Pathfinders for a Radio Telescope on the Far Side of the Moon

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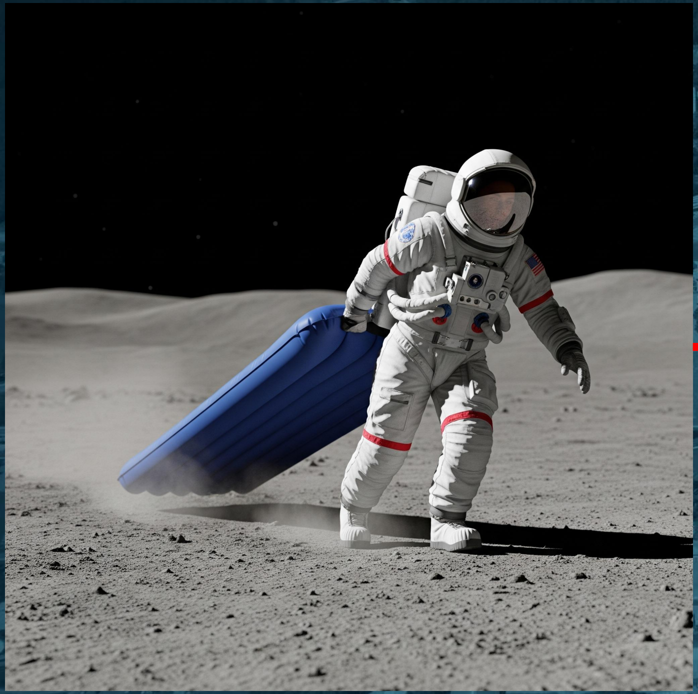


Where we are

Where we want to be

TL;DR

Lunar radio sciences holds big promise, but **significant technical and scientific challenges remain unanswered.**

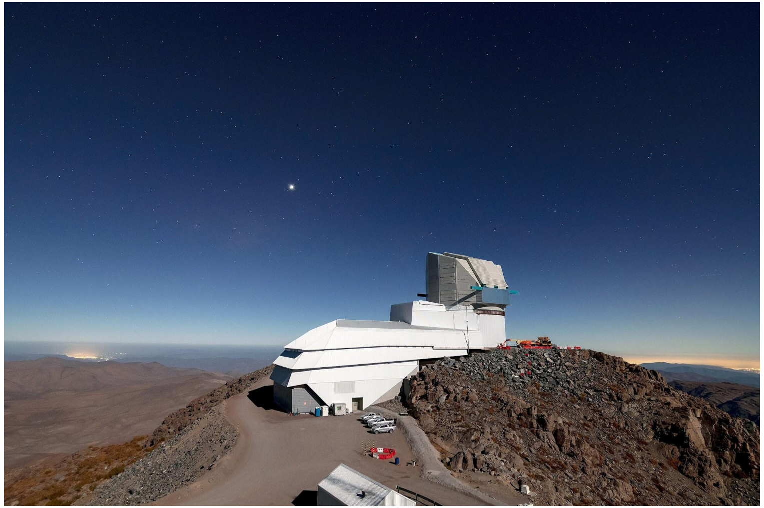
The best way to solve technical challenges is through a rapid iteration/test cycle. Lunar path-finders will tell us:

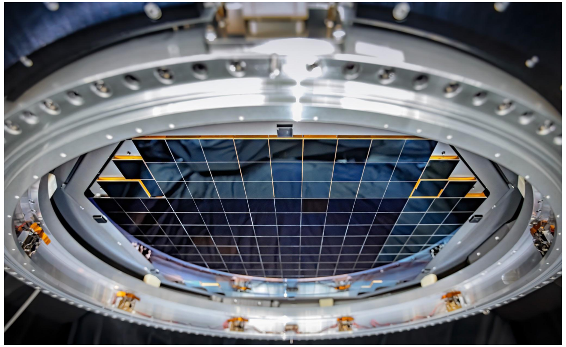
- how to survive the lunar night
- how to efficiently solve thermal & power issues on the Moon
- how to calibrate instruments on the Moon
- how to analyze the lunar data
- what are the actual requirements for successful science

Astronaut assisted deployments can play a crucial role in the process by speeding up the development cycle.

An illustrative story

- LSST focal plane is made of 3x3 rafts
- Requirements on inter-raft abutting were set to 0.5mm in 2000s:
  - the science driver was that we don't want to loose uniformity, because it is bad for lensing science
  - those requirements were challenging to meet
- In the hindsight it was unnecessarily stringent. In the intervening time we learned that:
  - edge sensor effects make lensing measurements useless near the edges: a 200 pixel buffer around CCD edges is discarded anyways
  - analysis has learned how to deal with non-uniformity
- Lessons:
  - **build precursors early and often**
  - **use precursors to set requirements for the flagship missions**
  - **use precursors to design flagship missions based on approaches with heritage**
  - **use them to get to the known unknowns**





Challenge #1: Survive the Lunar Night

- Same things that make Moon appealing (no atmosphere and long, stable lunar nights) make it very inhospitable.
- No modern US robotic mission to the Moon survived the lunar night.
- Surviving the lunar night is deemed #1 priority by NASA Civil Space Shortfall Ranking

Moon is harder than Mars:

ENVIRONMENTAL COMPARISON

Planet	distance	temperature °C		darkness	atmosphere		magnetic field	radiation
	10^6 km	max	min	hrs	gas	pressure psi	μT	rad/year
Earth	-	+30	-35	12	N_2/O_2	14.7	50	0.3
Mars	50	+20	-140	12.3	CO_2	0.1	1.5	25
Moon	0.4	+120	-180	354	-	-	< 0.1	50

In 21st century there were 6 Mars rovers driving over 80km and 1 (chinese) lunar rover driving 0.8km.

Integrated Shortfall Ranking (1-30)

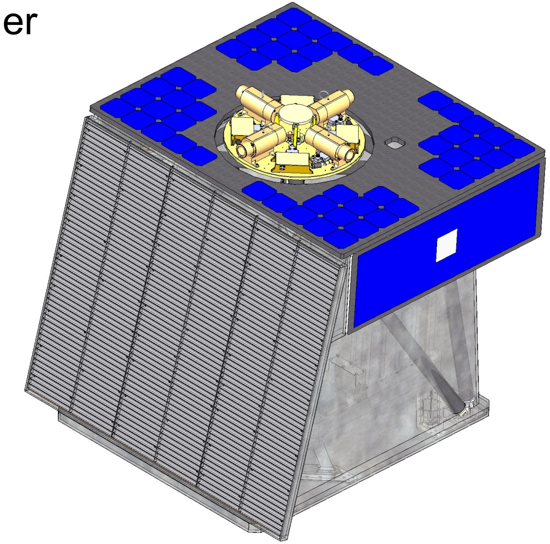
Integrated Rank	Average Integrated Score	Shortfall ID
1	8.1035	1618: Survive and operate through the lunar night
2	7.6118	1596: High Power Energy Generation on Moon and Mars Surfaces
3	7.4345	1554: High Performance Onboard Computing to Enable Increasingly Comp

Challenge #2: thermal + power

- Closely related to surving the night are thermal and power issues.
- Commercial lander providers cannot (yet) use nuclear tech for either heat or power
- 14 days of darkness requires big batteries or their economic use
- The power consumption of a radio array goes with

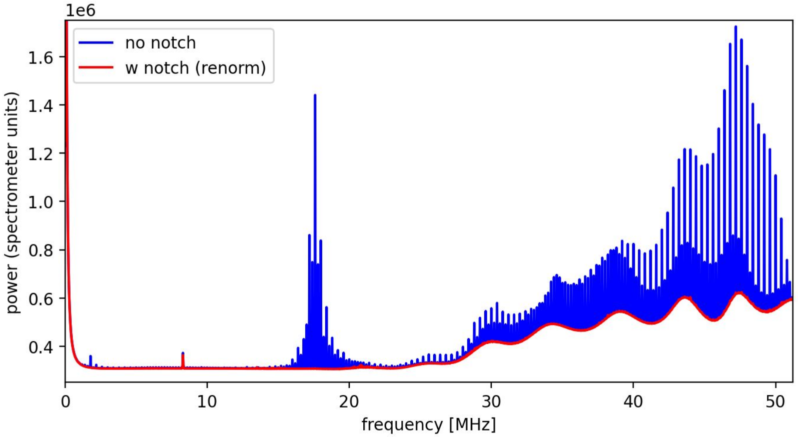
  (Bandwidth) * (# antennas)^2

- An interesting trade-off is that memory is light and batteries are heavy:
  - 100 MHz BW ↔ 0.5-2 W
  - you might be better of storing the data and correlating during the day, when the power is plentiful



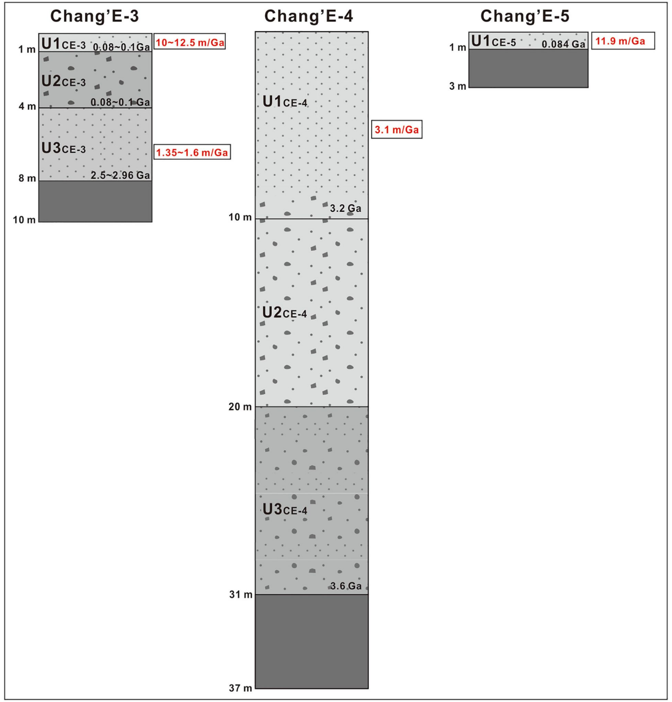
Challenge #3: self-RFI

- At very low frequencies, there is no escaping from switching noise, it is endemic to the system
- The standard approach is using the “picket-fence” approach
- This requires all the hardware that is enabled during data taking to be RFI disciplined:
    - **incompatible with commodification of lunar landers**
    - **(for example in LN we cannot charge the battery and take data at the same time)**



Challenge #4: Regolith / surface plasma effects

- The regolith under the lander will modulate the beam response through its non-zero EM properties (permittivity, loss tangent, etc) and through multi-layer reflections
- The current state of the art is largely made of best guesses about the importance of these effects on the lunar far-side
- In addition to regolith, there could be important surface plasma effects.

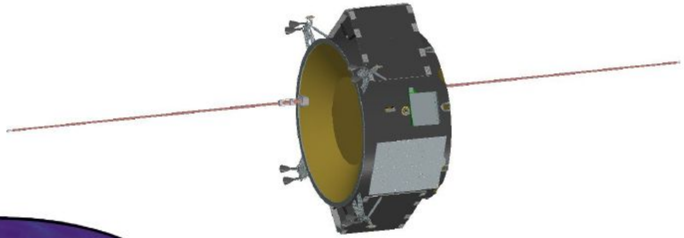


From Liu et al 2023

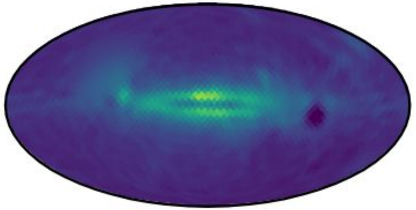
LuSEE-Night

- Pathfinder mission to lunar far-side
- Collaboration of NASA & DOE
- Will demonstrate surviving the lunar night and far-field calibration
- Uses picket-fence to control self-RFI
- Will measure the effects of the regolith
- Will make low-resolution maps of the at the longest wavelengths
- **It is the crucial first step in many to large lunar telescopes**

LuSEE-Night

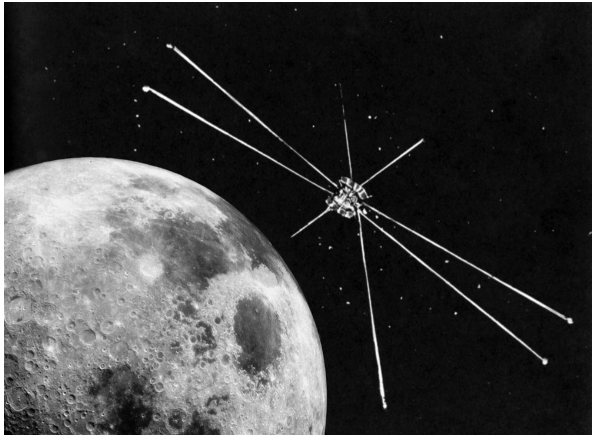


Far-field calibrator



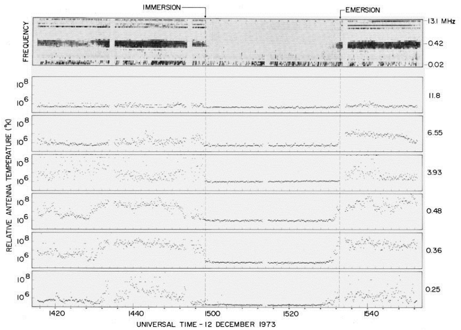
What about science with pathfinders?

- Path-finder experiments will not detect Dark Ages
- However, last real data on the low-frequency sky from the late 1970s by RAE-2
- Remains the state-of-the-art dataset to be superseded
- There could be a Nobel-level prize discoveries hidden in low-frequency data



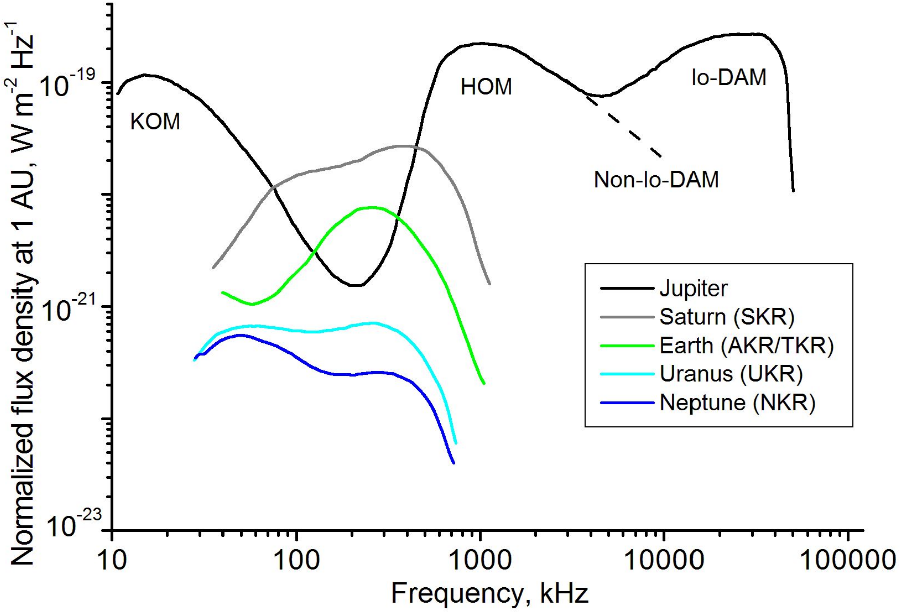
Radio-Astronomy-Explorer-2 was the largest spacecraft ever built with four 230m antennas

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



Interesting science

- Heliophysics:
  - sun bursts during the day
- Decametric radio emission from planets:
  - solar system
  - exoplanets (by gating on orbital phase)
- Moon's exosphere:
  - expected to have plasma frequency at around 30kHz during the day, falling to about 3kHz during the night



More science

- Blind search for monochromatic lines:
  - in monopole (DM interactions)
  - towards the sun (axion DM)
- Hot CMB in RJ-tail
- technosignatures
- new time-domain phenomena:
  - low dispersion measure events
  - normally flagged by RFI excision on Earth

***In Situ* Measurements of Dark Photon Dark Matter Using Parker Solar Probe: Going beyond the Radio Window**

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Dark
detectal

Searches for signatures of ultralight axion dark matter in polarimetry data of the European Pulsar Timing Array

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New Physics in the Rayleigh-Jeans Tail of the CMB

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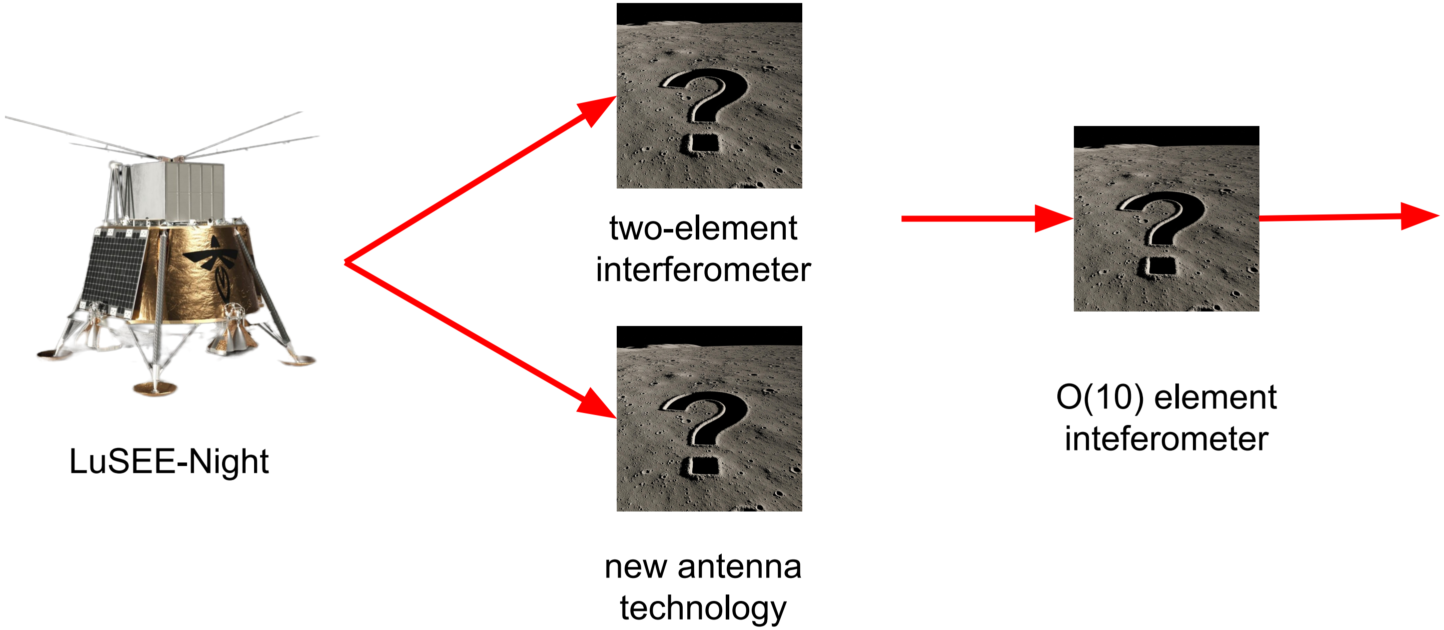
(Dated: September 14, 2018)

We show that despite stringent constraints on the shape of the main part of the CMB spectrum, there is considerable room for its modification within its Rayleigh-Jeans (RJ) end, $\omega \ll T_{\rm CMB}$. We construct explicit New Physics models that give an order one (or larger) increase of photon count in the RJ tail, which can be tested by existing and upcoming experiments aiming to detect the cosmological 21 cm emission/absorption signal. This class of models stipulates the decay of unstable

The decade-long program…

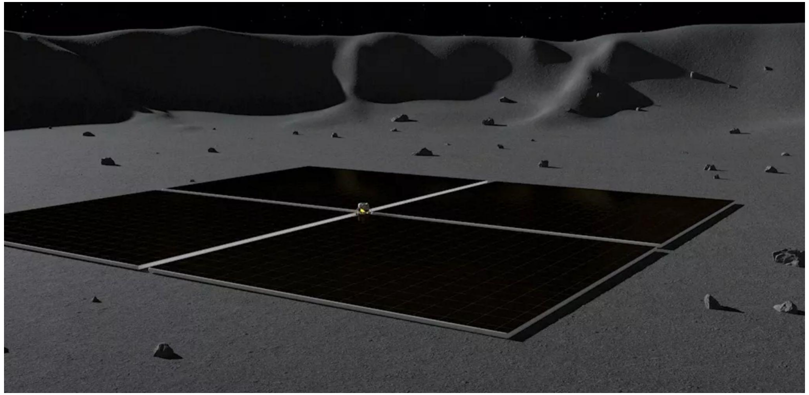


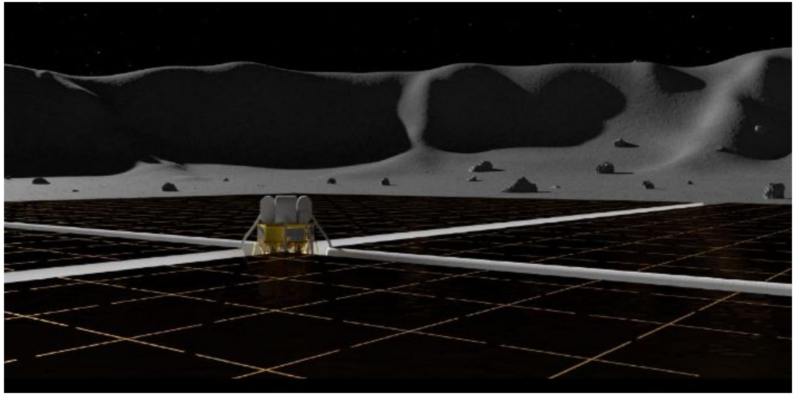
Effective antenna designs

- The weakest part of current generation designs are antennas
- STACER antennas deployed on LuSEE-Night are in many respects a pessimal choice:
  - very chromatic
  - strongly coupled to the ground
- Good antennas are naturally large, because the wavelength is large:
  - heavy, cumbersome
  - requiring actuation to deploy
- Astronauts can play a crucial role in debugging them

Future Antenna Concept: inflatable bed

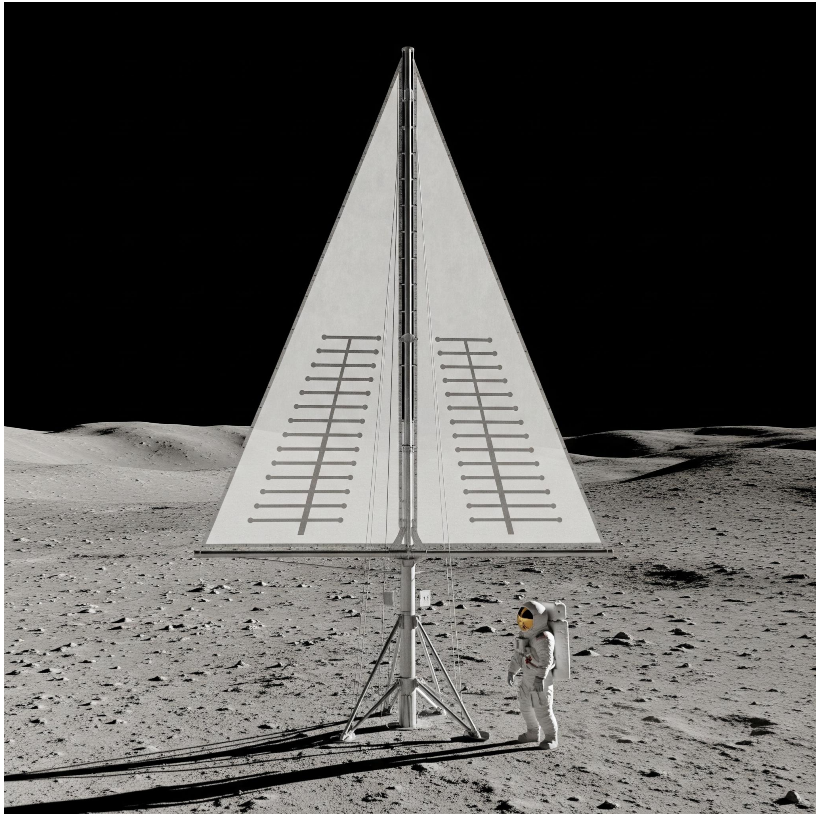
- Promoted by the European ALO group
- A printed antenna pattern on top of an inflatable bed
- Prototypes with 2x2 array can be ~9m x 9m, but eventual idea would be 64x64 or 128x128 elements reaching 300m
- If bed deflates after deployment: so be it
- Astronaut deployments can simplify design:
  - they can choose the deployment site after landing
  - they can thug, push and pull the antenna to assist its deployment
  - they can perform metrology on the deployed antenna

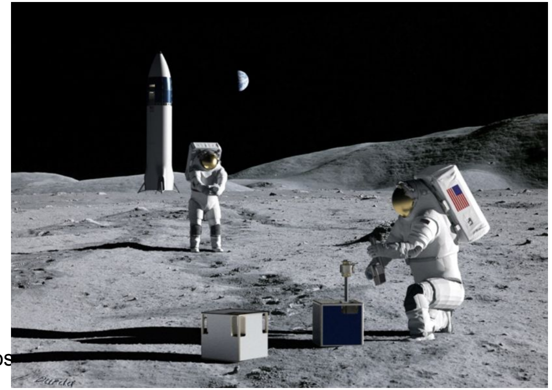




Future antenna concept: sail

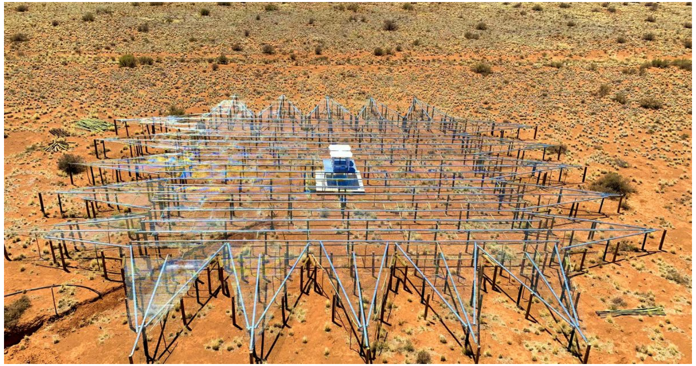
- A version proposed for ChAMP
- A printed antenna (log-periodic, bow-tie or a version), raised on mast, not unlike a sail on a sailboat
- Allows you to look straight away from regolith
- Astronaut deployments can simplify design
    - Astronaut perform the work of raising the antenna
    - they can choose the deployment site after landing
    - they can perform metrology on the deployed antenna



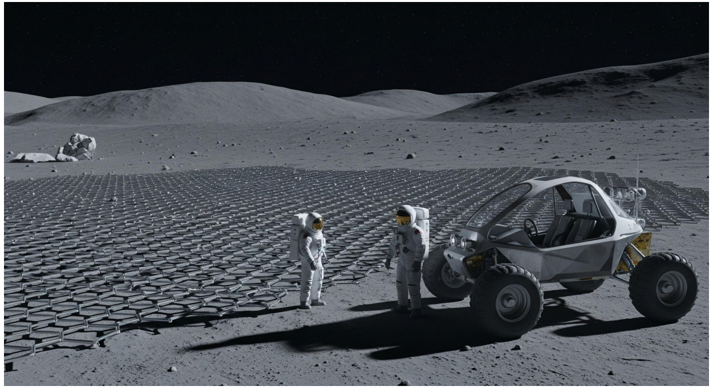


Future antenna concept: ground-plane

- A ground plane could be a possible way to ameliorate sensitivity to regolith
- A useful ground plane need to be very large (REACH example)
- One possible corner in solution space is to have simple antennas and a ground-plane
- Ground plane will almost certainly have to be installed by astronauts
- This could be synergistic with LCRT concept.



REACH telescope in South Africa



Deployment survey

- Astronauts could scout the site and decide, in-situ, where to place the array elements
- They could carry around a ground penetrating radar and decide positioning based on:
    - complexity of structure below ground
    - distribution of baselines
    - difficulty in deployment (obstacles)

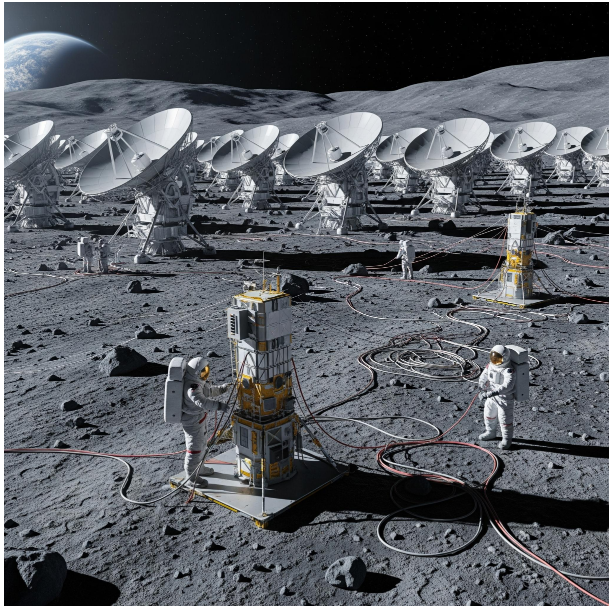
Connecting antennas to correlator

The next step after LuSEE-Night will almost certainly be some form of interferometer.

Interferometer stations need to talk to each other at high BW.

Letting a generic rover design drag a cable behind is a risk, so we have been mostly thinking about RF comm at higher frequency.

Astronauts physically delivering station hardware to remote places and connecting cables is a major design simplification.



Conclusions

- We need a roadmap of path-finders to demonstrate technology for radio observations from the lunar farside
- They can do impactful science before we are ready to detect the Dark Ages
- Radio hardware at low-frequencies is large and clunky
- Astronauts can assist with one-off tasks during deployment:
  - choosing optimal deployment sites in-situ
  - delivering hardware
  - ensuring it deploys/unfolds/… correctly
  - connecting it all together
  - performing metrology post deployment