 0.01-0.1/cm^3 - plasma peak
- Other effects: micro-meteorities, unexpected stuff



Sky Monopole Sensitivity plot



We are looking for a postdoc!



Conclusions

- If many things go to plan
  - LuSEE-Night will establish the viability of radio observations from the Lunar surface
  - LuSEE-Night will produce the most accurate sky map at 1-50MHz
- Project fully funded and manifested on CLPS CS-3 mission
- CLPS provider will be announced 3/13
- For the first time in my life I pray for project delay