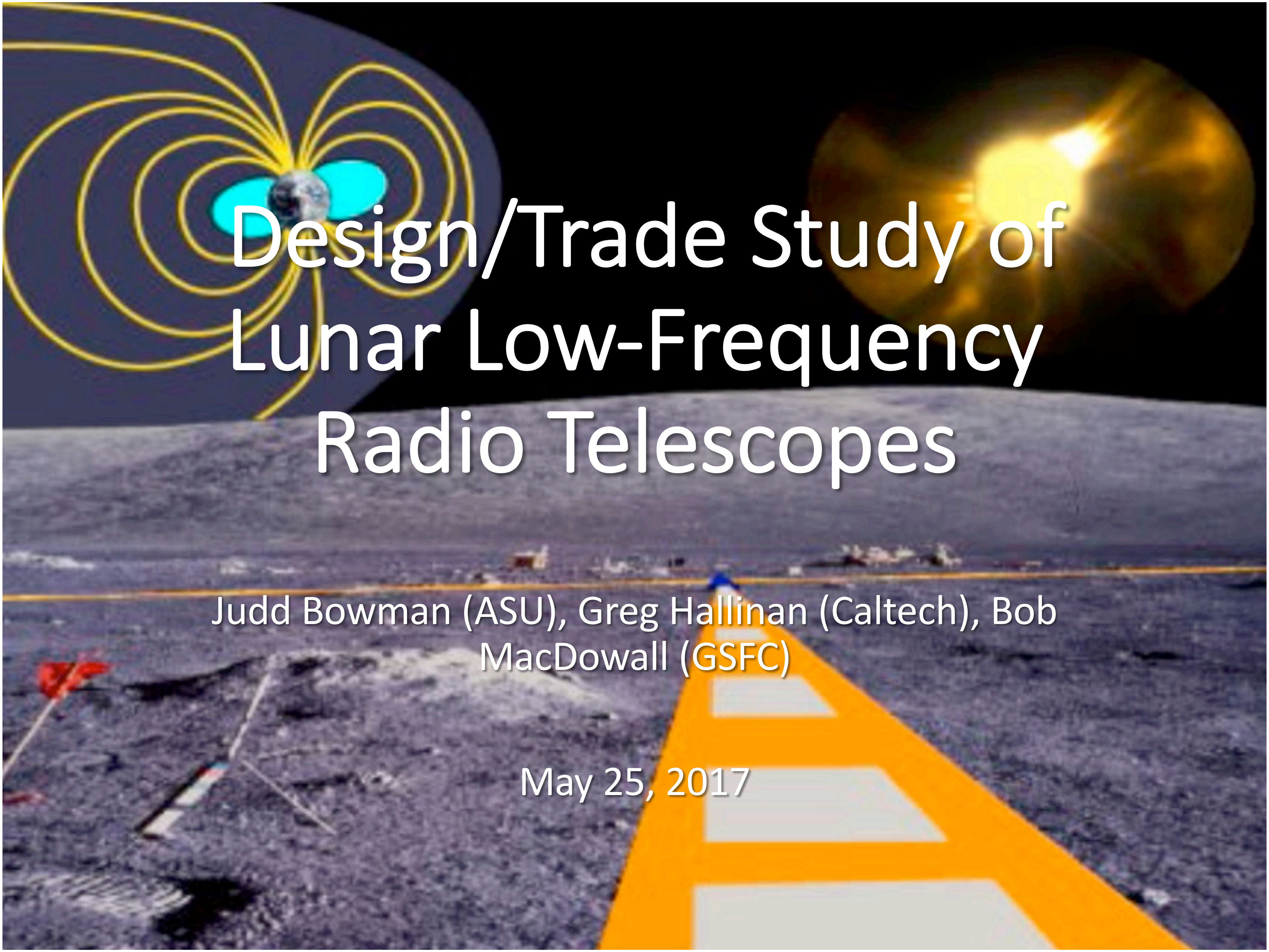

Design/Trade Study of Lunar Low-Frequency Radio Telescopes

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Context

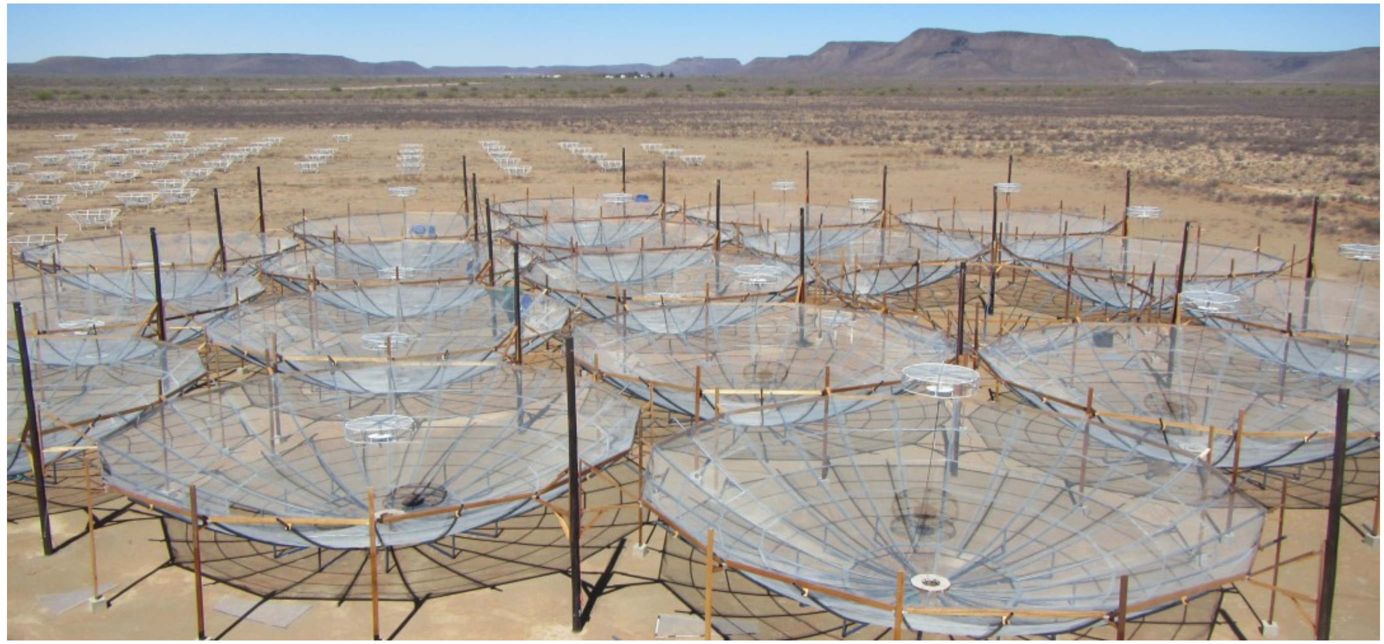
- Four key science themes:
  - Heliophysics / solar radio burst imaging
  - Earth's electron radiation belt synchrotron emission
  - Exoplanet magnetic fields
  - Cosmic Dawn / 21 cm cosmology
- Assume optimistic NASA roadmap
  - Return to lunar (farside) surface by 2025
  - Possibility of full scale array as early as 2030
  - Communications satellite in lunar orbit/L2
- Small prototype array as a precursor
  - Identify scientific goals
- Evolutionary design philosophy
  - Lessons learned from PAPER, HERA, MWA, EDGES, etc.

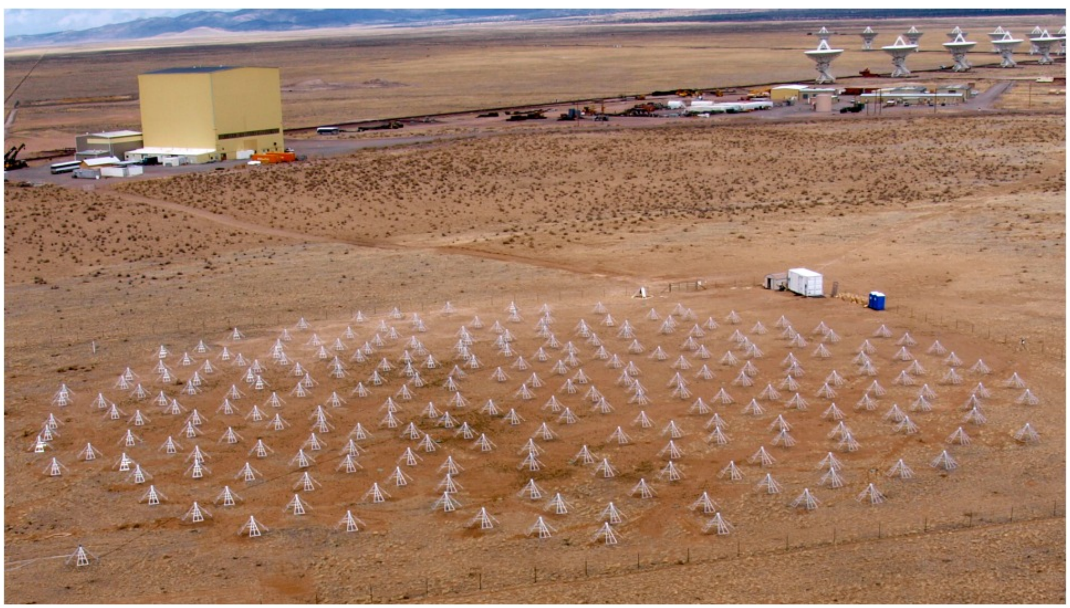
Timeline and outputs

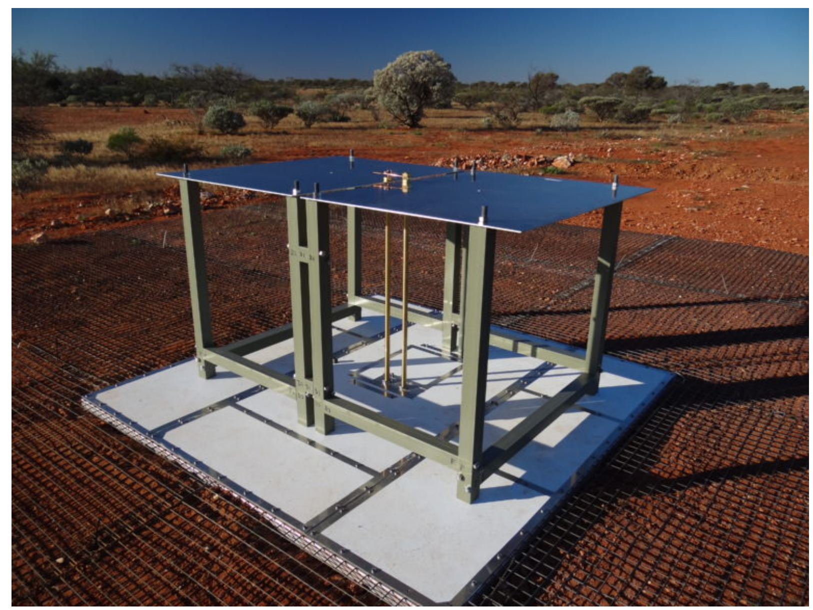
- Timeline
  - Year 1 (2017): Trade study with emphasis on prototype
  - Year 2-5 (2018-2021): Full-scale design study and development
    - Detailed work plan TBD (hopefully good start today!)
  - Plan for 2020 astrophysics decadal review
    - Be prepared for writing white papers by 2019
    - Aim to secure recommendation in decadal

- Outputs
  - Report on trade study by end of Y1
  - Publications and documentation of designs, science traceability matrices, etc.
  - Roadmap for technology development
  - Follow-up proposals for technology development (SAT, APRA, etc.)

Ground-based instruments







Lessons from ground arrays (1)

- Phased development
  - Enables revision/refinement
  - Spreads out costs, risk
  - Almost all ground-based arrays started with small prototype systems (MWA-32, HERA-19, PAPER-16, EDGES-1, etc.)

- Plan for hardware failures
  - Large-N arrays lead to many component failures
    - What (if any) maintenance options exist for a lunar array?
    - How well can we predict failures?
    - How well can the array tolerate failures? Design to accommodate failures (e.g. MWA, LWA with so many elements individual failures can be tolerated)
    - Or, consider limiting the number of elements (sometimes fewer, bigger, more-engineered elements may be more efficient in the long run, e.g. HERA)

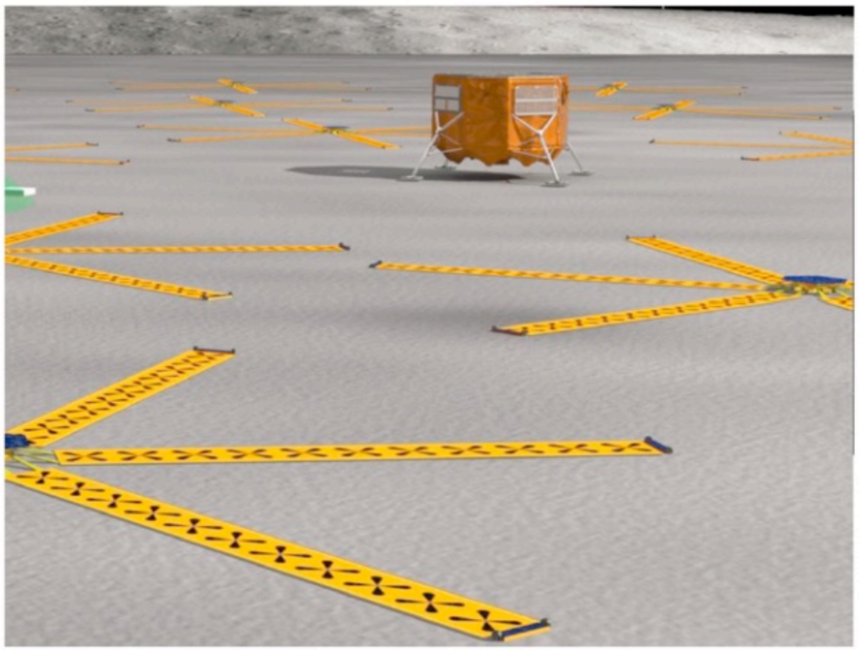
Lessons from ground arrays (2)

- Processing architecture
  - MWA and HERA spread out channelization throughout the array, LWA is more-centralized -- pros and cons to both
  - Do as much processing as close to data as possible
  - But, be able to transfer significant amounts of raw data (voltage samples, visibilities) back to Earth for debugging

- Calibration
  - Try to solve problems/enable calibration through hardware design, not after the fact with software/analysis
  - It takes years to fully commission and characterize an array
    - Recursive (bootstrap) improvements to beams, gains, cable properties, cross-polarization, sensitivity to environmental changes, sky models, etc.
    - Design for sufficient operational lifetime to take advantage of improved instrument knowledge
  - Helps to already know what the sky looks like
    - To what extent can we use existing sky maps/models to enable initial calibration and imaging?

Previous Studies (circa 2009)

DALI / ROLSS



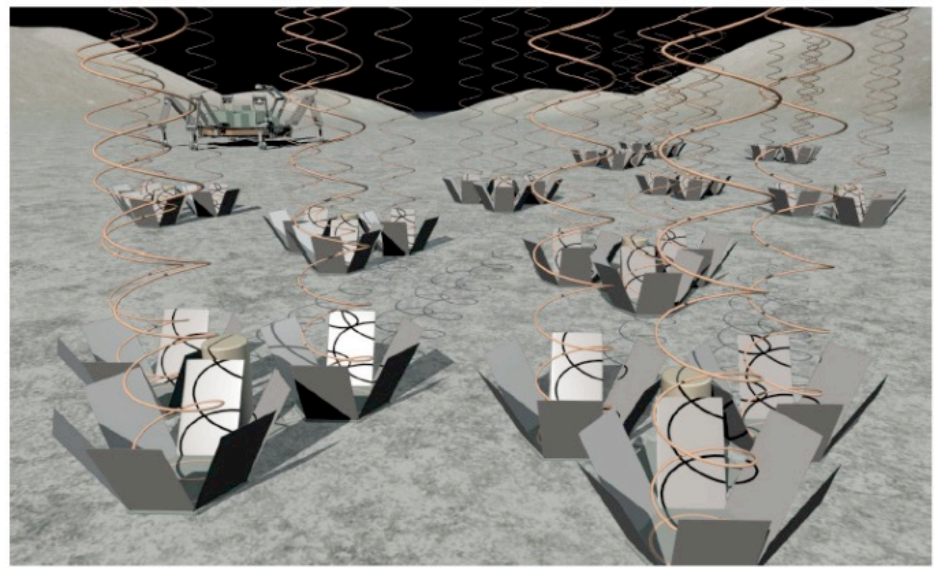
Dipoles (1x1 m) on Kapton

1500 dipoles/station

DALI: 300 stations

ROLSS: 1 station

LARC Cosmic Dawn array



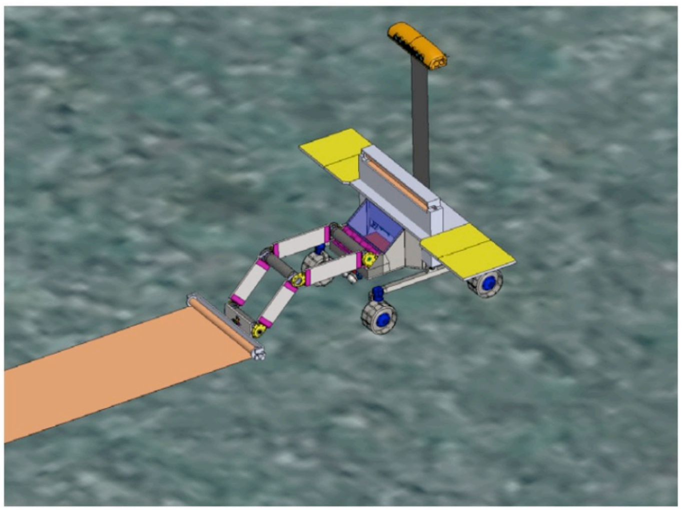
Helical stances: 1.2 x 8.2 meters

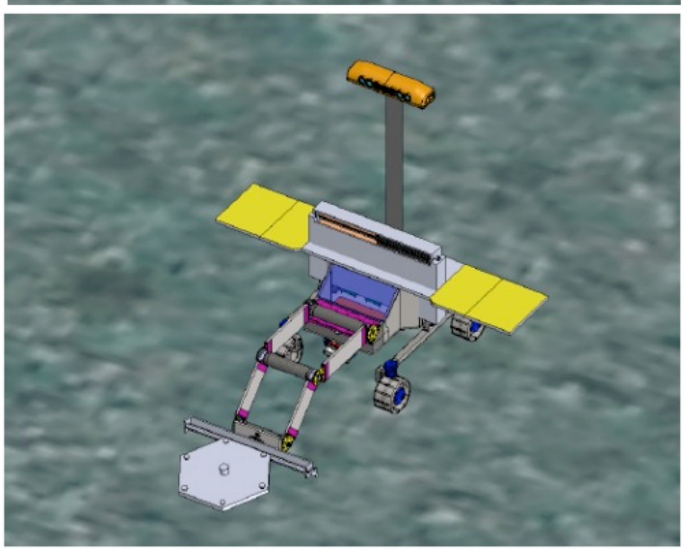
10,000 stances

Lazio et al. 2009

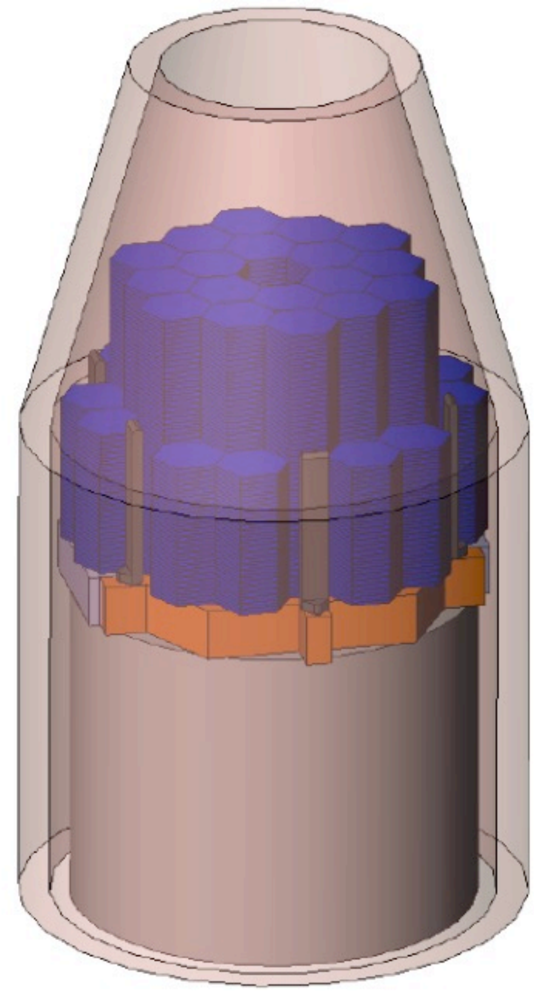
Previous Studies (circa 2009)

Deployment concepts





Volume, mass, packing



Lazio et al. 2009

From the proposal – Solar array

Table 3.4.1. Summary of ROLSS parameters

Parameter	Value	Comment
Wavelength (Frequency)	30–300 m (1–10 MHz)	• Matched to radio emission generated by particle acceleration in the inner heliosphere • Provide context for observations during Solar Probe Plus perihelion passes • Detect lunar ionosphere • Operate at frequencies below the terrestrial ionospheric cutoff
Angular Resolution	2° (at 10 MHz)	• Localize particle acceleration sites of CME shocks and Type III solar bursts • Order of magnitude improvement from present
Bandwidth	≥ 100 kHz	Track time-evolution of particle acceleration
Minimum Lifetime	~1 year	Obtain measurements during several solar rotations; avoid solar minimum

From the proposal – 21cm array

Table 3.5.1. Science-Antenna trade studies

Trade Study	Design Considerations or Questions
Target Era	• **Target observations of the Dark Ages ($z \sim 50$) or Cosmic Dawn ($z \sim 20$)?** Science return vs. feasibility. Coupled to Operations Mode, Performance, and Deployment
Operations Mode	• **Phased array / interferometer?** Most suitable for power spectra measurements of Cosmic Dawn, but requires large numbers • **Incoherently combined antennas?** Most suitable for sky-averaged measurements of the Dark Ages, requires smaller numbers, but more challenging control of systematics
Performance	• **Do candidate technologies meet the science-based performance requirements?** o Spectral bandwidth o Beam pattern, sidelobe levels, and chromaticity o Mechanical and thermal stability • **Candidate antenna technologies include:** o **Dipole?** Simple structure with demonstrated deployment strategies, but spectral coverage challenging o **Dish?** Recent ground-based work is moving toward the use of dishes (e.g., HERA), but potentially a complex structure to deploy o **Magnetic helix?** Relatively simple but large structure, less well characterized than other topologies
Deployment	• **Feasibility of deployment on lunar surface?** Evaluation of candidate antennas and arrays for deployment (in conjunction with tasks in §3.2, Surface Telerobotics)

Can a single array do Cosmic Dawn, Heliophysics, & Exoplanets?

		Science objective				
		Earth's electron radiation belt synchrotron emission	Solar burst imaging	Exoplanet magnetic fields	21 cm power spectrum/imaging	21 cm global signal (single antenna)
Instrument parameter	**Frequency range**	<1 MHz?	1-10 MHz	<20 MHz	a) cosmology: <30 MHz b) first light: 50-100 MHz	first light: 50-100 MHz
	Spectral resolution	?	~1% (10-100 kHz)	Not critical	<50 kHz (RRL/RFI excision)	<50 kHz (RRL/RFI excision)
	Field of view	12 degrees (diameter of radiation belts as seen from Moon)	+/- 90 deg	the larger the better to capture occasional 1000-fold increases in planetary radio power	>10 degrees	Not critical - beam chromaticity requirement more important
	Pointing	Fixed to Earth only - depends on array location	horizon to horizon	horizon to horizon	zenith-only is probably ok	zenith-only is probably ok
	Angular resolution	few arcmin	~ 1 degree	~ 1 degree	~1 degree	N/A
	Sensitivity	?	~ 10^4 Jy	>10^5 sq. m Earth is 1 mJy at 5pc w/ geomagnetic storm	>5x10^4 sq. m should be more sensitive than HERA	1 mK/MHz
	Location on Moon	Near side (must see Earth)	Ideally both near and far sides for continuous coverage	far side because of contamination from RFI and AKR	far side because of RFI	far side because of RFI
	Polarization	?	Full Stokes for science	Full Stokes -- high fidelity Stokes V imaging required for science	Full Stokes for foregrounds	Full Stokes for foregrounds

Ballpark numbers

At 10 MHz:

- 1 degree resolution requires ~2km baselines
  - Filled aperture: 1 element / 3600sq. m
  - Circle layout: 1 element / 6 meters
- 10^5 square meters collecting area requires >1000 dipoles
- 1000 dipoles * 2 pol * 20 MHz bandwidth → ~40GB/s

- Power
  - Analog: 1000 dipoles * 0.1W = 200 W
  - Channelization: 2000 channels * 10W/32channels (FPGA) = 600W
  - Correlation: Currently ~5 GPU servers * 500W = 2500W
  - Can likely reduce by order of magnitude with ASICs, etc.
    - LARC estimated 200W using GeoSTAR correlator

Goals for a Trade Study in Year 1

- Step 1 – Literature review (summer 2017)
  - Previous design/trade studies (LARC, ROLSS, etc.)
  - Lunar conditions/development: RFI measurements/models, technology, etc.

- Step 2 – Refine science objectives (fall 2017)
  - Identify reference/”notional” full-scale array design that meets science objectives – for context to frame prototype array design
    - Total collecting area, observation band, angular resolution, etc.
  - Select subset of science scoped to a small prototype array

- Step 3 – Trade study of design options for prototype array (spring 2018)
  - Goal to identify reference prototype design:
    - Antenna design, polarization, etc.
    - Array configuration
    - Location on lunar surface
    - Processing, data rate, data volume, etc.
    - Deployment methods
    - Mass, power, cost

Trade study – parameter details

- Array configuration:
  - Angular resolution → maximum baseline, stations vs. single array
  - Sensitivity/collecting area → # of antennas
  - Imaging/cal performance → redundant vs. pseudo random vs. geometric layout
- Antenna design:
  - Log-periodic, helical, dish, dipole (polyimide, metal planar, 3D), other?
    - Field of view vs. gain (collecting area)
    - Other considerations: ground loss and other performance, durability, mass, cost, etc.
  - Full polarization – yes, almost certainly
- Analog
  - Active antennas (embedded amplification) vs. passive
  - Transmission lines
  - RFoF?
- Digital
  - Bit depth
  - In-situ correlation vs. transfer data back to satellite or Earth for processing?
  - FX vs. MOFF vs. beamforming only
- For all design cases, consider power and mass, estimate of cost
  - Trade mass vs. science

Lunar environmental issues

- Thermal environment: ranges -150 C -- +100 C
- Power at night
  - Options: New generation batteries, RTG's, microwave beaming
- Deployment & maintenance
- Dust & micro-meteorites
- Solar wind and charged particle environment
- Data downlink
- Placement on planar region