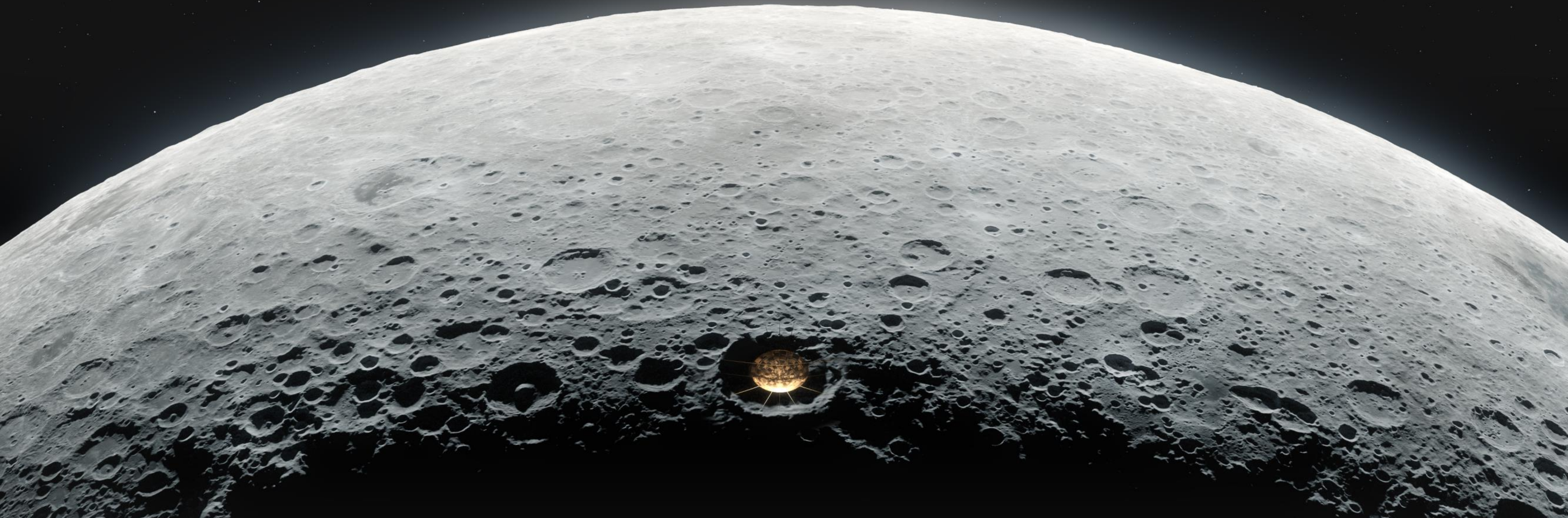
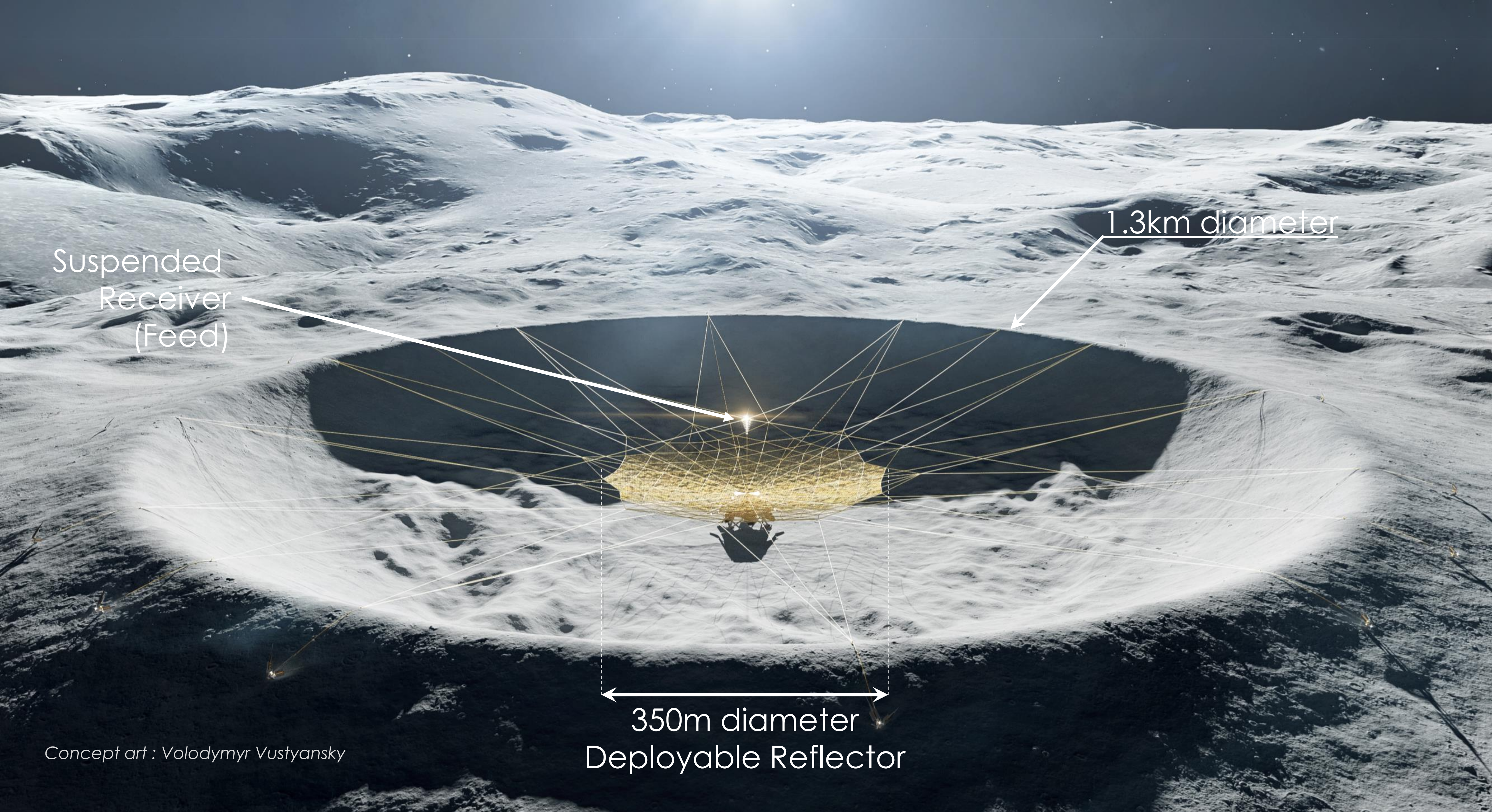
Lunar Crater Radio Telescope (LCRT) on the Far-Side of the Moon



PI: Saptarshi Bandyopadhyay, Jet Propulsion Laboratory, California Institute of Technology

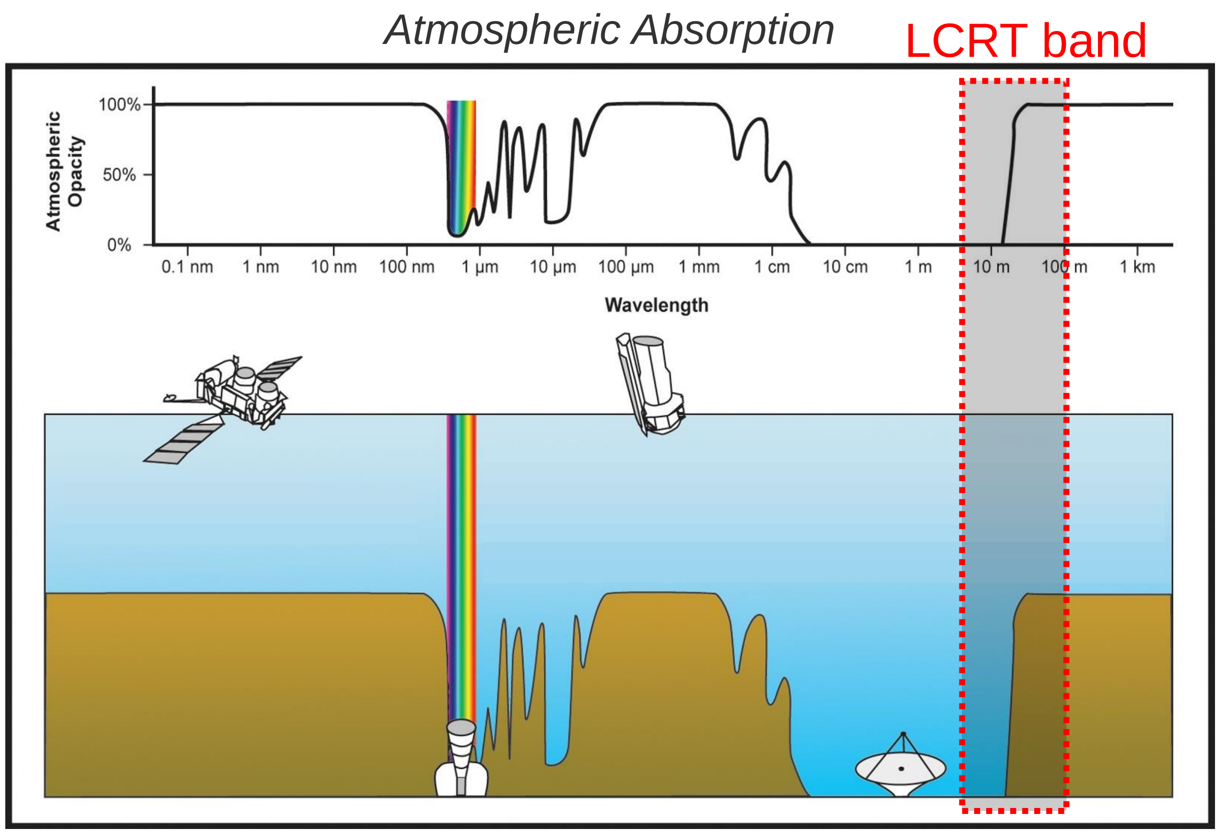
Team: A. Goel, M. Arya, N. Chahat, J. Lazio, P. Goldsmith, K. Jenks, R. Wilson, V. Vustyansky, D. Pisanti, G. Gupta, V. Gehlot, P. McGarey, K. Carpenter, S. Moreland, E. Jens, B. Hockman, A. Tang, J. Jewell

Jet Propulsion Laboratory
California Institute of Technology


1.3km diameter
Suspended
Receiver
(Feed)
350m diameter
Deployable Reflector
Concept art : Volodymyr Vustyansky

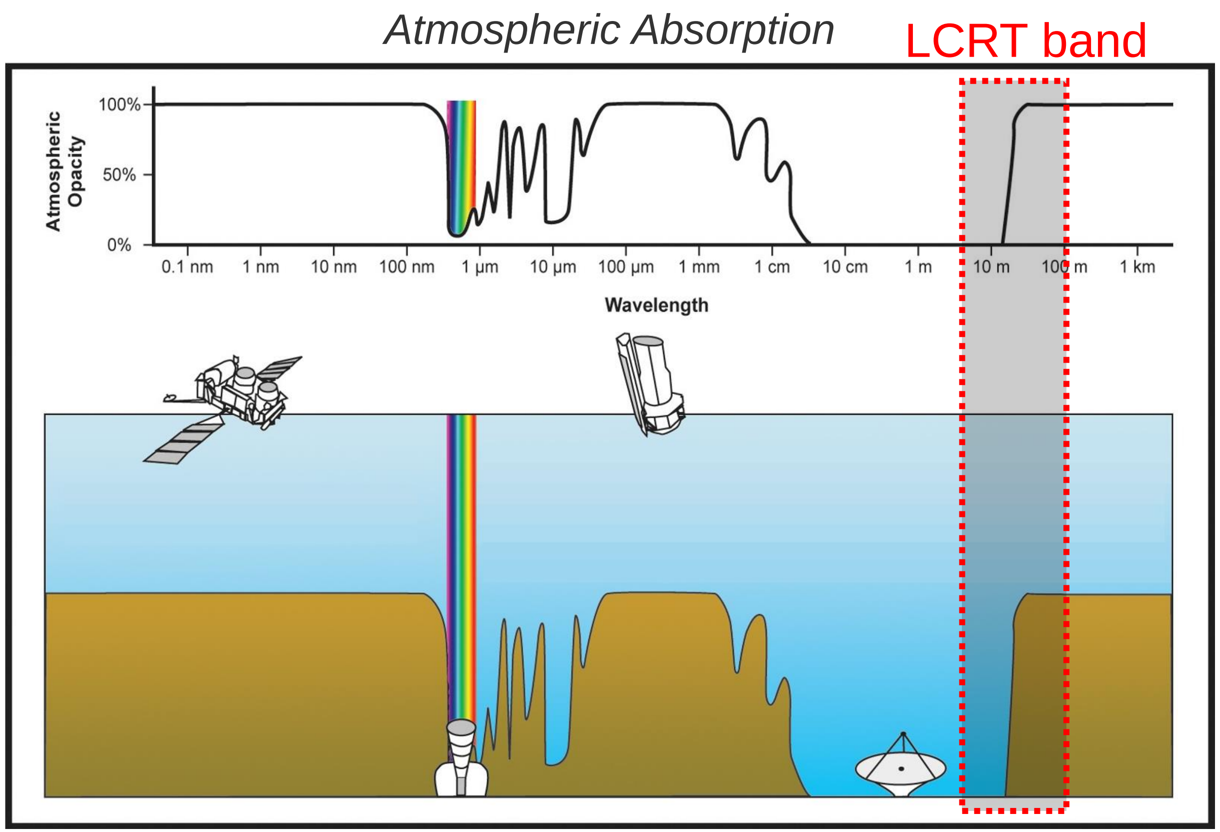
Science Motivation

- Observe our universe in poorly explored 6-64m wavelength band (4.7-47MHz radio frequency)



Science Motivation

- Observe our universe in poorly explored 6-64m wavelength band (4.7-47MHz radio frequency)
- Moon physically shields LCRT from Earth's noise

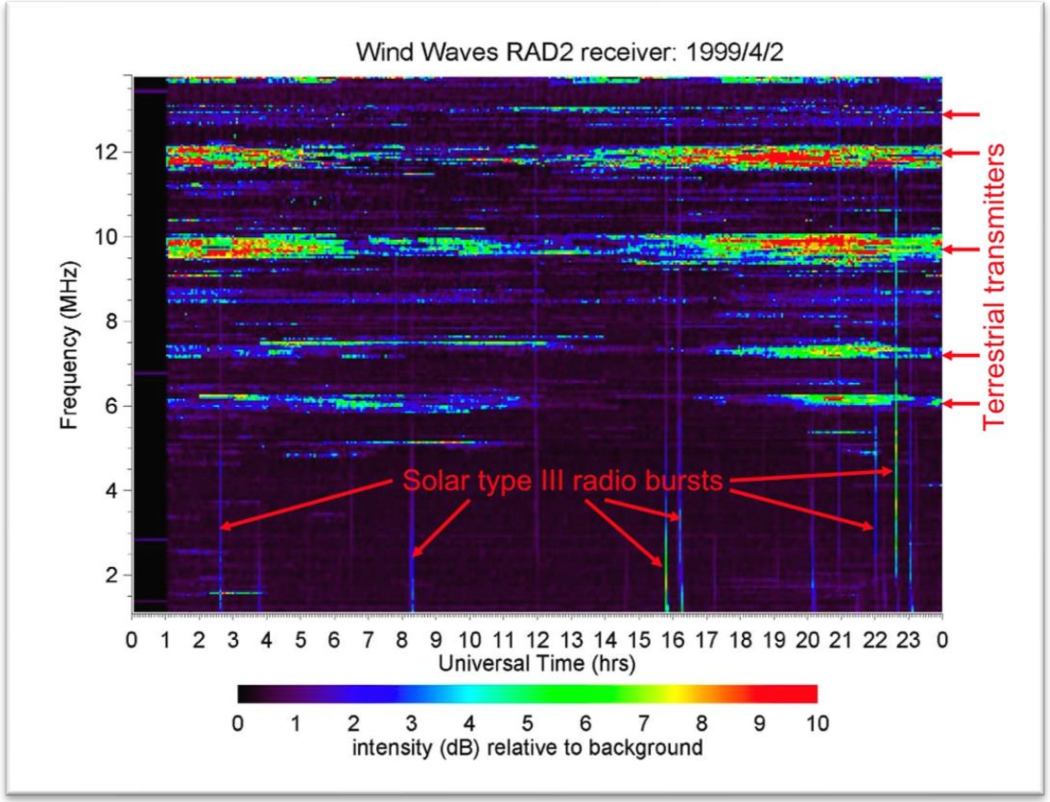


Science Motivation

Challenging Noise Sources :

- 💥Earth
- 💥Sun
- 💥Jupiter + Saturn
- 💥Galactic foreground

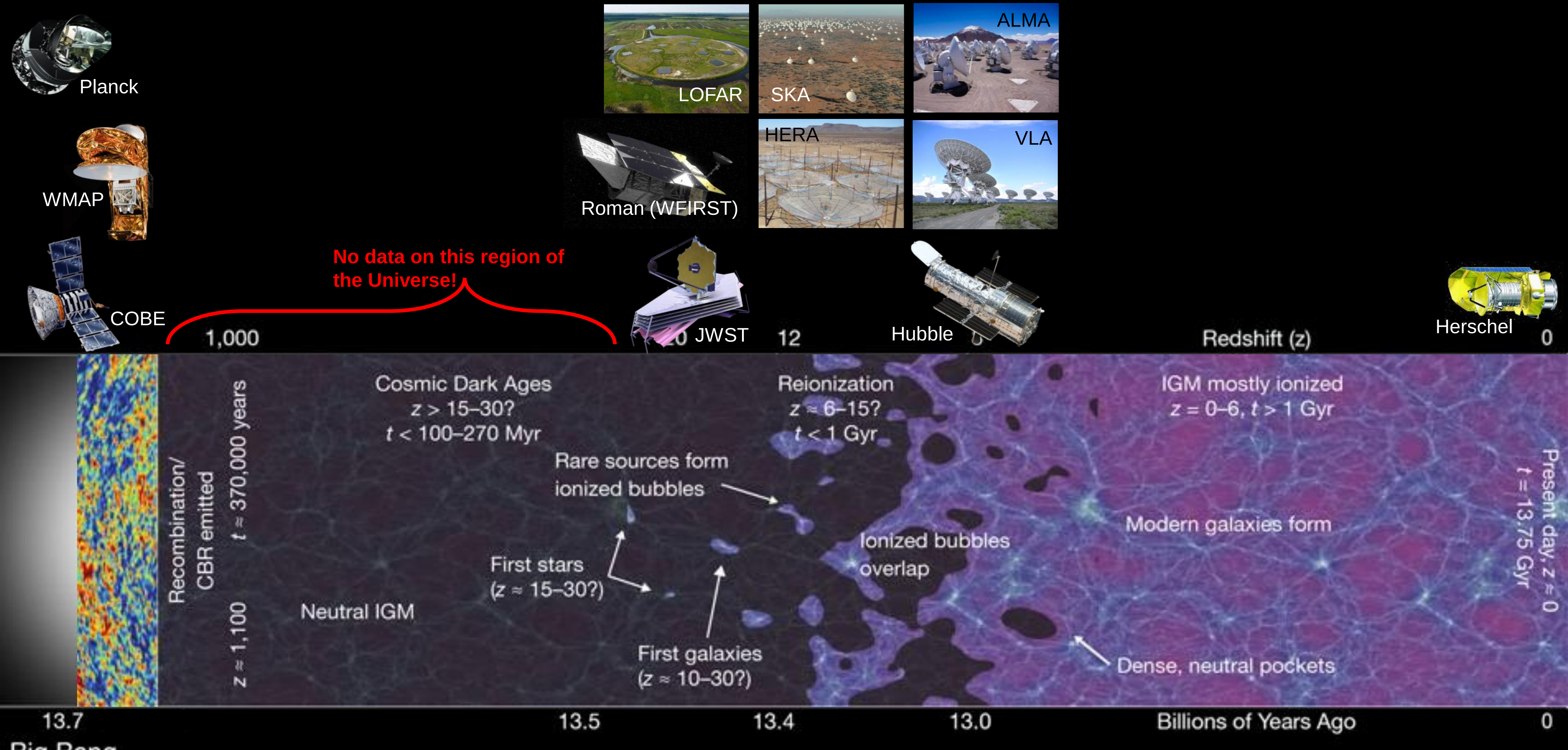
[1] Bassett et. al. "Characterizing the Radio Quiet Region Behind the Lunar Farside for Low Radio Frequency Experiments" Advances in Space Research, 2020



Science Motivation

- Observe our universe in poorly explored 6-64m wavelength band (4.7-47MHz radio frequency)
- Moon physically shields LCRT from Earth's noise
- LCRT (350m diameter) will be one of the largest filled-aperture telescopes in the Solar System!

Evolution of the Universe



Nobel Prizes in Cosmology

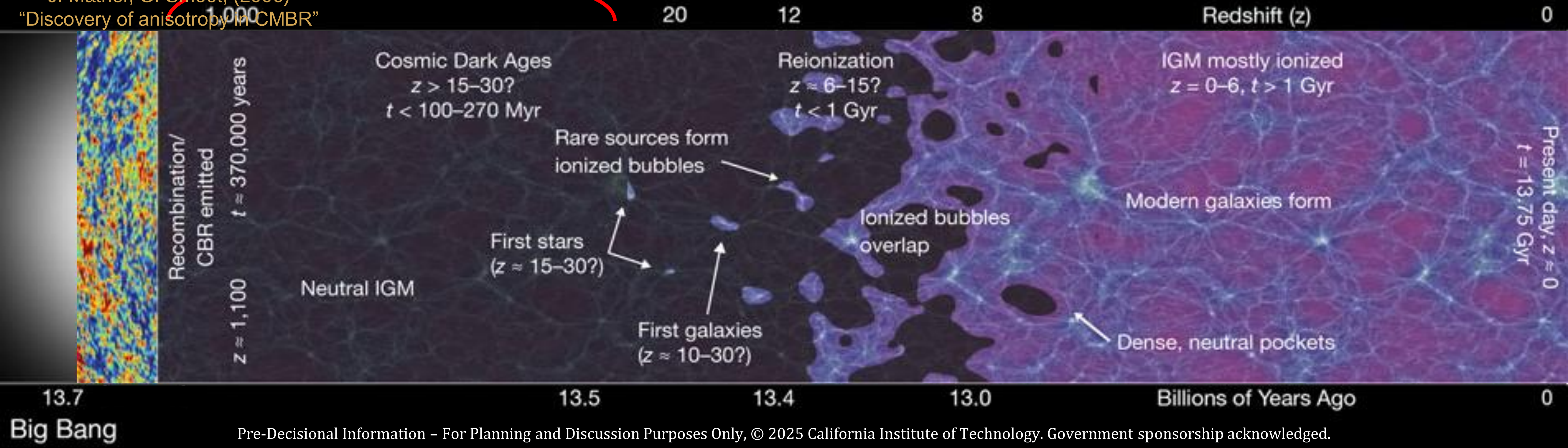
A. Penzias, R. Wilson (1978)
“Discovery of CMBR”

J. Mather, G. Smoot, (2006)
“Discovery of anisotropy in CMBR”

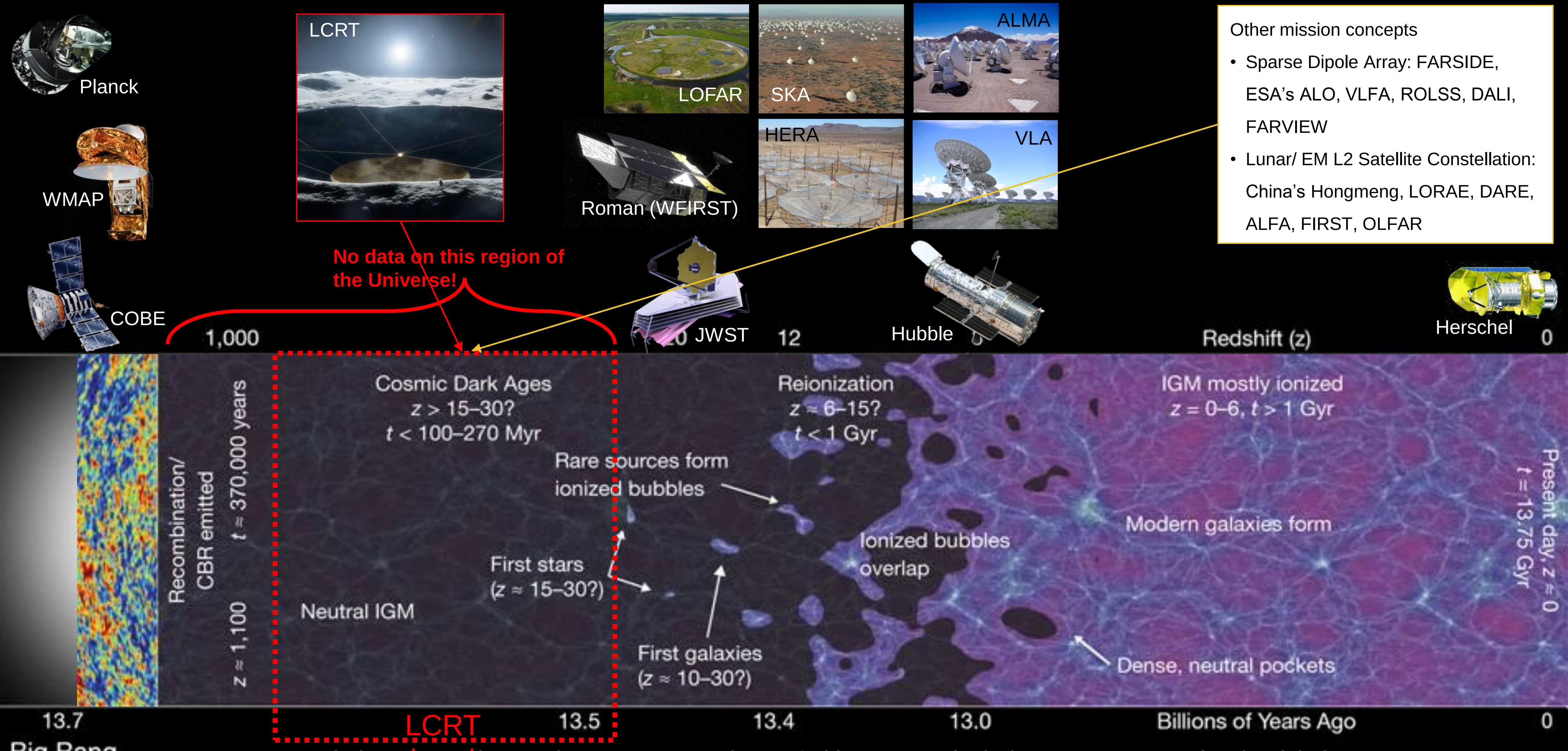
S. Perlmutter, B. Schmidt, A. Riess (2011)
”Discovery of the accelerating expansion of the Universe through observations of distant supernovae."

James Peebles (2019)
“Theoretical discoveries in physical cosmology”

No data on this region of the Universe!

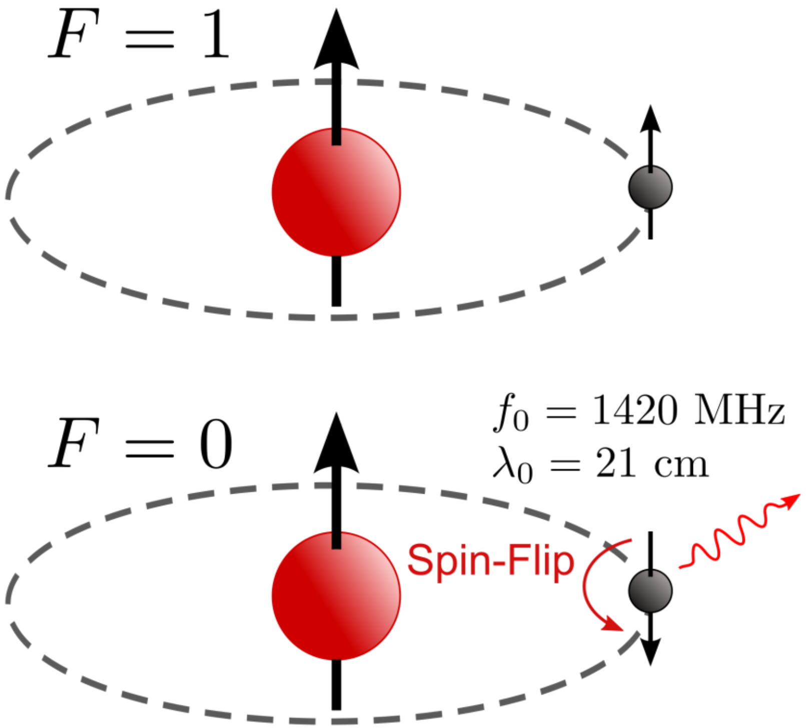


Evolution of the Universe

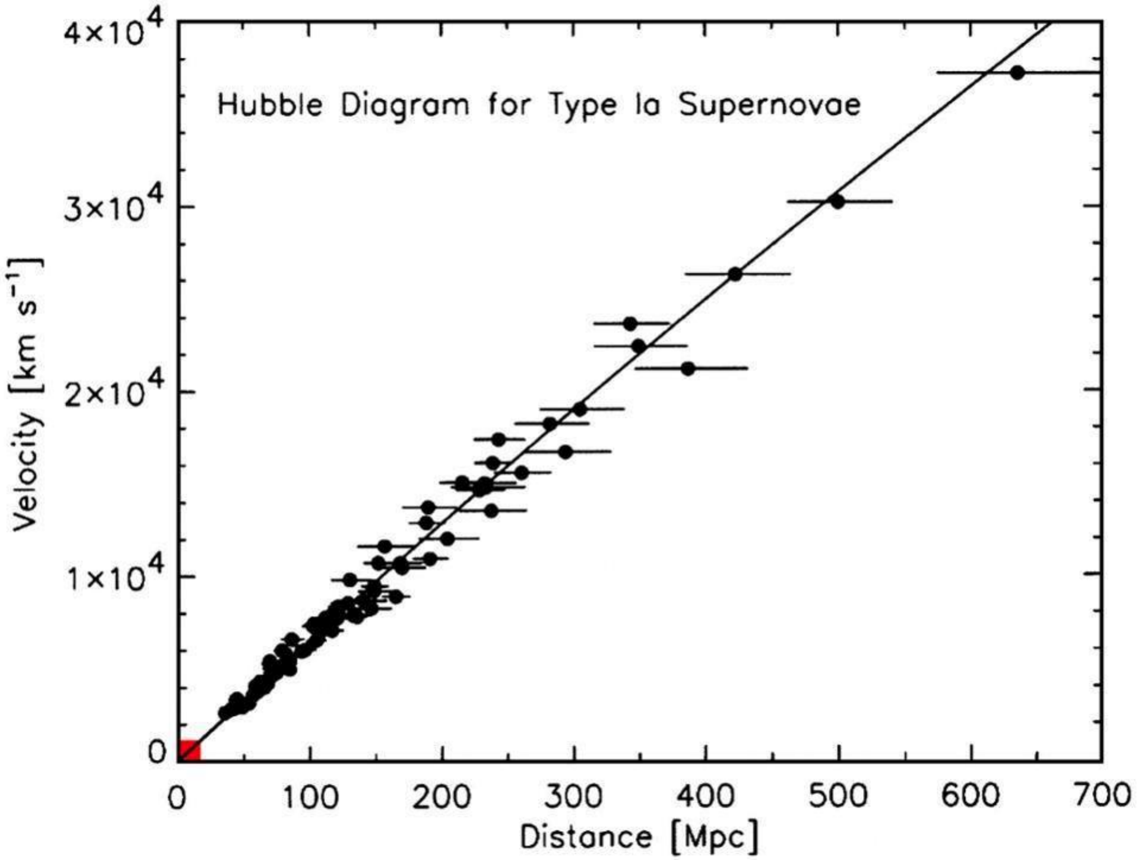


What is this Signal?

Neutral Hydrogen Hyperfine Transition



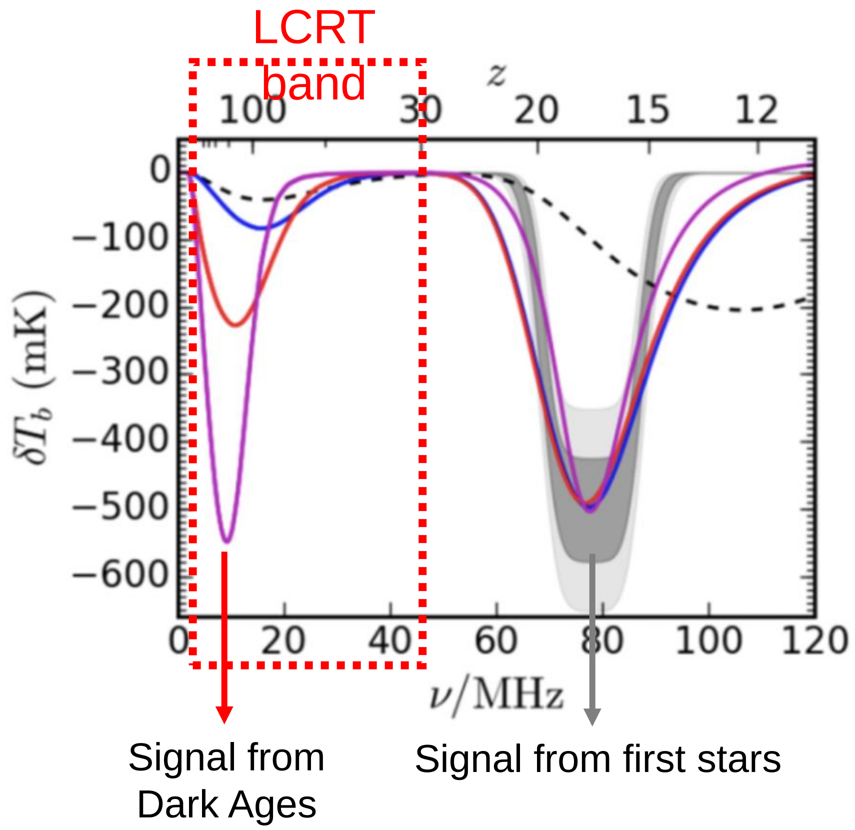
Cosmological Redshift due to Expanding Universe



What is this Signal?

Observe the global absorption spectrum of the highly redshifted ($z \approx 30 - 300$) hyperfine transition of neutral hydrogen ($\lambda = 21\text{cm}$, $\nu = 1420\text{MHz}$)

Best astro-free theoretical model (ΛCDM model)



[1] S. R. Furlanetto et. al., "Astro 2020 Science White Paper: Fundamental Cosmology in the Dark Ages with 21-cm Line Fluctuations "
[2] Mirocha, Jordan, and Steven R. Furlanetto. "What does the first highly redshifted 21-cm detection tell us about early galaxies?." Monthly Notices of the Royal Astronomical Society, 2019.

What is this Signal?

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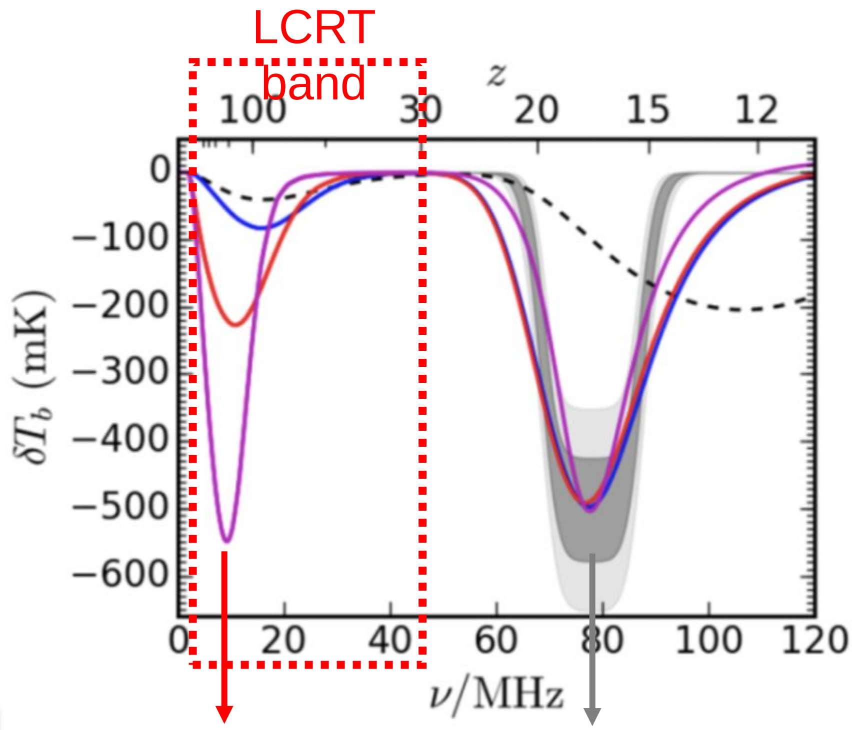
EDGES (Experiment to Detect the Global EoR Signature) measurements



Signal from Dark Ages

Signal from first stars (can be observed on Earth - eg. EDGES)

[1] S. R. Furlanetto et. al., “A ... er: F ... ges with 21-cm Line Fluctuations ”
[2] Mirocha, Jordan, and S ... es t ... n tell us about early galaxies?."
Monthly Notices of the Roy ... .

What is this Signal?

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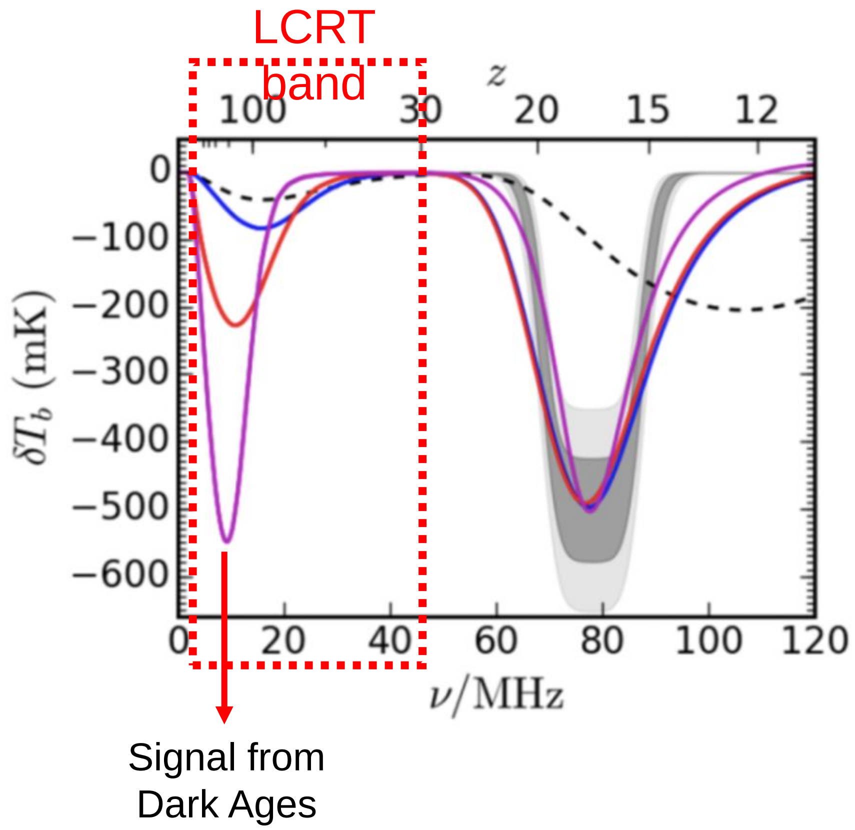
Best astro-free theoretical model (ΛCDM model)

EDGES (Experiment to Detect the Global EoR Signature) measurements

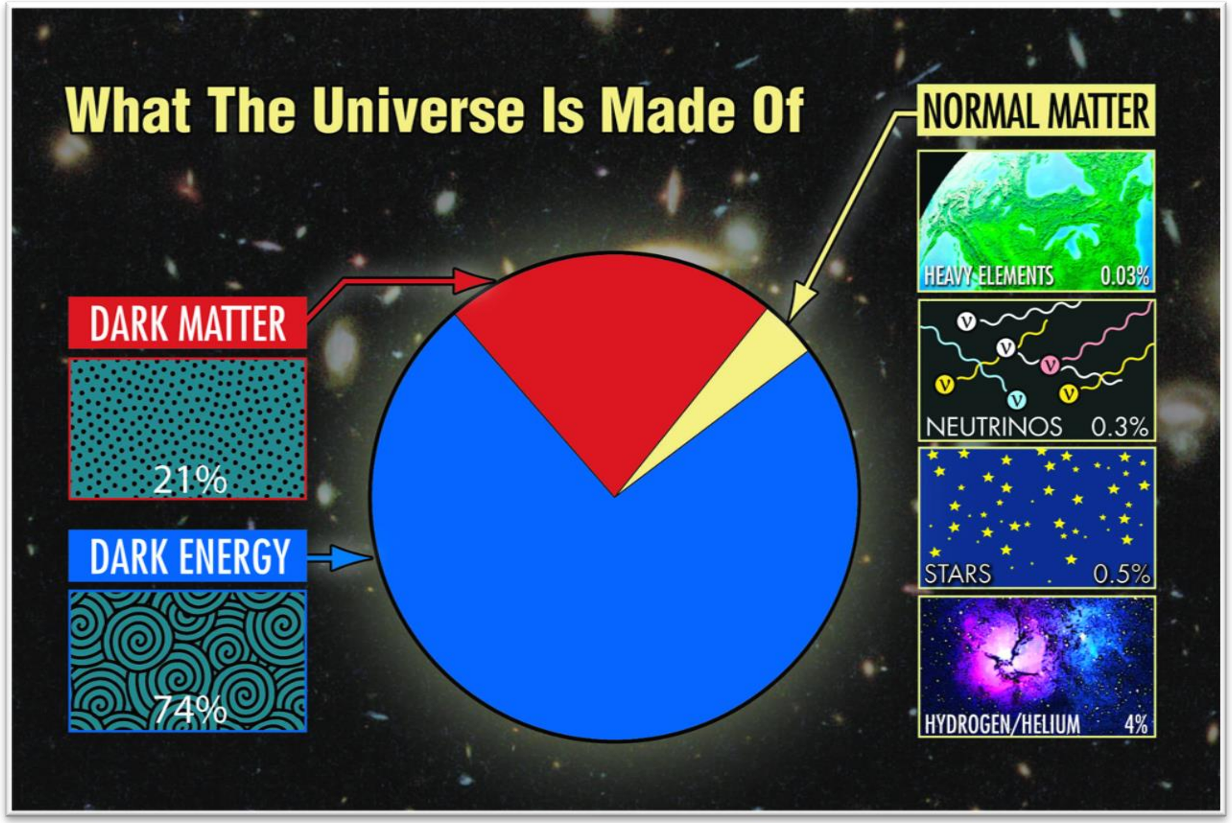
Different cosmology models (to fit EDGES measurements)



[1] S. R. Furlanetto et. al., "Astro 2020 Science White Paper: Fundamental Cosmology in the Dark Ages with 21-cm Line Fluctuations "
[2] Mirocha, Jordan, and Steven R. Furlanetto. "What does the first highly redshifted 21-cm detection tell us about early galaxies?." Monthly Notices of the Royal Astronomical Society, 2019.

Why is this Important?

- 🚀 Understand dark matter physics
- 🚀 2020 Astrophysics Decadal Survey:
  “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.”



[1] National Academies of Sciences, Engineering, and Medicine. Pathways to Discovery in Astronomy and Astrophysics for the 2020s. 2023.
[2] McDonald Observatory, University of Texas at Austin, https://mcdonaldobservatory.org

2020 Astrophysics Decadal

- **C. Report of the Panel on Cosmology (pg 247--263)**
- **LCRT's Science Goals**

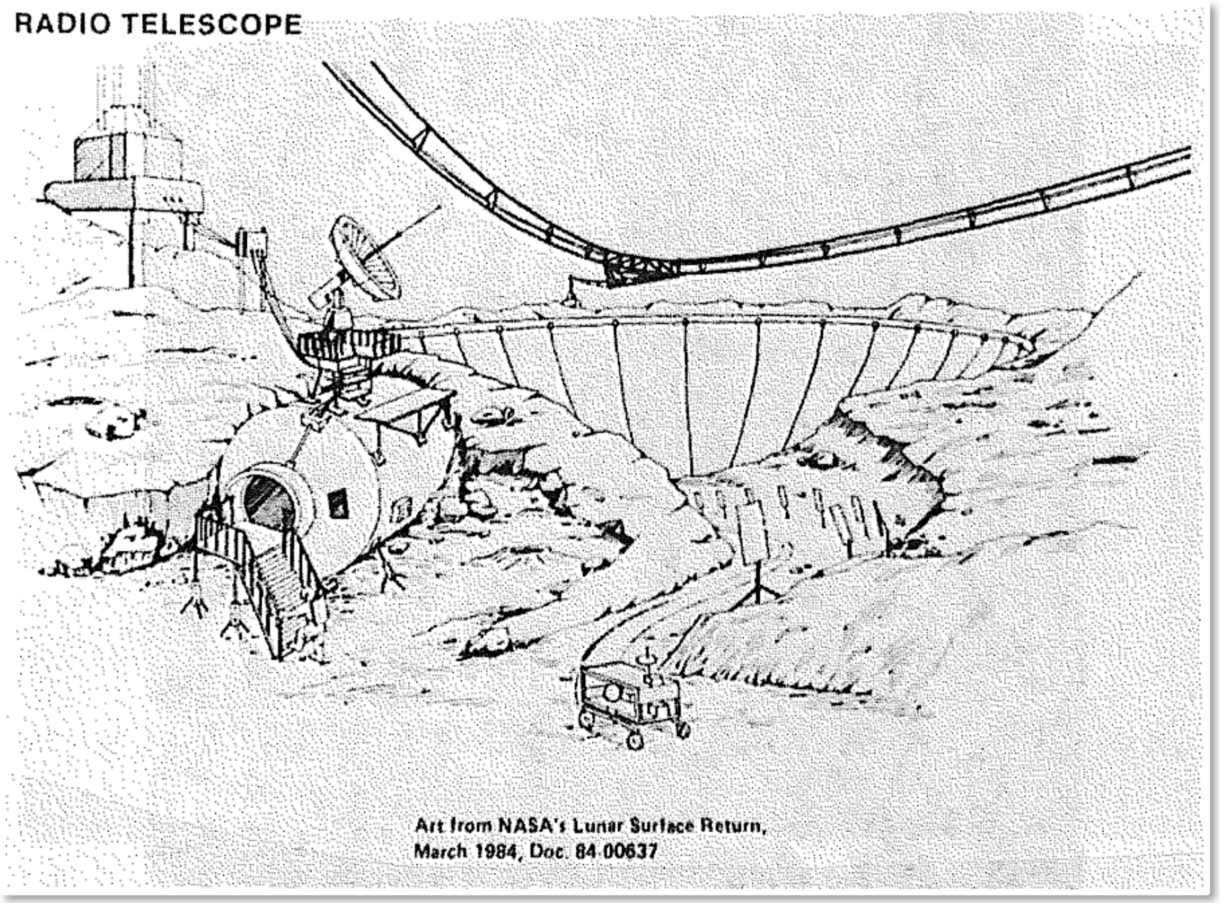
BOX C.1 **Summary of Science Questions**	
C-Q1: What set the Hot Big Bang in motion?	C-Q1a: Primordial gravitational waves C-Q1b: Non-Gaussianity of the large-scale structure of the universe C-Q1c: The initial power spectrum of density fluctuations
C-Q2: What are the properties of dark matter and the dark sector?	C-Q2a: Dark sector signatures in small-scale structure C-Q2b: Dark sector imprints on Big Bang nucleosynthesis and recombination C-Q2c: Annihilation by-products
C-Q3: What physics drives the cosmic expansion and large-scale evolution of the universe?	C-Q3a: The physics of cosmic acceleration C-Q3b: The properties of neutrinos C-Q3c: End-to-end tests of cosmology
C-Q4: How will measurements of gravitational waves reshape our cosmological view?	C-Q4a: The stochastic gravitational wave background C-Q4b: Standard sirens as a new probe of the cosmic distance scale C-Q4c: Light fields and other novel phenomena
Discovery Area: The Dark Ages as a cosmological probe	C-DA1: The end of the Dark Ages C-DA2: The future of primordial density mapping

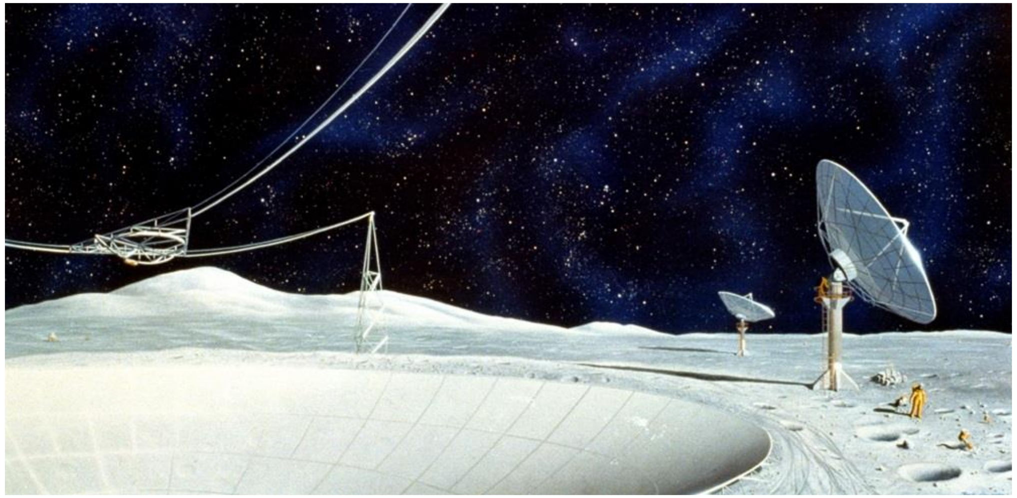
[1] National Academies of Sciences, Engineering, and Medicine. Pathways to Discovery in Astronomy and Astrophysics for the 2020s. 2023.

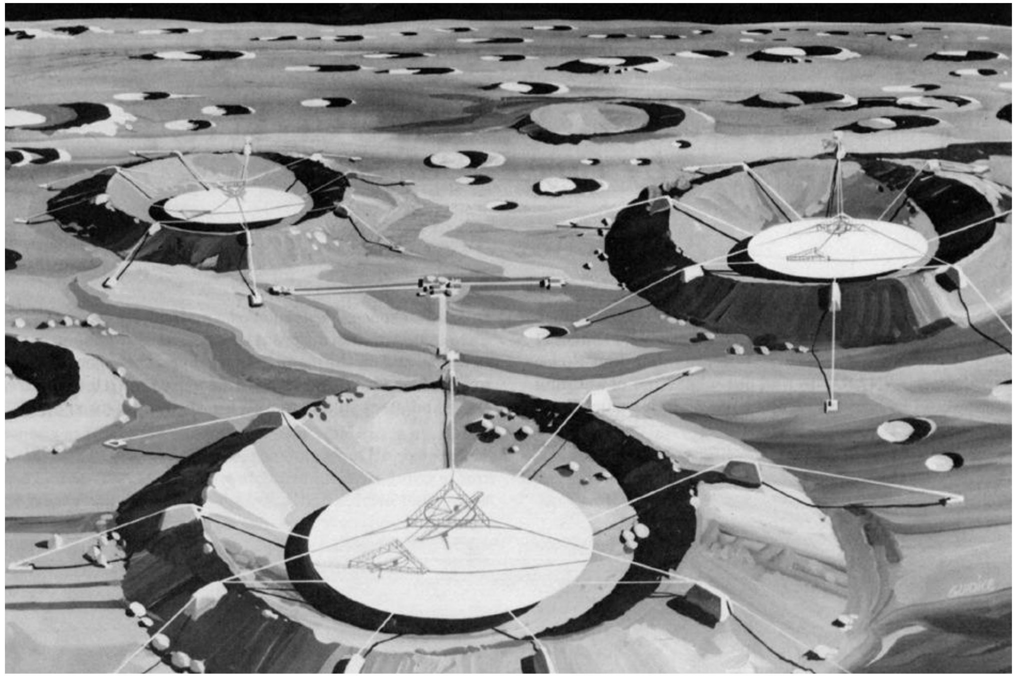
Science Traceability Matrix

Science Goals from 2020 Astro Decadal	*Science Objectives*	*Scientific Measurement Requirements*	*Instrument Performance Requirements*	*Mission Requirements*
Goal 1: Understand the cooling profile of the Universe during the Cosmic Dark Ages and the role of dark matter in the transition from a gas comprising mostly neutral hydrogen, to the formation of first stars and galaxies (Cosmic Dawn). **Goal 2:** Establish the role of dark energy in the early evolution and growth in the scale of the Universe. From 2020 Astro Decadal: - ***C-Q2*** [p.252] - ***C-Q3a*** [p.254] - ***C-Q3c*** [p.256] - ***C-DA1*** [p.258]	**Objective 1:** Ascertain which cosmological model (cold dark matter, warm dark matter etc.) can explain the cooling behavior of the Universe during the Dark Ages **Objective 2:** To provide an independent measurement of the Hubble constant and settle the discrepancy in our current estimates of one of the most critical and fundamental parameters in Cosmology.	Measure the global spectral profile of the highly-redshifted HI transition (21cm, 1420MHz) with [Furlanetto et al., 2019]: (i) Frequency range of 4.7–47 MHz, (ii) Spectral resolution of 1 MHz, (iii) Noise temperature less than 15 mK, - Wavelengths > 10 m not observable from Earth due to ionospheric effects [Datta et al., 2016, Shen et al., 2021] - HI signal expected to disappear below 4.7 MHz due to opacity of early Universe [Furlanetto et al., 2006]	**Frequency Range:** 4.7 – 47 MHz **Detector Requirements:** - System temperature < 1000 K - Antenna directivity: > 35.2 dBi at 47 MHz (beamwidth < 2.0°), > 17.7 dBi at 4.7 MHz (beamwidth < 12.0°) - Galactic foreground suppression better than 10^{-8} - Parabolic reflector, stationary feed - Focal length to diameter ratio (F/D) ≈ 0.5 **Reflector Requirements:** - Diameter ≥ 350 m - Resistivity < 0.5Ω/m - Surface RMS error from desired parabolic shape ≤ 0.64 m - Mesh Spacing ≥ 0.04 openings per inch (OPI) **Feed Requirements:** - Polarization measurement with cross polarization levels < 20 dB - Spectral resolution: 1 MHz	**Location on Moon:** - Latitude: 20° ± 20°N - Longitude: 180° ± 45°E, to avoid Earth's RFI [Bassett et al., 2020] - *Selected Crater*: 14.9°N, 170°E **Preferred Observation Time:** Lunar night, to avoid Sun's radio emissions [Gopalswamy, 2004, Alibay et al., 2017] - Operating temperature range: 90–100 K - Survivability temperature range: 90–400 K **Data generation rate:** 10 kbit/sec during night time operation **Mission duration** ≈ 1 year [Bandyopadhyay et al., 2021, Rapetti et al., 2020]

Lunar Arecibo-type Concept

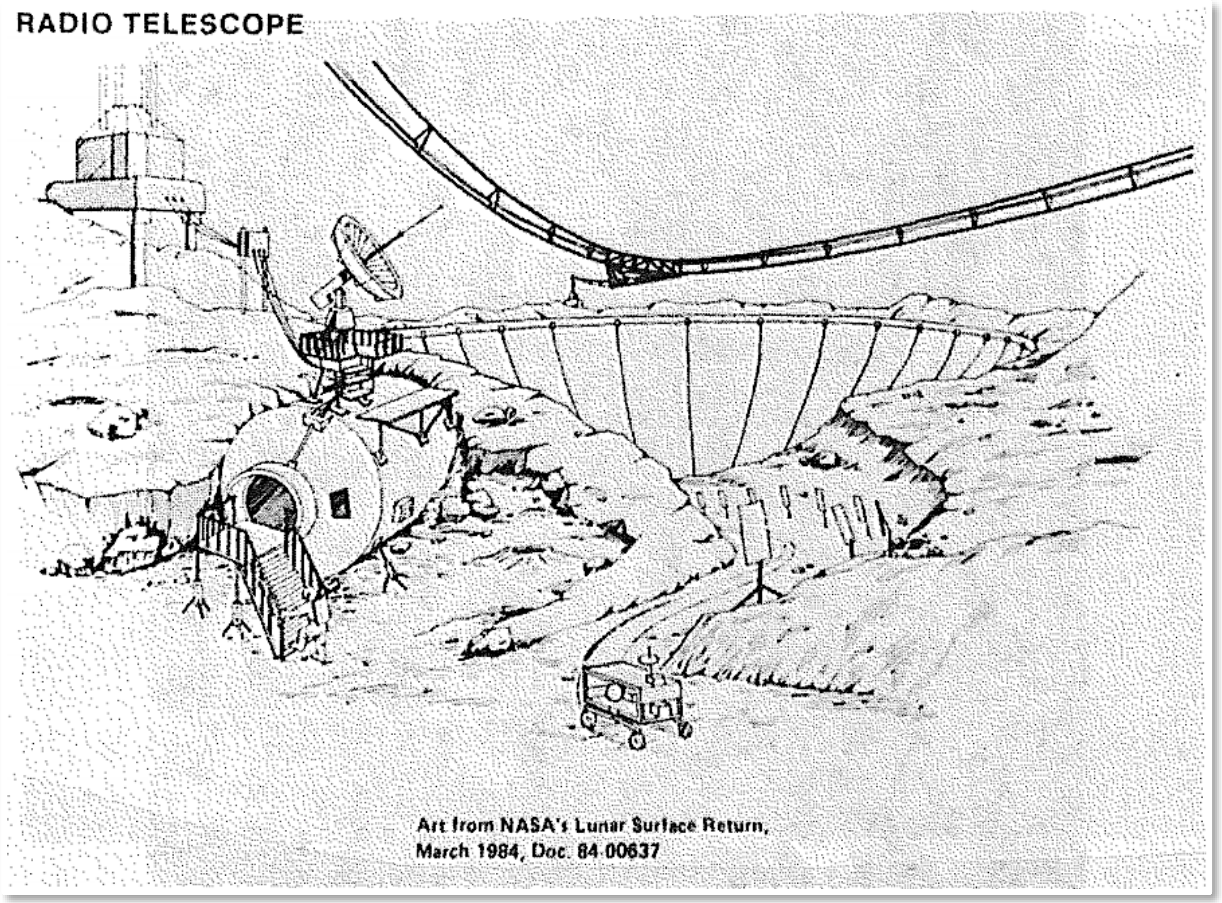






[1] Burns,J.O., Duric,N., Taylor,G.J., and Johnson,S.W., "Observatories on the Moon," *Scientific American*, 1990.
[2] Johnson,S.W., "Engineering for a 21st century lunar observatory," *Journal of Aerospace Engineering*,1988.

Lunar Arecibo-type Concept



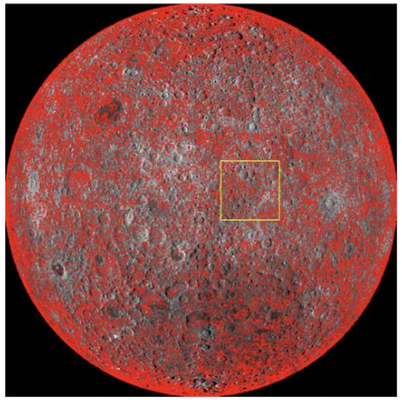
Technical Challenges

- Selection of lunar crater
- Arecibo-type support structures
- Thermal strain compensation
- Rim to floor transportation

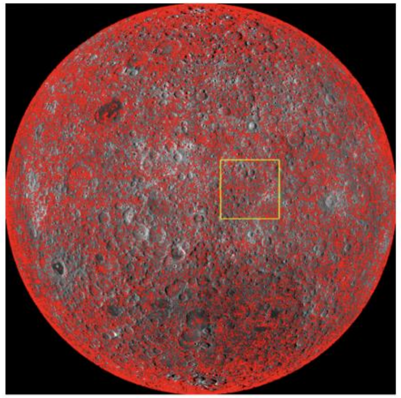
[1] Burns,J.O., Duric,N., Taylor,G.J., and Johnson,S.W., "Observatories on the Moon," *Scientific American*, 1990.
[2] Johnson,S.W., "Engineering for a 21st century lunar observatory," *Journal of Aerospace Engineering*,1988.

Lunar Crater Selection

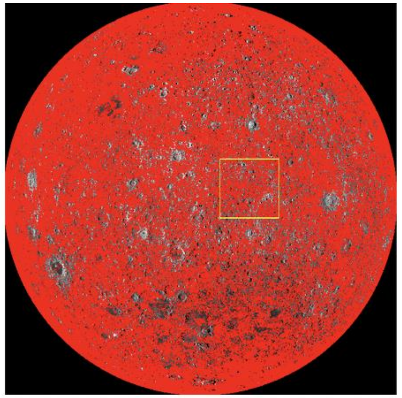
Lunar Reconnaissance Orbiter Camera (LROC) database



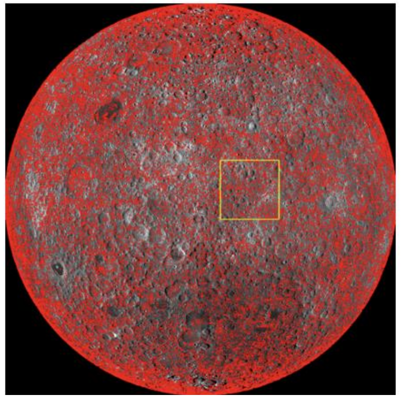
70K craters
(1 - 1.1 km)



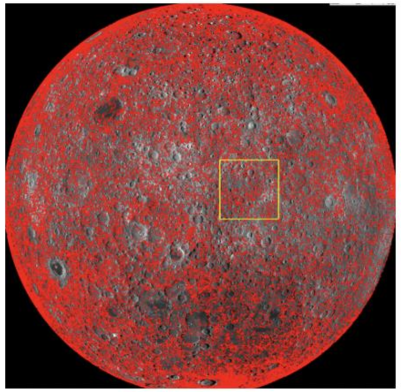
66K craters
(1.1 - 1.2 km)



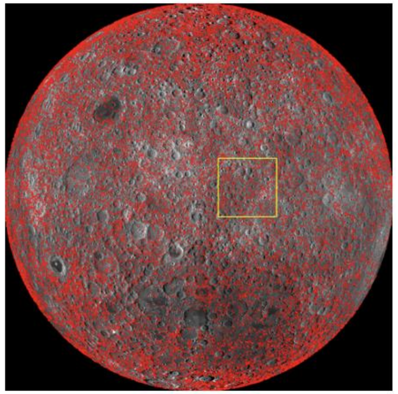
324K craters
(1.2 - 2 km)



140K craters
(2 - 3 km)



82K craters
(3 - 5 km)



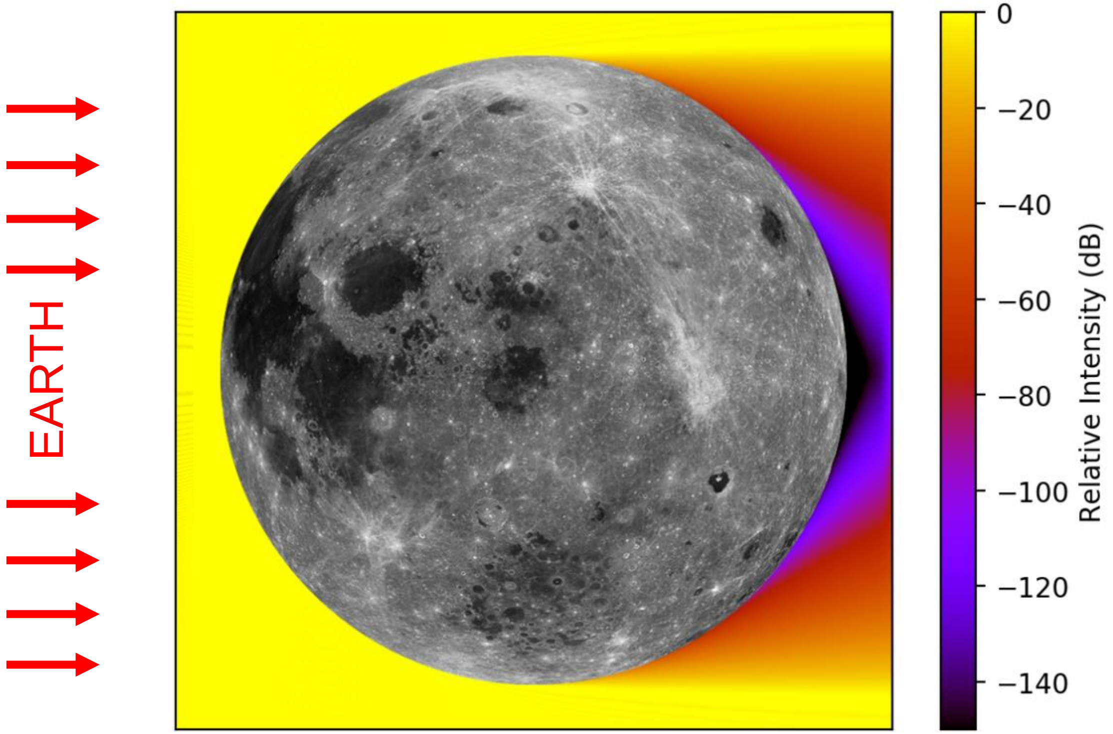
39K craters
(5 - 10 km)

LRO Spacecraft

Lunar Crater Selection

Crater Requirements

- Diameter: 1-2 km
- Minimum Depth: 200 m
- Location: 20ºN, 180±45ºE
- No boulders or outcrops
- Complete crater rim
- Level surface outside crater



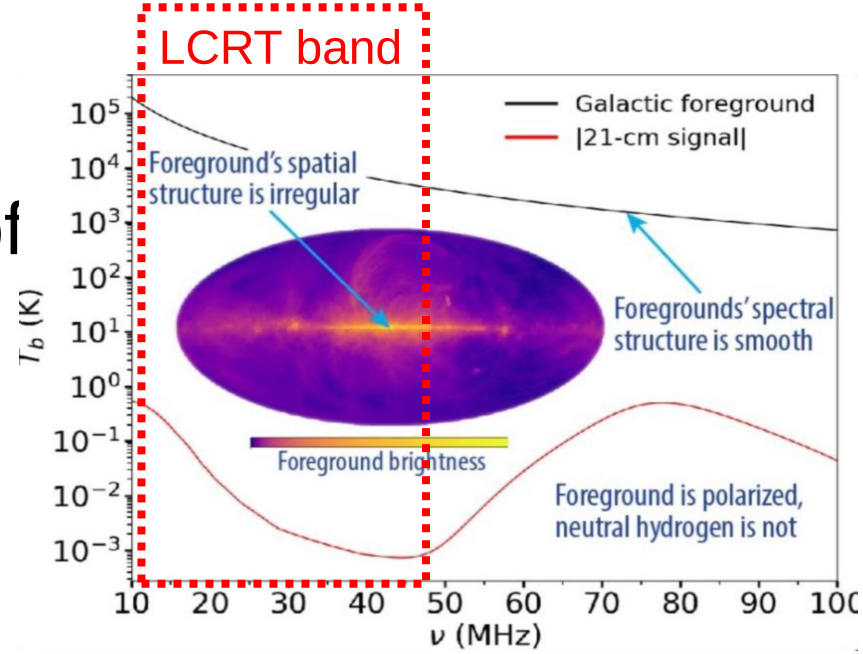
RFI from Earth at 30kHz

[1] Bassett et. al. "Characterizing the Radio Quiet Region Behind the Lunar Farside for Low Radio Frequency Experiments" Advances in Space Research, 2020

Galactic Foreground

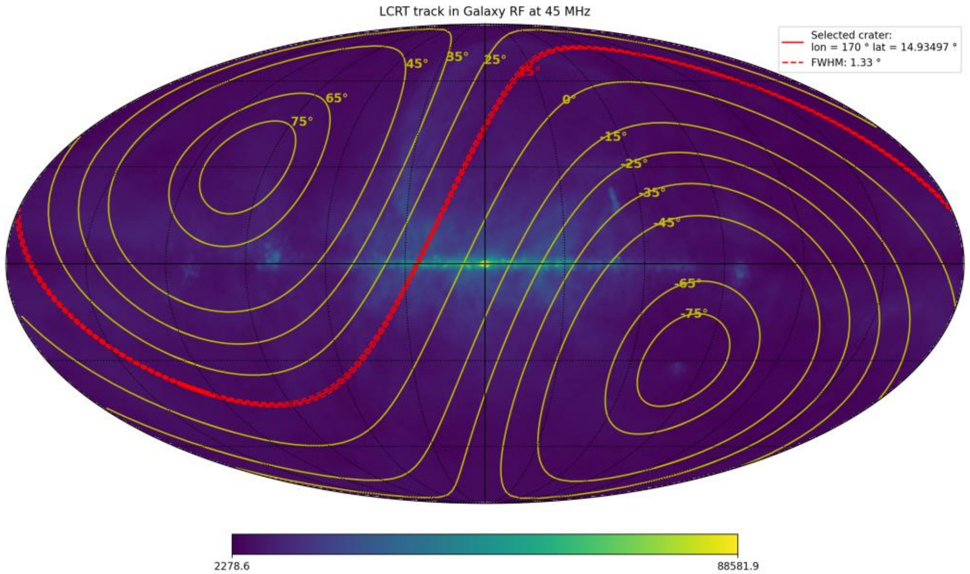
- <u>Challenge :</u>

  Galactic foreground several orders of magnitude stronger than signal



(Adapted from Prof. Jack Burns' slides)

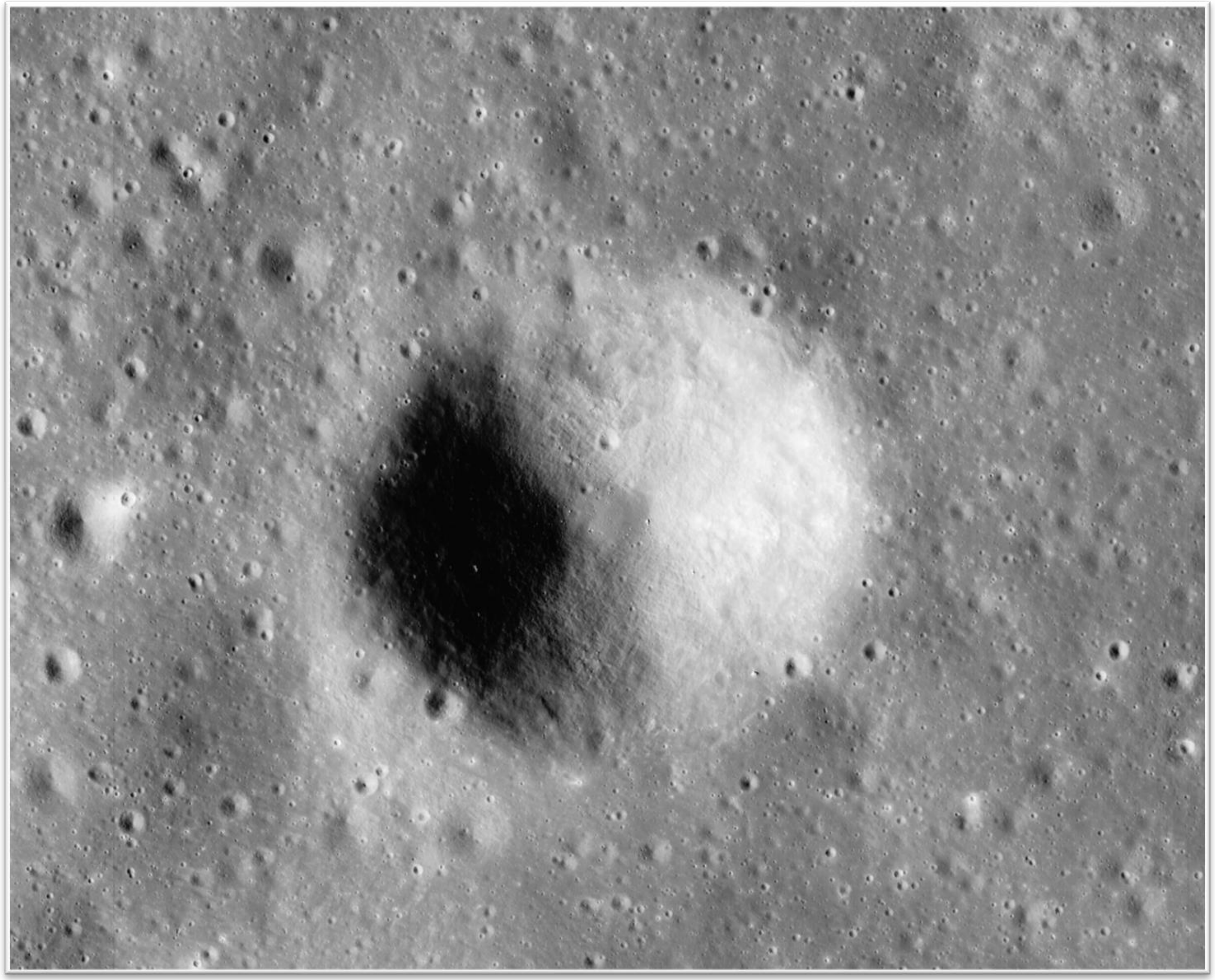
- Variation of galactic signal with lunar latitude



Selected Lunar Crater

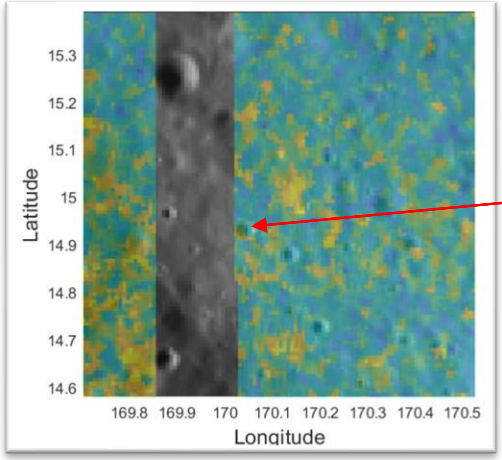
Selected Crater

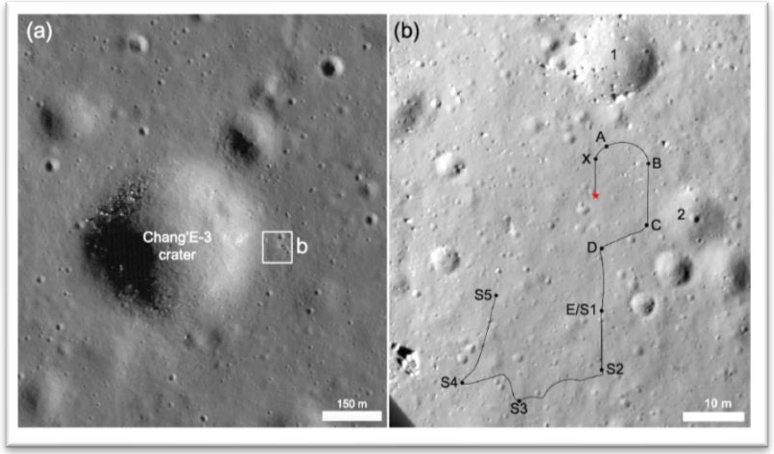
- Diameter: 1.33 km
- Depth: 275 m
- Depth to Diameter ratio: 0.21
- Location: 14.93497^{o}N, 170.05050^{o}E
- 1m/pixel resolution Digital Elevation Model (DEM)



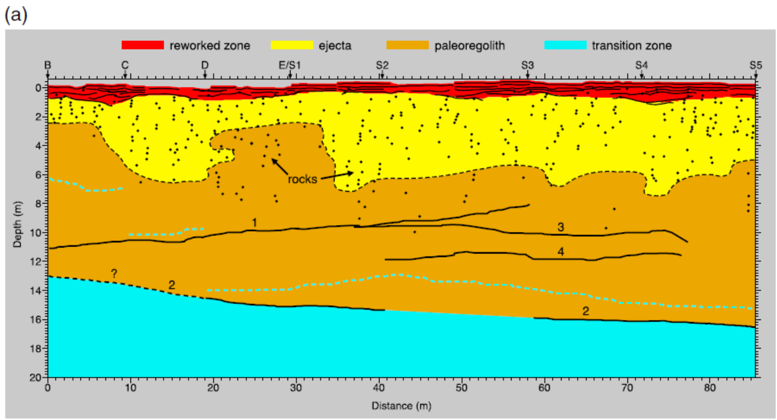
Subsurface Properties

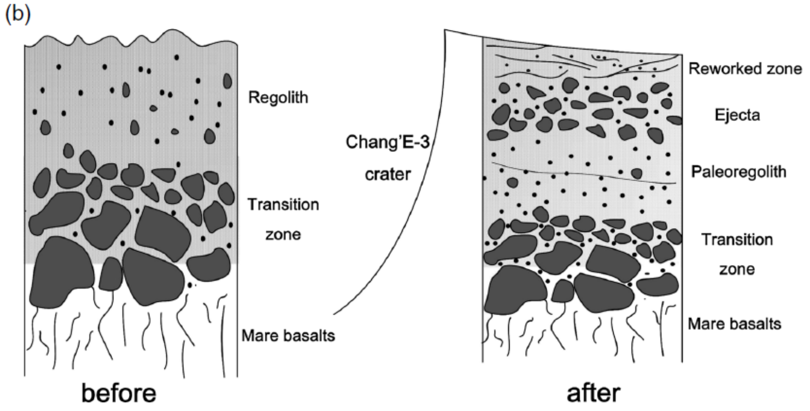
- Circular Polarization Ratio (CPR) from Mini-RF instrument on LRO Spacecraft
- Interpretation from Chang'E 3 Lunar Penetrating Radar data (500 MHz)





Lon: 44.1E Lat: 340.5N, Diameter: 450m, Depth: 50m

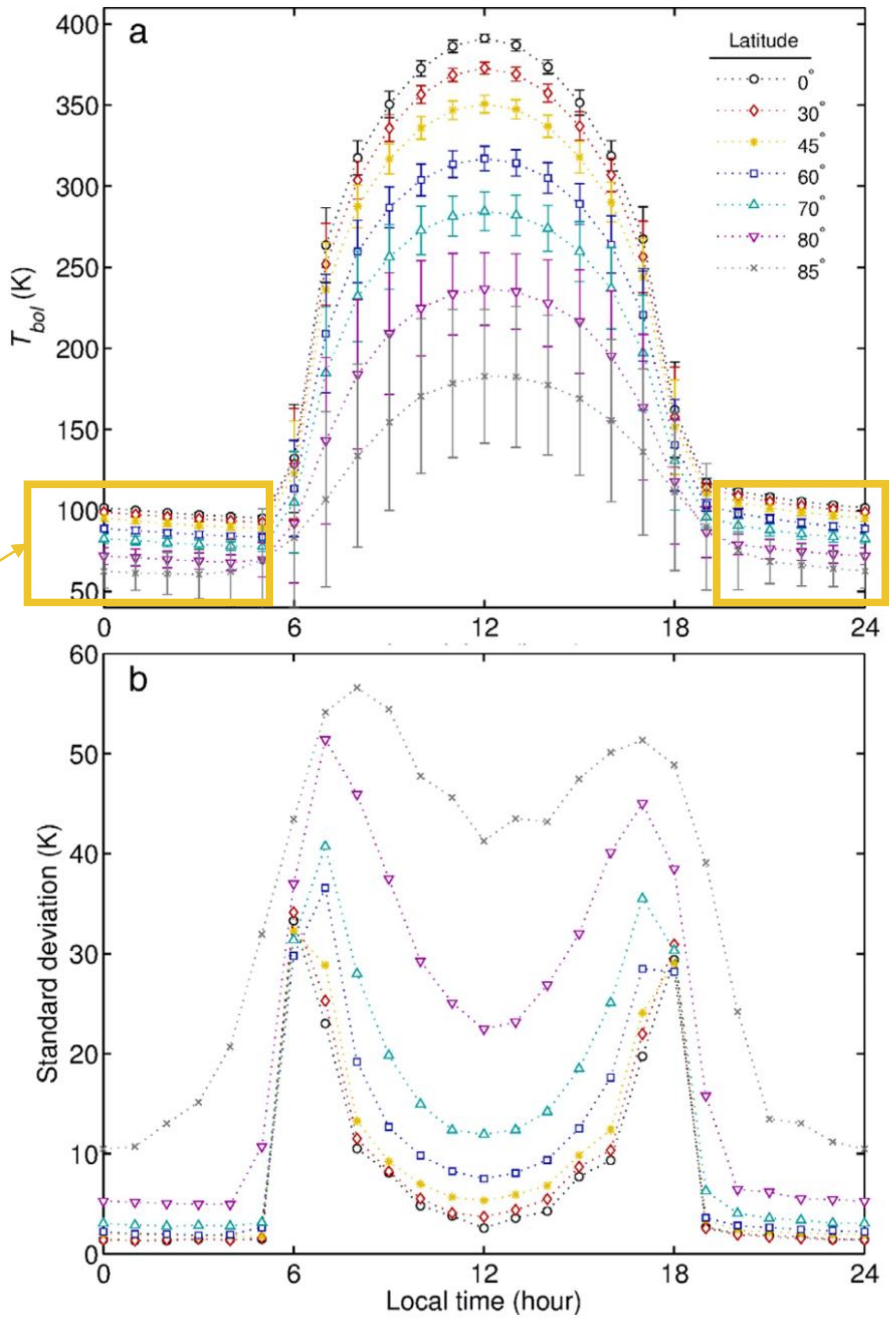




[1] W. Fa et, al., "Regolith stratigraphy at the Chang'E-3 landing site as seen by lunar penetrating radar," Geophysical Research Letters, 2015.

Temperature during Lunar Night

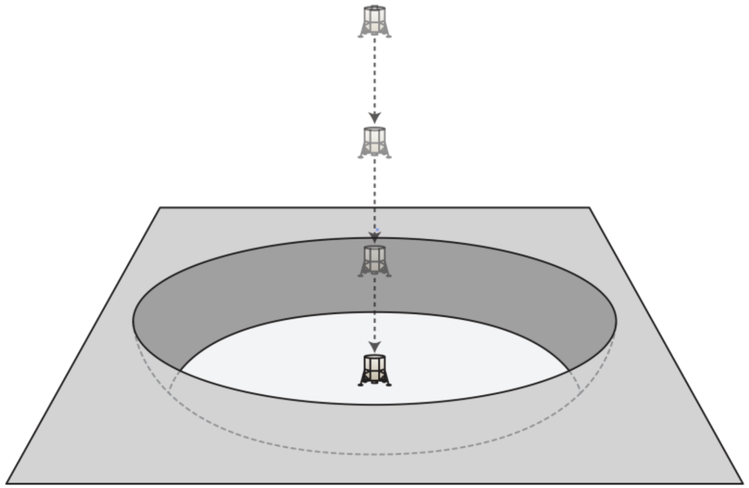
- Lunar Surface Temperatures
- ΔTemp = 10K (during lunar night)



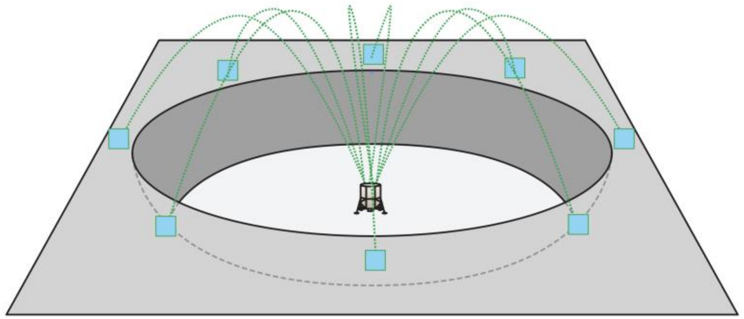
[1] J.-P. Williams, D. Paige, B. Greenhagen, and E. Sefton-Nash, "The global surface temperatures of the moon as measured by the diviner lunar radiometer experiment," Icarus, 2017.

Concept of Operations

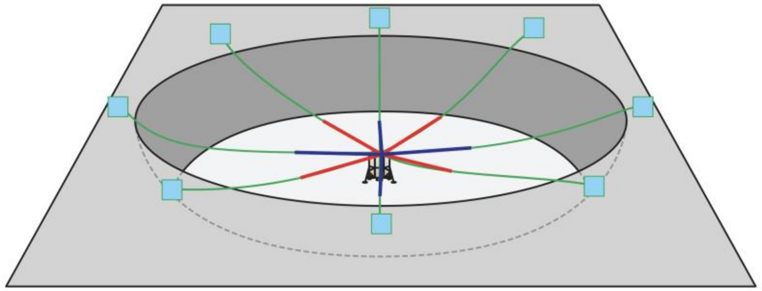
Step 1: Land in Crater



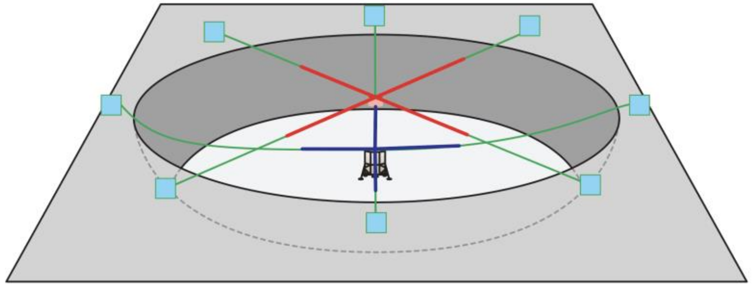
Step 2: Fire Anchors to Crater Rim



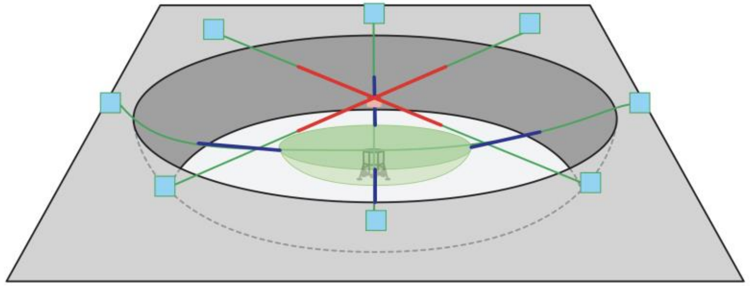
Step 3: Tension Lift Wires



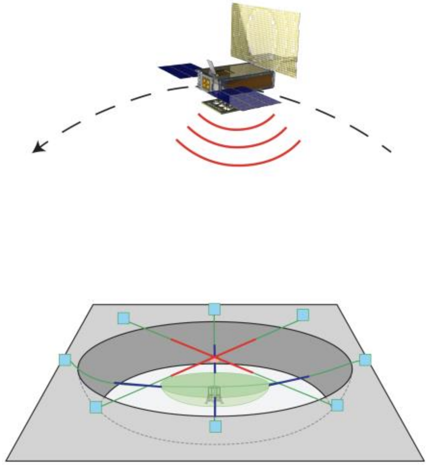
Step 4: Deploy Feed

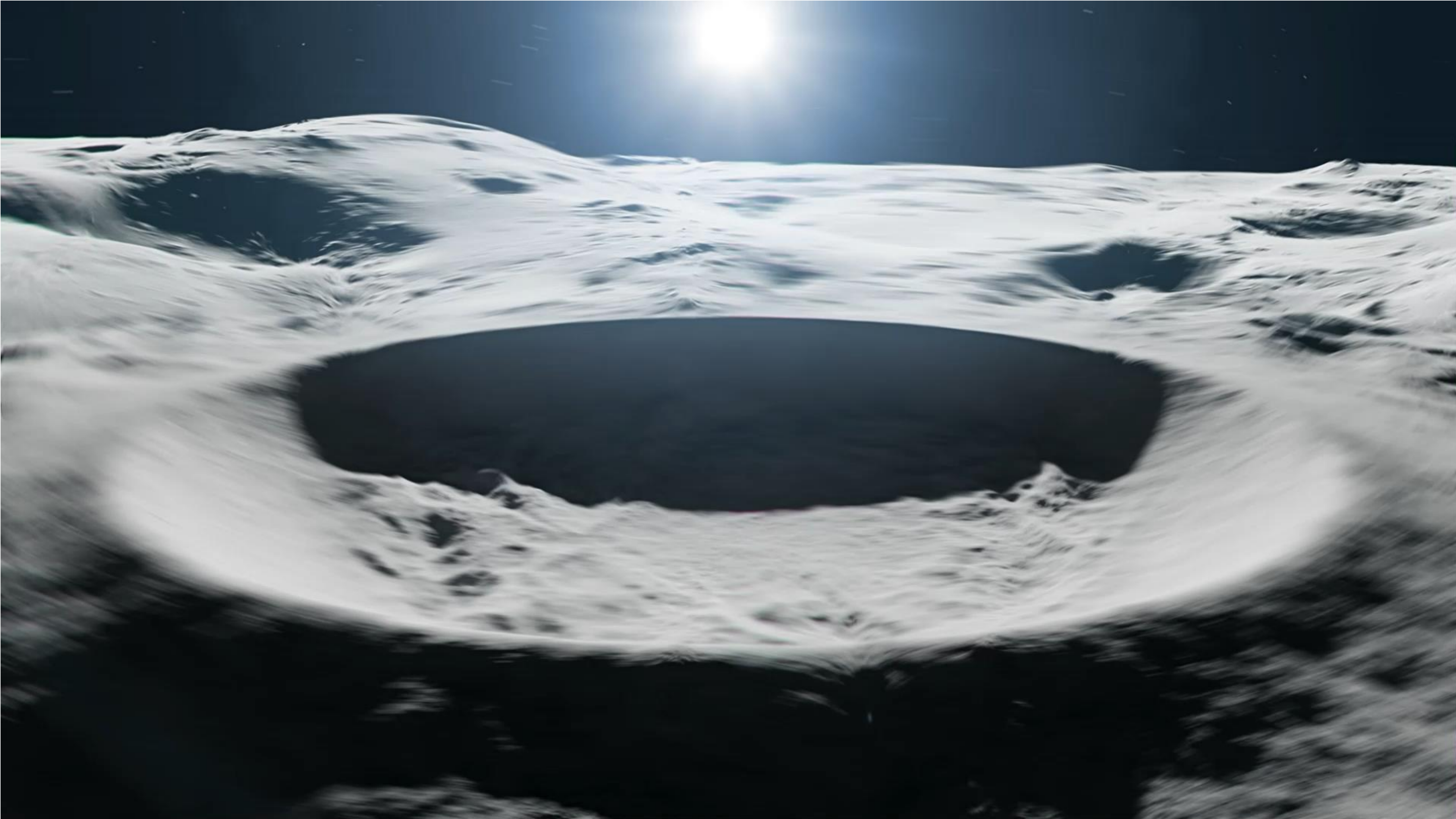


Step 5: Deploy Reflector

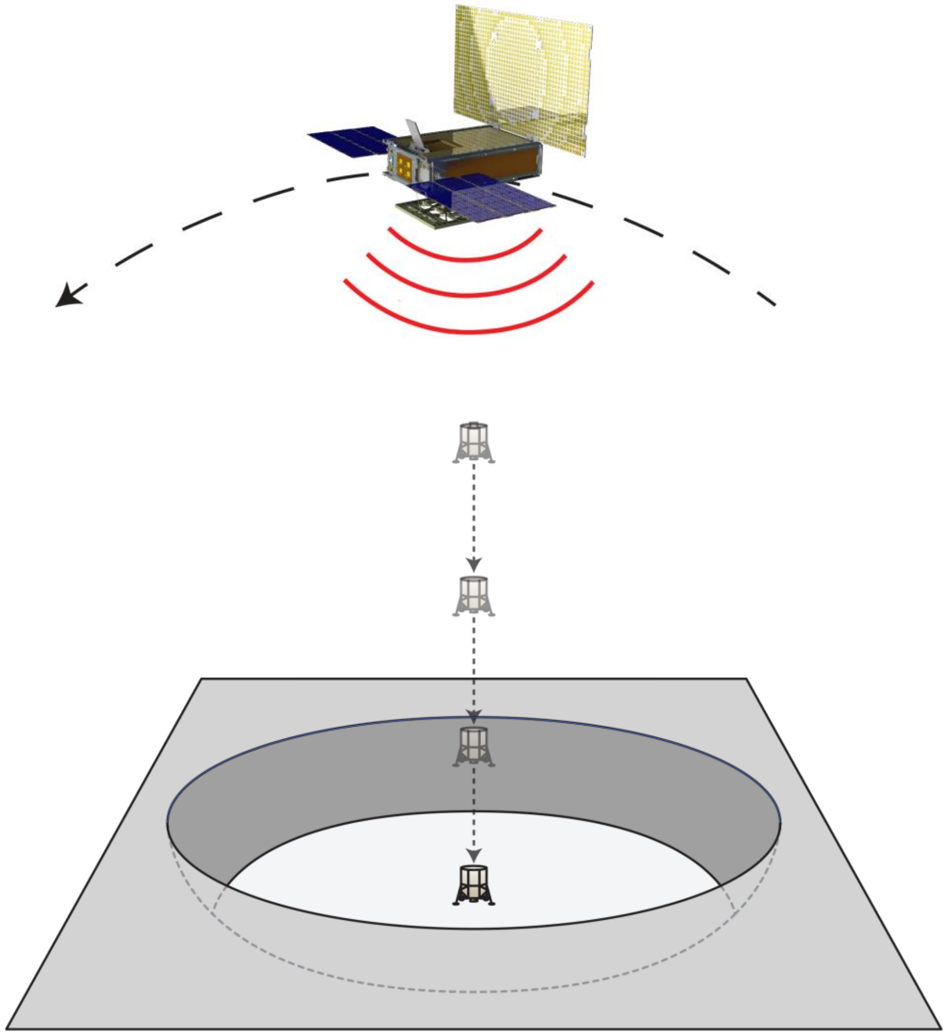


Step 6: Calibrate LCRT





ConOps Step 1: Land in Crater

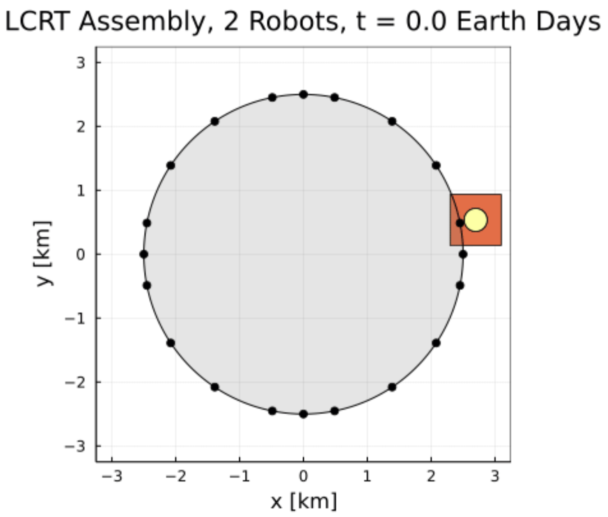


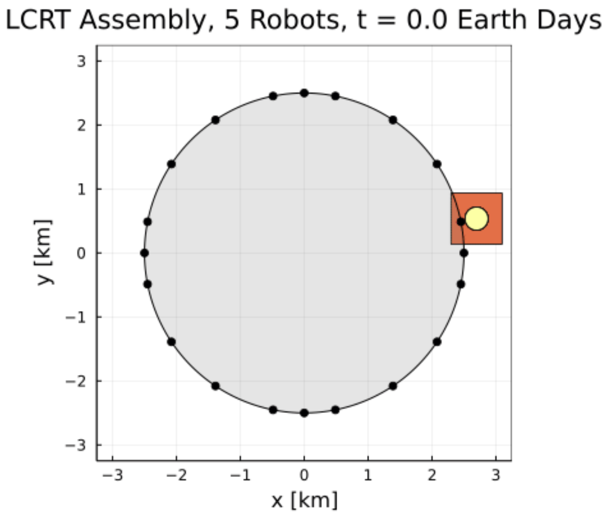
	Current Best Estimate (kg)	Mass Growth Allowance	Predicted Mass (kg)
Payload	745	20%	894
Feed + Reflector	510		
Anchors + Projectile	207		
Beacon Spacecraft X 2	14 X 2		
Spacecraft Bus	473	20%	567
ACS Subsystem	9		
CDS Subsystem	28		
Mechanical Subsystem	220		
Power Subsystem	161		
Telecom Subsystem	30		
Thermal Subsystem	25		
Total Predicted Mass			**1461**
		JPL DP9 Mass Margin	**23%**
Total Launch Mass			**1741**

Why Projectile-based Deployment?

Rover-based and projectile-based deployments were studied

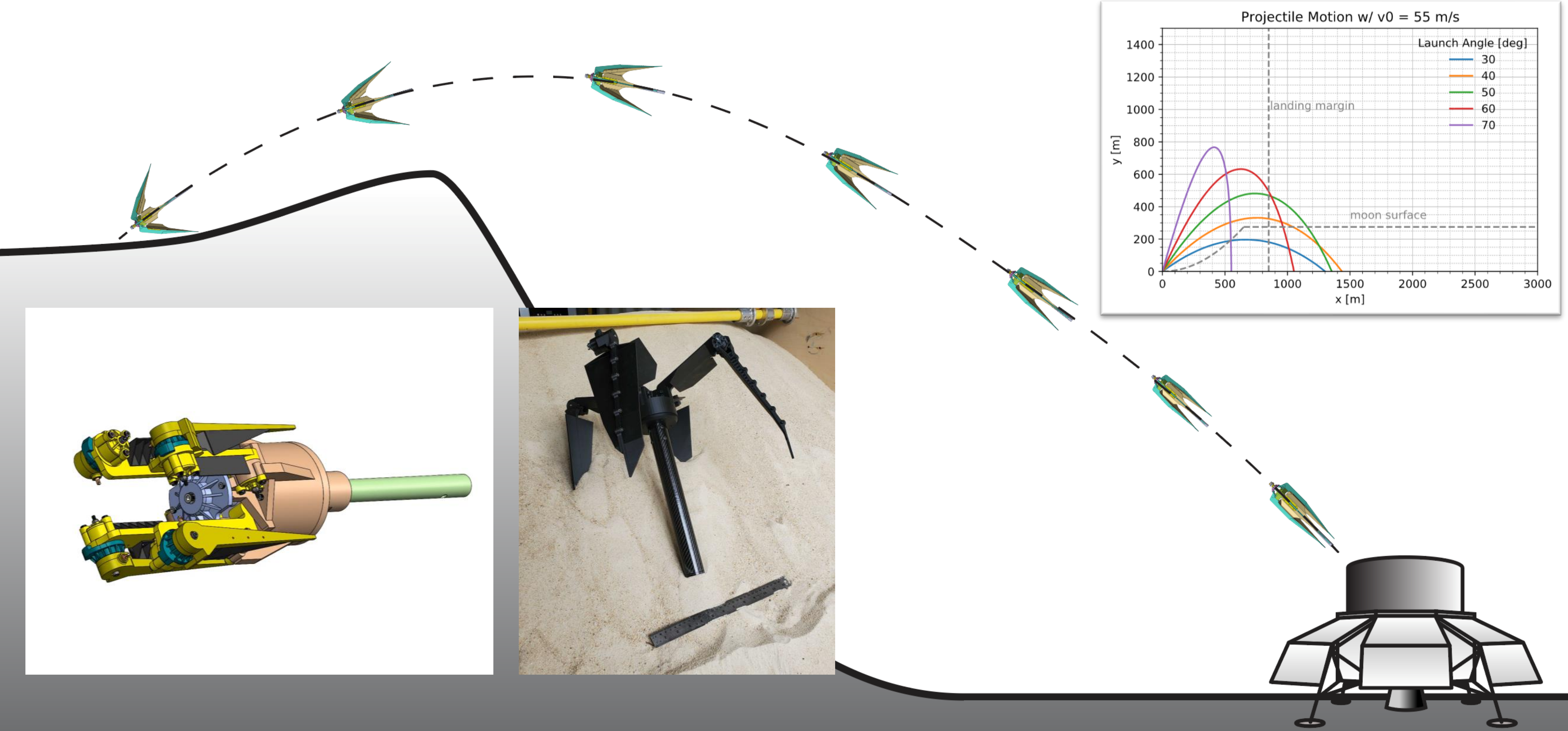
- 1.3km dia. crater is within the reach of projectiles
- We need 8 rover to construct LCRT in 1 lunar day, or the rovers need to survive lunar night
- Rovers need lander at crater rim



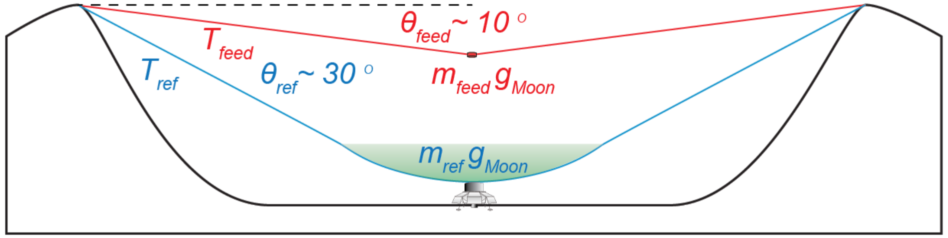


[1] P. Culbertson, A. Goel, P. Mcgarey, M. Schwager, S. Bandyopadhyay, "Multi-Robot Assembly Scheduling for the Lunar Crater Radio Telescope on the Far-Side of the Moon," IEEE Aerospace Conference, Big Sky, MT, Mar. 2022.

ConOps Step 2: Fire Anchors



Testing of Plow Anchors

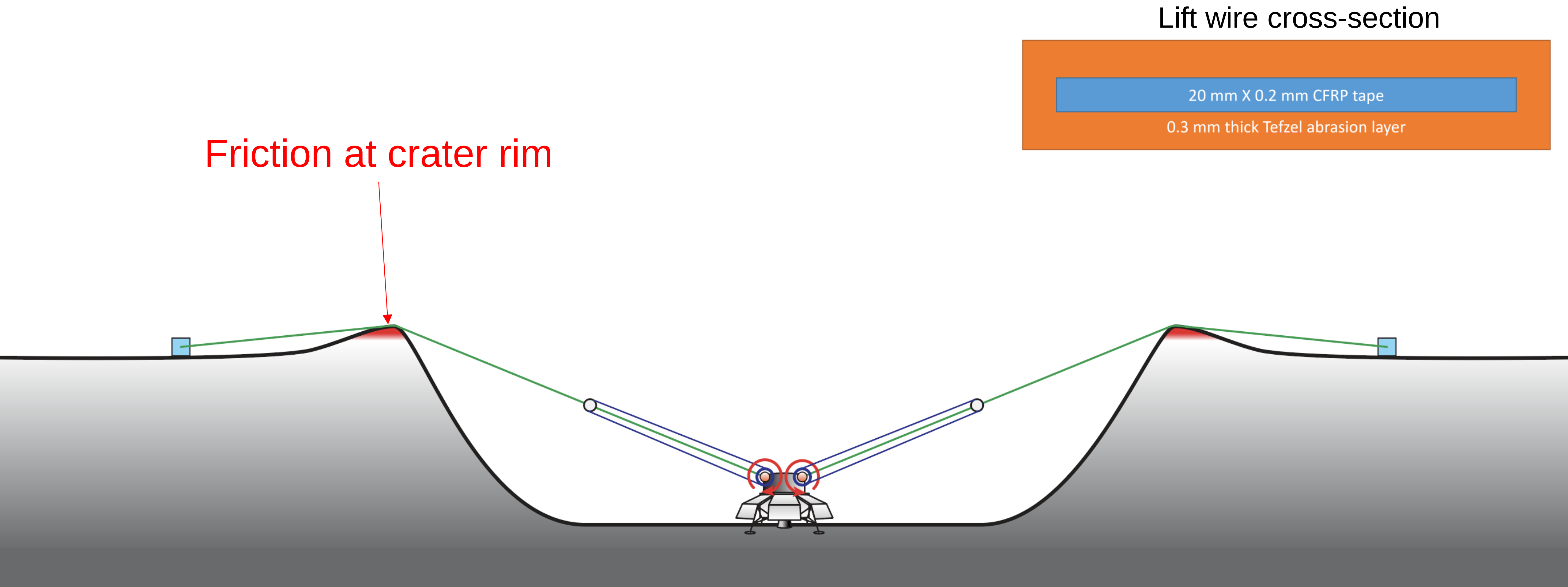


$$T_{ref} = 321 \text{ N}, T_{feed} = 317 \text{ N}$$

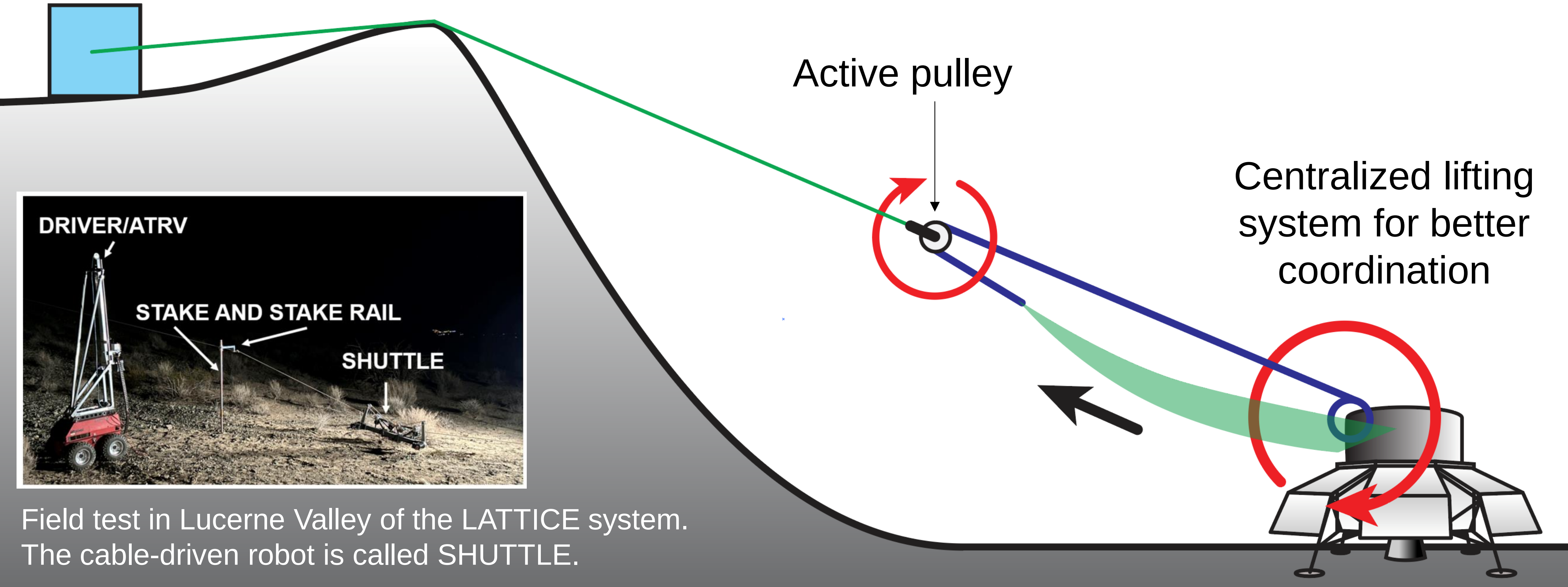
[1] K. Carpenter, S. Bandyopadhyay, H. Stuart, A. Goel, S. Moreland, C. Gebara, E. Jens, B. Hockman, "Launchable Lunar Anchors", Structures and Materials in Extreme Environments, SciTech, Jan 2025.

[2] R. Wang, V. Gehlot, S. Bandyopadhyay, A. Goel, B. Byron, P. McGarey, R. Wilson, K. Jenks, "Lift Wire Deployment and Anchoring System for the Lunar Crater Radio Telescope on the Far Side of the Moon," AIAA SciTech Space Exploration, National Harbor, MD, January 2023.

ConOps Step 3: Tension Lift Wires



ConOps Step 4: Deploy Feed

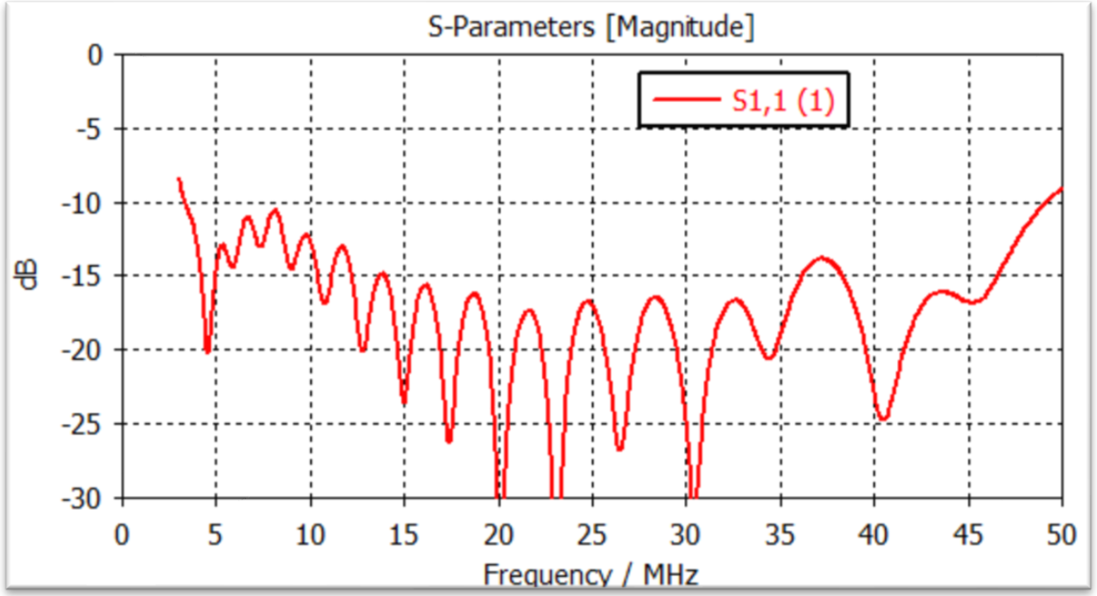


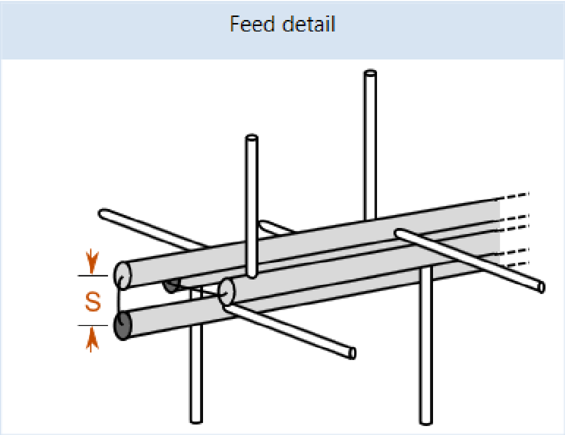
Field test in Lucerne Valley of the LATTICE system.
The cable-driven robot is called SHUTTLE.

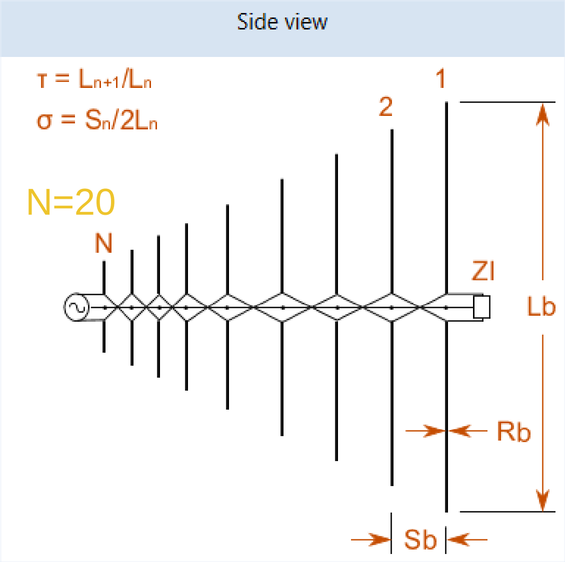
Design of the Feed

Log Periodic Antenna:

- Provides V, H, and C polarization
- Length = 37.5m



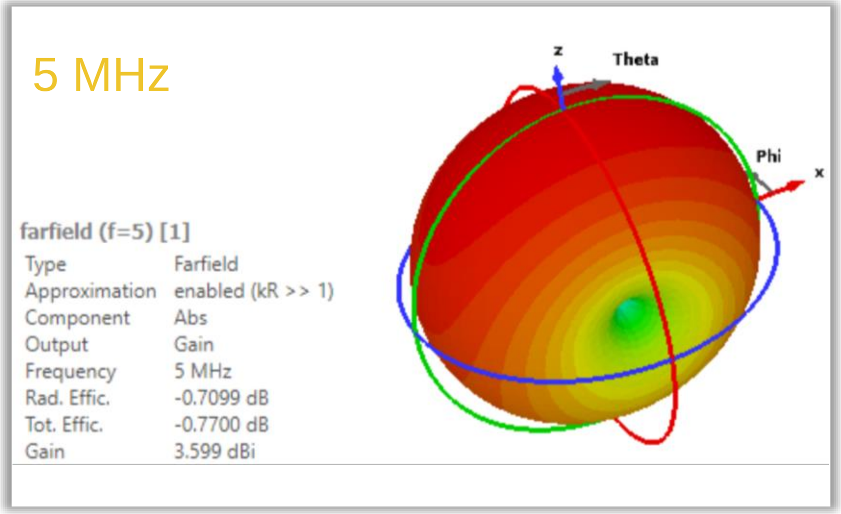


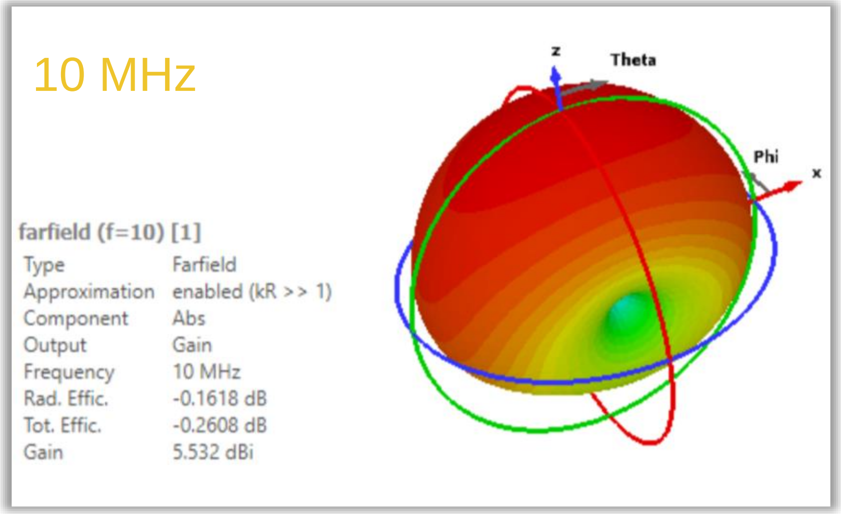


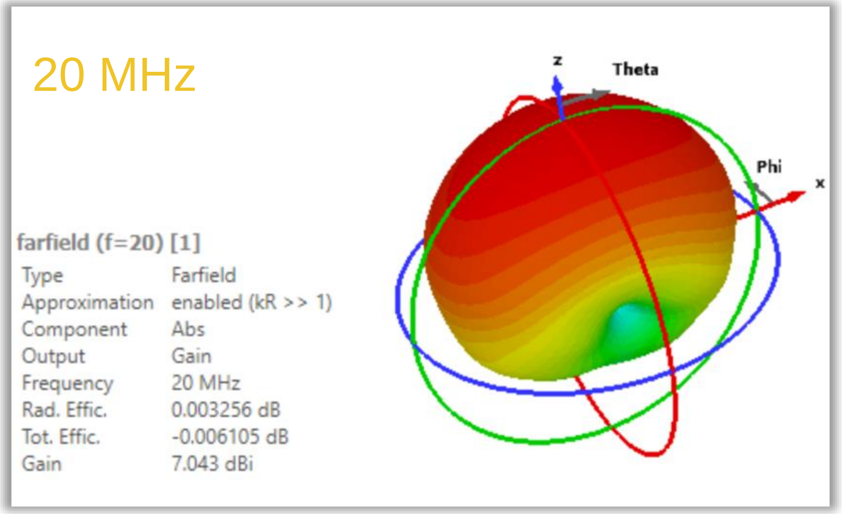
Lb = 37m

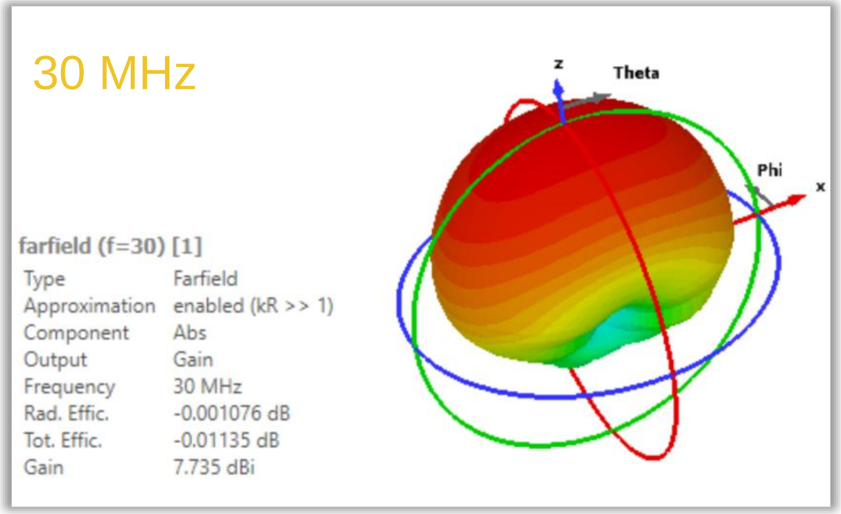
Sb = 2.3m

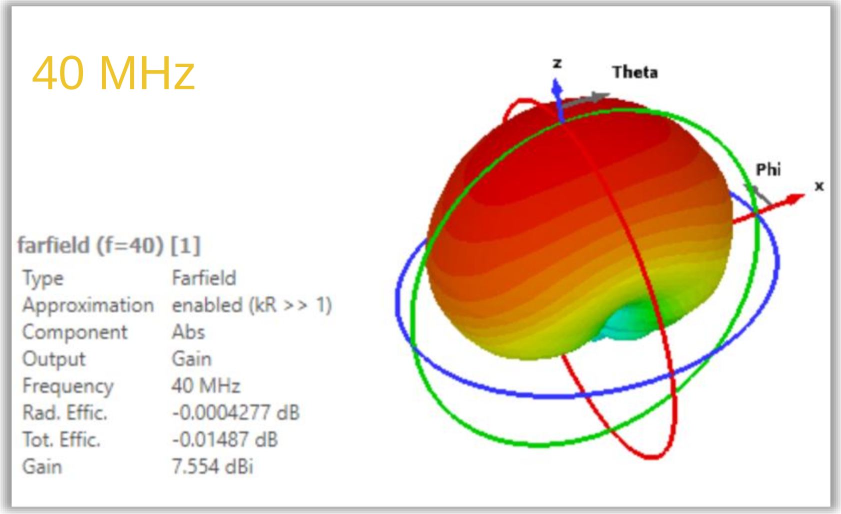
RF Performance of the Feed

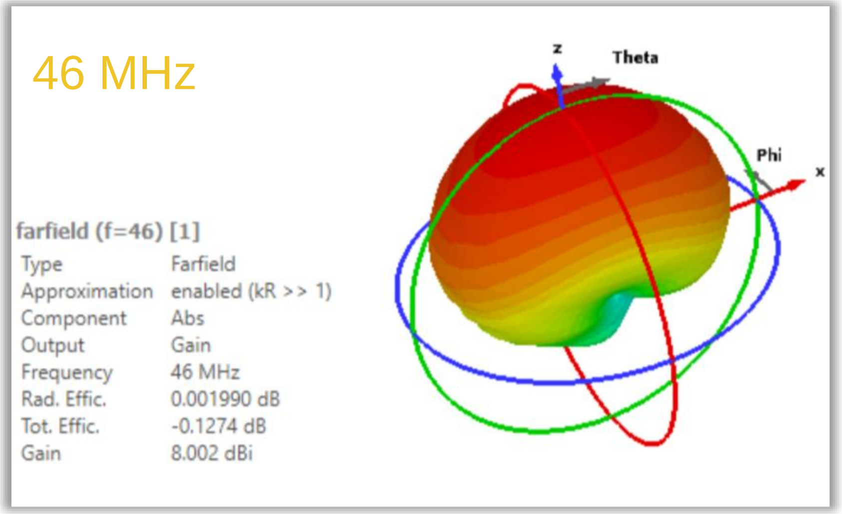




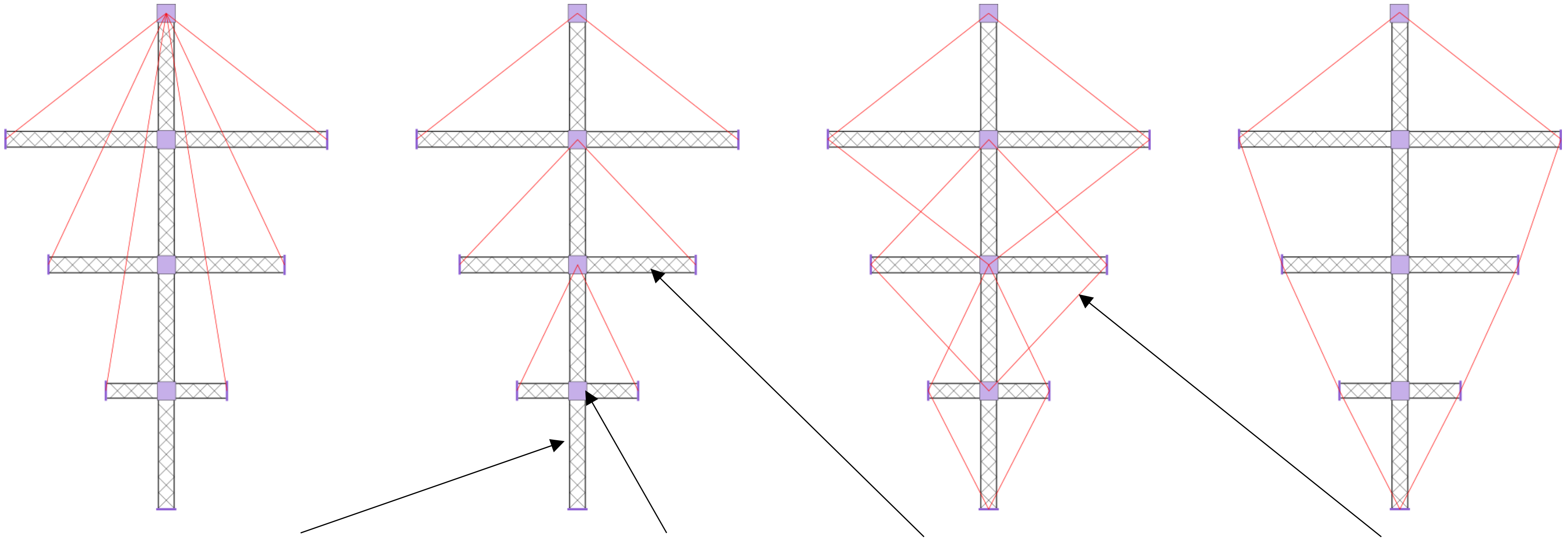








Deployment of the Feed

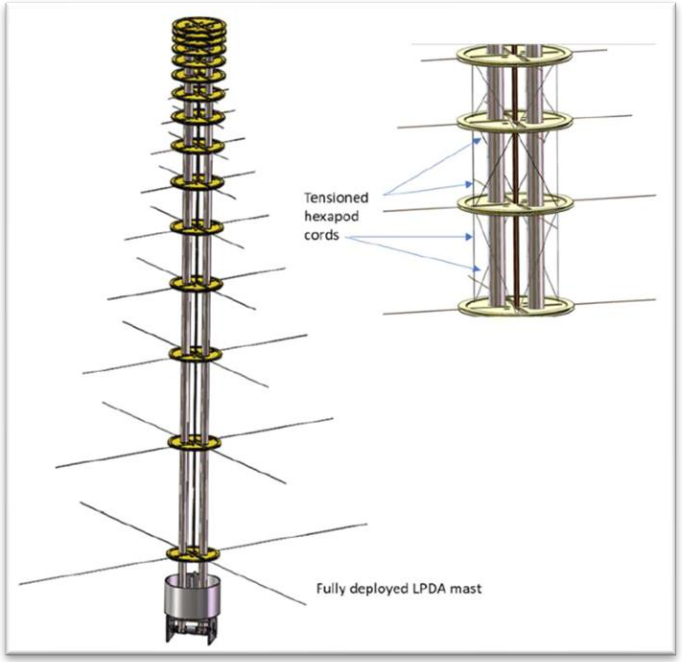


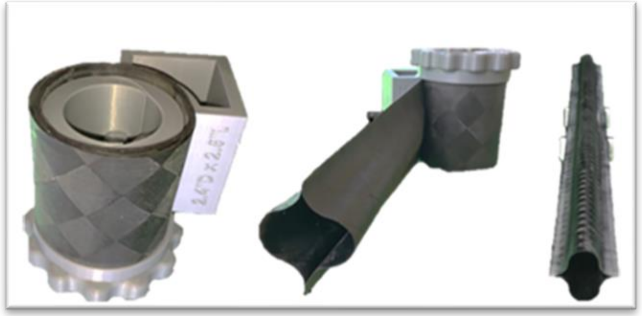
Central mast
AstroMast or
similar

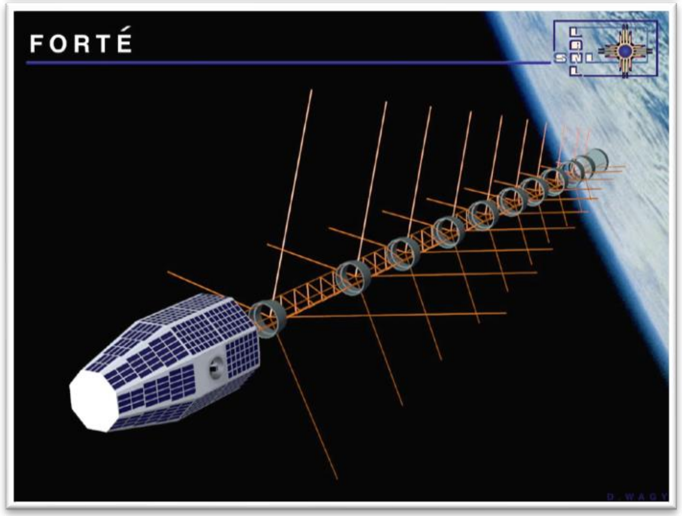
Non-deployable
nodal structures

Dipole booms
AstroMast (or similar), or
coiled CFRP booms

Tension cables

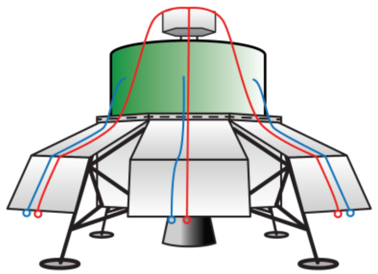




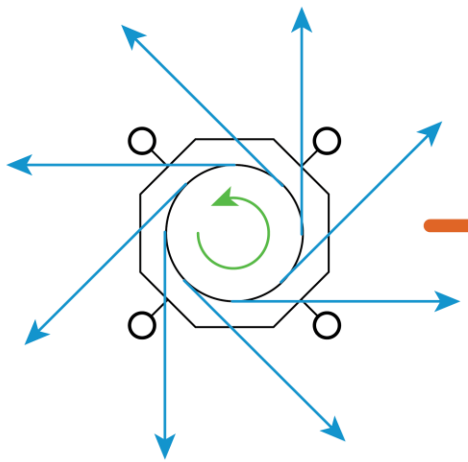


ConOps Step 5: Deploy Reflector

Rotating Disk with embedded antenna
(blue deployment wires)

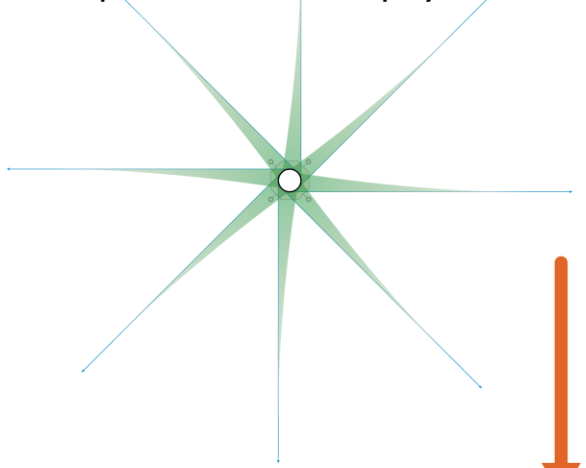


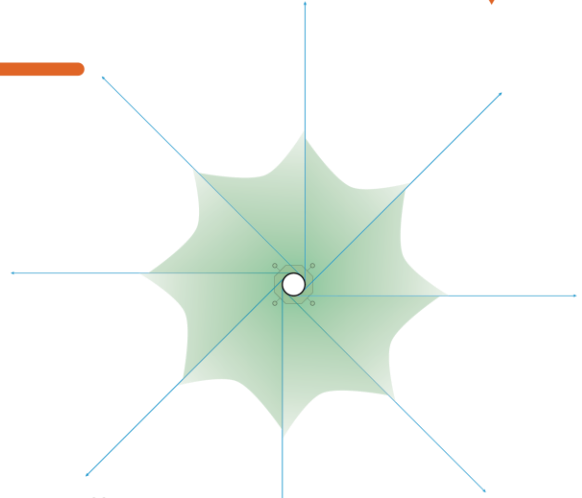
Red Wire for receiver deploy first
(not as complex simple lift)



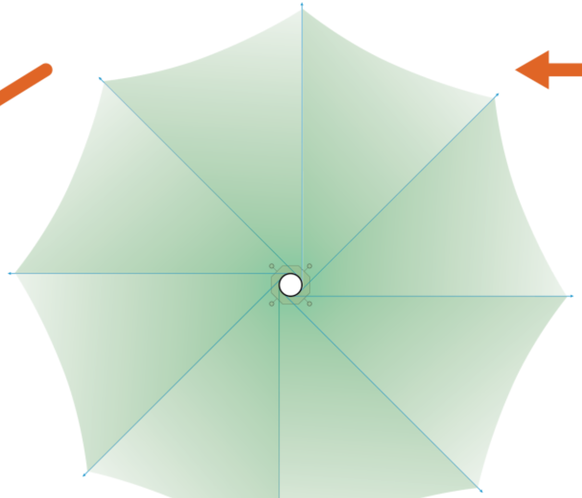
Pulled guide wire spins the
disc, releasing constraints

Origami folding of mesh allows
for compact and reliable deployment

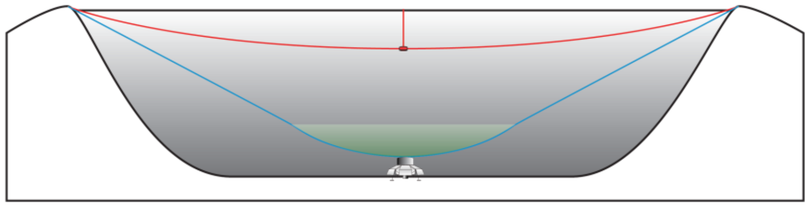




Stiff outer wires provide structure
to the mesh at the pull out points



Fully deployed (top view)

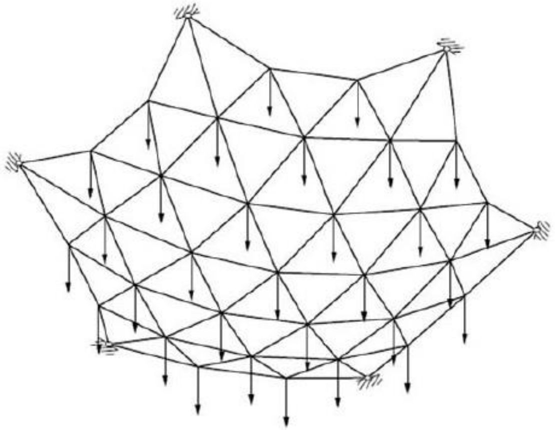


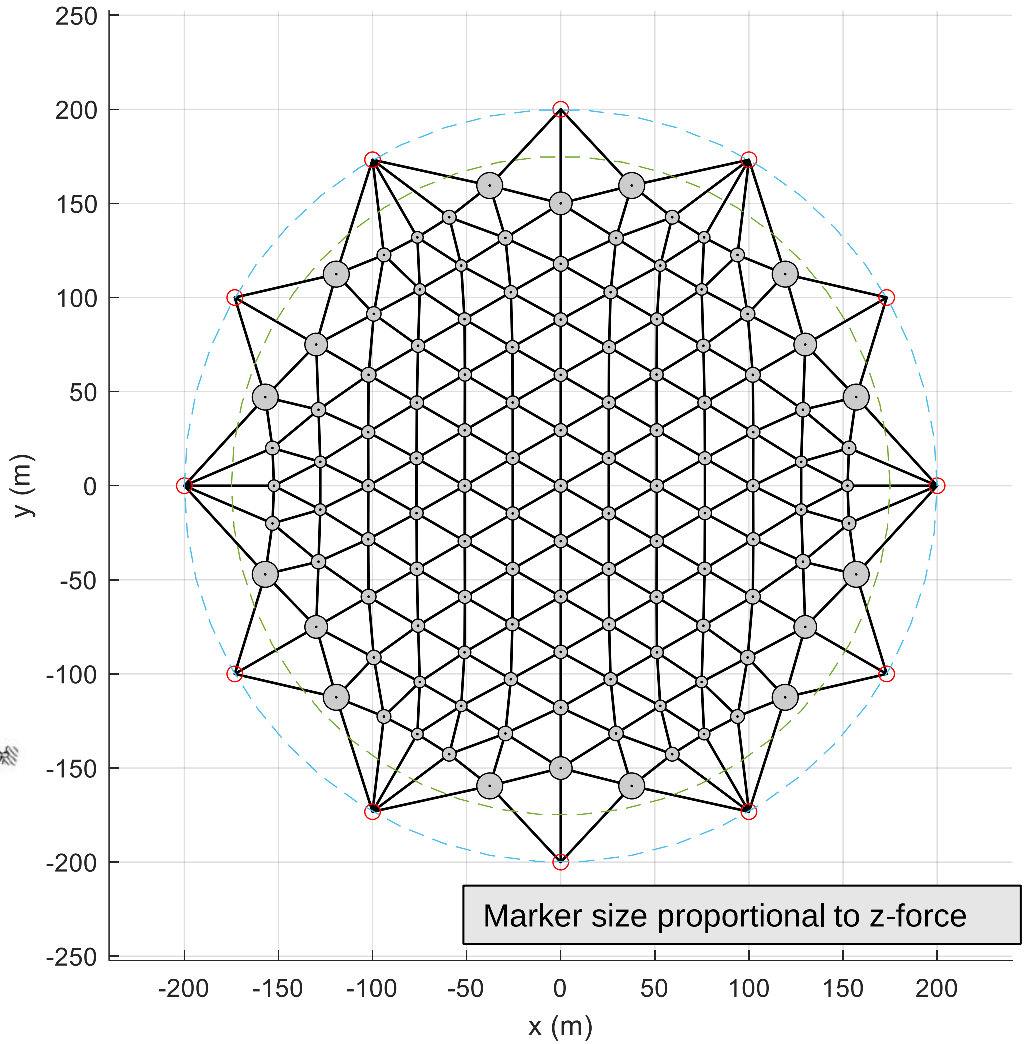
Fully deployed (side view)
Lander stays attached to bottom of antenna for support

Height of stack depends
of number of folds
h = 2πr / folds

Design of the Reflector

- Structural network of tensioned cables
- Structural net supports compliant metallic mesh



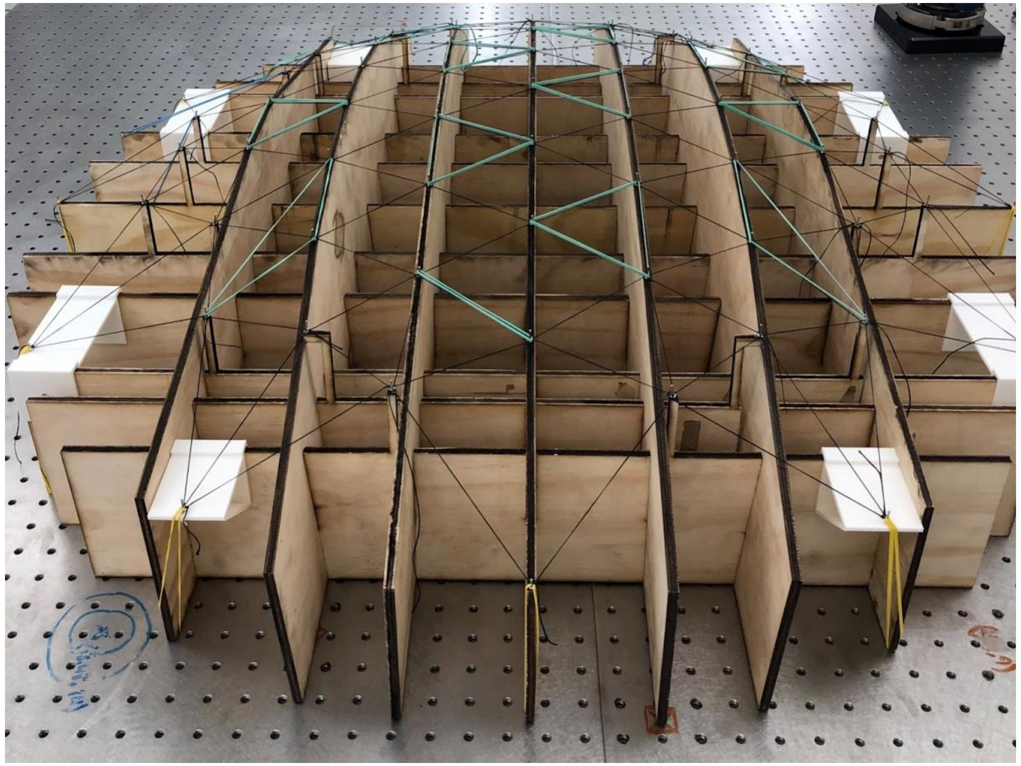


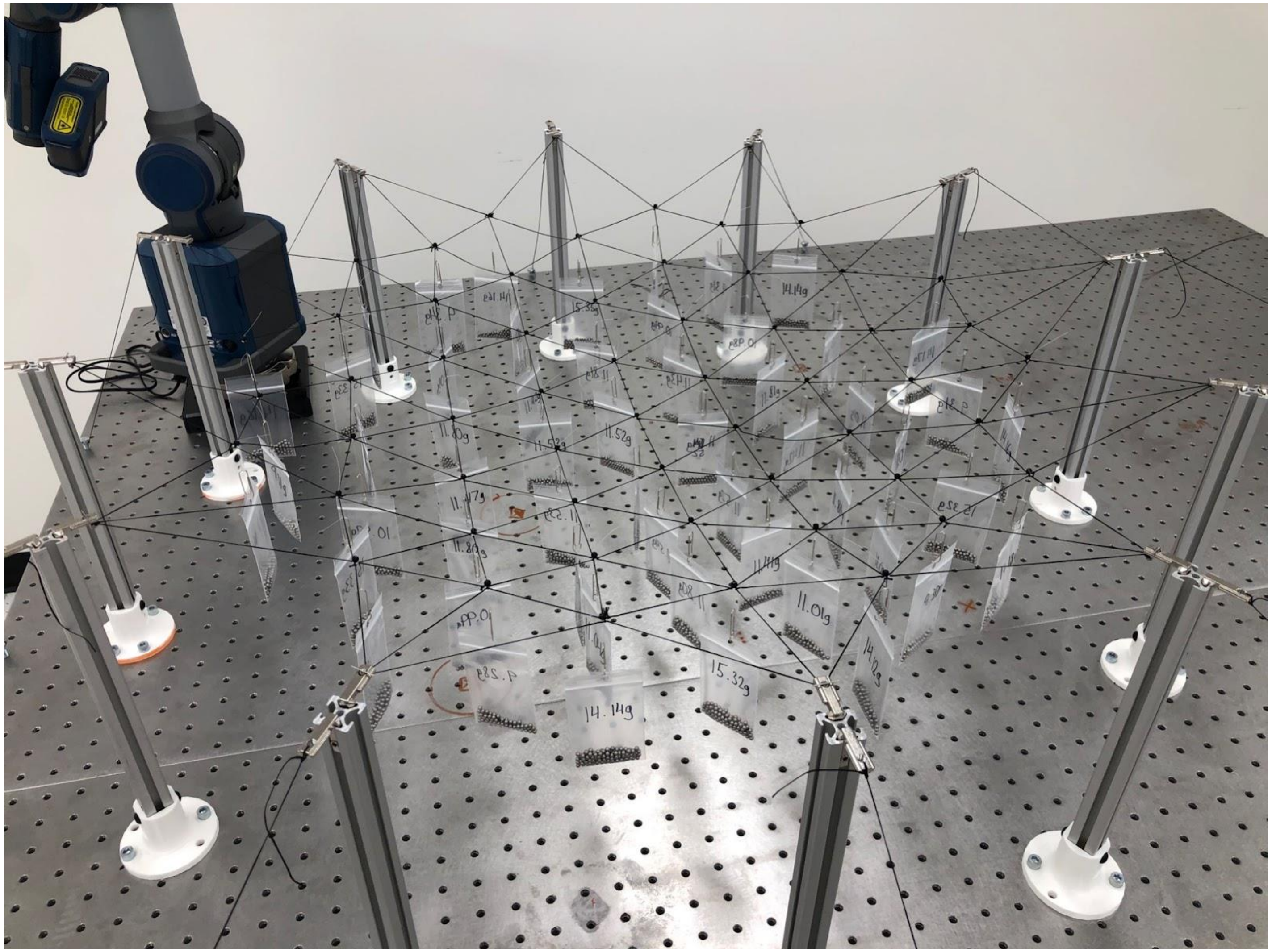
[1] G. Tibert. "Deployable tensegrity structures for space applications". PhD thesis. Dept. of Mechanics, KTH Royal Institute of Technology, 2002.
[2] G. Tibert. "Optimal design of tension truss antennas". 44th AIAA/ ASME/ASCE/ AHS/ ASC Structures, Structural Dynamics, and Materials Conference, 2003.

Subscale Reflector Prototype

~1 m-scale reflector prototype to check:

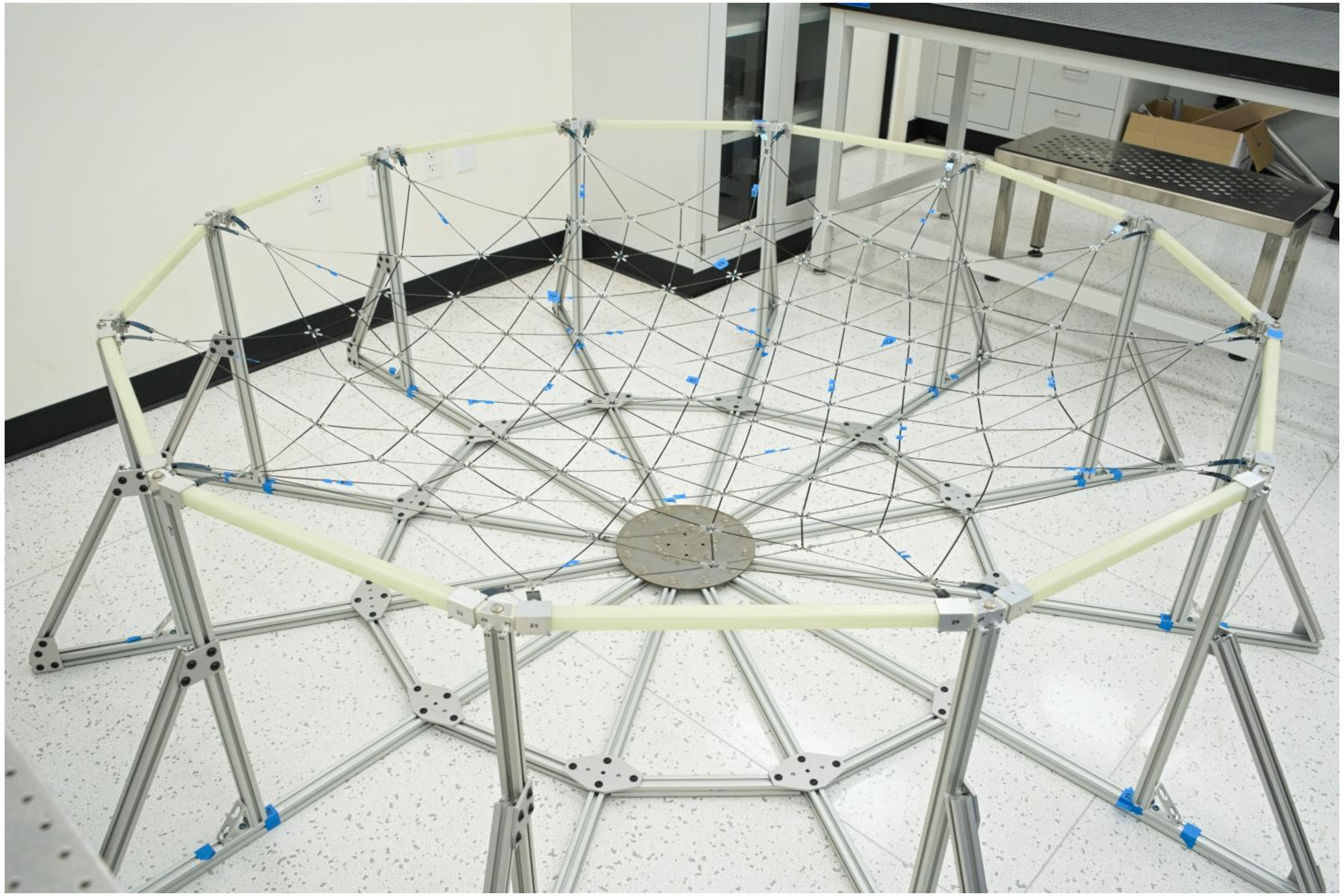
- Hanging net is stable and stiff
- Hanging shape matches as-designed

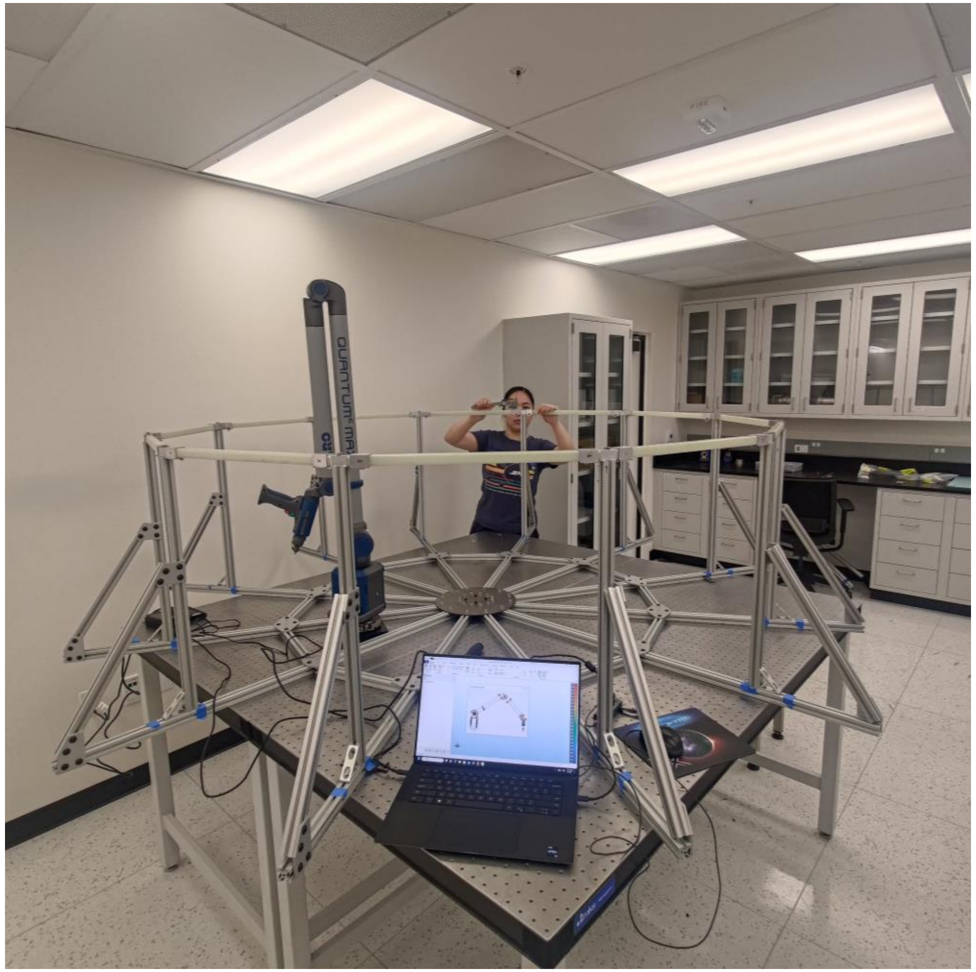




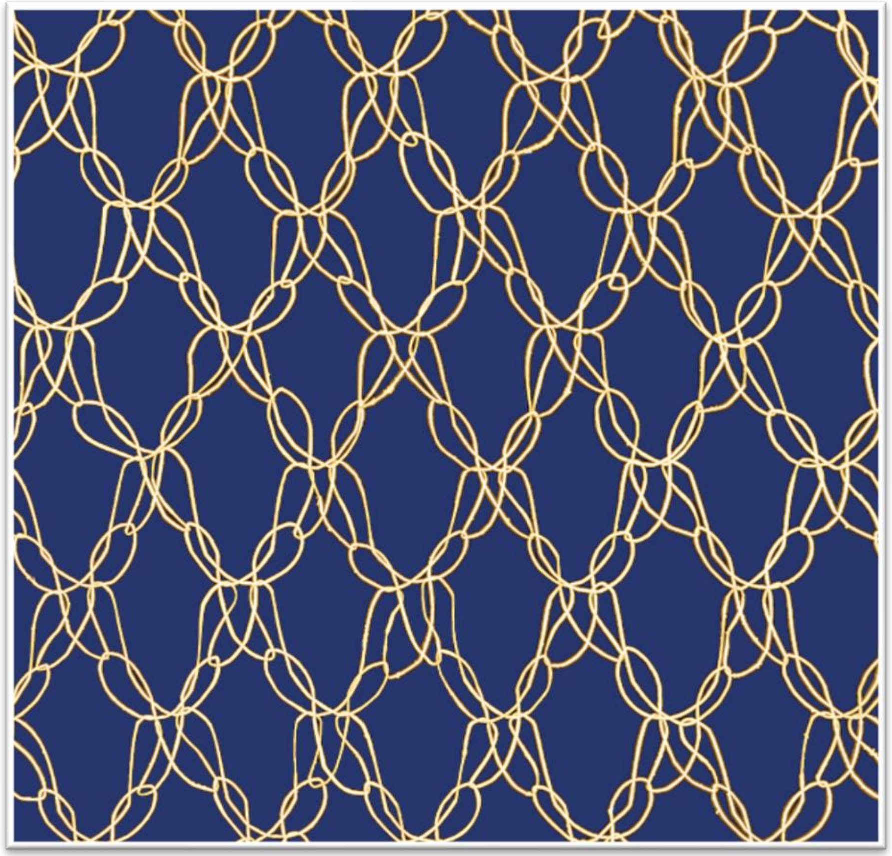
Subscale Reflector Prototype

1/200 scale reflector prototype in crater for RF testing:



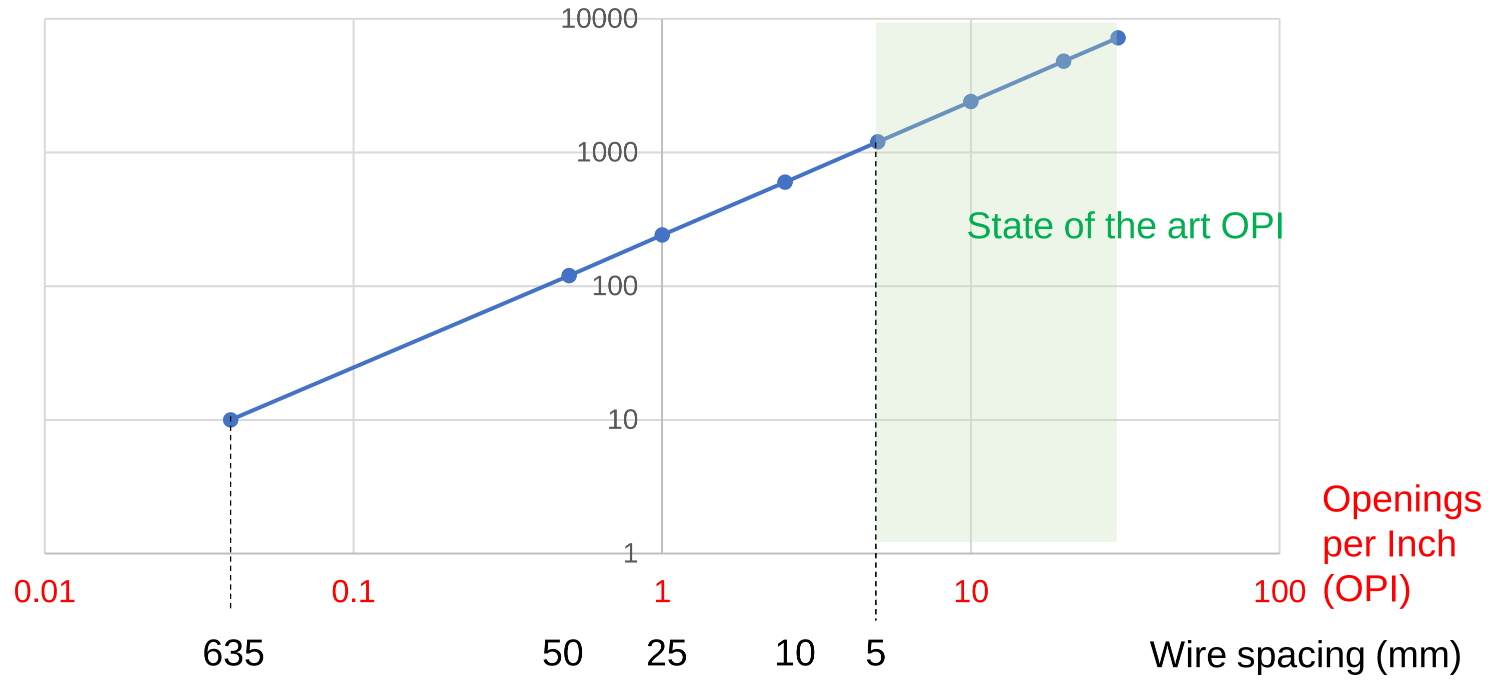


Design of the Reflector Mesh

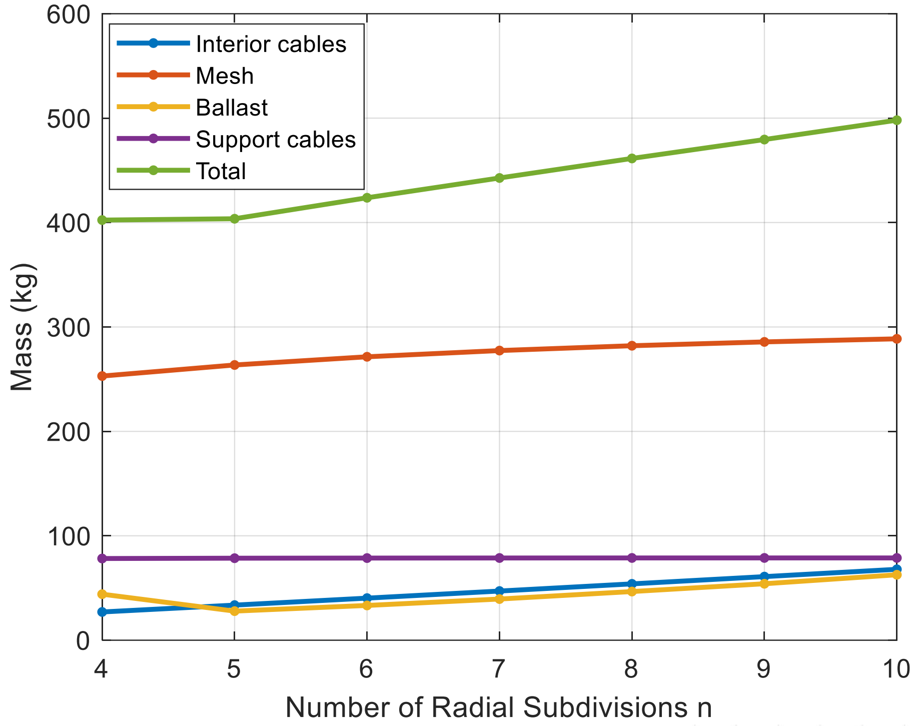


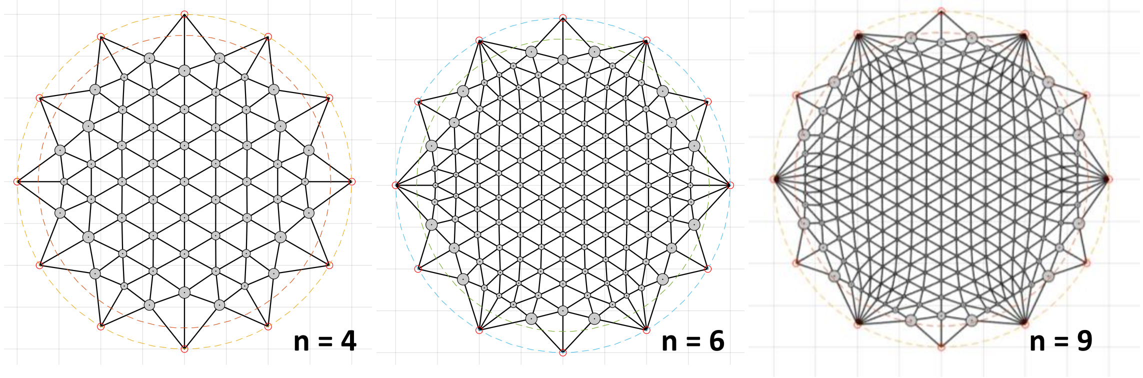
Secant Group's Knit Gold Antenna Mesh

Mesh mass for 350 m diameter (kg)

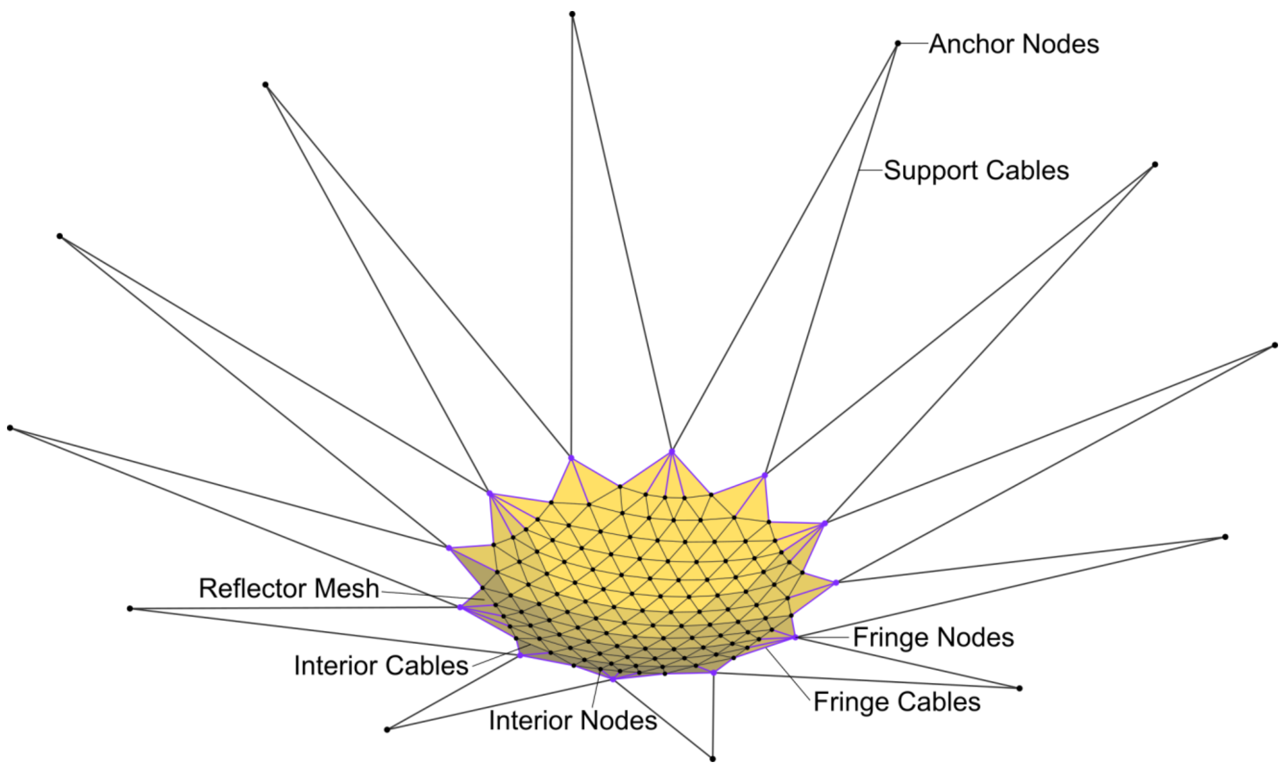


Design of the Reflector



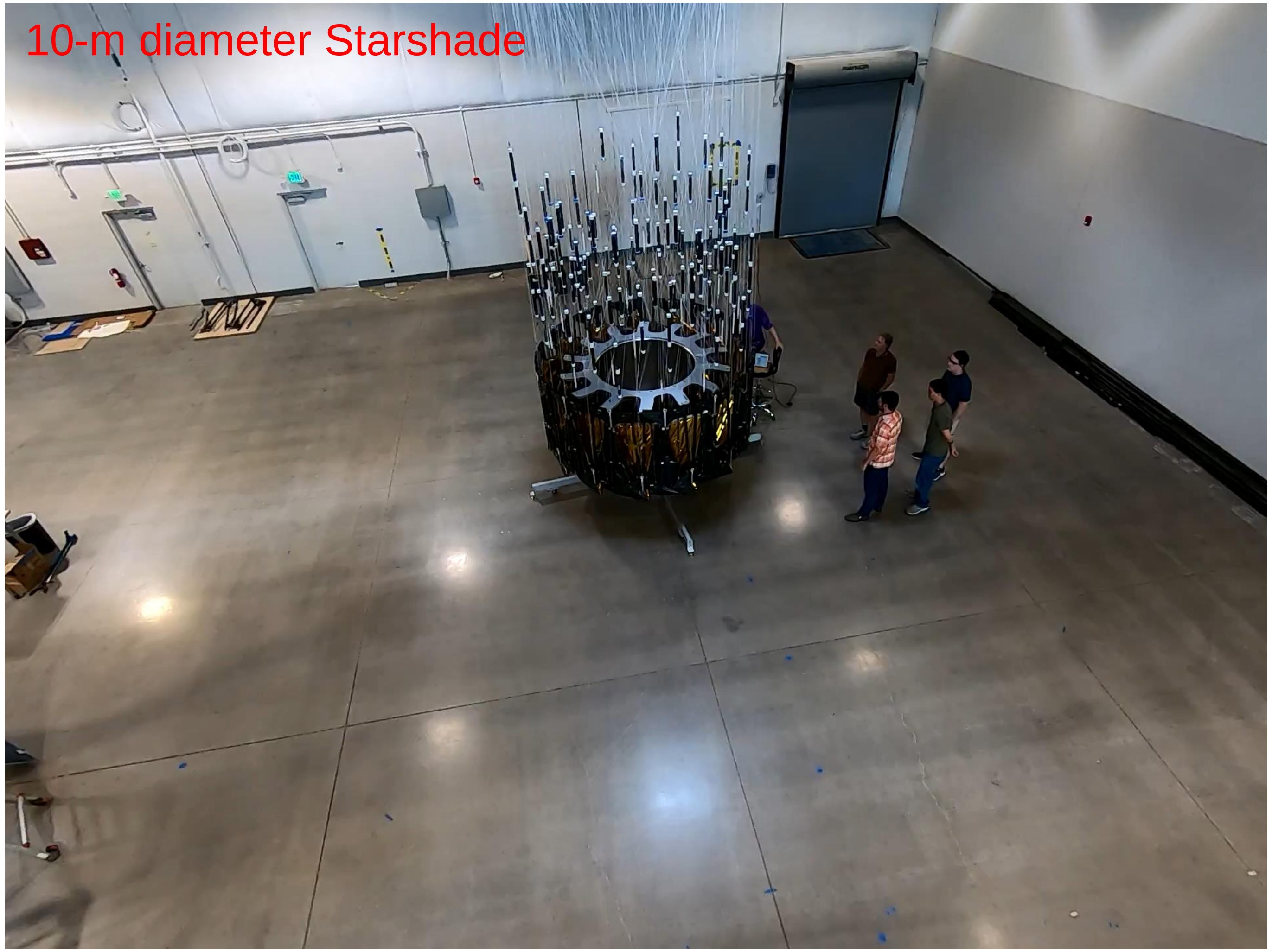


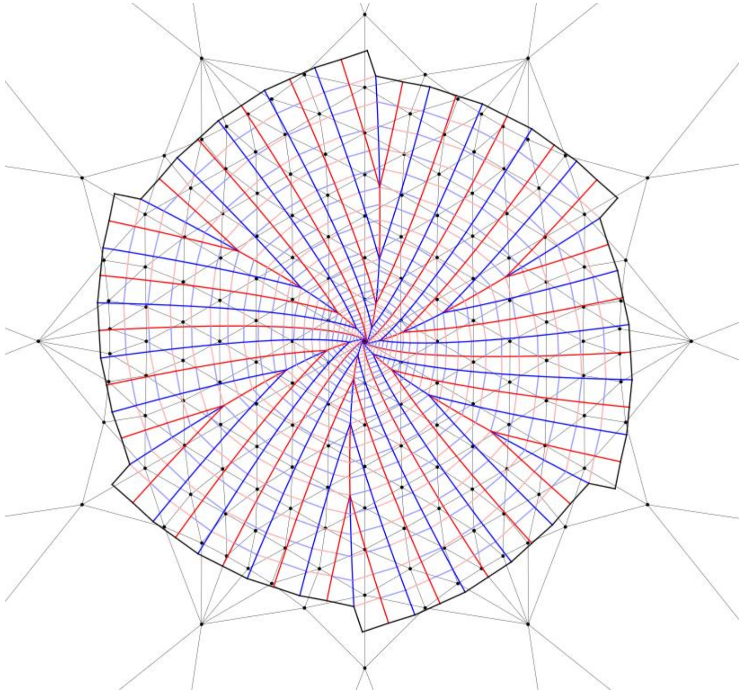
Proposed architecture for support cables

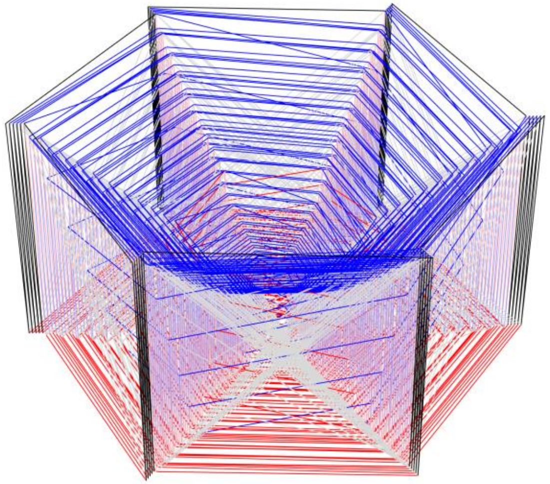


[1] M. Arya, A. Verniani, M. Delapierre, D. Pisanti, G. Gupta, A. Goel, J. Lazio, P. Goldsmith, S. Bandyopadhyay, "Kilometer-Scale Parabolic Reflector for a Radio Telescope in a Lunar Crater," AIAA SciTech Spacecraft Structures, National Harbor, MD, January 2023. **[2023 AIAA Spacecraft Structures Best Paper Award]**

Deployment of the Reflector

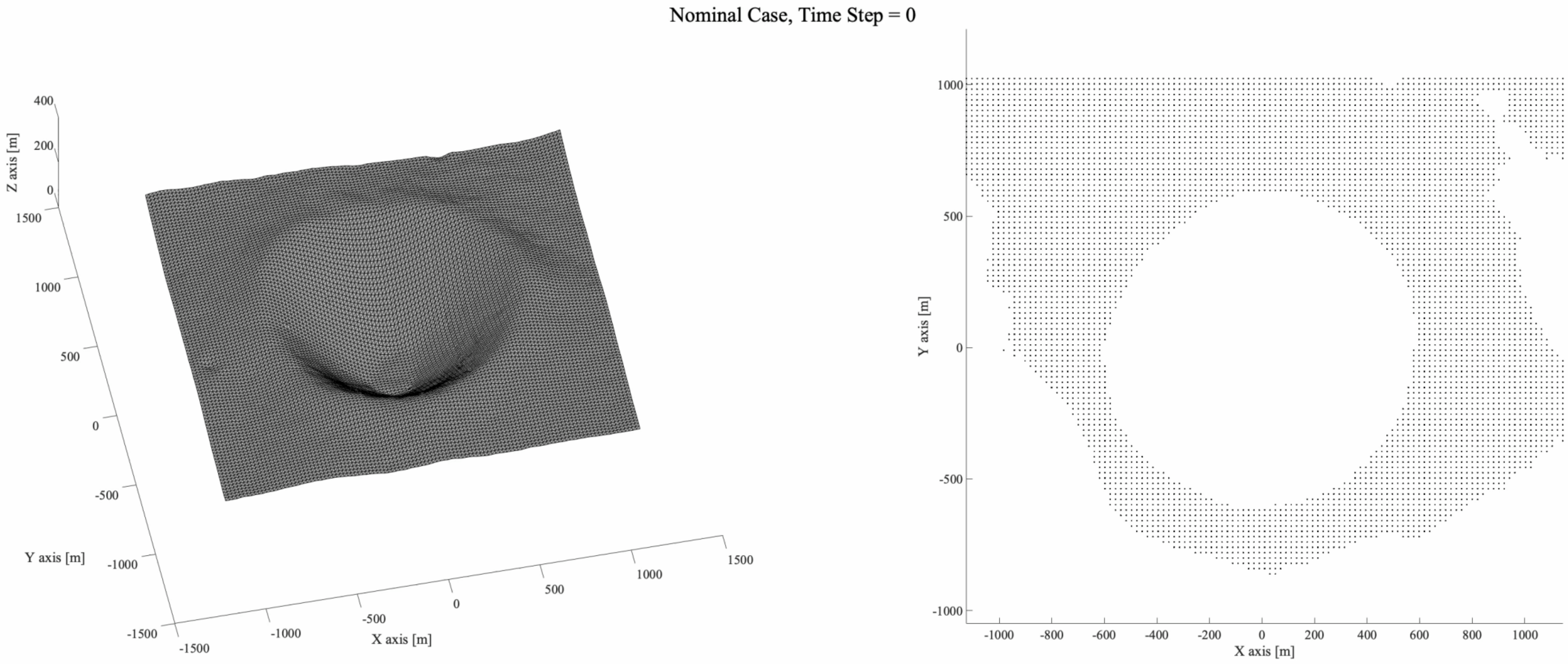






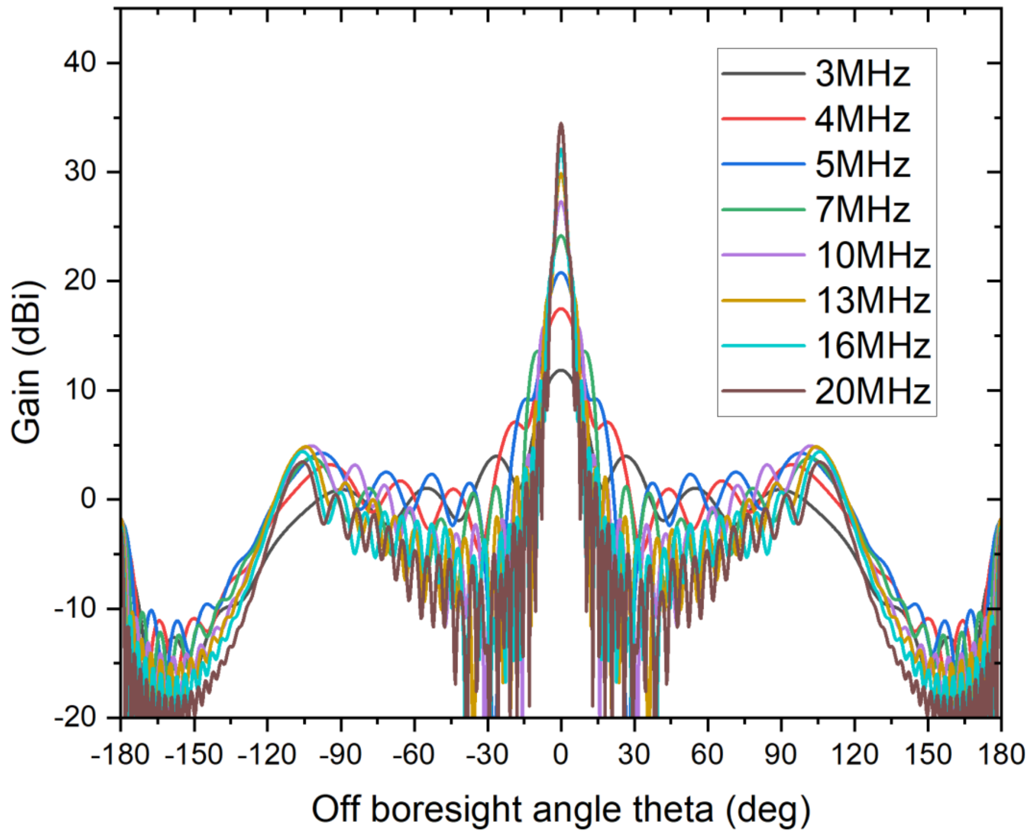
[1] Zirbel, Shannon A., Robert J. Lang, Mark W. Thomson, Deborah A. Sigel, Phillip E. Walkemeyer, Brian P. Trease, Spencer P. Magleby, and Larry L. Howell. "Accommodating thickness in origami-based deployable arrays." Journal of Mechanical Design 135, no. 11 (2013).

Error Correction in Deployment

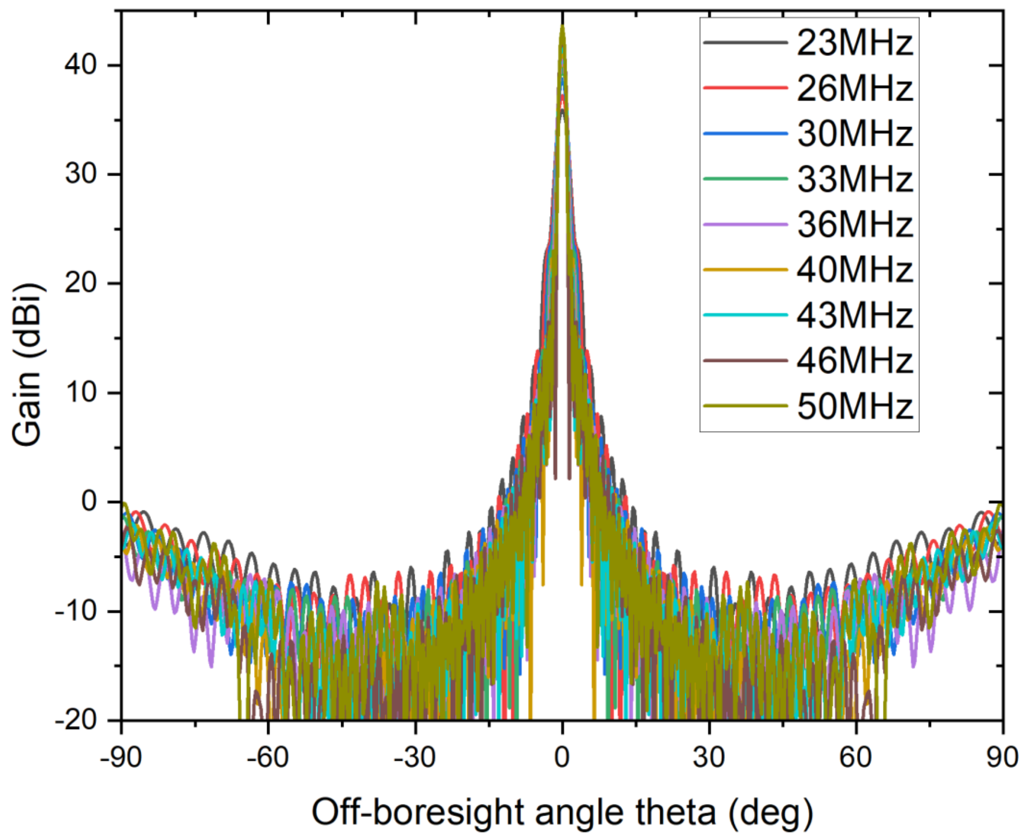


RF Performance of LCRT

3 MHz – 20 MHz

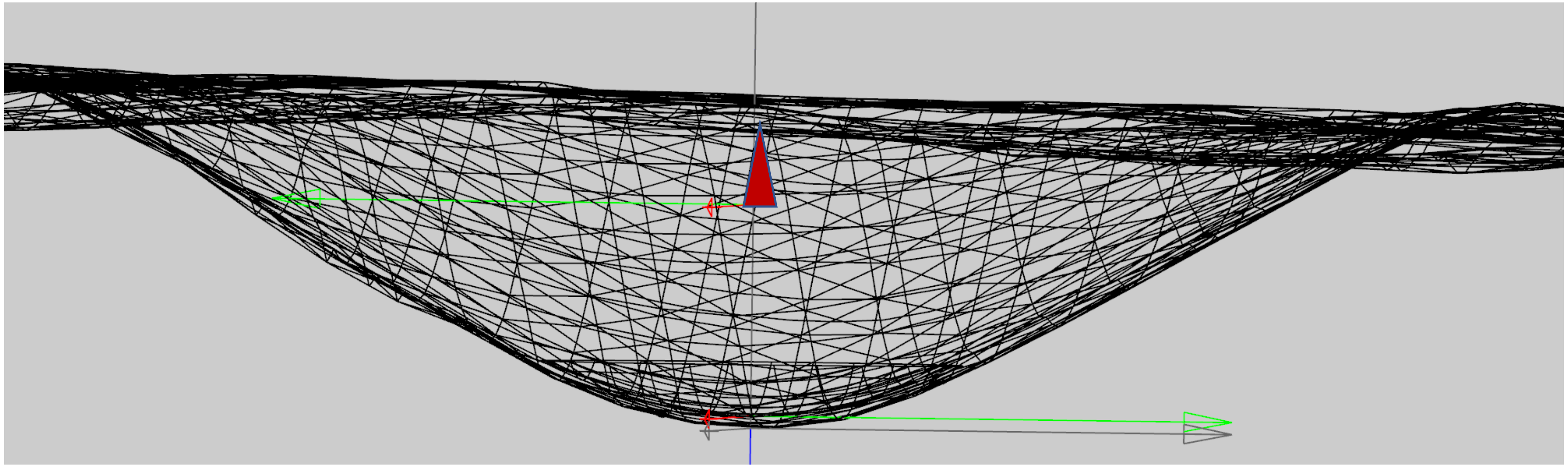


23 MHz – 50 MHz



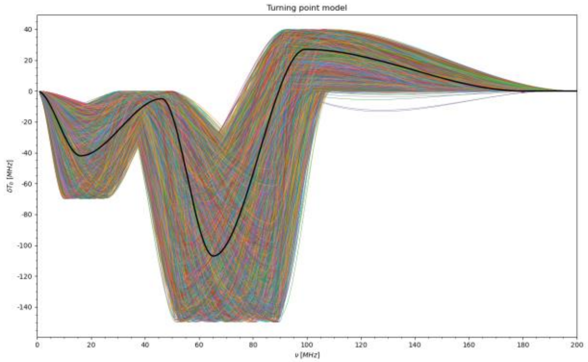
Frequency (MHz)	Maximum Gain (dBi)
3	11.84
4	17.47
5	20.78
7	24.17
10	27.29
13	29.86
16	32.08
20	34.47
23	35.89
26	37.23
30	38.75
33	39.77
36	40.74
40	41.71
43	42.37
46	43.08
50	43.63

RF Performance with Subsurface

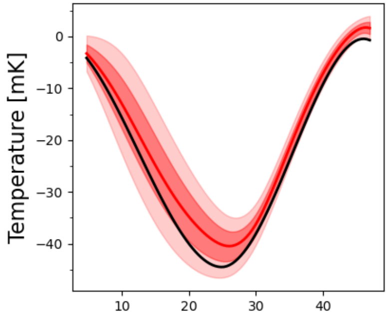


	No crater				Crater present				
Freq	(-60°to 60°)	±(90° to 60°)	total incoming power	Suppression beyond ±60°	(-60° to 60°)	±(90° to -60°)	total incoming power	Suppression beyond ±60°	Contribution of regolith in the signal
4.7 MHz	5439.191	430.24	5869	-11.02 dB	5874.2	398.57	6272.8	-11.67 dB	0.064
10 MHz	16282.92	353.74	16636.66	-16.63 dB	16671.1	288.06	16959.16	-17.61 dB	0.019
30 MHz	68614.36	82.45	68696.81	-29.20 dB	69112.97	63.83	69176.8	-30.34 dB	0.0069
47 MHz	113498.6	58.154	113556.8	-32.90 dB	113673.6	41.58	113715.2	-34.36 dB	0.0014

Proving the STM



LCRT's Measurements at Moon



Dark Ages Signal

Galactic Foreground

Instrument Model

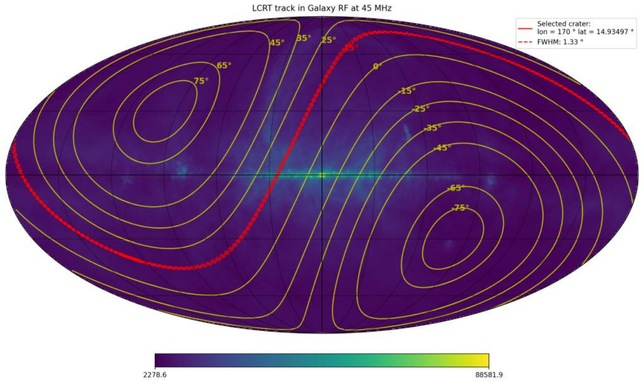
Reflector

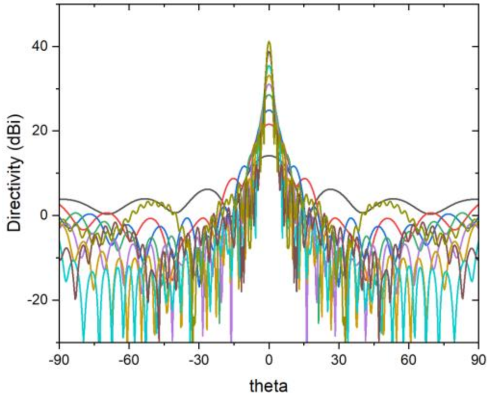
Feed

Receiver

Postprocessing

Recovered Dark Ages Signal



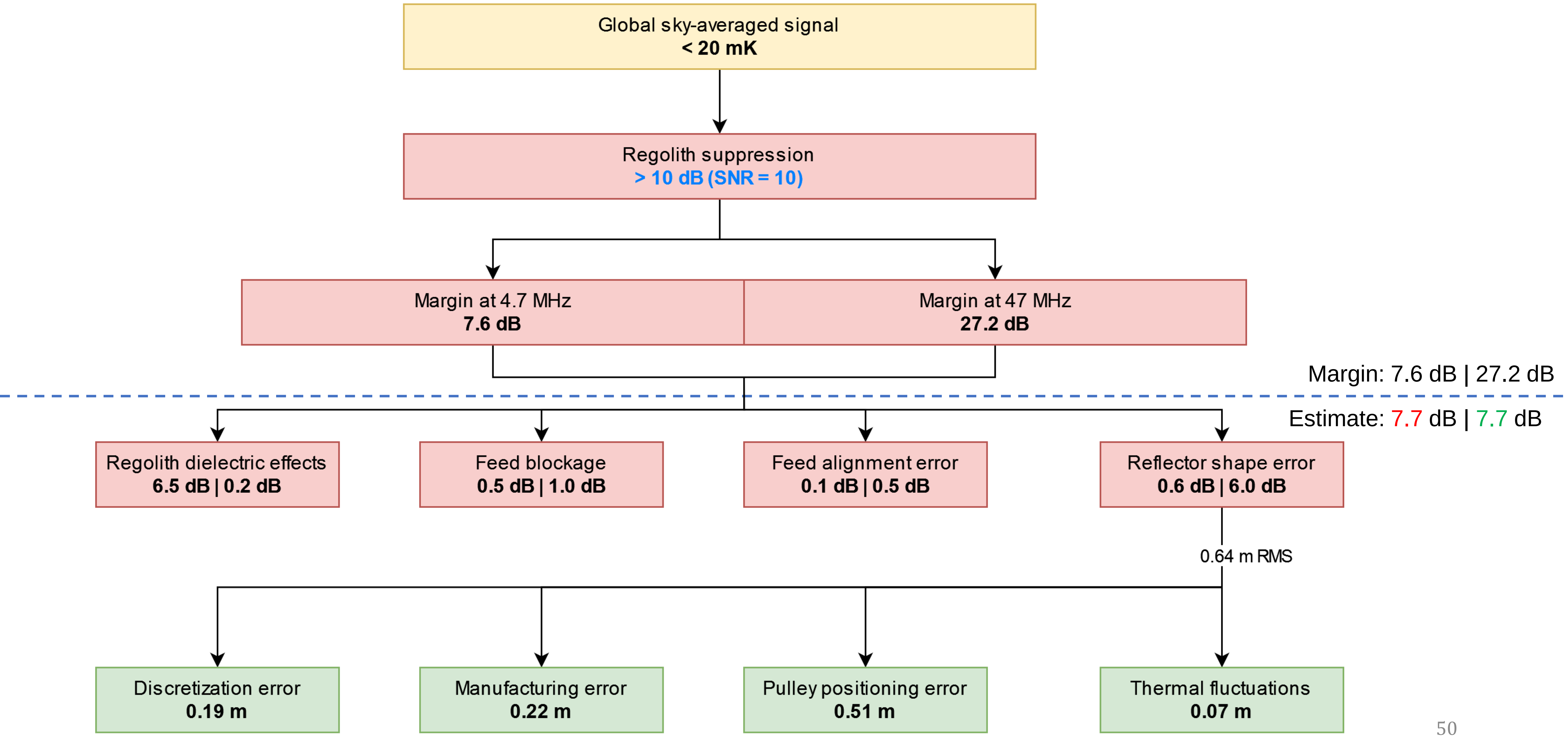


Extract signal using machine learning:

- Spatial structure
- Spectral shape
- Polarization

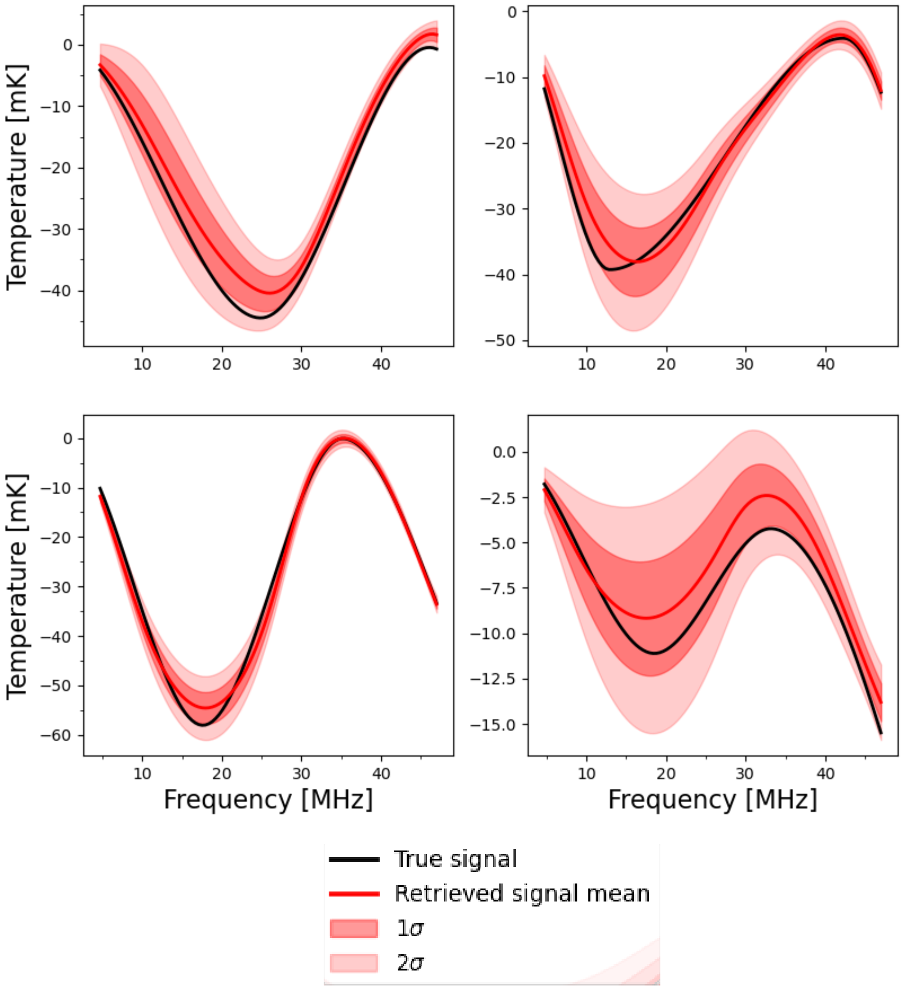
[1] Tauscher, Keith, David Rapetti, Jack O. Burns, and Eric Switzer. "Global 21 cm signal extraction from foreground and instrumental effects. I. pattern recognition framework for separation using training sets." *The Astrophysical Journal*, 2018.

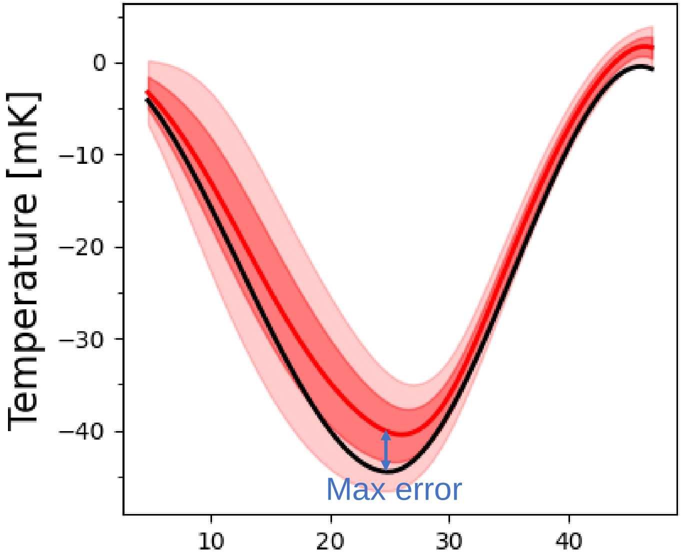
Telescope Error Budget



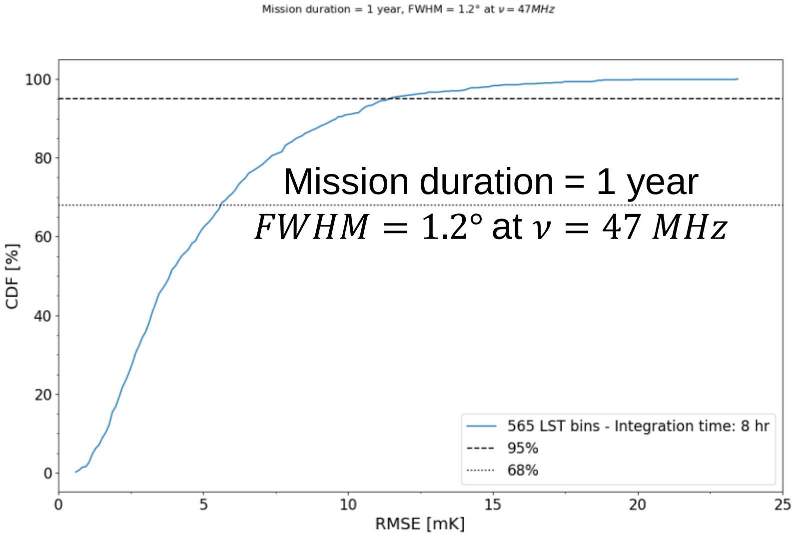
Preliminary Results

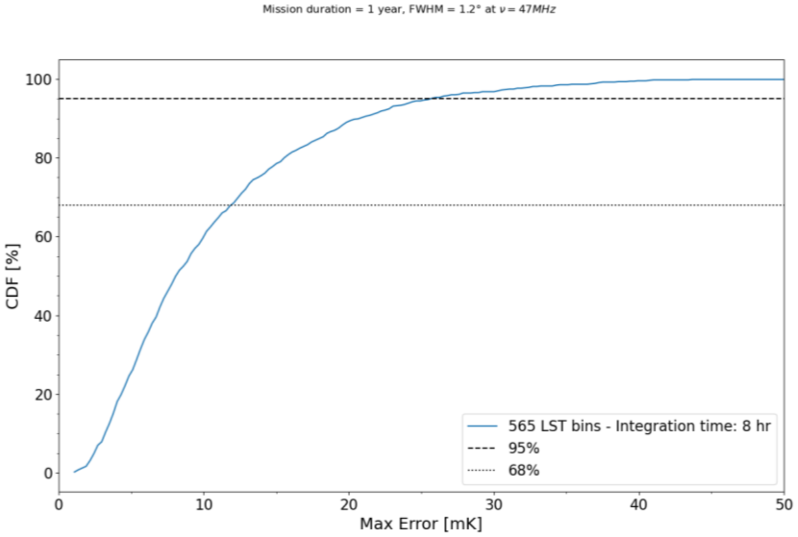
Sample retrievals





Error Statistics

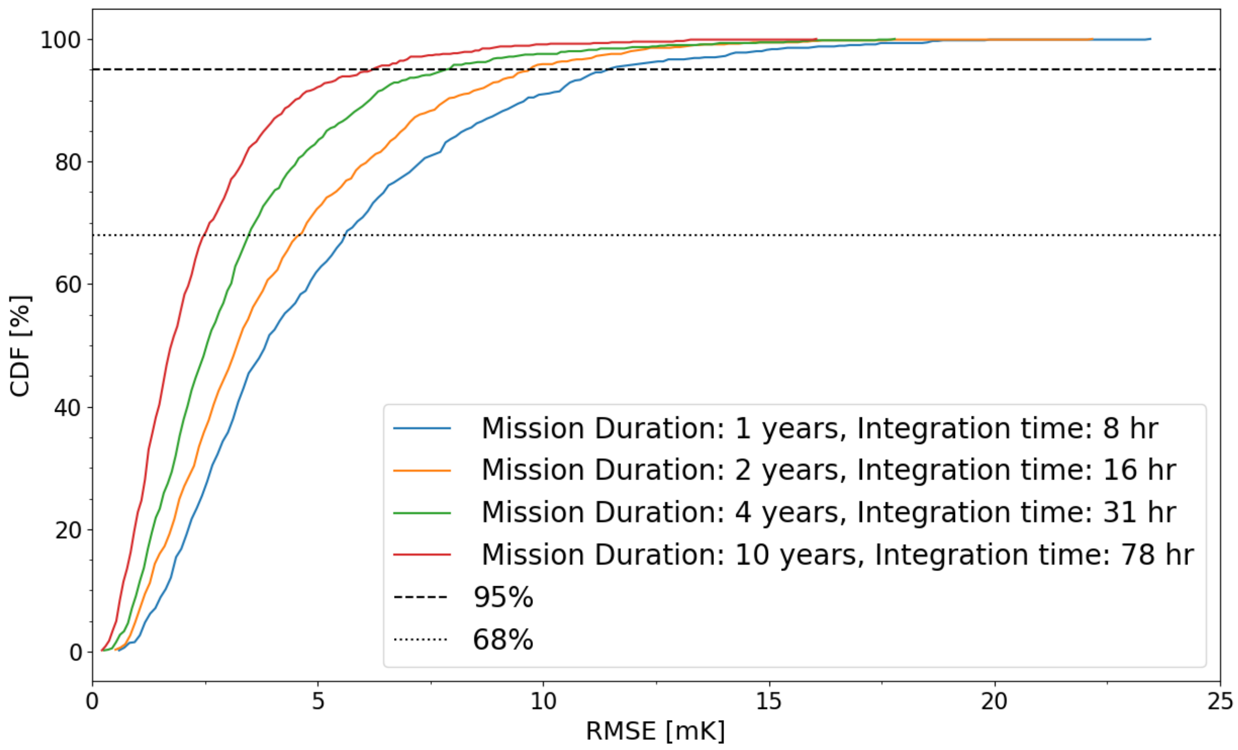


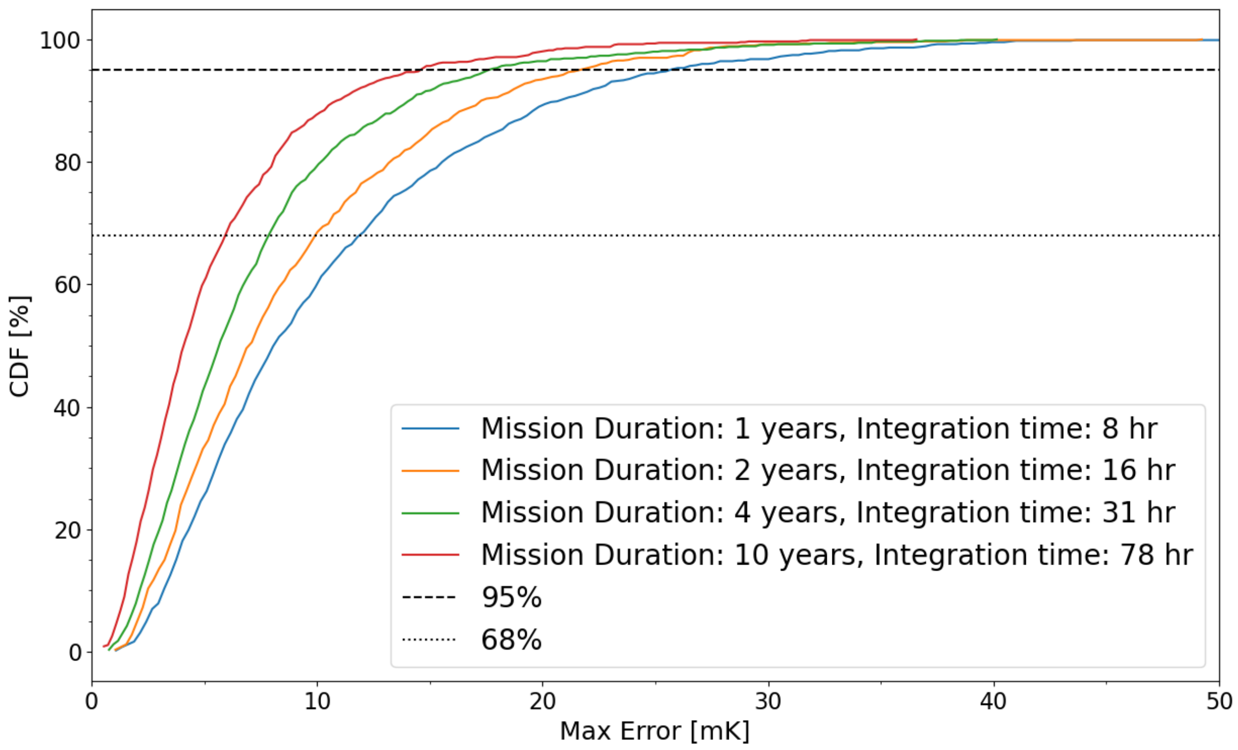


Evaluated using 900 curves from Training Set:
30 Beam-weigthed Foregrounds x 30 Signals

Varying Mission Duration

- $FWHM = 1.2°$ at $\nu = 47\ MHz$
- Increasing mission duration decreases thermal noise
- Tested on 900 curves from Training Set: 30 Beam-weigthed Foregrounds x 30 Signals





[1] D. Pisanti, A. Goel, G. Gupta, M. Arya, J. Lazio, P. Goldsmith, S. Bandyopadhyay, "Modeling Science Return from the Lunar Crater Radio Telescope on the Far Side of the Moon," Philosophical Transactions Royal Society A, March 2024.

Summary

- LCRT concept
  - Deploy 350m wire mesh in a suitable lunar crater on the far side
  - Observe the universe in (so far unexplored) 6−64m radio wavelengths
  - Scientific insights into the evolution of the Universe
  - Many technical challenges being addressed

- Create a lot of public excitement!

LCRT Team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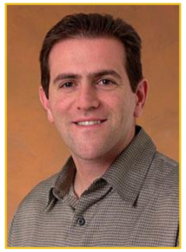
Paul Goldsmith (JPL)


Marco Quadrelli (JPL)


Adrian Stoica (Ex-JPL)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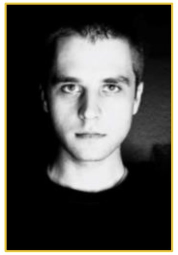
Nacer Chahat (JPL)


Rebecca Wang (Stanford)


Kenneth Jenks
(NASA JSC)


Ron Wilson
(Ret. Brig. Gen. USAF)


Vladimir Vustyansky
(CG Artist)


Gregg Hallinan (Caltech)


Robert Miller (JPL)

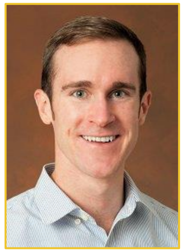

Vinod Gehlot (JPL)


Patrick McGarey
(Blue Origin)


Kalind Carpenter (JPL)


Scott Moreland (JPL)


Elizabeth Jens (JPL)


Benjamin Hockman (JPL)

Adrian Tang (JPL)


Jeff Jewell (JPL)

Making LCRT a Reality…

Concept art : Volodymyr Vustyansky

Thank You!

ACKNOWLEDGMENT

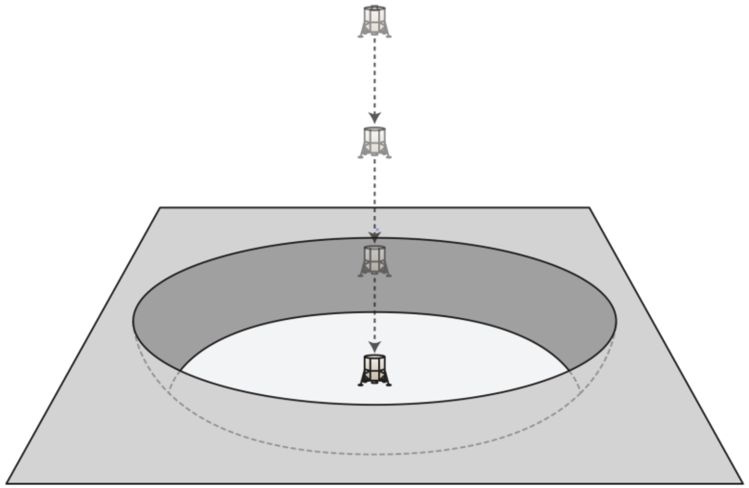
This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Jet Propulsion Laboratory
California Institute of Technology

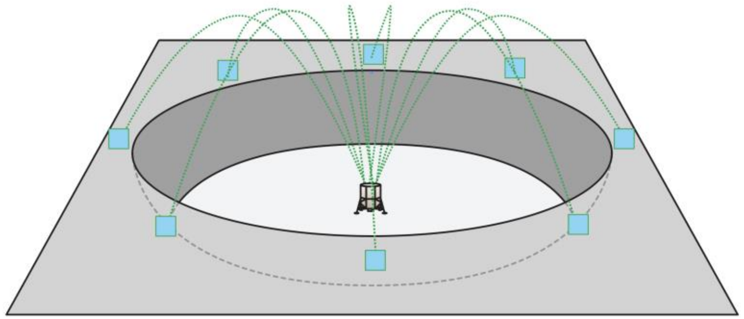
Backup Slides

Concept of Operations

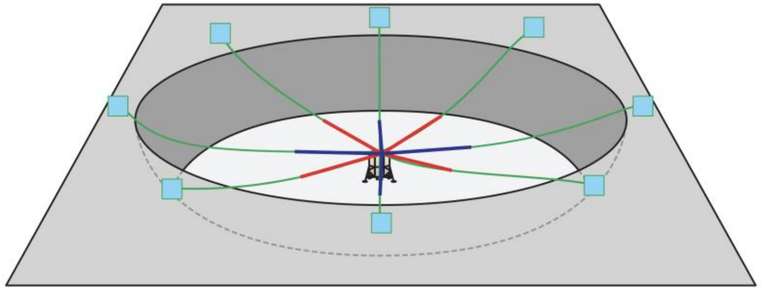
Step 1: Land in Crater



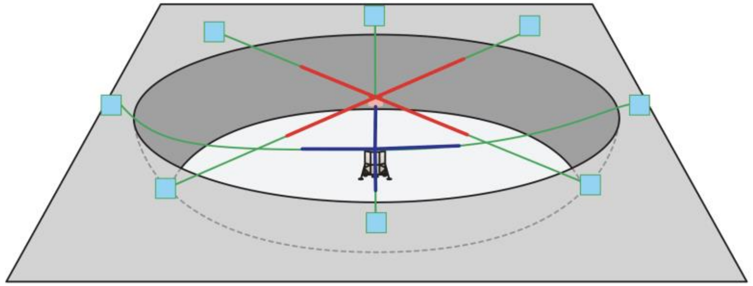
Step 2: Fire Anchors to Crater Rim



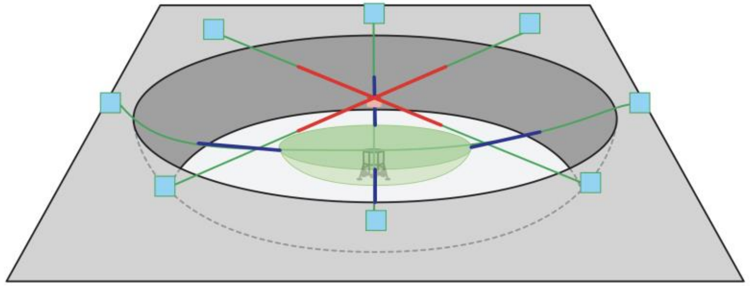
Step 3: Tension Lift Wires



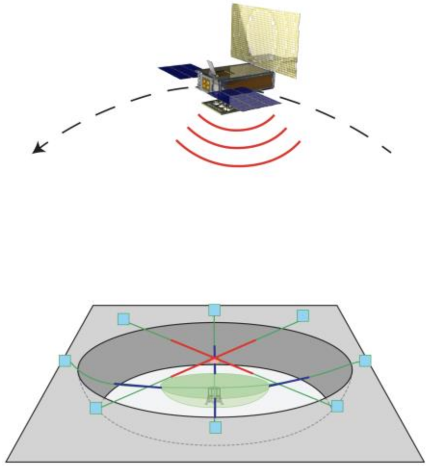
Step 4: Deploy Feed



Step 5: Deploy Reflector

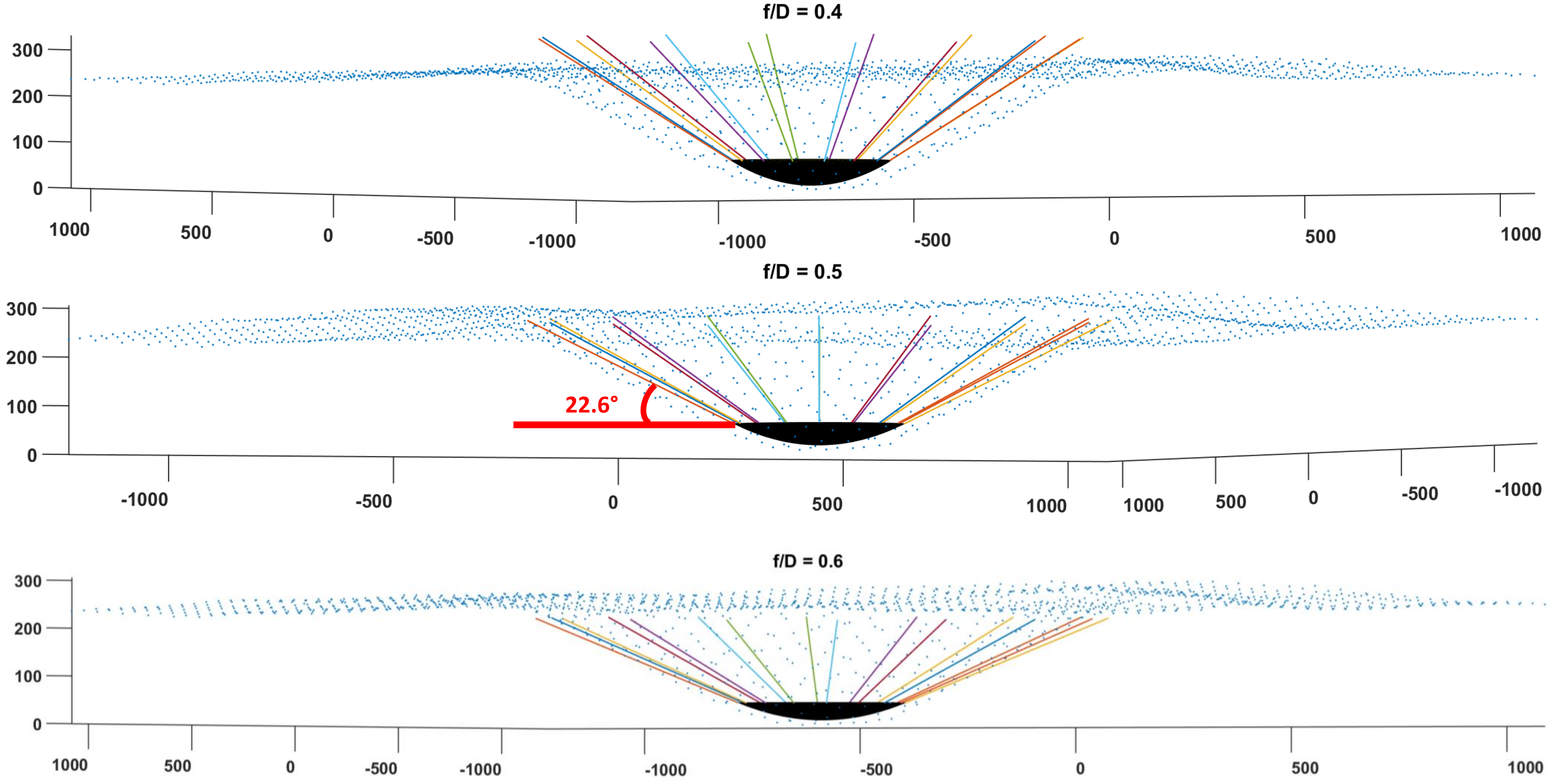


Step 6: Calibrate LCRT



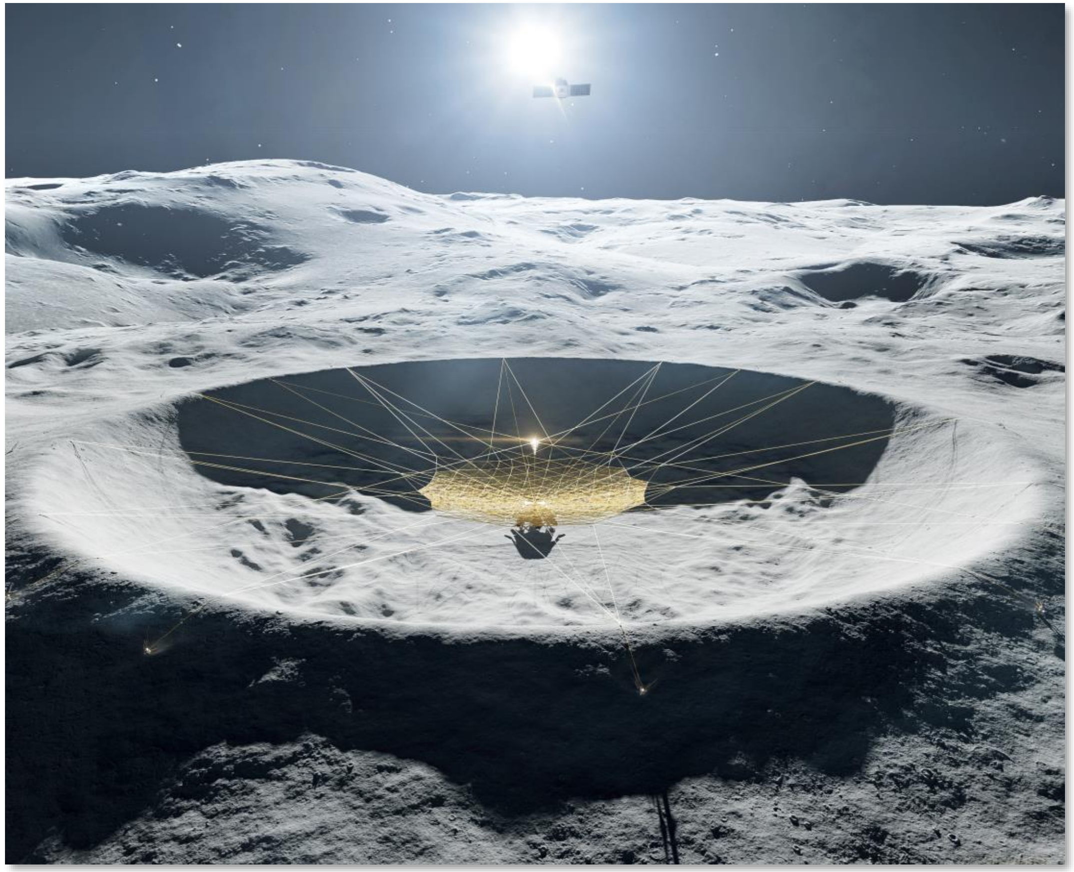
Focal Length/Diameter Ratio

Selected →



Mass Budget

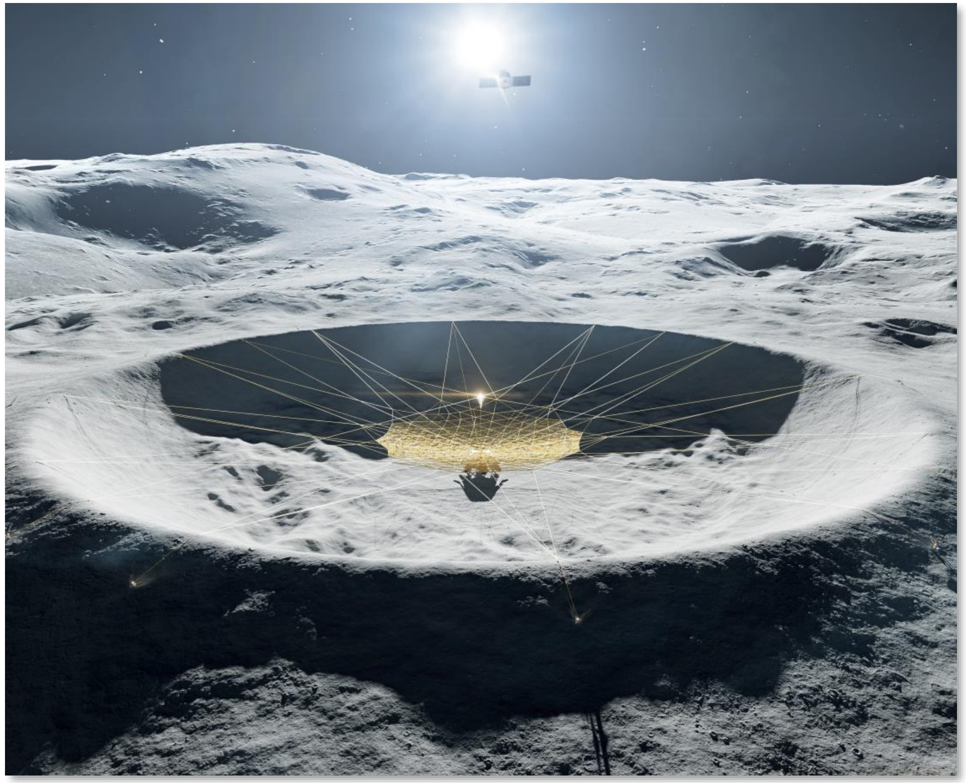
Mission Risk Classification



[NASA Risk Classification & Safety]

We believe LCRT will be a CLASS A mission

Mass Budget



	Current Best Estimate (kg)	Mass Growth Allowance	Predicted Mass (kg)
Payload	745	20%	894
Feed + Reflector	510		
Anchors + Projectile	207		
Beacon Spacecraft X 2	14 X 2		
Spacecraft Bus	482	20%	578
ACS Subsystem	11		
CDS Subsystem	38		
Mechanical Subsystem	220		
Power Subsystem	161		
Telecom Subsystem	32		
Thermal Subsystem	20		
Total Predicted Mass			**1472**
		JPL DP9 Mass Margin	**23%**
Total Launch Mass			**1754**

Mass Budget

	NUMBER OF UNITS			MASS				POWER							NOTES AND INFORMATION	
	Flight Units	Flight Spares	Ems and Prototypes	Basic Unit Mass [kg]	Basic Total Mass [kg]	Mass Growth Allowance [%]	Predicted Total Mass [kg]	Unit Standby [W]	Unit Nominal [W]	Unit Peak [W]	Power Growth Allowance [%]	Predicted Standby [W]	Predicted Nominal [W]	Predicted Peak [W]	Notes	Level
CARRIED ELEMENTS					745.0	20%	894.0									1
Anchors and Projectiles	1	0	0	207.0	207.0	20%	248.4					0.0	0.0	0.0		3
Radar Antenna	1	0	0	510.0	510.0	20%	612.0					0.0	0.0	0.0		3
Beacon Spacecraft	2	0	0	14.0	28.0	20%	33.6									
																3
																3
PAYLOAD					0.0	0%	0.0									1
Payload Subsystem 1					0.0	0%	0.0									2
Payload Subsystem 2					0.0	0%	0.0									2
Payload Subsystem 3					0.0	0%	0.0									2
SPACECRAFT BUS					481.6	20%	577.9									1
Bus Passthrough					0.0	0%	0.0									2
ACS Subsystem					10.6	20%	12.7									2
Engineering Camera	6	0	0	1.5	9.0	20%	10.8	1.0	4.0	4.0		6.0	24.0	24.0	Cameras to cover 360 deg view for anchors and projectiles. Reference M2020 EDL Camera Mass. Other options r	3
IMU - LN-200S	2	0	0	0.8	1.5	20%	1.8					0.0	0.0	0.0	May want an IMU (landers typically have them). Baseline heritage IN Link	3
Sun Sensor	6	0	0	0.01	0.1	20%	0.1									
															May need/want sun sensors.	
																3
CDS Subsystem					38.0	20%	45.6									2
Standard Avionics Design	2	0	0	9.5	18.0	20%	21.6	0.0	20.0	50.0		0.0	40.0	100.0	Only one unit needs to be on at a time. Dual string cold.	3
Solid State Recorder	2	0	0	8.0	16.0	20%	19.2	5.5	11.0	22.0		11.0	22.0	44.0	Single unit capable of storing up to 8 TB. May only need one unit. Link	3
Interface Board and Controller	4	0	0	1.0	4.0	20%	4.8	1.0	2.0	2.5		4.0	8.0	10.0	Generic interface board to control/interface with motors or other elements.	3
																3
																3
Mechanical Subsystem					220.0	20%	264.0									2
Structure (assuming carried elements)	1	0	0	160.0	160.0	20%	192.0					0.0	0.0	0.0	Estimated from parametric model (w/ carried elements)	3
Structure (assuming no carried elements)	0	0	0		0.0	20%	0.0					0.0	0.0	0.0	Estimated from parametric model (w/o carried elements)	3
Cabling	1	0	0	60.0	60.0	20%	72.0					0.0	0.0	0.0	Estimated from parametric model.	
																3
																3
Power Subsystem					160.6	20%	192.7									2
EPS / PCDU	1	0	0	11.0	11.0	20%	13.2					0.0	0.0	0.0	Estimated from parametric model.	3
Solar Arrays	1	0	0	1.4	1.4	20%	1.7					0.0	0.0	0.0	Pass through value from original MEL	3
Batteries	19	0	0	7.8	148.2	20%	177.8					0.0	0.0	0.0	Pass through value from original MEL. EnerSys ABSL 8s16p	3
																3
																3
Propulsion Subsystem					0.0	0%	0.0									2
Telecom Subsystem					32.4	20%	38.9									2
Small Deep Space Transponder (SDST)	2	0	0	3.2	6.4	20%	7.7					0.0	0.0	0.0	Typical deep space transponder Link	3
Amp Equipment	1	0	0	11.0	11.0	20%	13.2					0.0	0.0	0.0		3
HGA Antenna Gimbal	1	0	0	4.0	4.0	20%	4.8					0.0	0.0	0.0	Gimbal for HGA - May require to secure better telecom link	
High Gain Antenna (HGA)	1	0	0	8.0	8.0	20%	9.6					0.0	0.0	0.0	High gain antenna for high data rates - Patch or parabolic antenna	3
Medium Gain Antenna (MGA)	2	0	0	1.0	2.0	20%	2.4					0.0	0.0	0.0	Medium gain antenna with medium beam width - Patch or horn	
Low Gain Antenna (LGA)	2	0	0	0.5	1.0	20%	1.2					0.0	0.0	0.0		
															Low gain antenna (omni) with large beam width	3
																3
Thermal Subsystem					20.1	20%	24.1									2
MLI					0.0	30%	0.0					0.0	0.0	0.0		3
Sensors	50	0	0	0.001	0.1	20%	0.1					0.0	0.0	0.0		3
Heaters					0.0	20%	0.0					0.0	0.0	0.0		3
Thermal Control System	2	0	0	10.0	20.0	20%	24.0					0.0	0.0	0.0	Planetary and Lunar Environment Thermal Toolbox Elements (PALETTE)	3
																3
																3
PROPELLANT & PRESSURANT					0.0	0%	0.0									1

ROLLUP

Carried Elements		
Dry Basic Mass	745	kg
Dry Predicted Mass	894	kg
Payload		
Dry Basic Mass	0	kg
Dry Predicted Mass	0	kg
Base Station		
Dry Basic Mass	482	kg
Dry Predicted Mass	578	kg

FLIGHT SYSTEM ROLLUP

Flight System		
Dry Basic Mass	1227	kg
Dry Predicted Mass	1472	kg
DP9 Dry Mass Margin Percent	23	%
Dry Allowable Mass	1754	kg
Propellant Mass	0	kg
Wet Launch Mass	**1754**	**kg**
Total MGA	*43*	*%*

(Systems Margin)

Note: This design uses parametric models that assume carried elements are included and have to be supported by the mechanical subsystem.

MEL: Anchors and Lift Wires

	Equipment	Units	CBE / unit	Total	Details
Anchor module	Anchor for Reflector	12	3.27	39.24	(Vinod - 2022/03/22) **Reference mass**: 90 kg **Lift wire inclination angle:** theta = 30 deg **Tension:** 42.15 N **Material:** AMS 5629 (Steel)
	Anchor for Receiver	4	3.27	13.08	(Vinod - 2022/03/22) **Reference mass**: ? **Lift wire inclination angle:** theta = 10 deg **Tension:** 105.28 N **Material:** AMS 5629 (Steel)
	Projectile launch hardware (gas-compressed laur	1	5	5	(Rebecca - 2022/03/31) **Gas-compressed launcher** Pressure Vessel: 5 kgLaunch Barrel (20x): 1 (20) kgGa
	Projectile launch hardware (launch barrel)	16	2.51	40.16	
	Projectile launch hardware (gas valve system)	16	0.3	4.8	
	Projectile launch hardware (shock structure)	16	2	32	
	Internal Spool (non powered)	16	1	16	Not updated
	Actuator (passive)	16	1	16	Not updated
	Electronics (limited life/complexity)	16	1	16	Not updated
	Anchor Module Subtotal			**182.28**	
Lift Wires Module – Receiver	Lift Wire	4	0.59	2.36	**Selected product for the Core Wire:** Emma Kites - Black Kevlar CordDiameter = 0.4 mmLinear Density
	Spool Actuators (per lift wire)	4	1	4	Not updated
	Receiver Subtotal			**6.36**	
Lift Wires Module – Reflecto	Lift Wire	12	0.59	7.08	Same as for the receiver
	Spool Actuators (per lift wire)	12	1	12	Not updated
	Reflector Subtotal			**19.08**	
	Lift Wire Module Subtotal			**25.44**	
Totals	**Total CBE Mass**			**207.72**	
	Assumed MGA	20%			According to JPL DP9 for MDR/PMSR
	Required Mass Margin	23%			According to JPL DP9 for MDR/PMSR
	MEV Mass = *CBE × (1 + MGA + Required Margin)*			297	

MEL: Antenna

	Equipment	Units	CBE / unit	Total	Details
Antenna – Receiver	Structure	1	80	80	(Gaurangi)
	Thermal	1	10	10	We don't really need thermal control (Saptarshi)
	Mechanical Subtotal			90	
	Avionics Subtotal			5	From Sunrise Mission (Joe Lazio)
	Receiver Subtotal			**95**	
Antenna – Reflector	Tension Cable Structure	1	240	240	(Manan)
	Compliant Knit Mesh	1	120	120	(Manan)
	Hub for Stowed Detector	1	50	50	(Manan)
	Mechanical Subtotal			**410**	
	Avionics Subtotal			5	(Saptarshi)
	Reflector Subtotal			**415**	
Totals	**Total CBE Mass**			**510**	
	Assumed MGA	20%			According to JPL DP9 for MDR/PMSR
	Required Mass Margin	23%			According to JPL DP9 for MDR/PMSR
	MEV Mass = *CBE × (1 + Contingency)*			729	

Potential Lunar Landers

Landers eligible to bid on CLPS Program contracts	Lander	Company	Launch Vehicle	PL Delivery Capacity [kg]	Min Surface Operations Duration [Earth days]	Cost per kg of PL [$ M/kg]	Nominal Power per kg of PL [W/kg]	Peak Power per kg of PL [W/kg]	Data rate per kg of PL (Downlink) [kbps/kg]	PUG availability
Awarded with a contract	Peregrine	Astrobotic Technology	ULA Vulcan Centaur	100	8	1.2	1.0	2.5	10	2021
	Griffin (Polar configuration)	Astrobotic Technology	Space X Falcon Heavy	625	14	1.2	1.0	2.5	10	2021
	Blue Ghost	Firefly	Space X Falcon 9	up to 150	14	/	3.0*	4.3*	67*	2021
	Nova-C	Intuitive Machine	Space X Falcon 9	100	14	/	2.0*	/	/	/
	XL-1	Masten Aerospace	Space X Falcon 9	100	<12	/	0.5-1.0	/	50*	2019^
Not awarded yet	Artemis-7	Draper Laboratory	/	16	<14	/	6.4*	15*	100*	2018
	McCandless Lunar Lander	Lockheed Martin	/	up to 350 (evolvable to 1000+)	14	/	1.1*	/	0.29 (evolvable to > 2.9)*	2019
	MX-1/MX-2/MX-5/MX-9	Moon Express	/	30/30/150/500	/	/	/	/	/	/
	Z-01/Z-02	OrbitBeyond	Space X Falcon 9	50/50	/	/	/	/	/	/
	Blue Moon	Blue Origin	Blue Origin New Glenn	4,500	/	/	/	/	/	/
	Starship	Space X		100,000+	/	/	/	/	/	/
Lander concepts by CLPS eligible contractors	Nova-D/Nova-M	Intuitive Machine	/	500+ /5000	/	/	/	/	/	/
	XL-2/Xeus	Masten Aerospace	/	500 /1500	/	/	/	/	/	/

Acronyms: **PL = Payload, PUG = Payload User Guide**

*estimated as the total available power/data rate to the PLs, divided by the PL delivery capacity in kg

^ not for general distribution

Power Budget

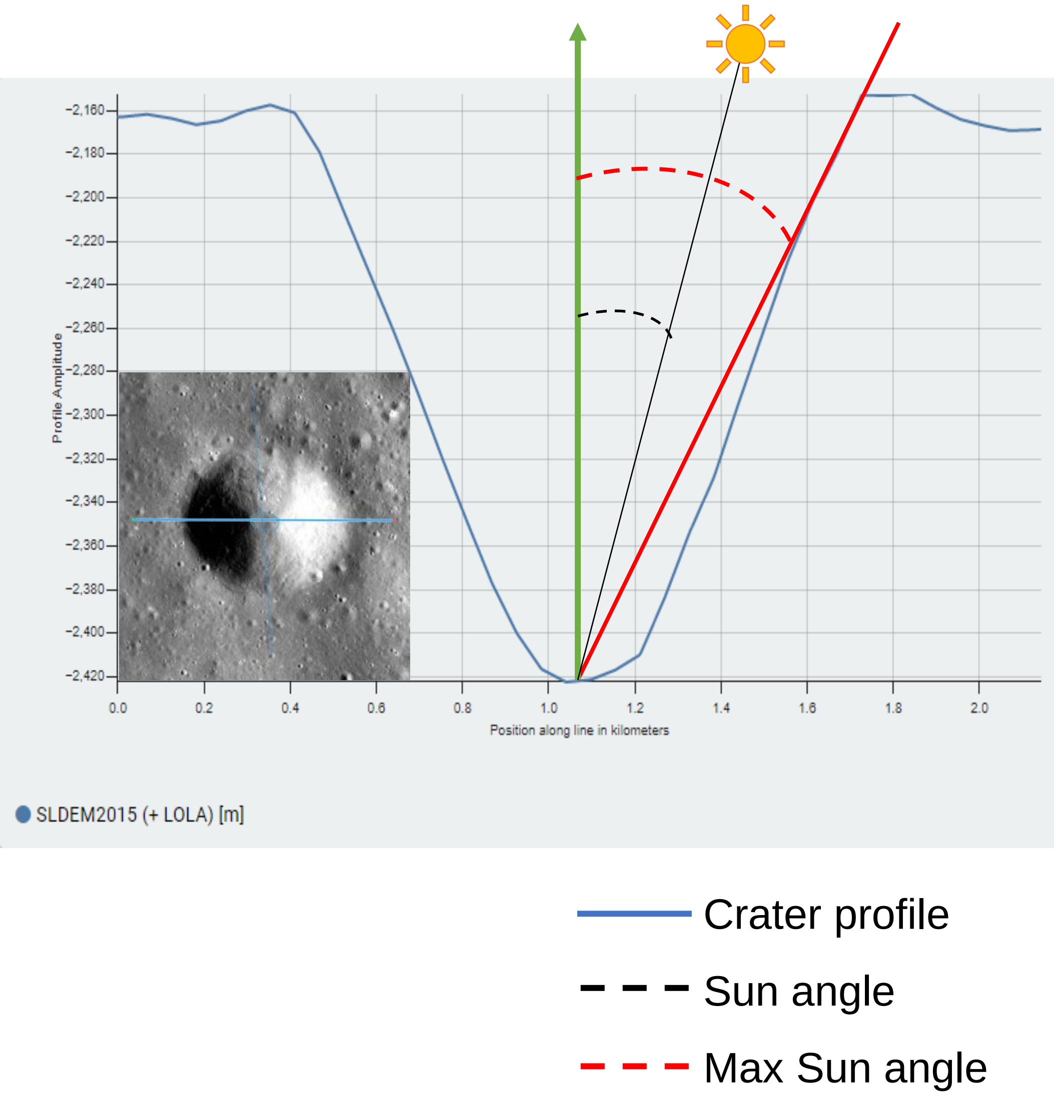
LCRT Power Budget

	Element	Description	Deploy Power CBE (W)	Operate (Day) Power CBE (W)	Operate (Night) Power CBE (W)
Receiver	Power	Distribution (175m cable/line loss)	5	5	5
	Receiver operating power	RF part of the receiver	-	-	7
	Deployment	actuators, sensors, efficiency losses	10	-	-
	GNC	cameras, IMU	5	5	-
	C&DH	computer, motor control, spool sensors	5	5	5
	Telecom	optical transceiver and conversion	10	10	-
	Thermal	active, TBD for lunar night	5	5	10 (0)
	Subtotal		**40**	**30**	**27**
Reflector	Power	distribution	5	-	-
	Deployment	actuators, sensors, efficiency losses	10	-	-
	GNC	cameras, IMU	5	-	-
	C&DH	computer, motor control, tether sensors	5	-	-
	Telecom	optical transceiver and conversion	10	-	-
	Thermal	passive only, TBD for lunar night	-	-	-
	Subtotal		**35**	**0**	**0**
Total	**Total CBE Power**		**75**	**30**	**27**
	Assumed PGA	**20%**			
	Required Power Margin	**23%**			
	MEV Power = *CBE × (1 + PGA + Required Margin)*		**107**	**43**	**39**

Battery Calculations

- Cater Illumination Conditions:
  - Min daytime: 10 Earth days
  - Max nighttime: 19 Earth days

SPICE

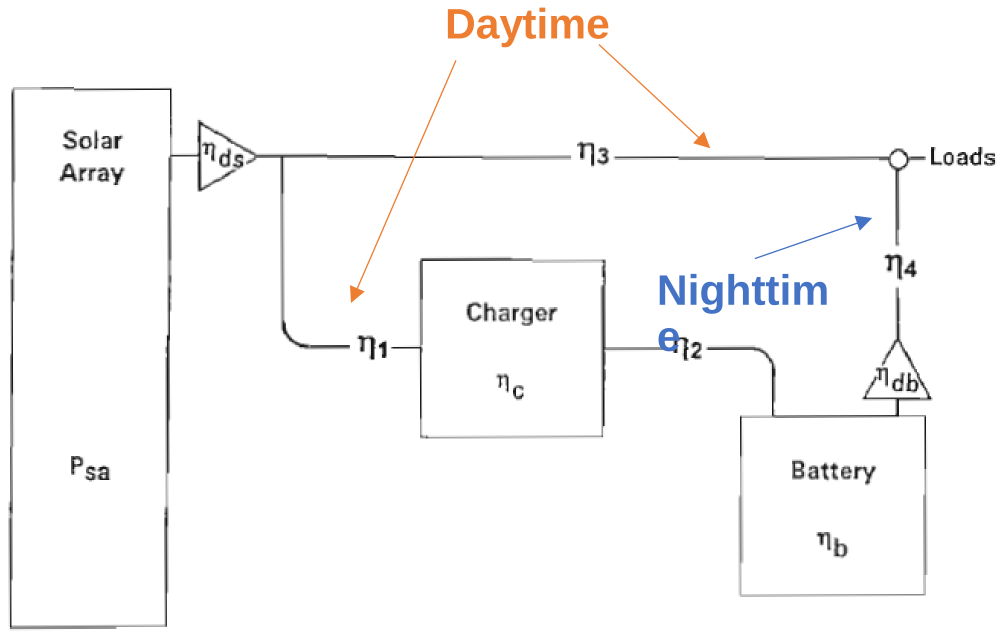


- Battery Options:

Overview		Properties		
Name	**Vendor**	**Mass (kg)**	**Energy (Whr)**	**Energy Density (Wh/kg)**
EaglePitcher	SAR-10197	63.50	6600.00	104
EaglePitcher	SAR-10199	35.00	3663.00	105
EaglePitcher	SAR-10211	38.60	4380.00	113
EnerSys	ABSL 8s16p 28V 24Ah	6.80	691.00	102
EnerSys	ABSL 8s16p 28V 56Ah	7.80	1628.00	209
EnerSys	ABSL 8s52p 28V 78Ah	22.80	2246.00	99
EnerSys	ABSL 8s84p 28V 126Ah	41.00	3628.80	89

Battery Calculations

- Architecture: Direct Energy Transfer
- Solar Panel Mass = 9kg
- Battery Mass = 148kg
  - Assuming maximum Depth of Discharge (DoD) of 70%



Data Budget

LCRT Data Budget

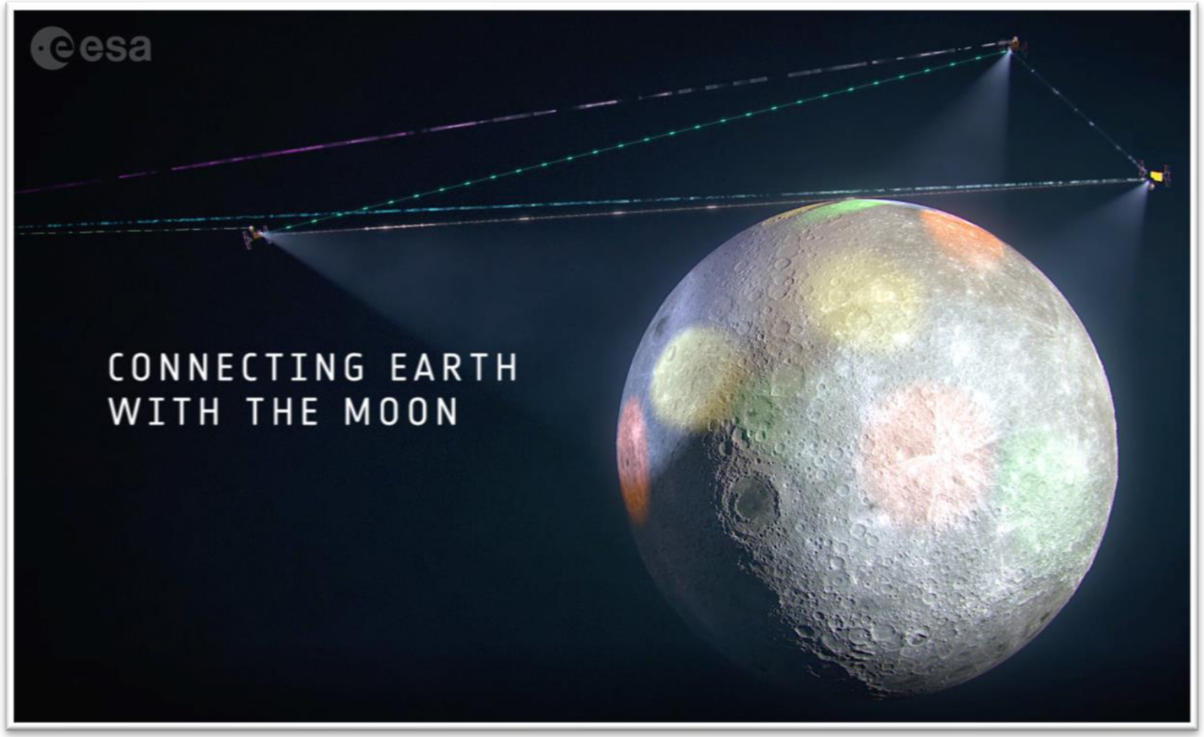
	Equipment	Units #	CBE / unit [bps]	Total [bps]	Acquisition Time (Earth days)	Total per lunar day + night (Kb)
Science	Science Payload	1	2.50E+03	2.50E+03	Lunar Night (19)	4.10E+06
	Subtotal			**2.50E+03**		**4.10E+06**
GNC	Camera	1	6.99E+02	6.99E+02	Lunar Day (10)	6.04E+05
	Subtotal			**6.99E+02**		**6.04E+05**
Health Monitoring Instruments	Receiver	1	2.20E-03	2.20E-03	Lunar Day + Night (10 +19)	5.51E+00
	Reflector	1	2.20E-03	2.20E-03		5.51E+00
	Anchor	20	2.20E-03	4.40E-02		1.10E+02
	Battery	7	2.20E-03	1.54E-02		3.86E+01
	Solar Panel	2	2.20E-03	4.40E-03		1.10E+01
	Lander thermal sensors	2	2.20E-03	4.40E-03		1.10E+01
	Subtotal	**33**		**7.26E-02**		**1.82E+02**
Totals	**Total CBE Data Rate**			**3.20E+03**		**4.71E+06**
	Contingency	**43%**				
	Total MEV Data Rate			**4.57E+03**		**6.73E+06**

Data generated: 0.84 GB per lunar day (Earth month)

Data Transfer to Earth: At a nominal data rate of 100KBps, we need 20hr to send 0.84 GB to Earth.

Earth-Moon Communication

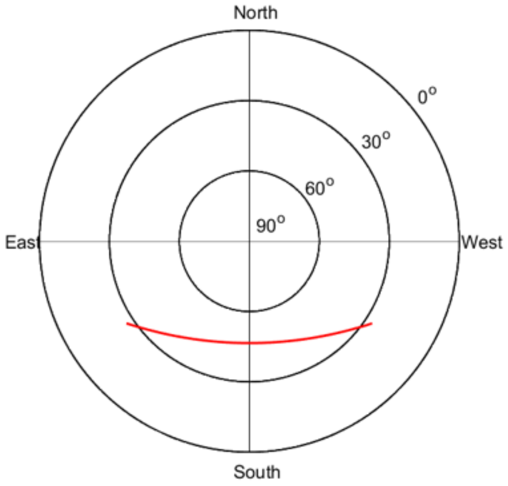
- Multiple COTS options:
  - LunaNet
  - Lunar Gateway
  - Nokia’s cellular network on the Moon
  - ESA’s Moonlight



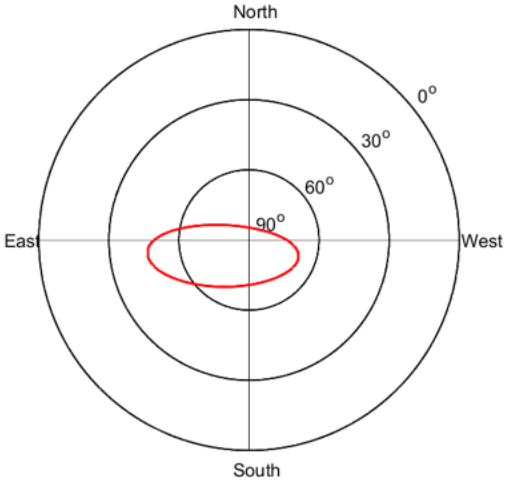
ESA’s Moonight, https://www.esa.int/Applications/Telecommunications_Integrated_Applications/Lunar_satellites

Earth-Moon Communication using Relay Spacecraft

Lunar Equatorial Orbit



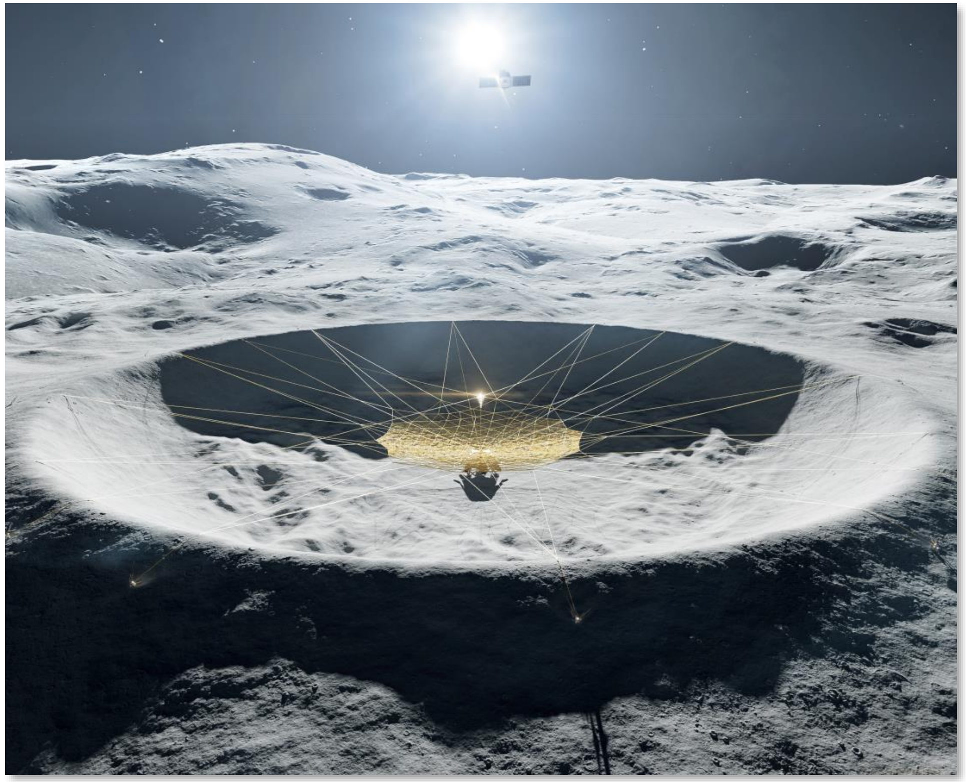
Earth-Moon L2 Point



Overhead trace of SC from base of the crater

Costing

Rough Cost Estimate



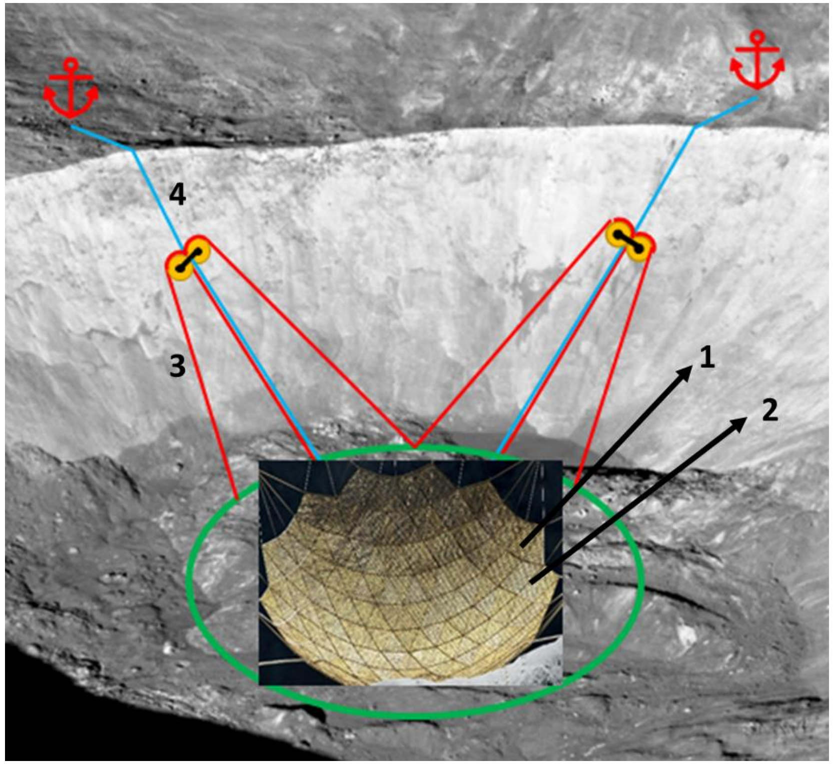
Item	Subsystem Cost ($M)	Total Cost ($M)
Flight Segment		**$450**
350m diameter Reflector + Feed	$140	
Beacon spacecraft (X2)	$50	
Projectile-based deployment system	$100	
Base station	$150	
Communication-relay	$10	
MOS + GDS		**$450**
Lunar Lander		**$1100**
Total Cost (before reserve)		**$2000**
	Reserves (30%)	**$600**
Total Cost with Reserve		**$2600**

Cost disclaimer: The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

Micro-Meteoroid Risk

Micro-Meteoroid Impact Risk

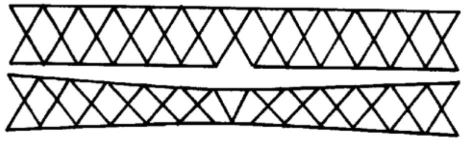
ID	Cable type	Cross section	Total surface area (m^2)	Consequence of Cut
1	Mesh	0.025 mm	577	Negligible impact on surface RMS error
2	Internal cable	10 mm x 0.2 mm	96	Small impact on surface RMS error
3	Support cable	20 mm x 0.2 mm	211	Significant impact on surface RMS error
4	Lift wire (beyond pulley)	2 mm	1.2	Significant impact on surface RMS error



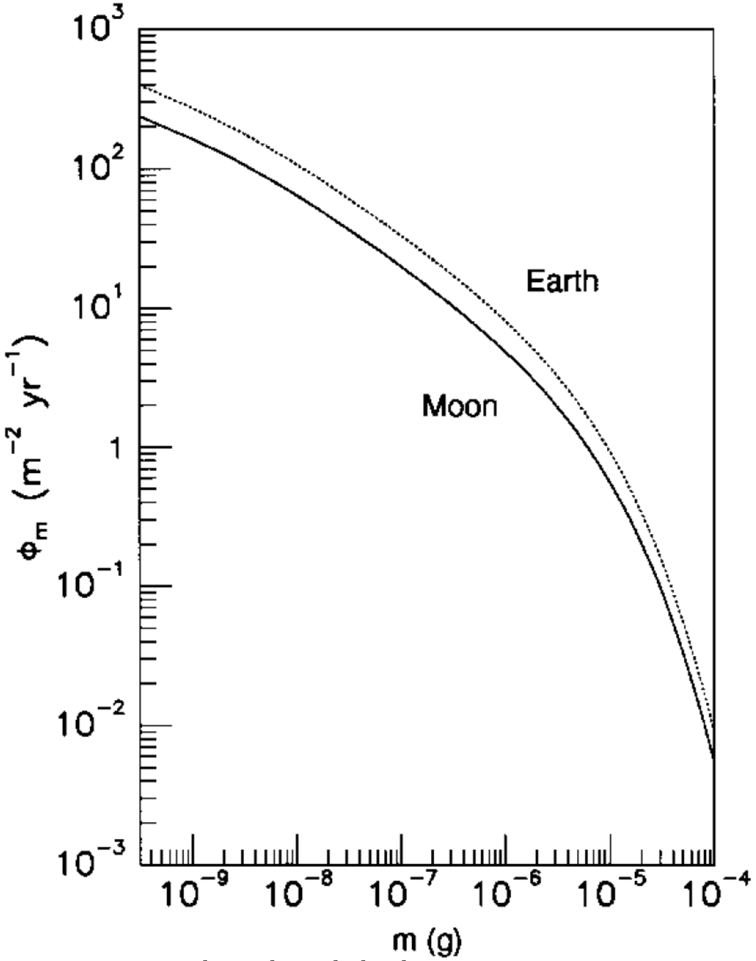
Severing Probability for Support Cables

Parameter	Value
Meteoroid density	**500 kg/m³**
Minimum crater size for cutting support cable = 1/2 width	**10 mm**
Meteoroid size for 10 mm crater (due to low cable thickness)	**5 mm**
Threshold meteoroid mass	**32.7 mg**

- Poisson statistics: $\mathrm{P(k)} = \frac{\lambda^k e^{-\lambda}}{k!}$
- Probability of severing impact in one year: 0.0014
- Failure resistant tether design not needed



Cumulative meteoroid flux

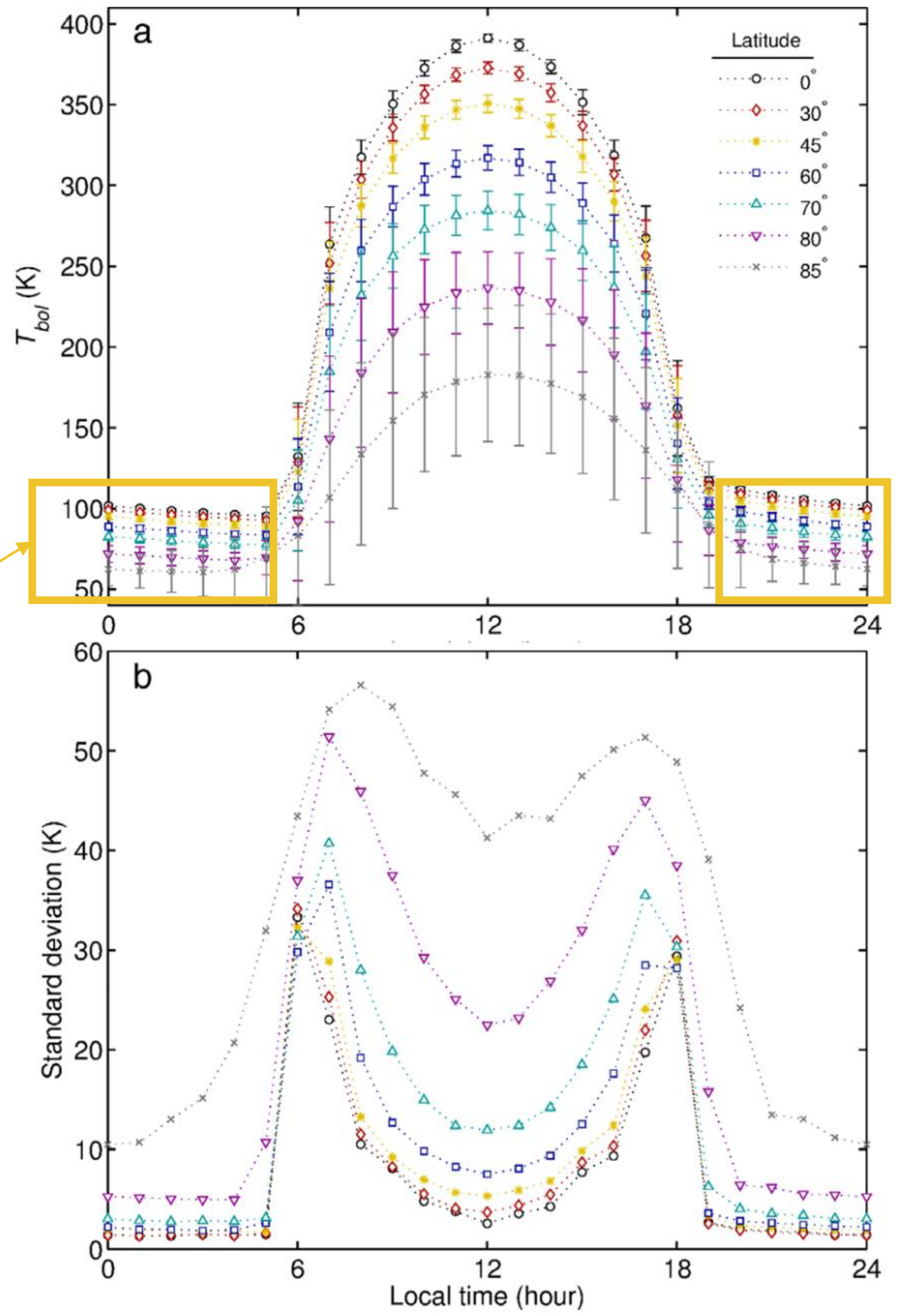


[1] V. Vanzani, F. Marzari, and E. Dotto, "Micrometeoroid impacts on the lunar surface," LPI, p. 1481, 1997.
[2] R. P. Hoyt and R. L. Forward, "Failure resistant multiline tether," Jan. 16 2001, uS Patent 6,173,922.

Thermal Management

Temperature during Lunar Night

- Lunar Surface Temperatures
- ΔTemp = 10K (during lunar night)



[1] J.-P. Williams, D. Paige, B. Greenhagen, and E. Sefton-Nash, "The global surface temperatures of the moon as measured by the diviner lunar radiometer experiment," Icarus, 2017.

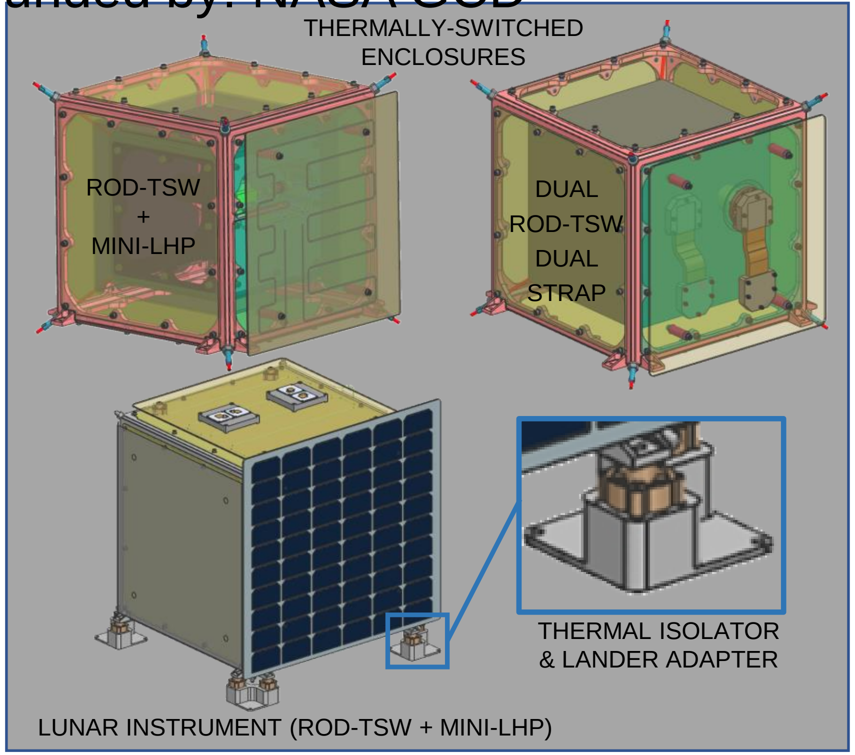
Thermal Enclosures

Planetary and Lunar Environment

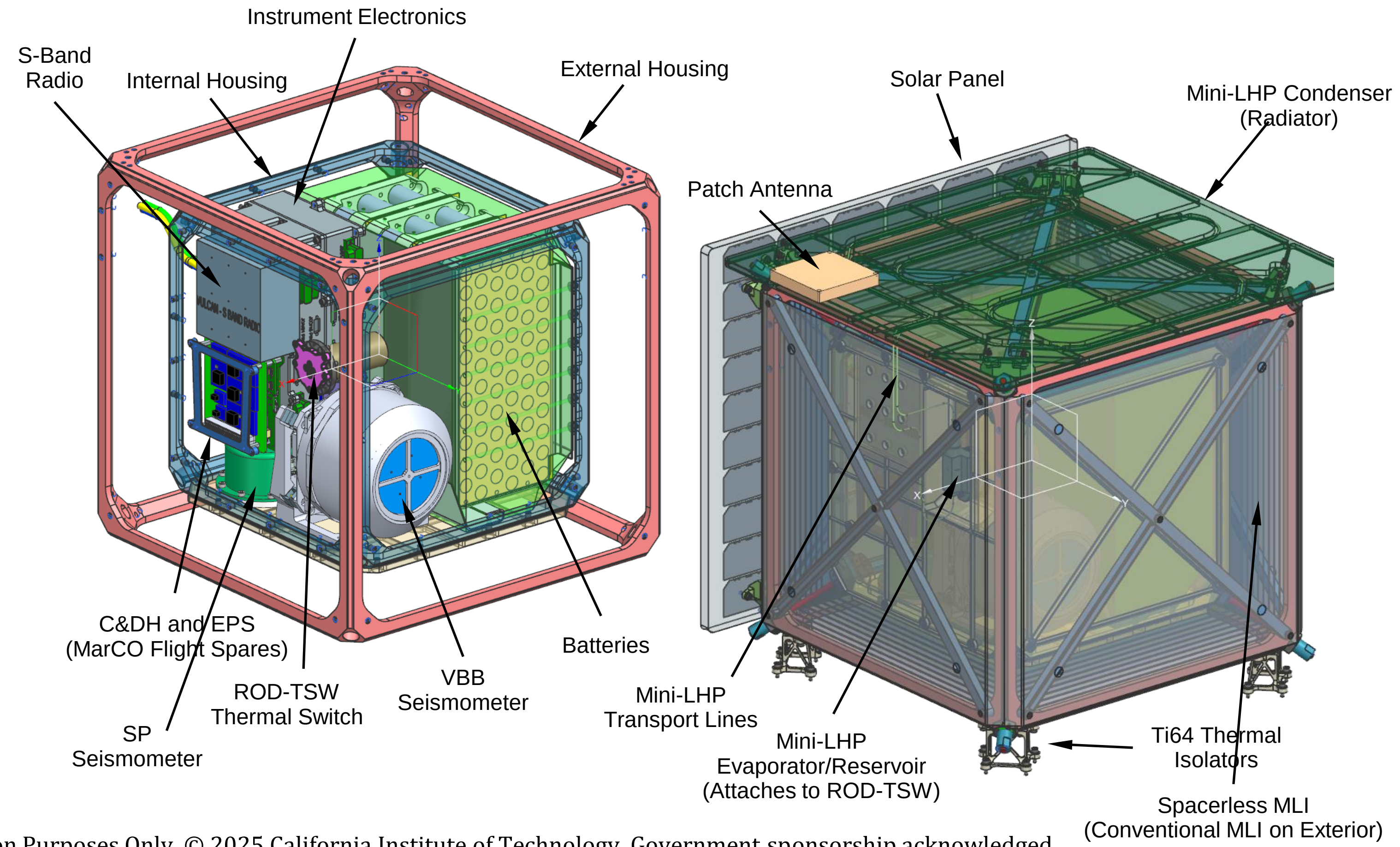
Thermal Toolbox Elements

(PALETTE)

Funded by: NASA GCD



Infusion: Farside Seismic Suite (FSS) in 2025



Lunar Dust Management

Lunar Dust – Mass

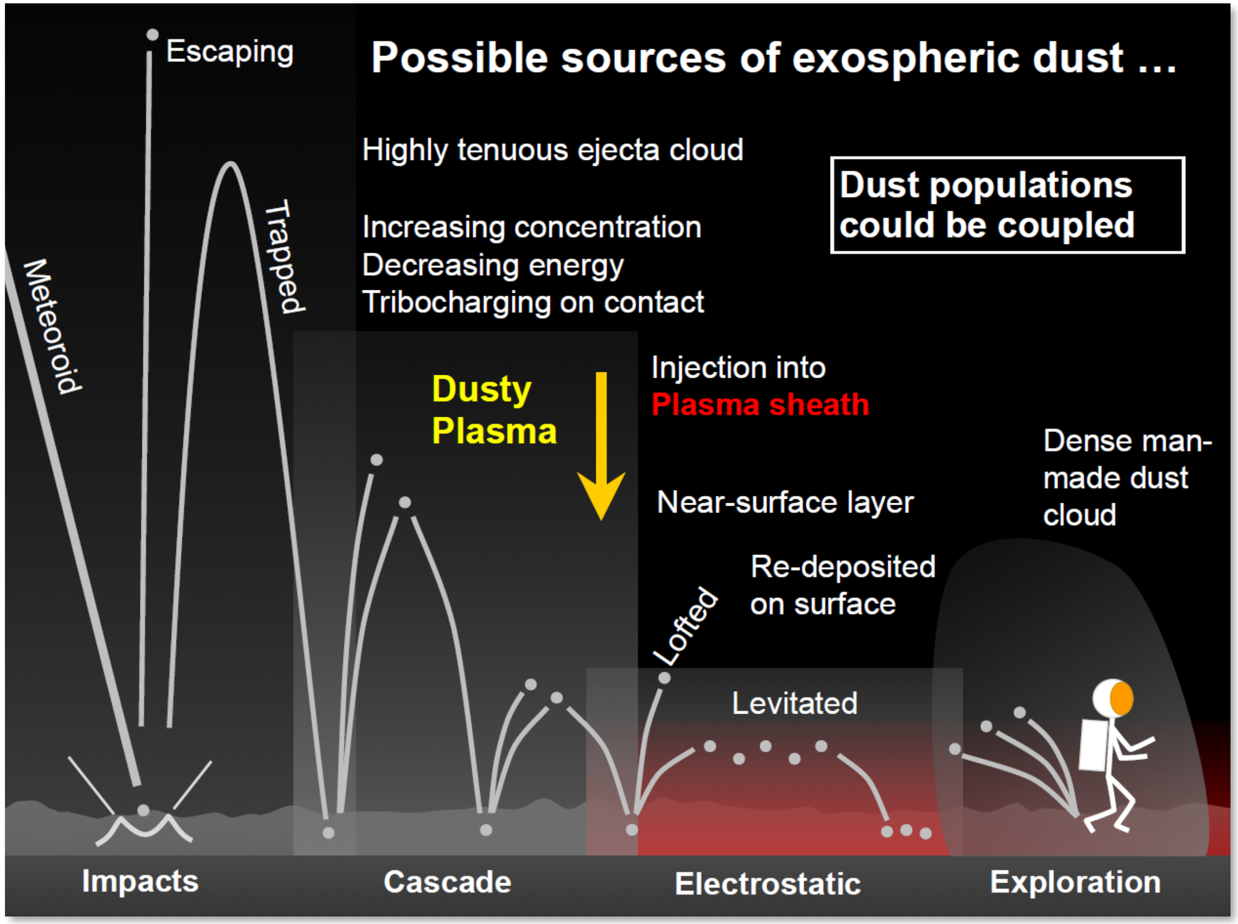


Figure from Tim Stubbs

- Additional Mass on Reflector
  - Dust deposition rate = 20-100 μg/cm^2/year
  - Mass added = 0.885kg per year

    Insignificant!

[1] Li et. al., "In situ measurements of lunar dust at the Chang'E-3 landing site in the northern Mare Imbrium." *Journal of Geophysical Research: Planets* 124, 2019

[2] Hollick, Monique, and Brian J. O'Brien. "Lunar weather measurements at three Apollo sites 1969–1976." *Space Weather*, 2013.

[3] Stubbs, Timothy J., Richard R. Vondrak, and William M. Farrell. "A dynamic fountain model for dust in the lunar exosphere." *Dust in Planetary Systems*, 2007.

Lunar Dust – RF

- Lofted dust is transparent in LCRT wavelength band
  - Size of lofted dust grains (0.1-10 μm) << wavelength of radio waves (10-50 m)
- Radio waves are unaffected by electrons in lofted dust
  - Total electron content of lofted dust along line of sight: $\epsilon = 1 - \frac{\omega_p^2}{\omega^2}$, where $n_e \sim 10^8 m^{-3}$, $\omega_p \sim 10^{11} s^{-1}$, $\omega \sim 10^{14} s^{-1}$
  - Plasma frequency << Radio frequency, so $\epsilon = 1$
- Lofted dust will not affect LCRT's science performance!

Lunar Dust Management

- Exploration-related dust will stick to instruments, solar panels, etc.
- Can cause thermal management issues

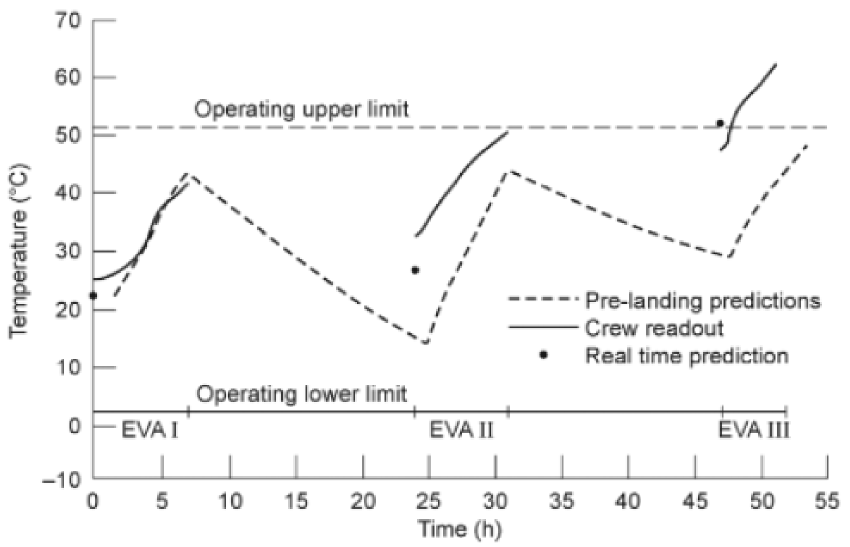


Figure 4-1. Plot of the LRV battery temperature for Apollo 16 (McKay, 1972). As shown in the plot, attempts to brush the dust off of the radiator between EVAs were largely ineffective in reducing the operating temperature.

- Recommended dust mitigation technologies

Application	Lunar/asteroidal environment
Solar panels and optical surfaces	Electrodynamic Dust Shield with transparent electrodes
Small lenses	SPARCLE
Large thermal control surfaces	Chemically pretreated surface coating
Small thermal control surfaces	Brush/wiper
Near terminator optical surfaces	Electrostatic Lunar Dust Repeller
Near terminator thermal surfaces	Electrostatic Lunar Dust Collector
Cabins	Ceramic nano/microfiber filter
Astronauts' suit	Brush

[1] McKay, Saturn V Launch Vehicle Flight Evaluation Report-AS-511, Apollo 16 Mission, Saturn V Flight Evaluation Working Group, 1972.
[2] Afshar-Mohajer, Nima et. al., "Review of dust transport and mitigation technologies in lunar and Martian atmospheres." *Advances in Space Research*, 2015.

Local Position System

Local Positioning System

Terrestrial Laser Scanner (TLS):

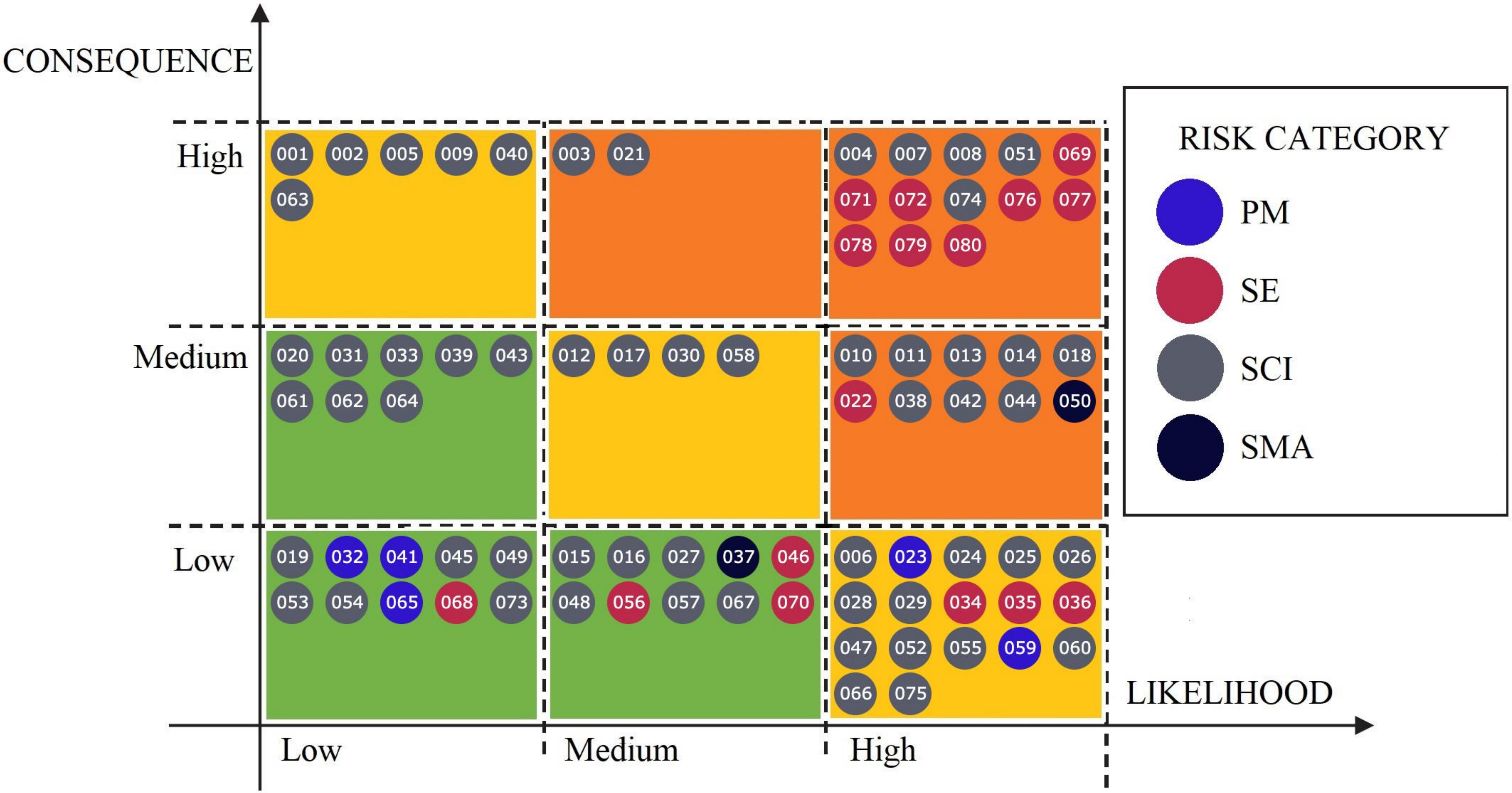
- Range: 2.5 km on Earth
- Accuracy: 5 mm
- Weight: 9.8 kgs
- Power: nominal 70 W, maximum 87 W
- Size: 206mm x 346mm
- Nominal Operating Temperature: 10◦C to 50◦C

Deployed at the 100 m Green Bank Radio Telescope

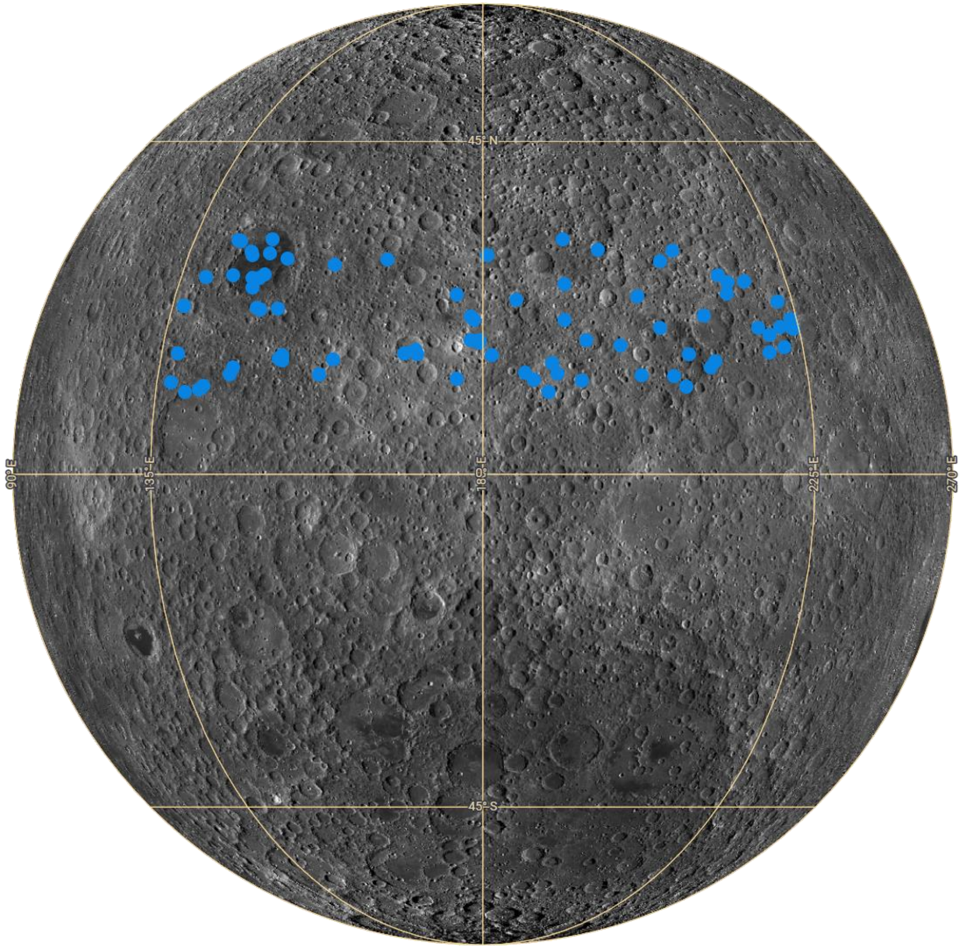
RIEGL VZ-2000i Terrestrial Laser Scanning System

Risk List

Risk Analysis



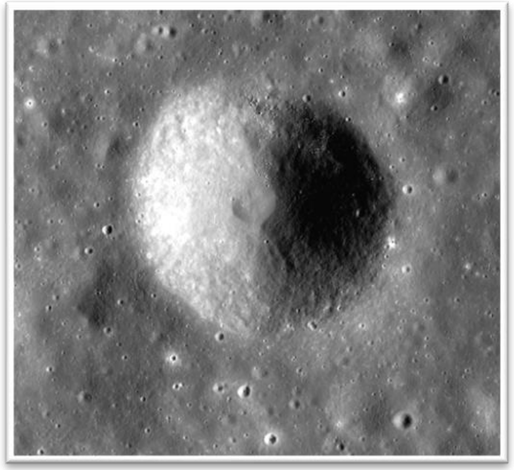
All Craters Studied



Backup Craters (Farside)

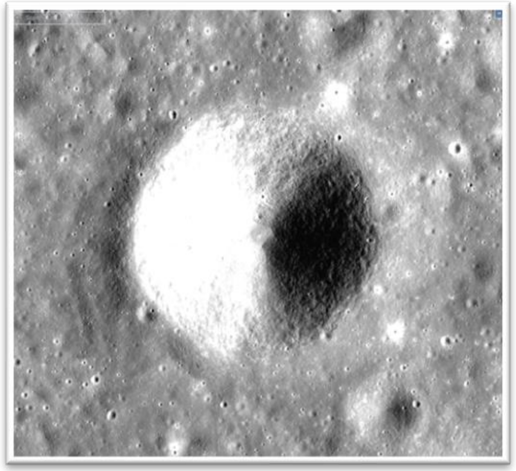
Lon: 141.9 E Lat: 4.85 N

Diameter: 1.26 km Depth: 0.217 km



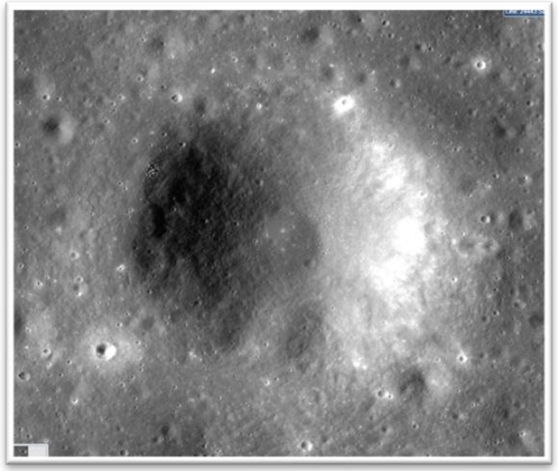
Lon: 142.2 E Lat: 4.02 N

Diameter: 1.51 km Depth: 0.289 km



Lon: 145.8 E, Lat: 9.57 N

Diameter:1.392 km, Depth: 0.243 km



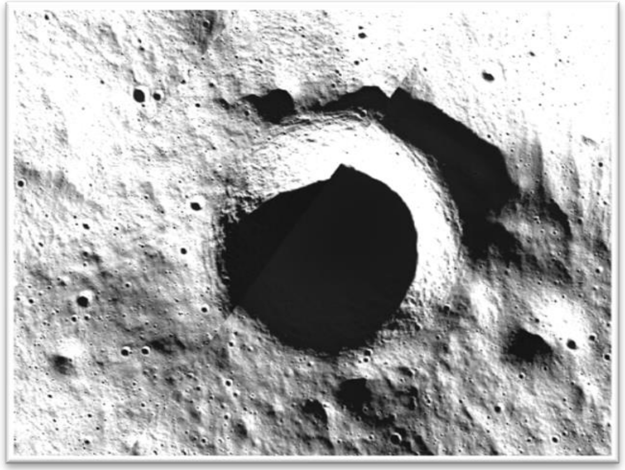
Lon: 147.0 E, Lat: 13.1 N

Diameter: 1.079 km, Depth: 0.202 km

Backup Craters (South Pole)

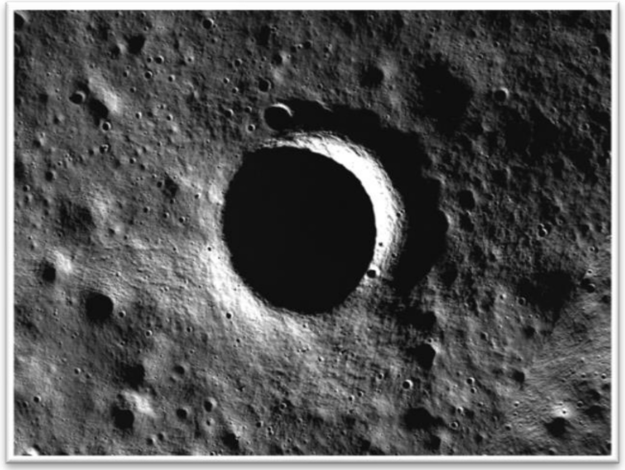
Lon: 206.20 E Lat: -88.99 N

Diameter: 1.1 km Depth: 0.200 km



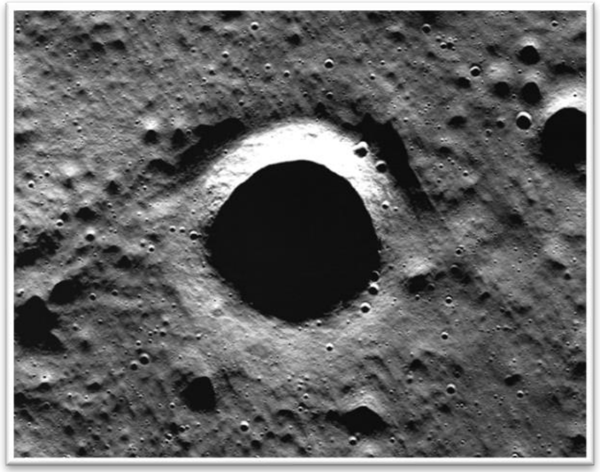
Lon: 224.40 E Lat: -87.41 N

Diameter: 1.2 km Depth: 0.225 km



Lon: 178.68 E Lat: -87.06 N

Diameter: 1.0 km Depth: 0.170 km



LCRT Publications

1. R. Wang, V. Gehlot, S. Bandyopadhyay, A. Goel, B. Byron, P. McGarey, R. Wilson, K. Jenks, "Lift Wire Deployment and Anchoring System for the Lunar Crater Radio Telescope on the Far Side of the Moon," AIAA SciTech Space Exploration, January 2023, accepted.

2. M. Arya, A. Verniani, M. Delapierre, D. Pisanti, G. Gupta, A. Goel, J. Lazio, P. Goldsmith, S. Bandyopadhyay, "Kilometer-Scale Parabolic Reflector for a Radio Telescope in a Lunar Crater," AIAA SciTech Spacecraft Structures, January 2023, accepted.

3. A. Goel, S. Bandyopadhyay, J. Lazio, P. Goldsmith, D. Bacon, A. Amara, S. Furnaletto, P. McGarey, R. Rafizadeh, M. Delapierre, M. Arya, D. Pisanti, G. Gupta, N. Chahat, A. Stoica, I. Nesnas, M. Quadrelli, G. Hallinan, K. Jenks, R. Wilson, "Probing the Cosmic Dark Ages with the Lunar Crater Radio Telescope," arxiv arXiv:2205.05745, White Paper to the Biological and Physical Sciences Decadal Survey 2021, DOE's Snowmass 2022

4. A. Goel, D. Pisanti, P. Mcgarey, G. Gupta, M. Arya, N. Chahat, P. Goldsmith, J. Lazio, S. Bandyopadhyay, "Ultra-Long Wavelength Radio Astronomy Using the Lunar Crater Radio Telescope (LCRT) on the Farside of the Moon," 240th American Astronomical Society (AAS) Meeting, Pasadena, California, June 2022. accepted. [*Abstract only*]

5. G. Gupta, M. Arya, A. Goel, S. Bandyopadhyay, P. Goldsmith, P. Mcgarey, J. Lazio, N. Chahat, "Detector Development for the Lunar Crater Radio Telescope," Wireless, Antenna and Microwave Symposium (WAMS), Rourkela, India, June 2022. accepted.

6. P. Culbertson, A. Goel, P. Mcgarey, M. Schwager, S. Bandyopadhyay, "Multi-Robot Assembly Scheduling for the Lunar Crater Radio Telescope on the Far-Side of the Moon," IEEE Aerospace Conference, Big Sky, MT, Mar. 2022.

7. A. Goel, S. Bandyopadhyay, P. McGarey, R. Rafizadeh, P. Goldsmith, J. Lazio, A. Stoica, M. Quadrelli, I. Nesnas, G. Hallinan, "Ultra-Long Wavelength Radio Astronomy using the Lunar Crater Radio Telescope (LCRT) on the Farside of the Moon," Lunar Surface Science Workshop, NASA Biological and Physical Sciences Division, Virtual, Aug. 2021. [*Abstract only*].

Big Picture Overview of the NASA Astrophysics Environment

2020 Astrophysics Decadal

- **C. Report of the Panel on Cosmology (pg 247--263)**
- **LCRT's Science Goals**

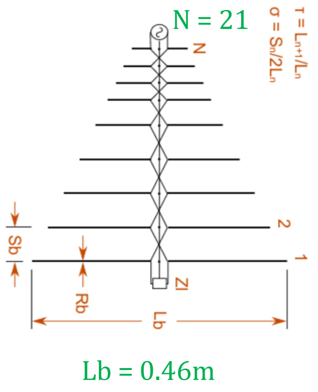
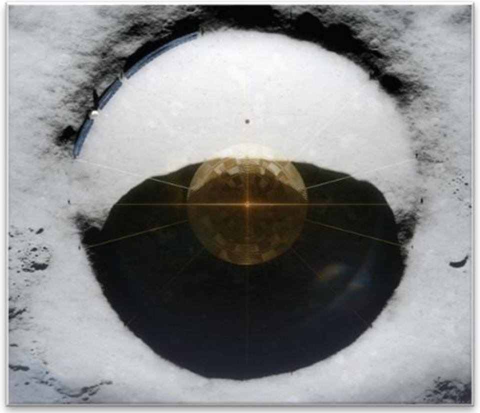
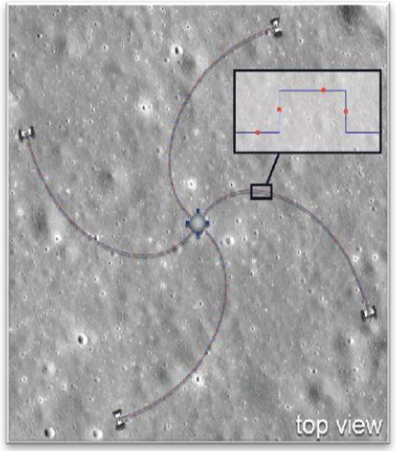
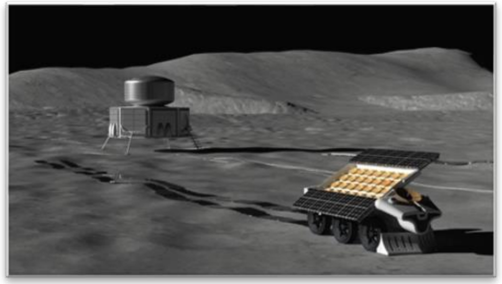
BOX C.1 **Summary of Science Questions**	
C-Q1: What set the Hot Big Bang in motion?	C-Q1a: Primordial gravitational waves C-Q1b: Non-Gaussianity of the large-scale structure of the universe C-Q1c: The initial power spectrum of density fluctuations
C-Q2: What are the properties of dark matter and the dark sector?	C-Q2a: Dark sector signatures in small-scale structure C-Q2b: Dark sector imprints on Big Bang nucleosynthesis and recombination C-Q2c: Annihilation by-products
C-Q3: What physics drives the cosmic expansion and large-scale evolution of the universe?	C-Q3a: The physics of cosmic acceleration C-Q3b: The properties of neutrinos C-Q3c: End-to-end tests of cosmology
C-Q4: How will measurements of gravitational waves reshape our cosmological view?	C-Q4a: The stochastic gravitational wave background C-Q4b: Standard sirens as a new probe of the cosmic distance scale C-Q4c: Light fields and other novel phenomena
Discovery Area: The Dark Ages as a cosmological probe	C-DA1: The end of the Dark Ages C-DA2: The future of primordial density mapping

2020 Astrophysics Decadal

- **C. Report of the Panel on Cosmology (pg 247--263)**

Unlocking this cosmological window will require advances in both measurements and theory, but it appears attainable in the coming decade. A goal for the coming decade is reconnaissance across a wide range of redshift, primarily with next-generation interferometric mapping supported by global single-receiver measurements, in order to map the temperature history of the intergalactic gas. While small changes in the timing of galaxy formation can be caused by astrophysical details, large changes in when structure formed would be a hallmark of new physics in the dark sector. As our understanding of reionization and the late Dark Ages improves, we will increasingly be able to disentangle the astrophysics of reionization from effects of cosmology.

Lunar Surface Concepts

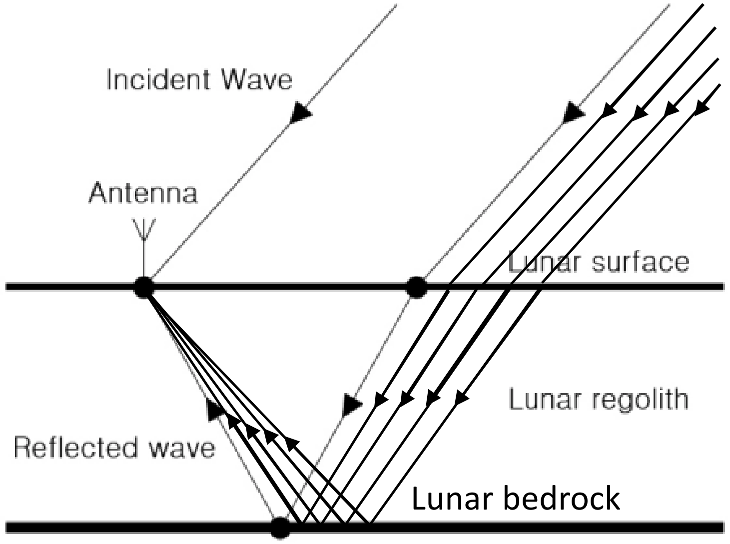
	CLIPART	LCRT	FARSIDE	FarView
				
Description	40 m Log Periodic Antenna on the surface	Lunar Crater Radio Telescope	128x2 dipole antennas on 4 spiral arms	100000+ dipole antennas, using ISRU
Science	• global Dark Ages signal?	• global Dark Ages signal	• global Dark Ages signal • exoplanetary magnetospheric emissions	• global Dark Ages signal • power spectrum of Dark Ages signal • exoplanetary magnetospheric emissions
Estimated Cost	$1B (cost + lander + reserves)	$0.9B (cost) + lander + reserves	$1.2B (cost + reserves) + lander	~$5B (not sure…)
Concerns	poor isolation from regolith		regolith interactions	regolith interactions

Cost disclaimer: The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

Lunar Surface Concepts

- Undesirable effects due to the interaction between lunar regolith and long-wavelength radio waves.

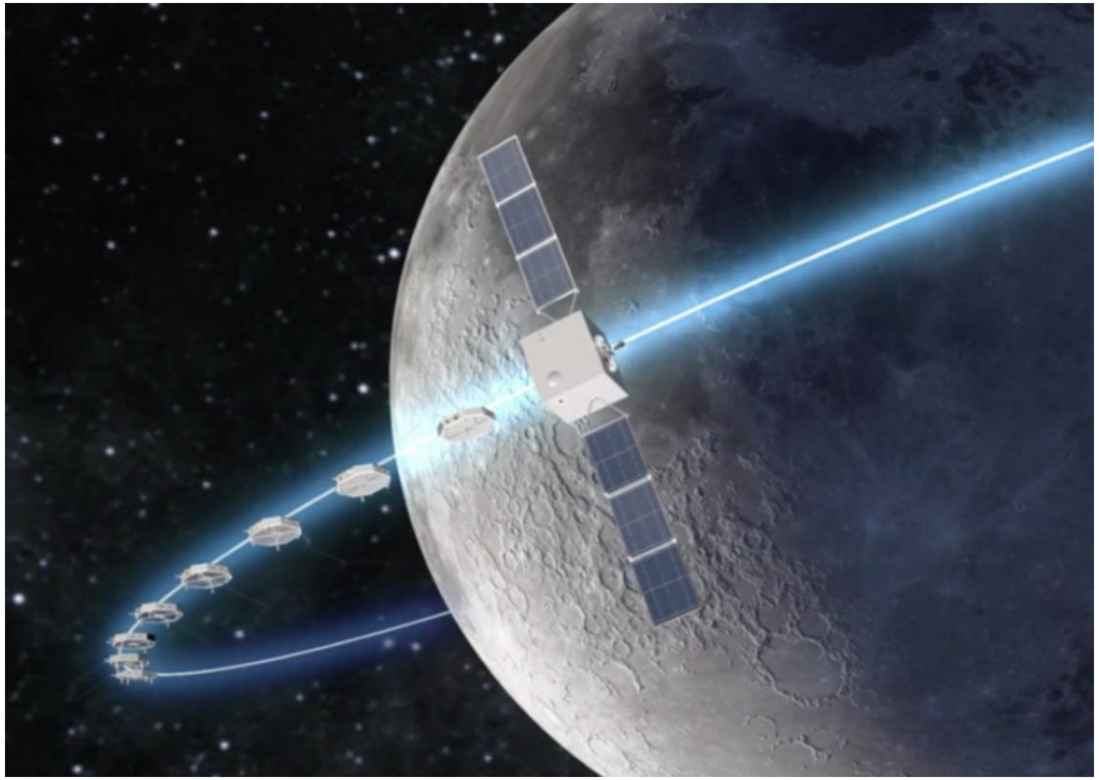
- LNSD (like sparse array) vs SNLD (like LCRT):
  - Every antenna has to be thermally regulated and powered
  - The data from every antenna has to be transported to a central hub, either using thermally-shielded and micrometeorite-resistant wires or using some lunar surface communication.



[1] X. Gong, D. A. Paige, M. A. Siegler, and Y.-Q. Jin, "Inversion of dielectric properties of the lunar regolith media with temperature profiles using Chang'e microwave radiometer observations," IEEE Geoscience and Remote Sensing Letters, vol. 12, no. 2, pp. 384–388, 2014.
[2] Z. Mo, H. Mao-Hai, and Y. Yi-Hua, "Simulations of ultra-long wavelength interferometers in earth orbit and on the lunar surface," Research in Astronomy and Astrophysics, vol. 15, no. 3, p. 443, 2015.
[3] B. M. French, G. Heiken, and D. Vaniman, Lunar sourcebook: A user's guide to the Moon. CUP Archive, 1991.

Sat. Constellation Concepts

- Lunar-orbiting satellite missions:
  - China’s Hongmeng Constellation
  - Lunar Observer Radio Astronomy Experiment (LORAE)
  - Dark Ages Radio Explorer (DARE)
  - Small time (25% per orbit) in radio quiet zone
  - Thermal-instability due to rapid thermal cycles while orbiting the Moon.
- Earth-Moon Lagrangian L2 point:
  - Astronomical Low-Frequency Array (ALFA)
  - Formation-flying sub-Ionospheric Radio astronomy Science and Technology (FIRST)
  - Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR)

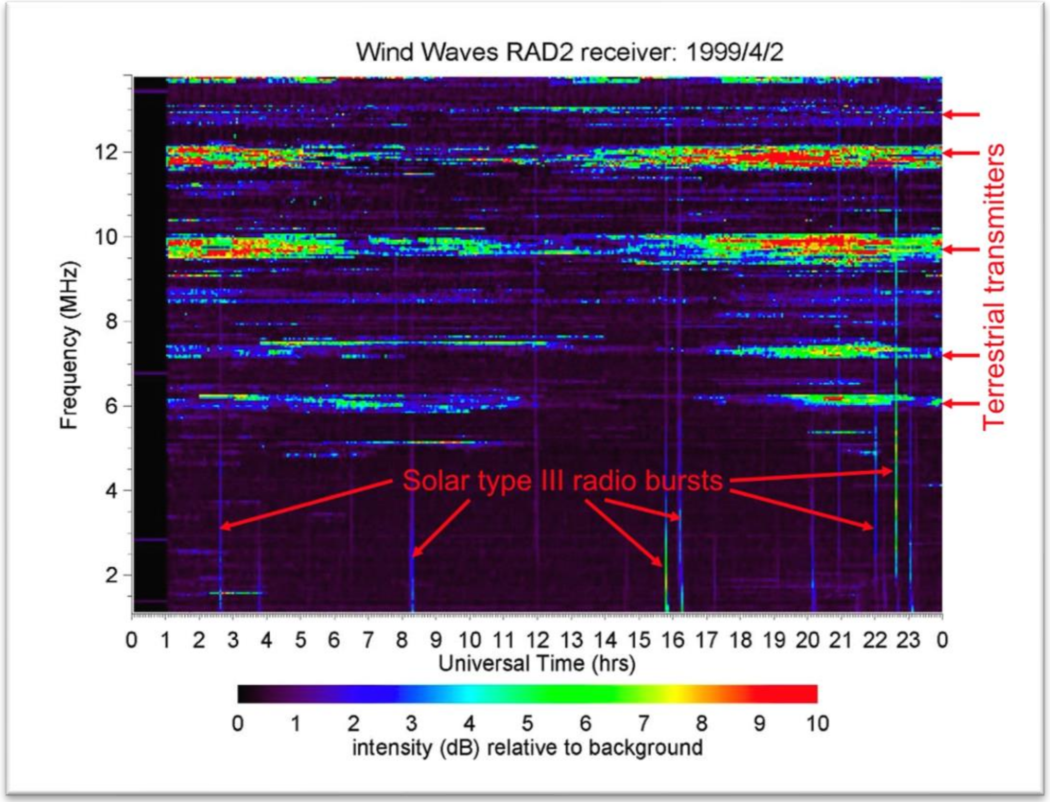


China’s Hongmeng Constellation

Farside's Advantages

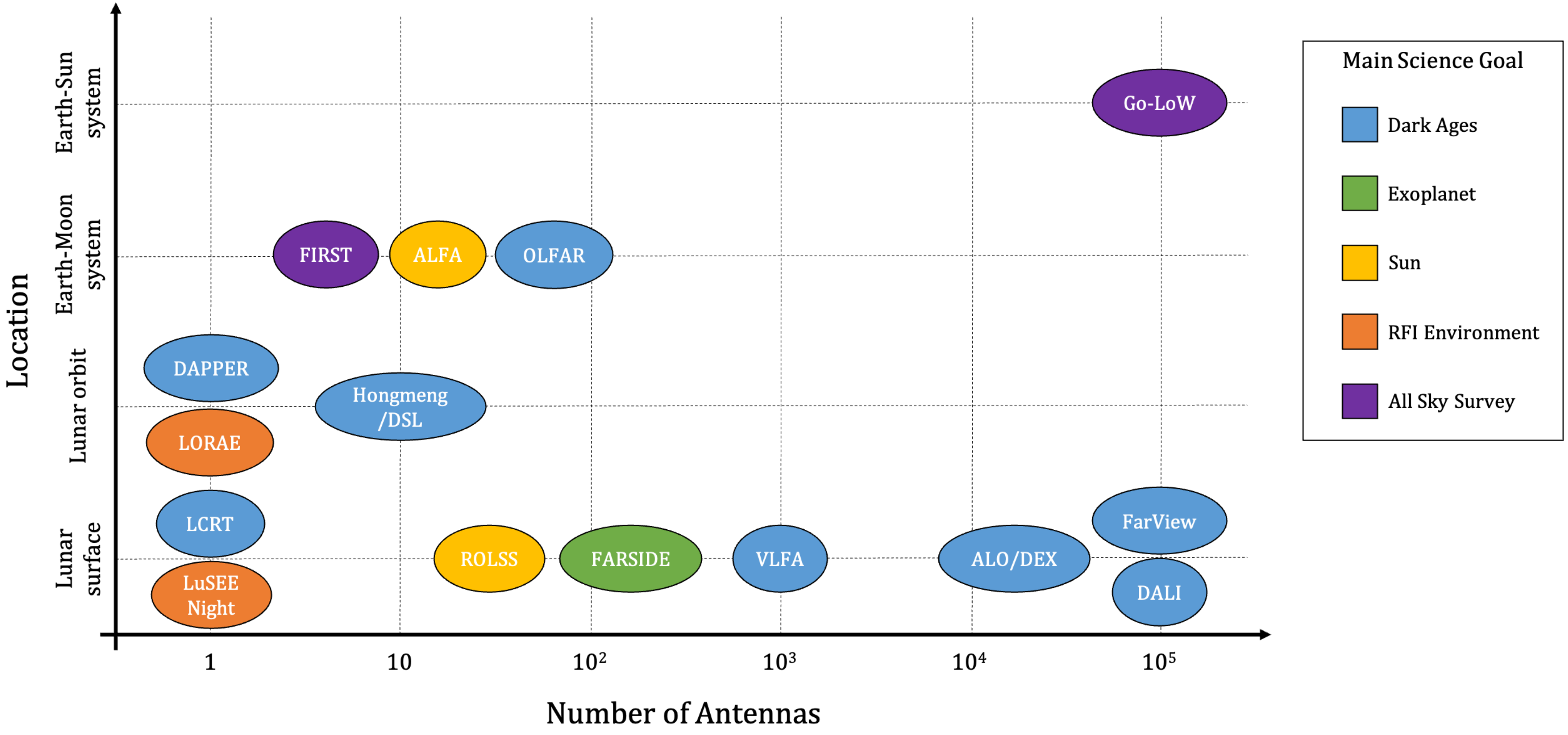
Challenging Noise Sources :

- Galactic foreground
- Earth
- Sun
- Jupiter + Saturn



Bassett et. al. "Characterizing the Radio Quiet Region Behind the Lunar Farside for Low Radio Frequency Experiments" Advances in Space Research, 2020

Survey of Dark Ages Missions

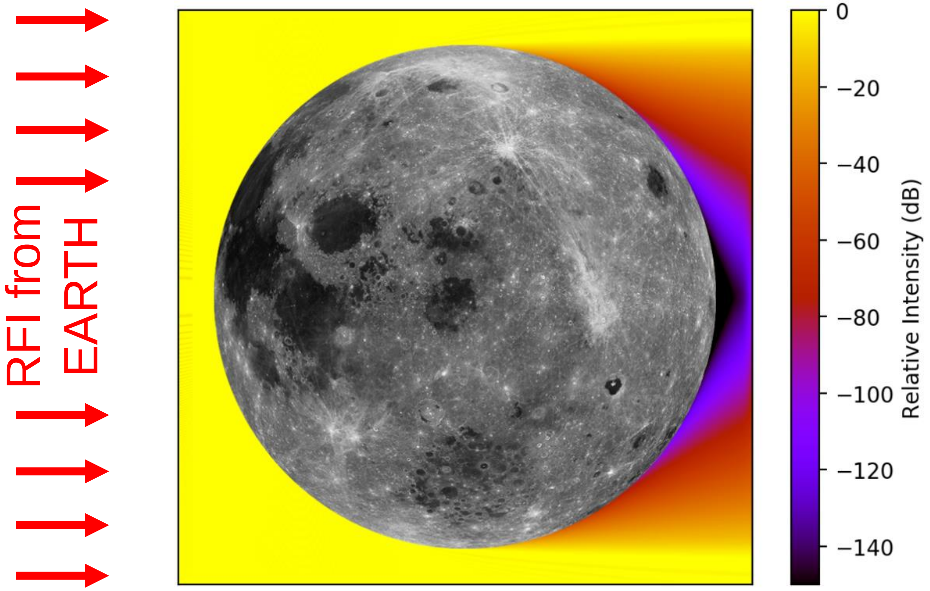


S. Bandyopadhyay, A. Goel, G. Gupta, D. Pisanti, P. Goldsmith, T.-C. Chang, M. Seiffert, C. Anderson, J. Lazio, "Survey of Mission Concepts for Exploring the Dark Ages Universe," IEEE Aerospace Conference, Big Sky, MT, Mar, 2025.

Astrophysics on the Moon using Artemis Mission?

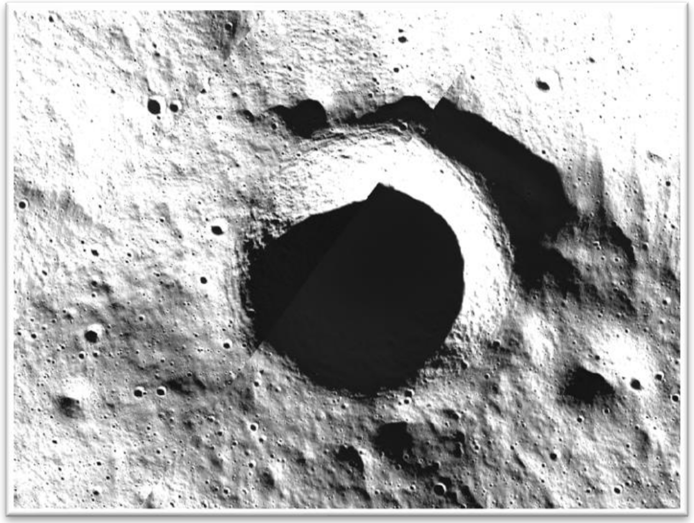
Artemis: Crater Location

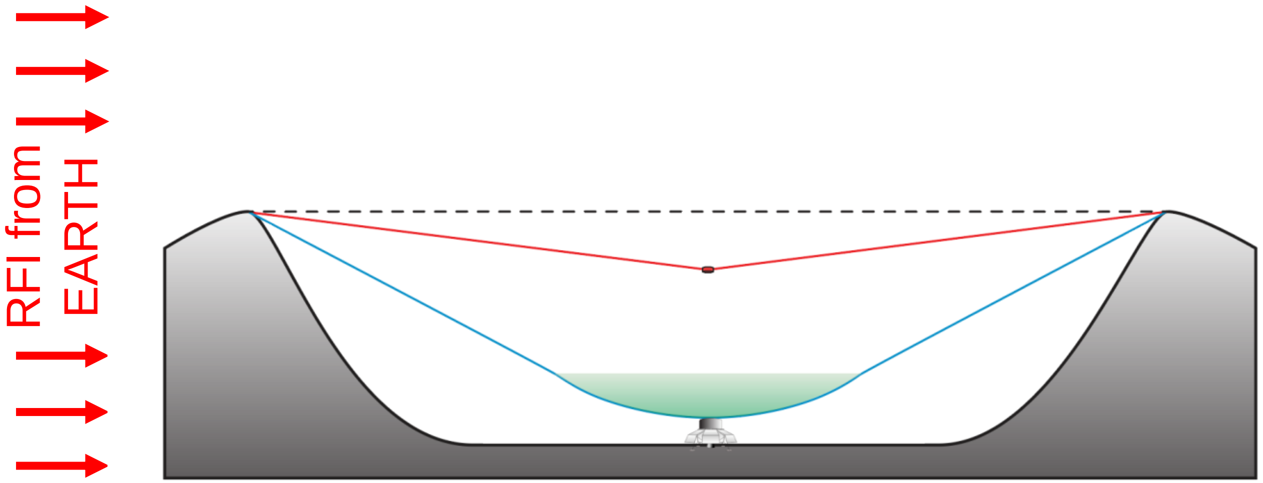
- Near-side polar craters might be fine
- We think crater walls might protect LCRT from Earth's RFI



Lon: 206.20 E Lat: -88.99 N

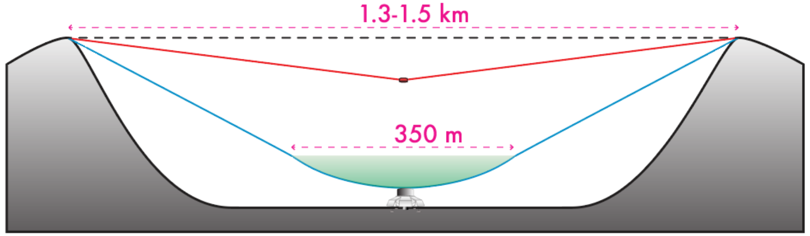
Diameter: 1.1 km Depth: 0.200 km

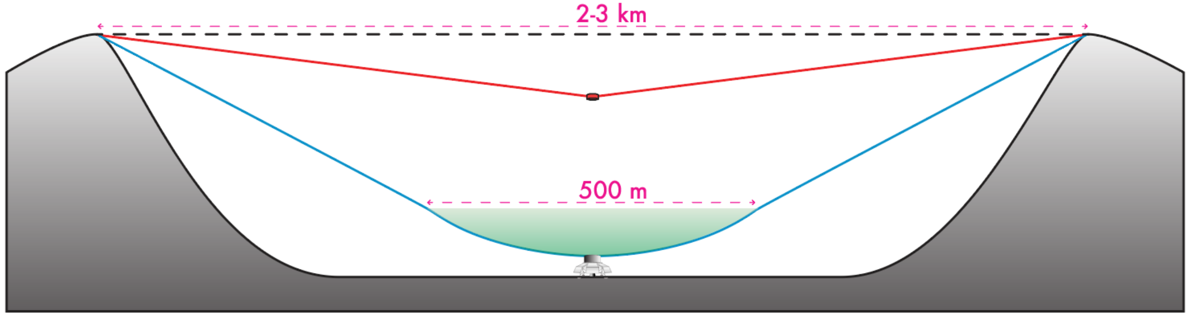


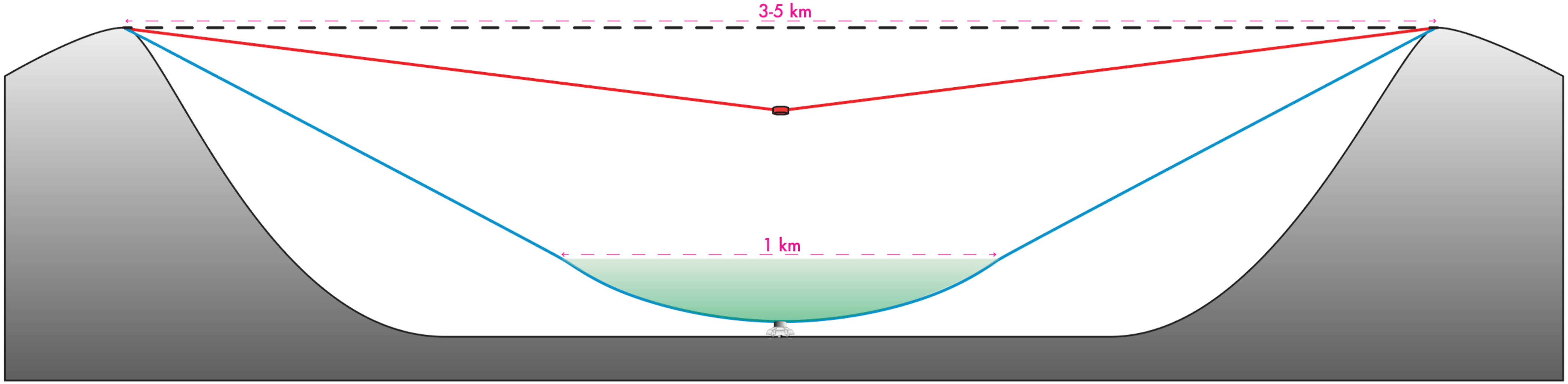


Artemis: LCRT Size

- Potentially larger sizes, with better SNR
- Concern: Structural integrity of crater walls

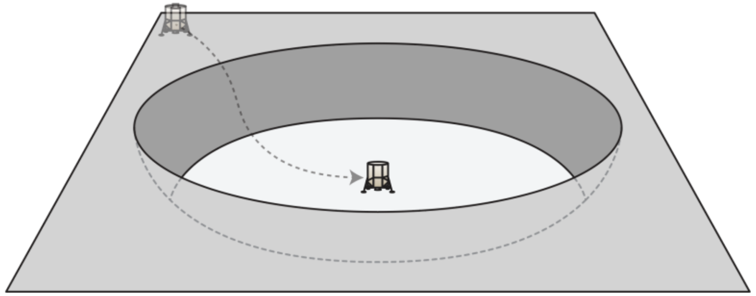




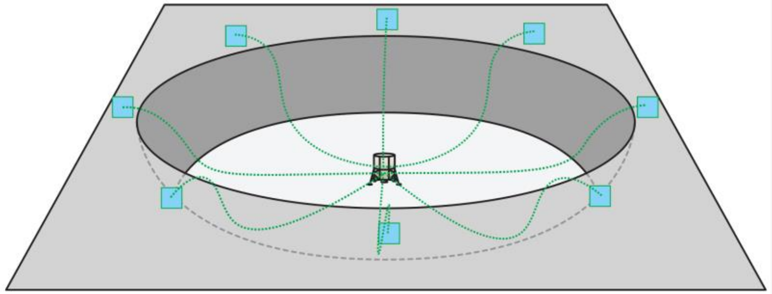


Artemis: ConOps with Astronauts

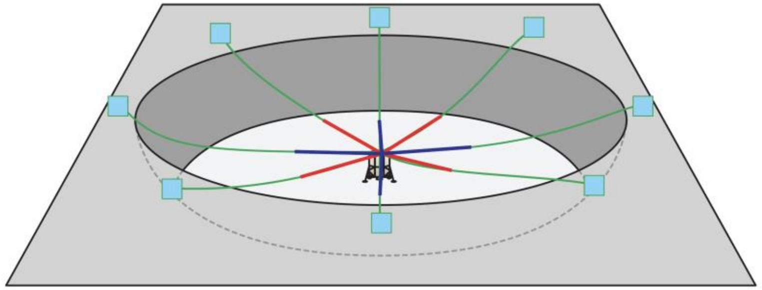
Step 1: Astronauts transport LCRT to Crater Floor



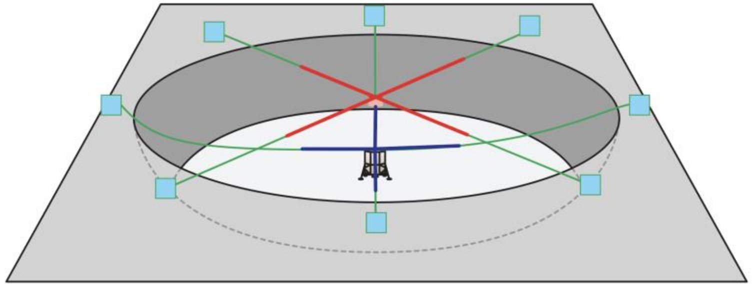
Step 2: Astronauts deploy Anchors at Crater Rim



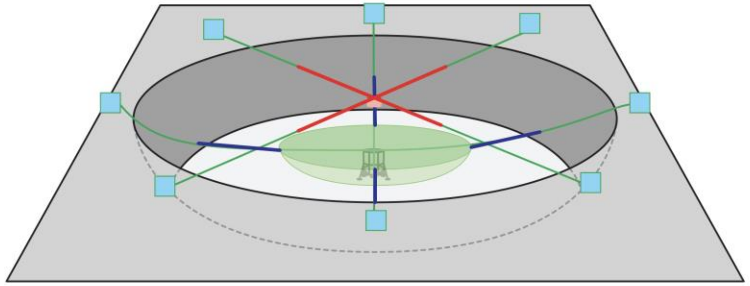
Step 3: Tension Lift Wires (using Teleoperation)



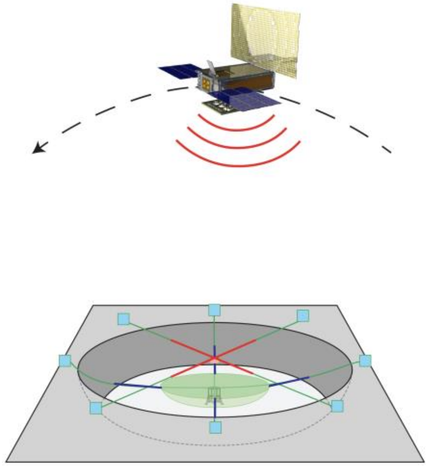
Step 4: Deploy Feed (using Teleoperation)



Step 5: Deploy Reflector (using Teleoperation)



Step 6: Calibrate LCRT



LCRT as a RADAR

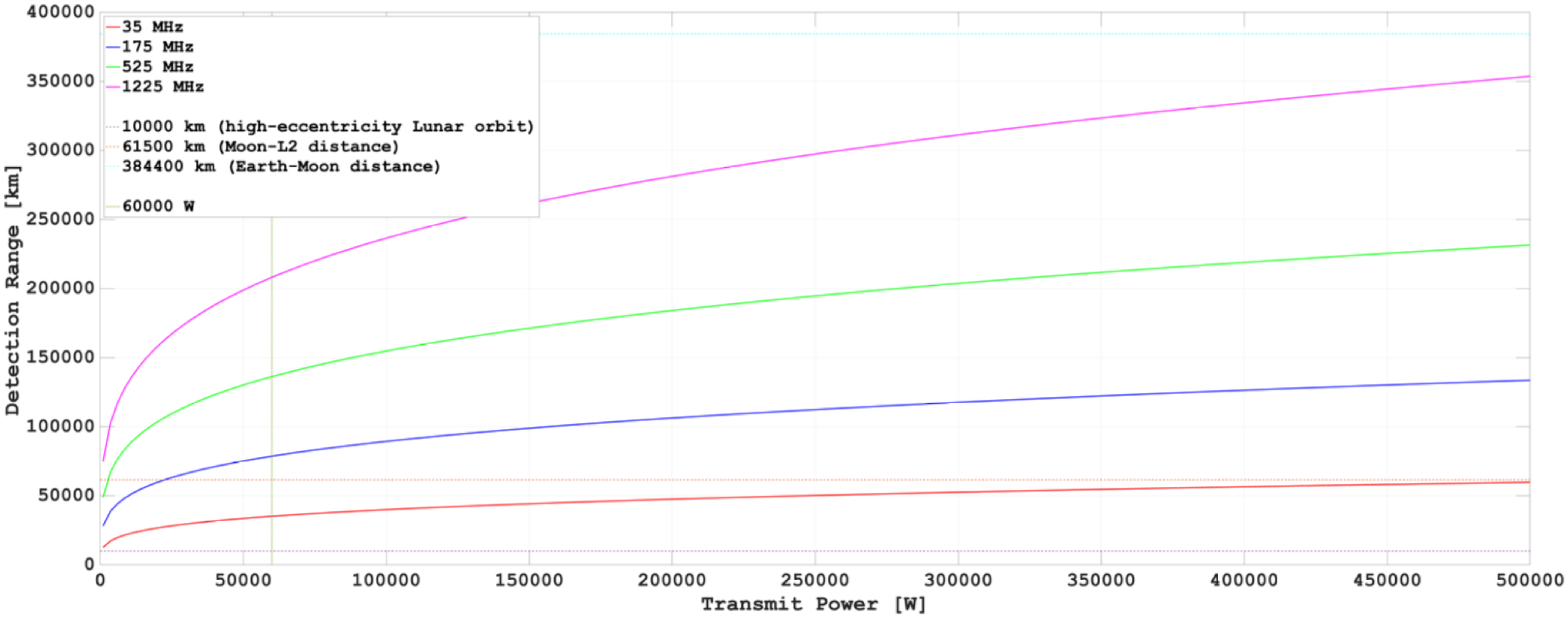


Figure 3: Transmit power vs. detection range for different frequencies with the 350 m diameter LCRT antenna.
Note the horizontal lines marking significant altitudes: 10000km is an exemplary high eccentricity lunar orbit.
615000 km is the nominal Moon to L_2 Lagrange point distance, but high-altitude halo orbits could be at distances of 800000km.
384400km is the Earth–Moon distance.
A transmit power of 60000 W is consistently used in all subsequent plots within this report.

Future Work

2022
2023
2024
2025
2026
2027
2028
2029
2030

LCRT concept is at CML 3. Subsystem technologies at TRL 3.

Improve LCRT subsystem technologies to TRL 5.

Improve LCRT concept to Concept Maturity Level (CML) 4.

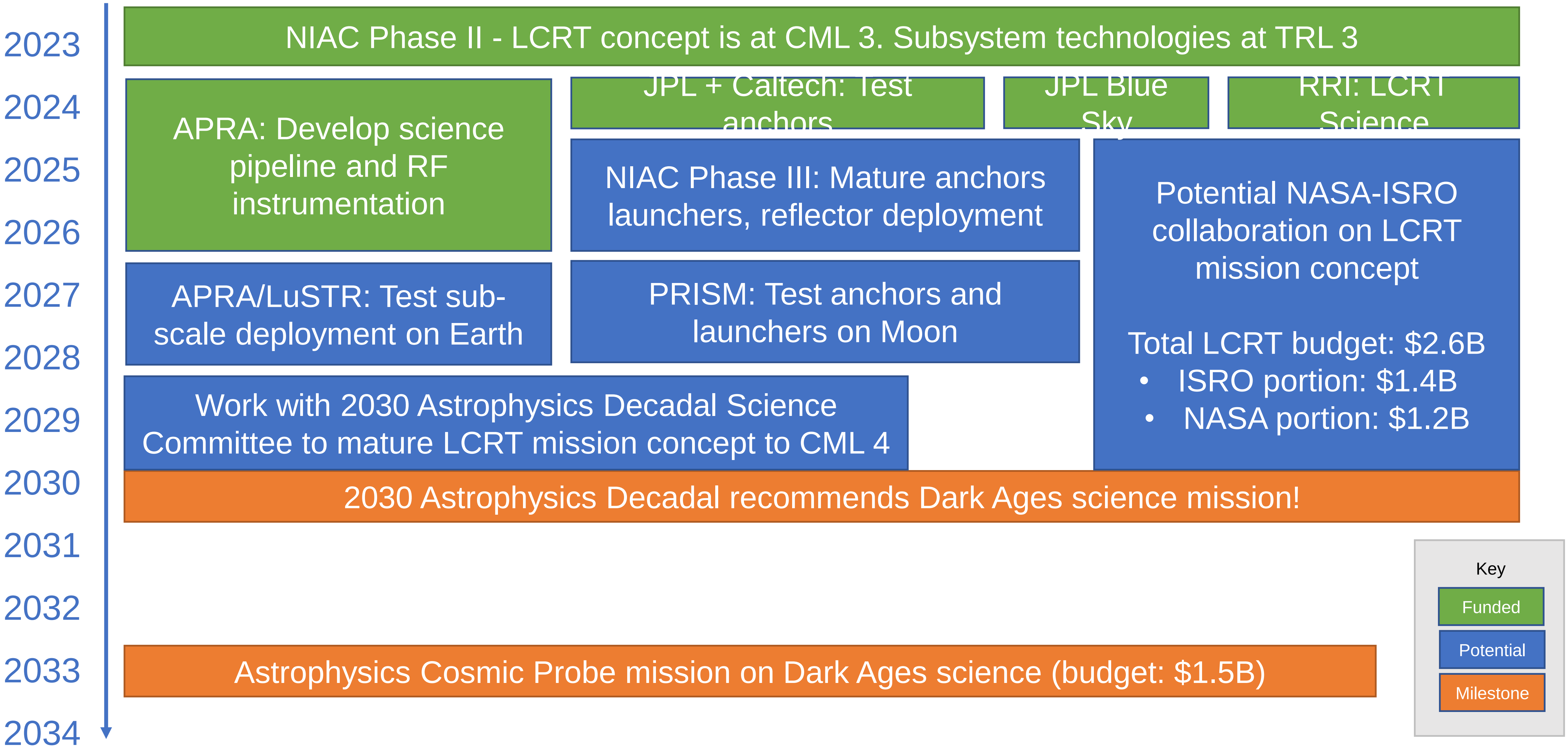
Dedicated Science campaign for Dark Ages science mission

Test some LCRT subsystem technologies on the Moon (TRL 6).

Work with 2030 Astrophysics Decadal Science Committee on the LCRT concept

2030 Astrophysics Decadal recommends Dark Ages science mission!

Future Work and Vision

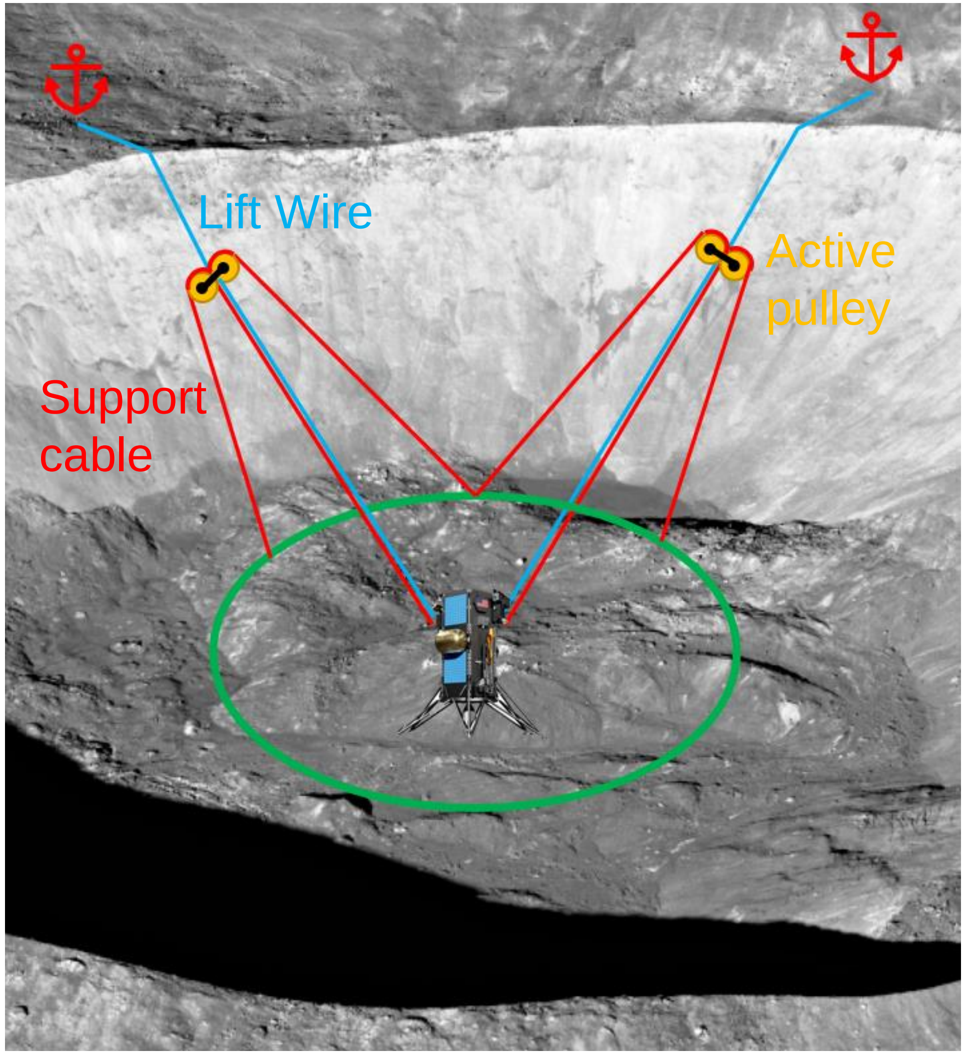


Cost disclaimer: The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

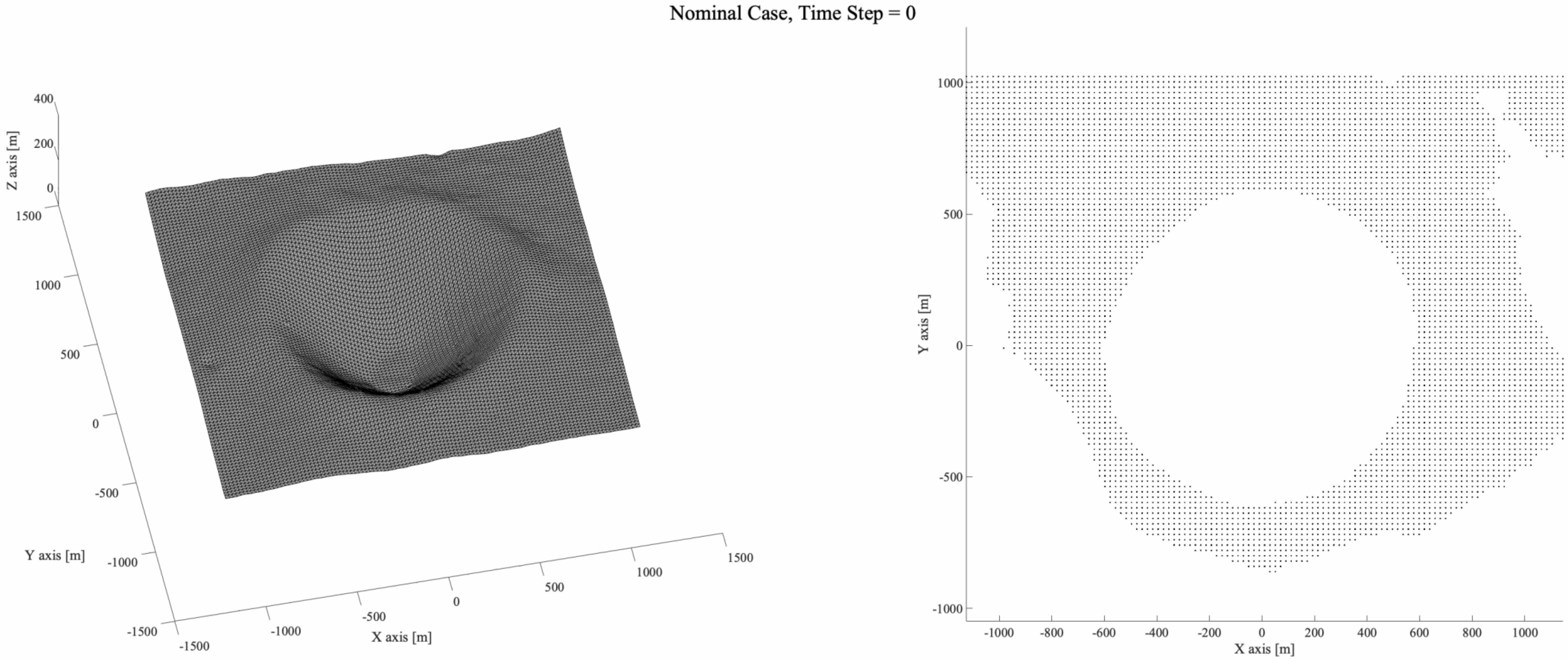
Control of Deployment

Control of Deployment

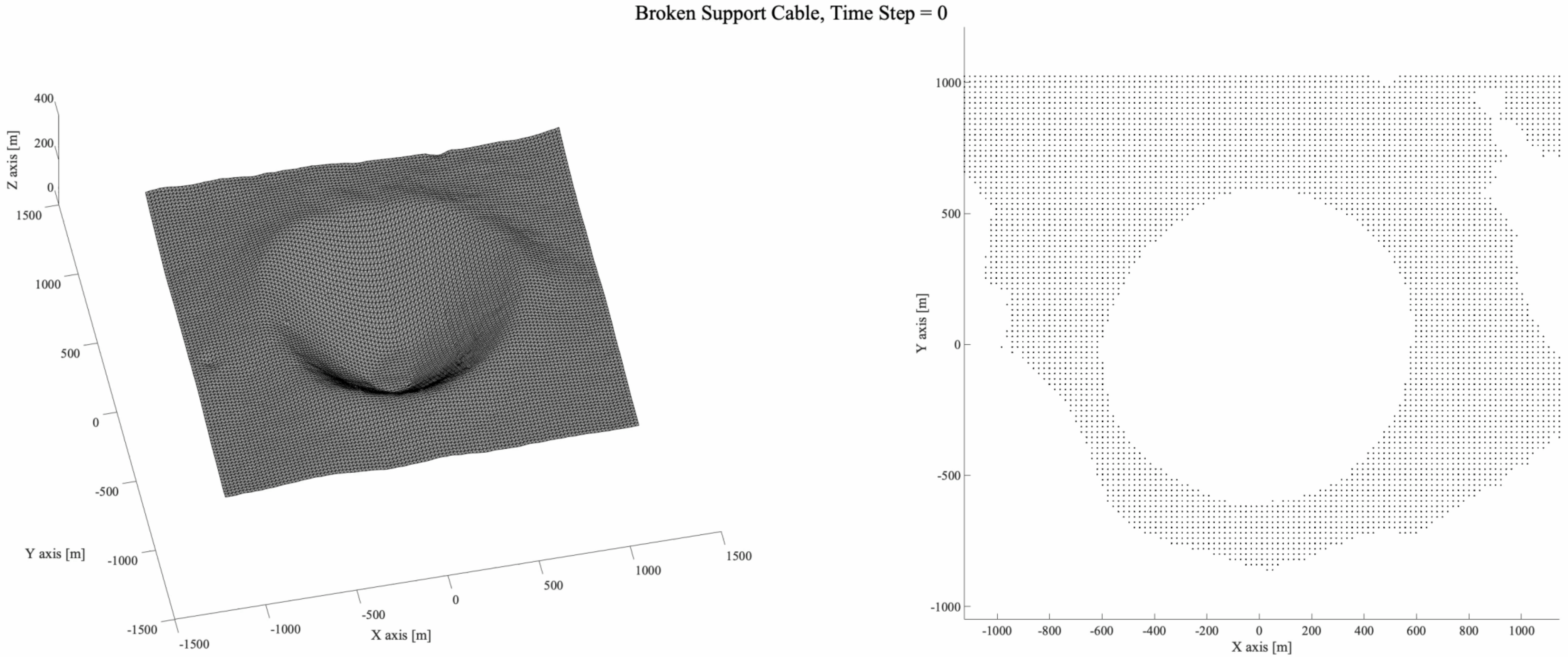
- Active pulleys can correct for radial/angular errors in the projectile system
- Control options include:
  - Active pulley can move up/down
  - Support cable length can increase/decrease
- Design is resilient to failures
  - 1 Support cable or 1 Lift Wire failure
  - Multiple support cables failure in some scenarios



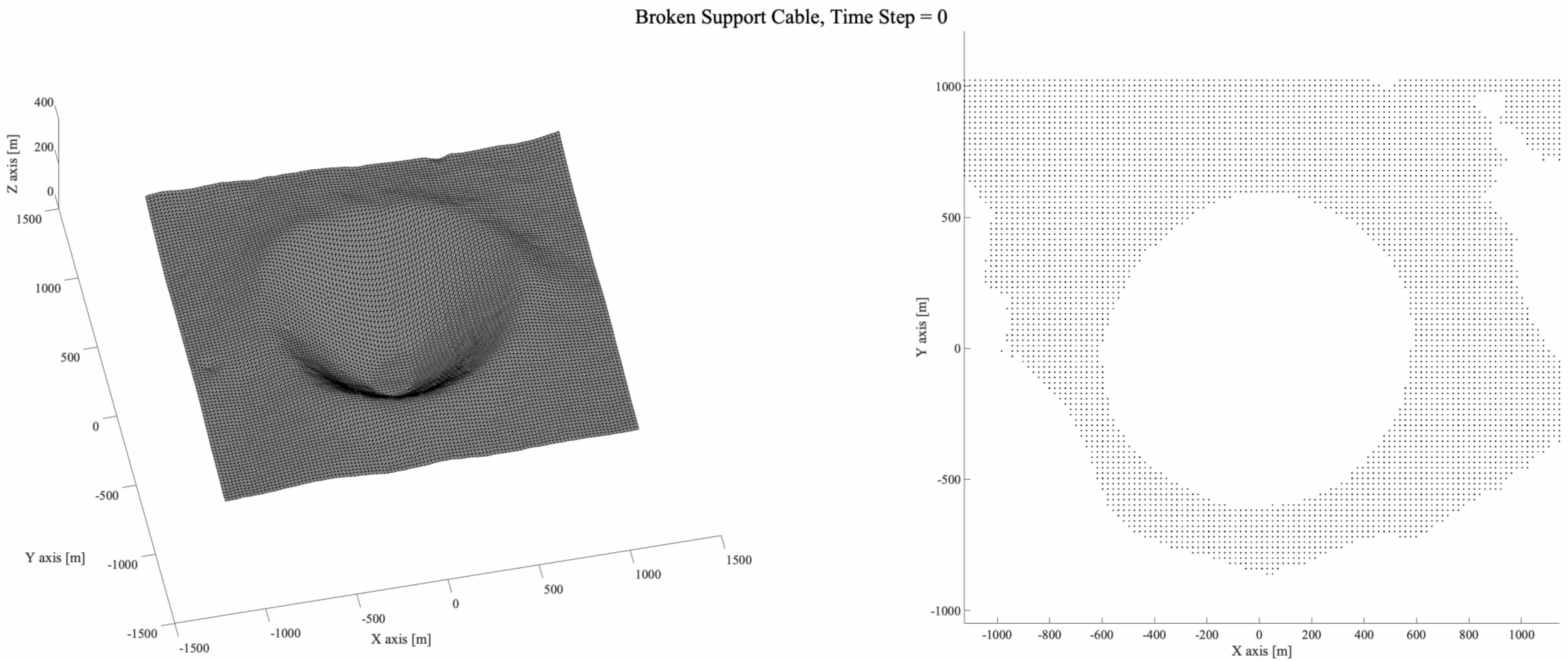
Control of Deployment: Nominal Case



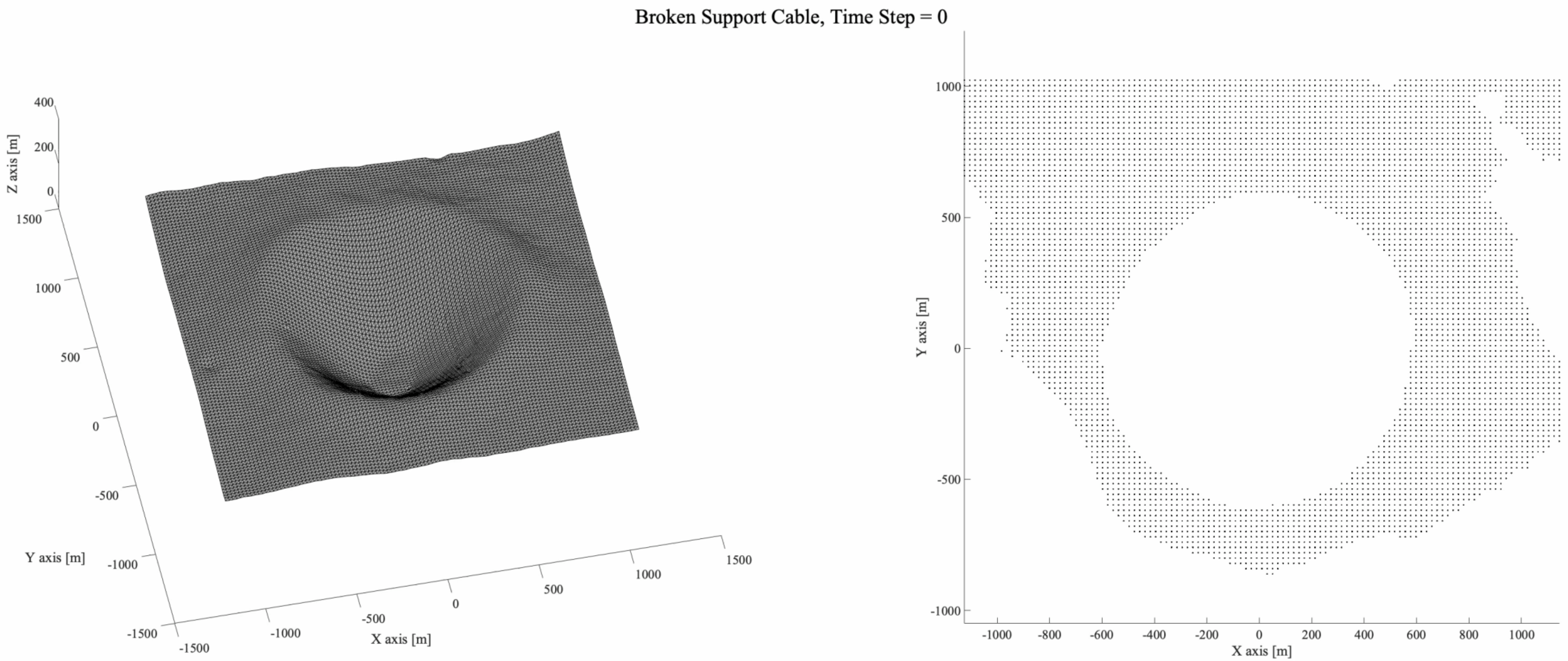
Control of Deployment: 1 Support Cable Fails



Control of Deployment: 1 Lift Wire Fails



Control of Deployment: 2 Support Cables Fail



Science Pipeline

Science Goal from 2020 Astro decadal:

Understanding the cooling profile of the Universe during the Dark Ages and the role of Dark matter in the transition to the Cosmic Dawn

Science Objective:

Ascertain which cosmological model can explain this cooling behavior during the Dark Ages

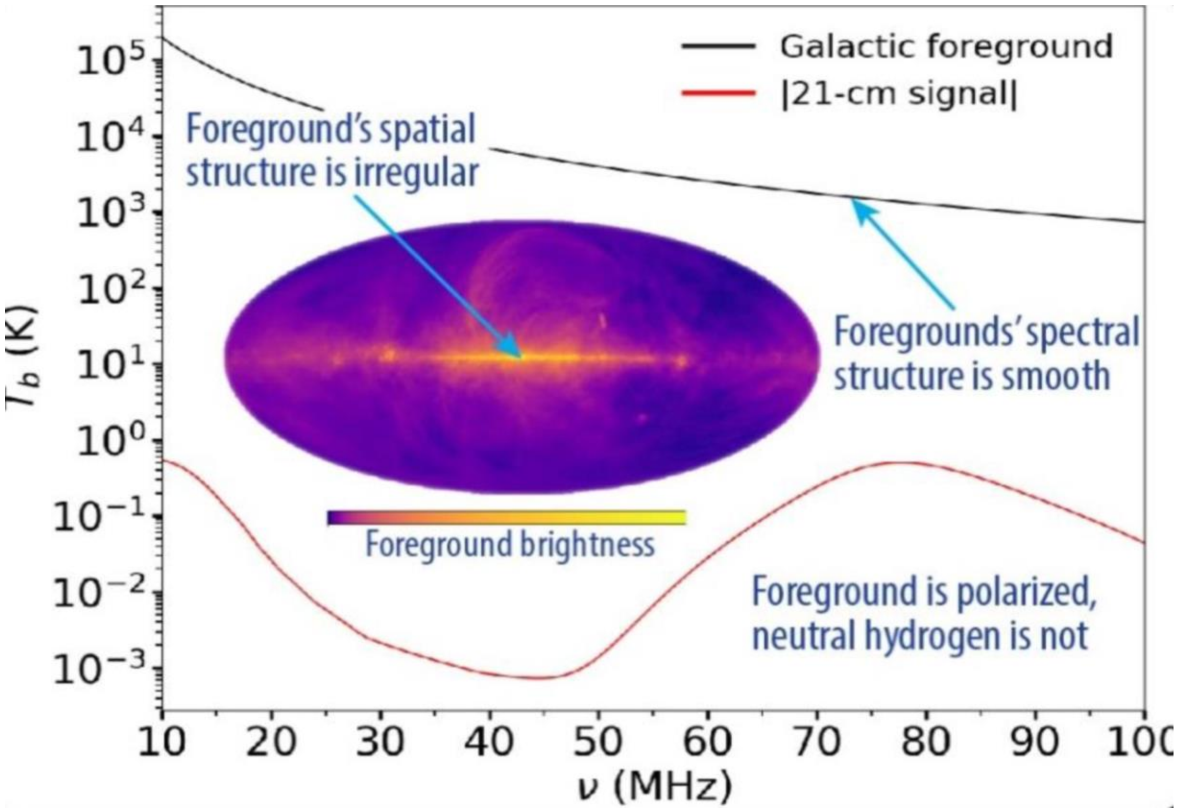
Science Measurement Requirements:

Measure the global spectral profile of the highly-redshifted H_I transition with:

- Frequency range of 4.7-47 MHz
- Spectral resolution of 1 MHz
- Noise temperature less than 20 mK

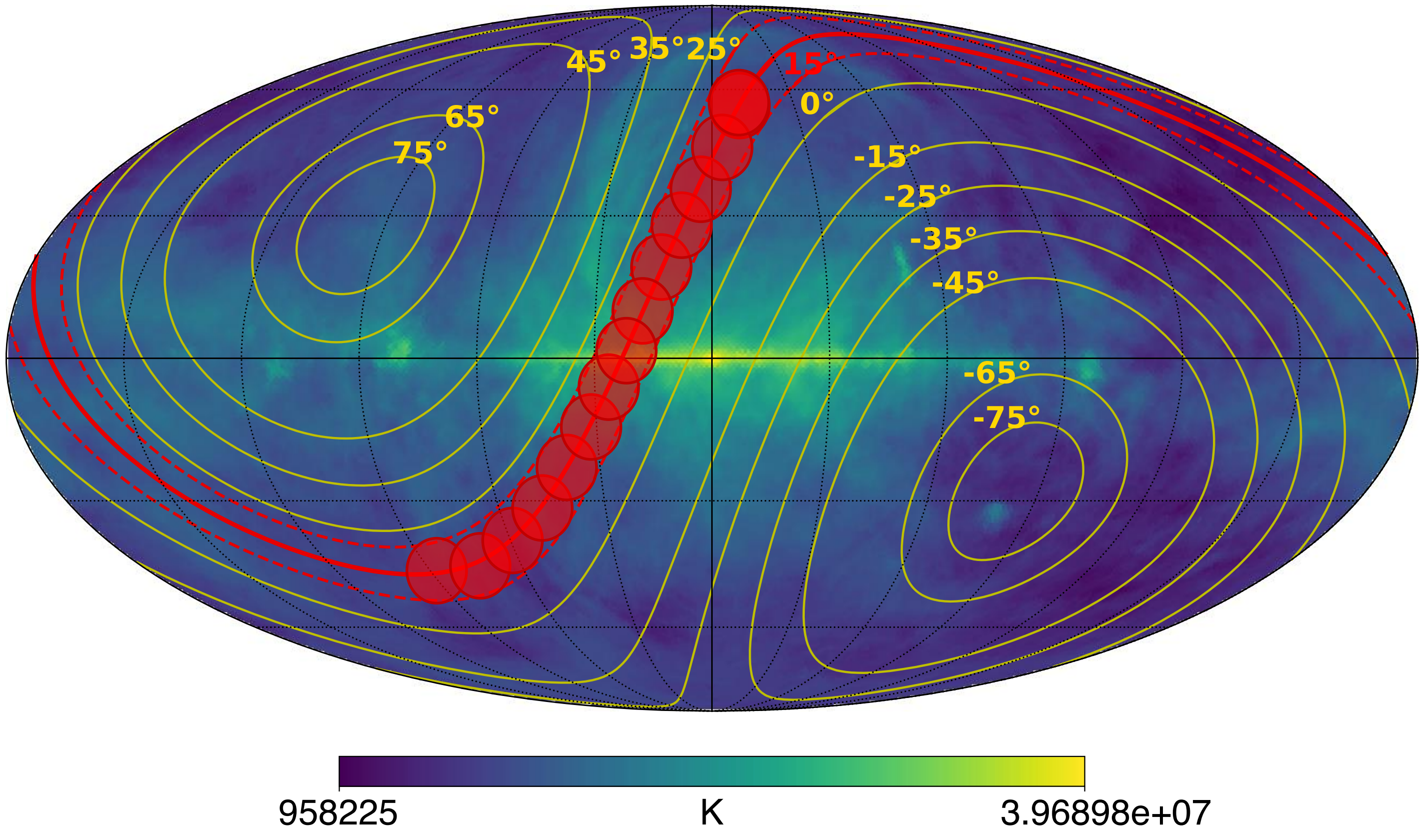
The farside of the Moon allows to access these frequencies from a radio-quiet environment

Still need to mitigate the Galactic foreground
(up to 10^8 stronger than 21cm signal)



J. O. Burns et al., "Dark cosmology: Investigating dark matter & exotic physics in the dark ages using the redshifted 21-cm global spectrum," arXiv

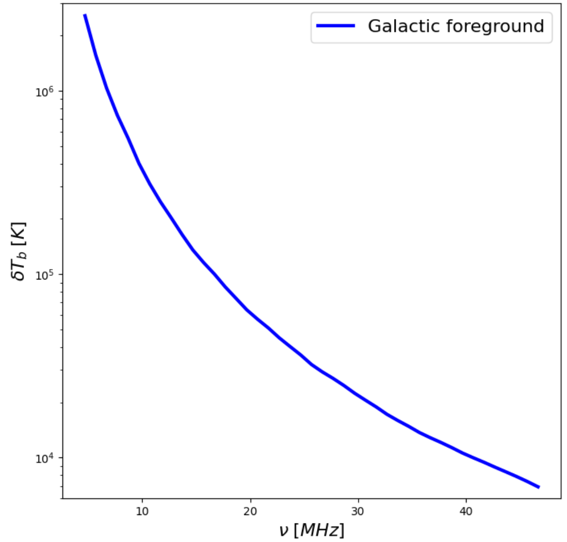
Science Pipeline – Pylinex (Drift-Scan)

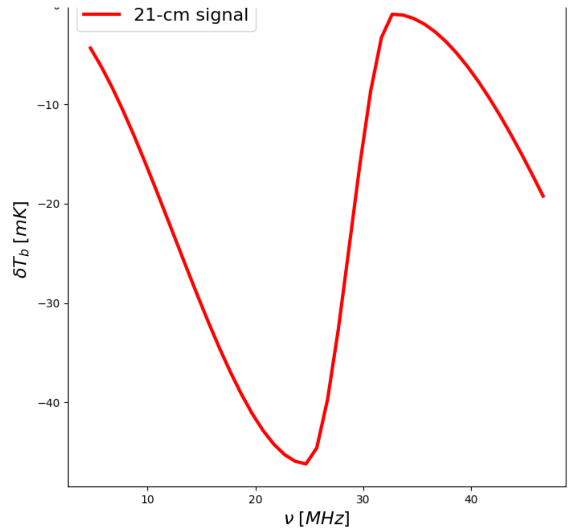


4.7 MHz, FWHM = 12.7°

The observation time of 1 lunar night is divided in multiple time bins

$$\mathbf{y} = \mathbf{y}_{fg} + \mathbf{\Psi}_{21}\mathbf{y}_{21} + \mathbf{n}$$ Gaussian noise





Tauscher K, Rapetti D, Burns JO, Switzer E. Global 21 cm signal extraction from foreground and instrumental effects. iii. Utilizing Drift-scan Time Dependence and Full Stokes Measurements. The Astrophysical Journal. 2020, DOI: 10.3847/1538-4357/ab9b2a

Science Pipeline – Pylinex (Modeling)

Raw data vector

Contains multiple individual spectra concatenated

$$\mathbf{y} = \mathbf{y}_{fg} + \mathbf{\Psi}_{21}\mathbf{y}_{21} + \mathbf{n}$$

Gaussian noise of covariance C

Generate multiple simulated realizations of foreground and 21-cm signal (**training sets**) to capture sky, antenna and signal uncertainty

Foreground Training Set → SVD → $\mathbf{F}_{fg}$

21cm signal Training Set → SVD → $\mathbf{F}_{21}$

Matrices of the singular vectors of the foreground and signal training sets

Data model

$$M(\boldsymbol{x}_{fg}, \boldsymbol{x}_{21}) = \boldsymbol{F}_{fg}\boldsymbol{x}_{fg} + \mathbf{\Psi}_{21}\boldsymbol{F}_{21}\boldsymbol{x}_{21}$$

Tauscher K, Rapetti D, Burns JO, Switzer E. Global 21 cm signal extraction from foreground and instrumental effects. iii. Utilizing Drift-scan Time Dependence and Full Stokes Measurements. The Astrophysical Journal. 2020, DOI: 10.3847/1538-4357/ab9b2a

Science Pipeline – Pylinex (Fitting)

Raw data vector: $\mathbf{y} = \mathbf{y}_{fg} + \mathbf{\Psi}_{21}\mathbf{y}_{21} + \mathbf{n}$ Gaussian noise of covariance C

Foreground Training Set

21cm signal Training Set

Data model: $M(\boldsymbol{x}_{fg}, \boldsymbol{x}_{21}) = \boldsymbol{F}_{fg}\boldsymbol{x}_{fg} + \mathbf{\Psi}_{21}\boldsymbol{F}_{21}\boldsymbol{x}_{21}$

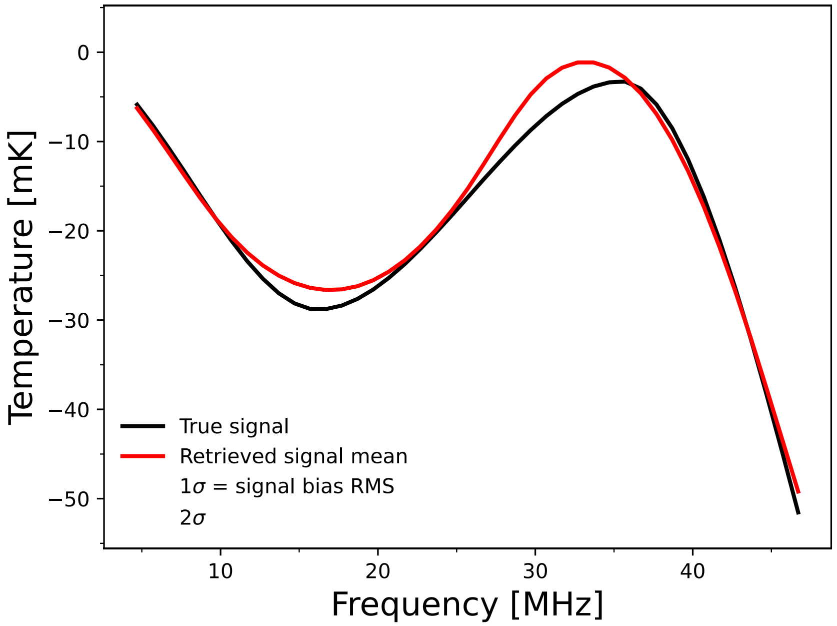
Raw data fit with MLE:

$$L(x) \propto exp\{-0.5[\boldsymbol{y} - \boldsymbol{Gx}]^T \boldsymbol{C}^{-1}[\boldsymbol{y} - \boldsymbol{Gx}]\}$$

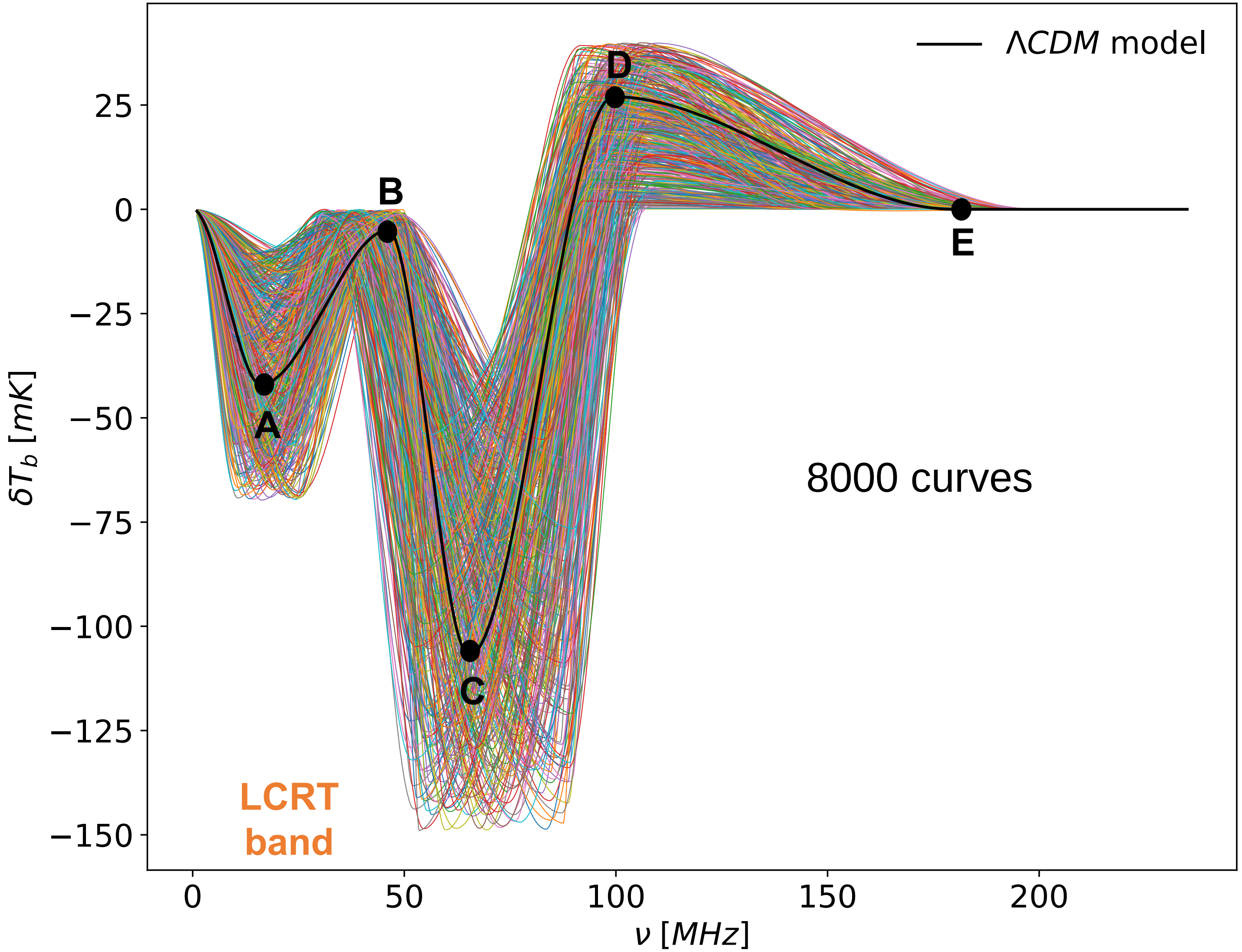
$$\boldsymbol{G} = [\boldsymbol{F}_{fg} \ \ \mathbf{\Psi}_{21}\boldsymbol{F}_{21}], \boldsymbol{x}^T = [\boldsymbol{x}_{fg}^T, \boldsymbol{x}_{21}^T]$$

Retrieved 21-cm signal: $\boldsymbol{\gamma}_{21} = \boldsymbol{F}_{21}\boldsymbol{\xi}_{21}$

(maximum likelihood estimation of $\mathbf{y}_{21}$)



Dark Ages Signal Training Set: the Turning Point Model



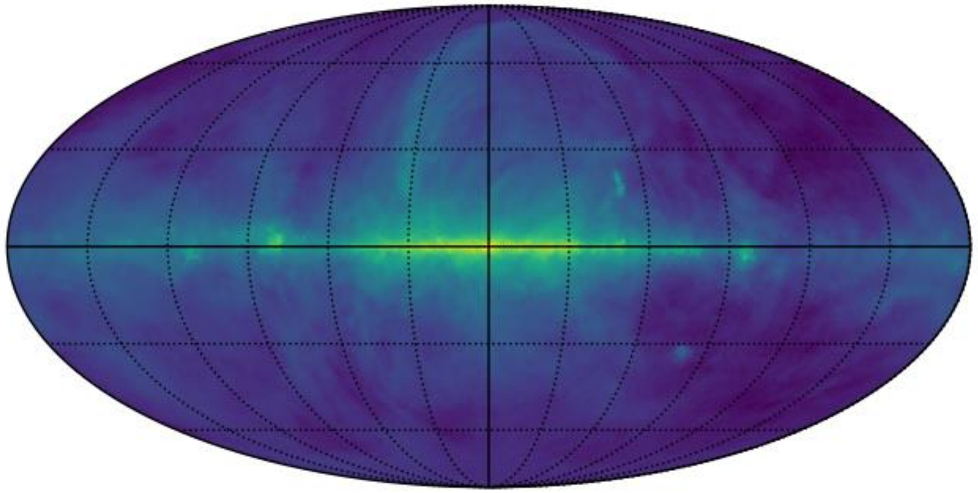
Turning point parameters for the $\Lambda CDM\ model$

Frequencies [MHz]	Temperature [mK]
$\nu_A = 16.1$	$\delta T_A = -42$
$\nu_B = 46.2$	$\delta T_B = -5$
$\nu_C = 65.3$	$\delta T_C = -107$
$\nu_D = 99.4$	$\delta T_D = -37$
$\nu_E = 180$	$\delta T_E = 0$

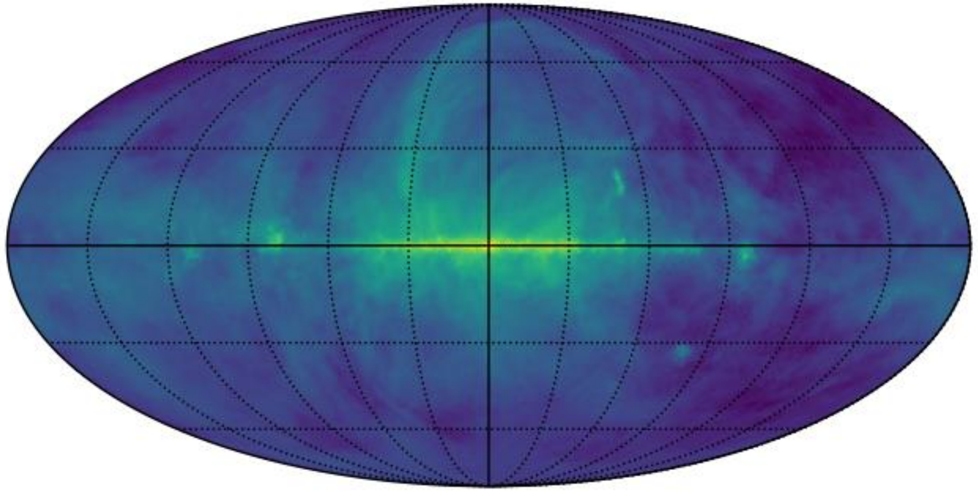
Pritchard JR, Loeb A., "Constraining the unexplored period between the dark ages and reionization with observations of the global 21 cm signal," *Physical Review D*. 2010;82(023006).

Foreground Training Set: Spectral Index Spatial Variation

Haslam map (408 MHz)



Scaled map (4.7 MHz)



$$T_{sky}(\nu,\theta,\phi) = T_{map}(\theta,\phi)\left(\frac{\nu}{\nu_o}\right)^{\beta(\theta,\phi,\nu)}$$

Multiple realizations of the foreground are sampled from a random spatial distribution of the spectral index $\boldsymbol{\beta}$

$$\beta(\theta) = O + M\,exp\left\{-\frac{(\theta-\pi/2)^2}{2\sigma^2}\right\}$$

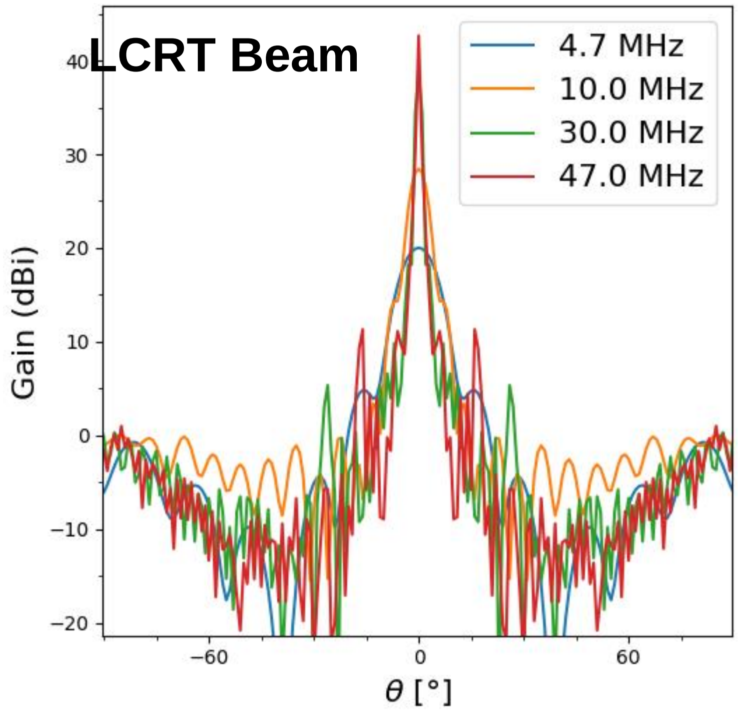
θ galactic co-latitude

$$O = \beta_{pole}, \qquad M = \beta_{plane} - \beta_{pole}, \qquad \sigma = 5°$$

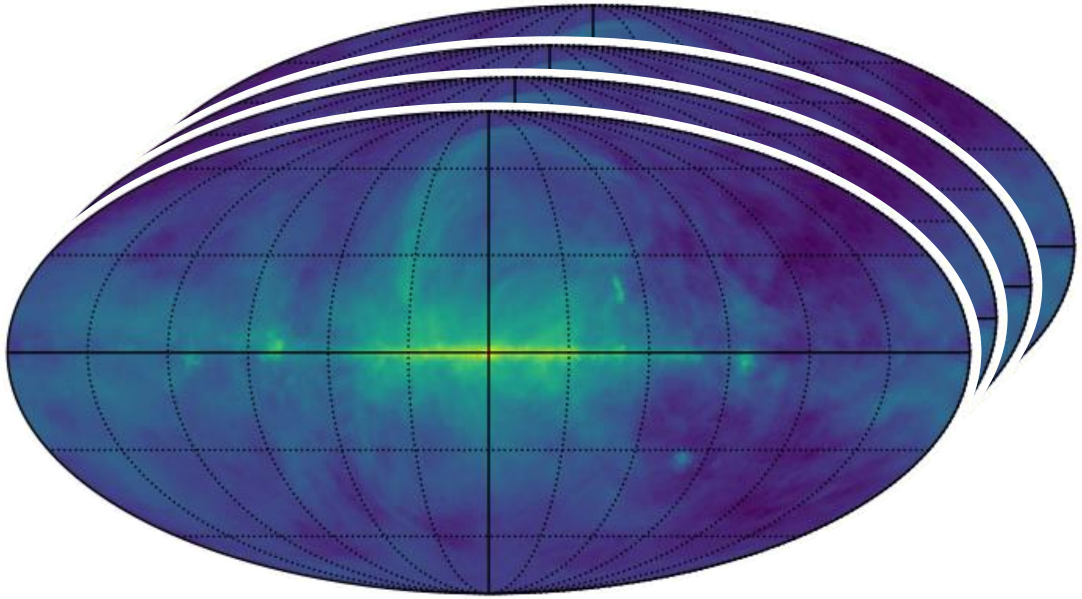
Term	Mean	Std dev	Distribution Type
O	-2.59	0.07	Gaussian
M	0.13	0.1	Truncated Gaussian ($M_{min} = 0$, $M_{max} = 0.2$)

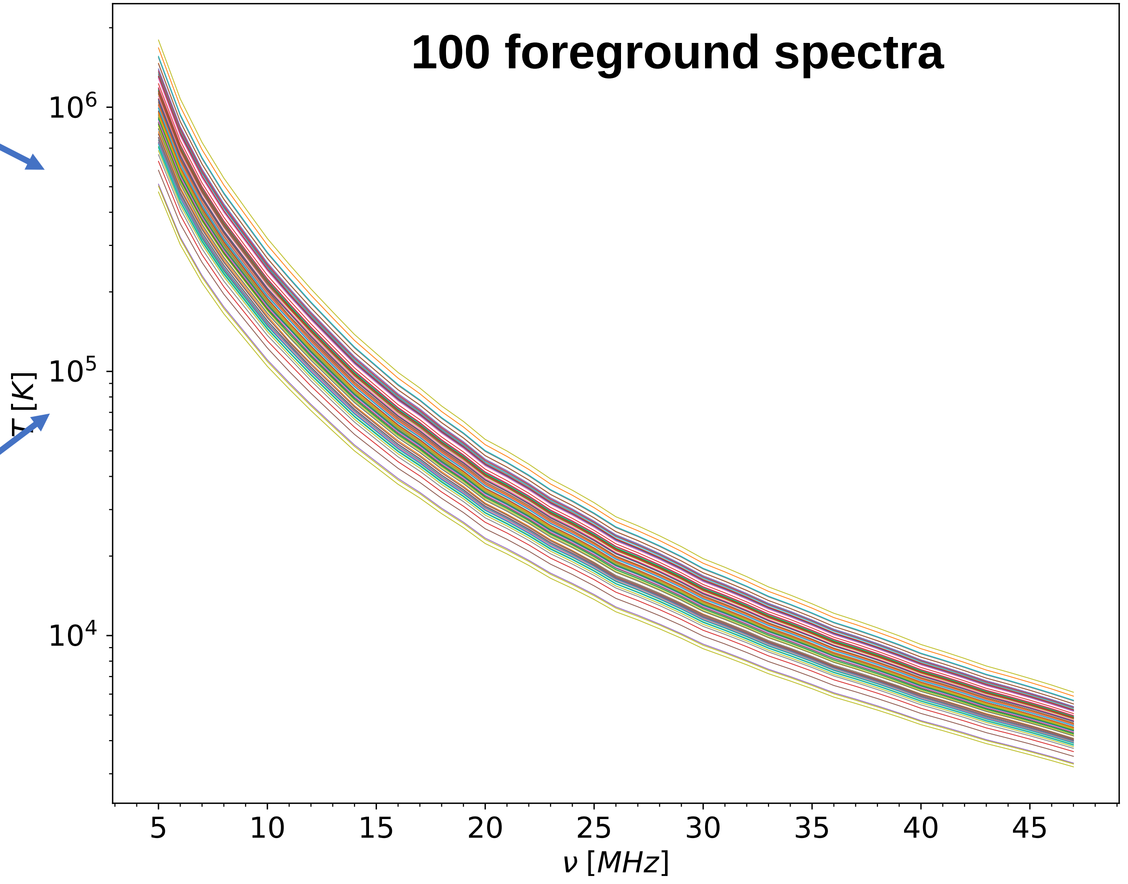
Hibbard JJ et al.,"Modeling the Galactic ForegroundandBeam Chromaticity for Global 21cm Cosmology, "The Astrophysical Journal.2020; 905(2):113

Foreground Training Set: Convolution with LCRT Beam

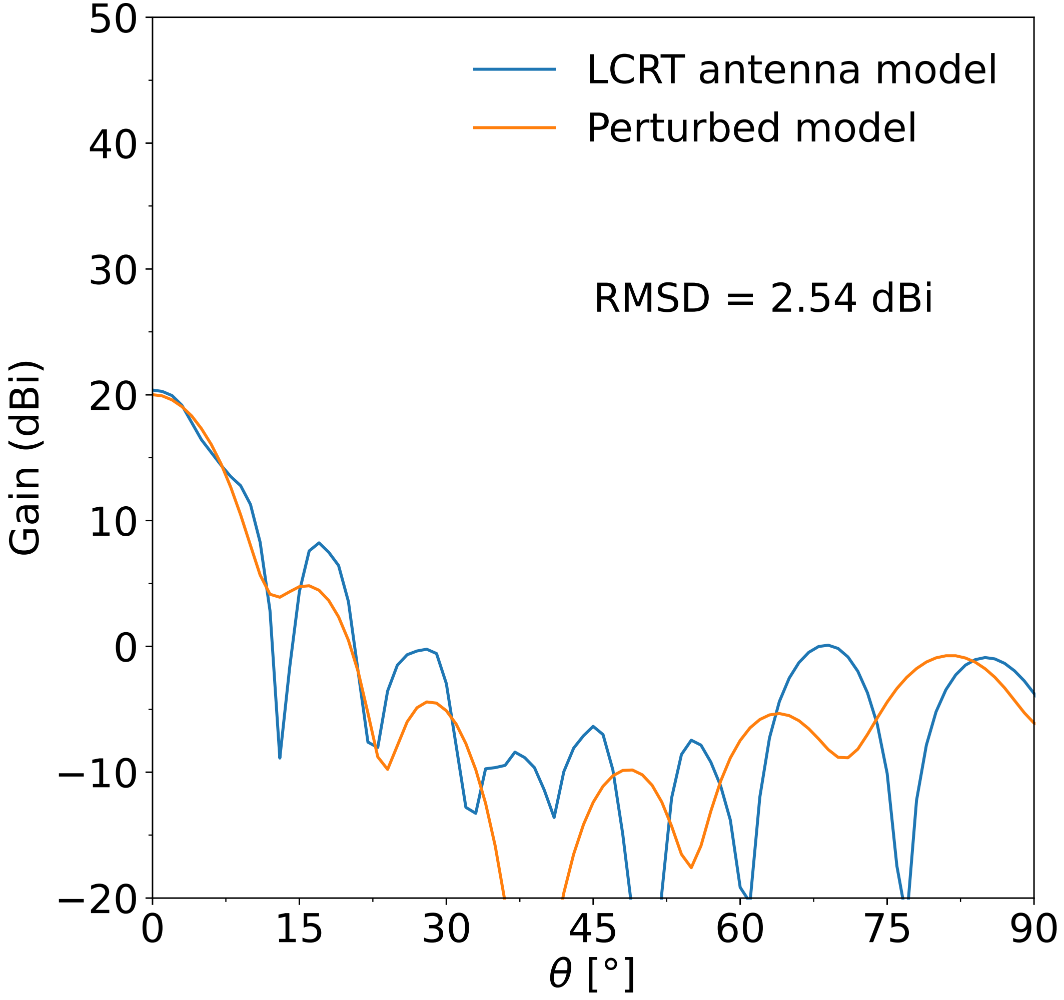


100 different simulated skies





Testing Framework: Perturbed Antenna Model



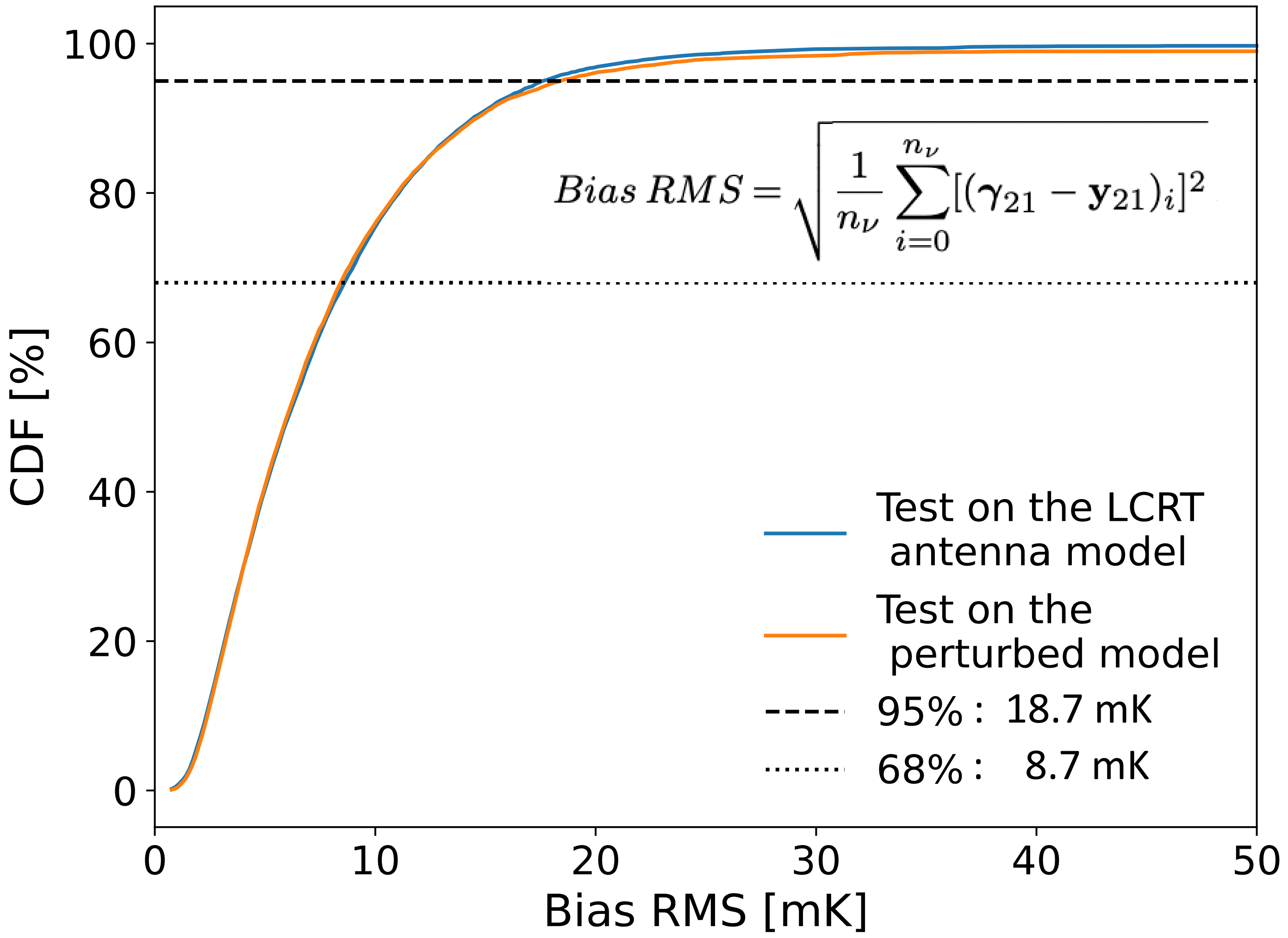
$$\mathbf{y} = \mathbf{y}_{fg} + \mathbf{\Psi}_{21}\mathbf{y}_{21} + \mathbf{n}$$

100
different foregrounds generated from random β and with a perturbed antenna model
(no overlap with training)

100
simulated signals
(no overlap with training)

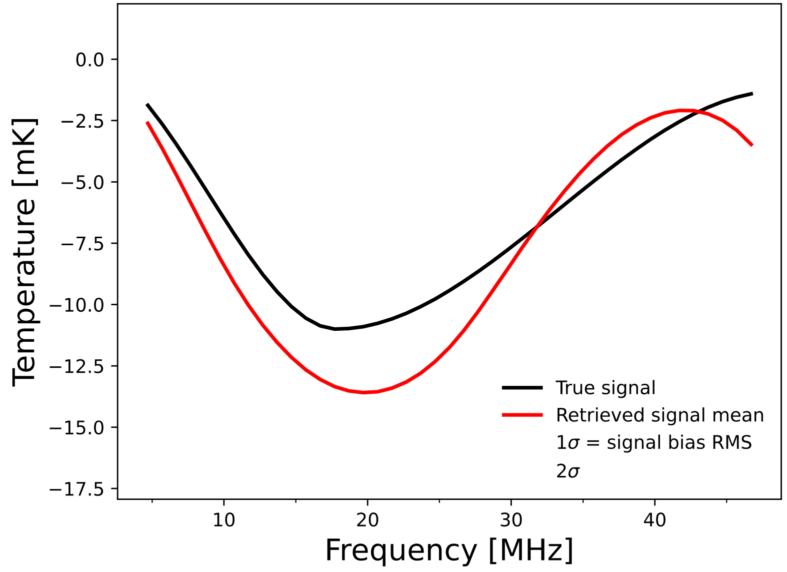
10,000
simulated raw data input

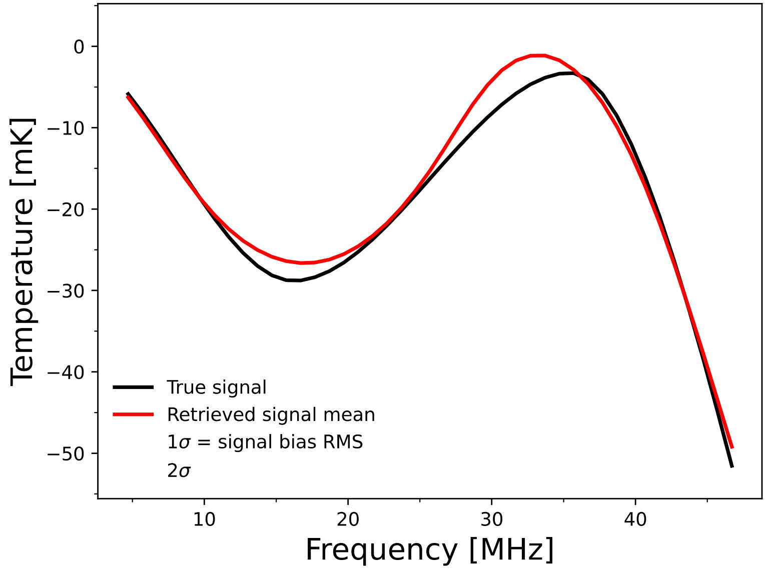
Results



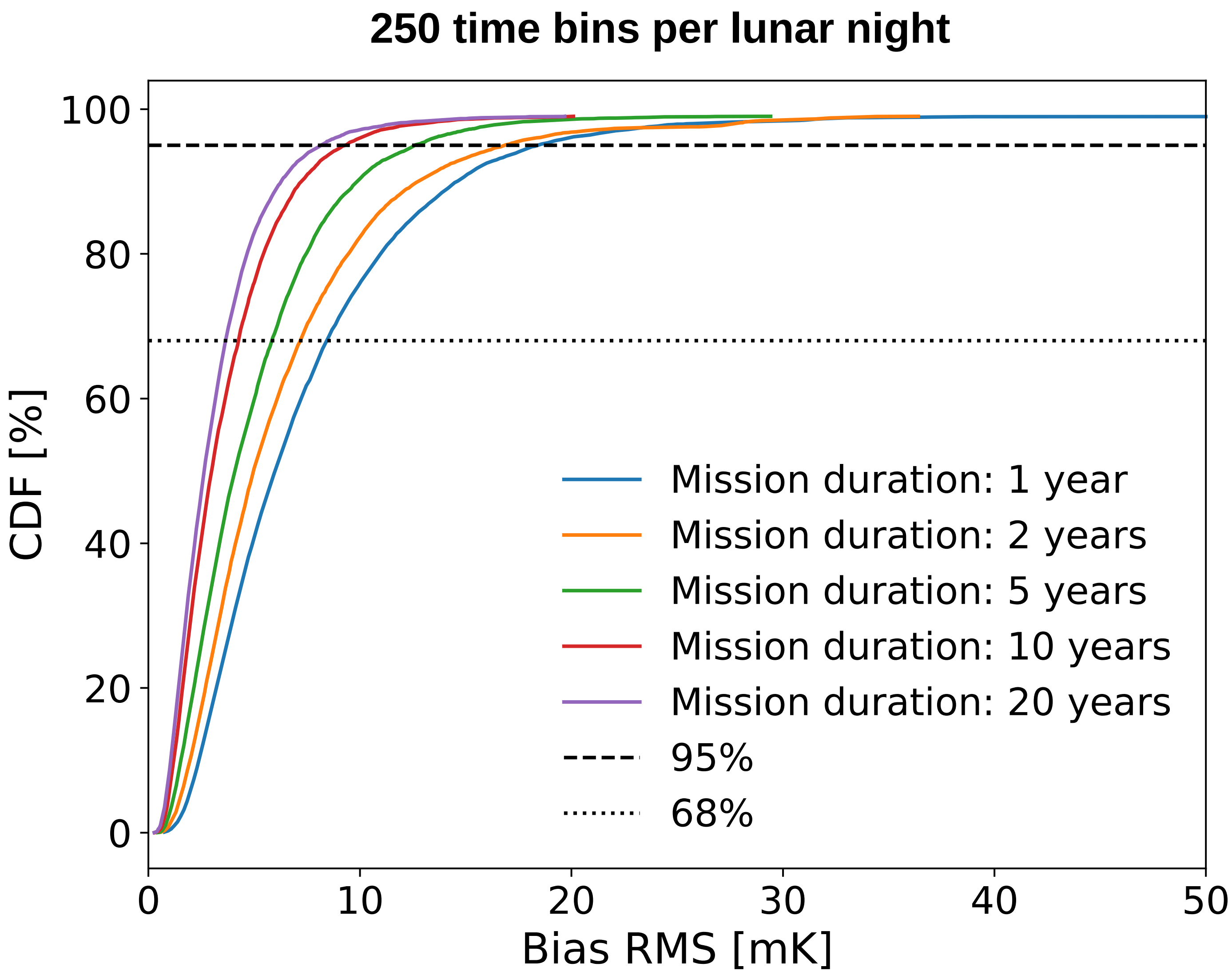
1 year of mission duration
250 time bins per lunar night

Examples of retrieved signal for different input, with confidence intervals



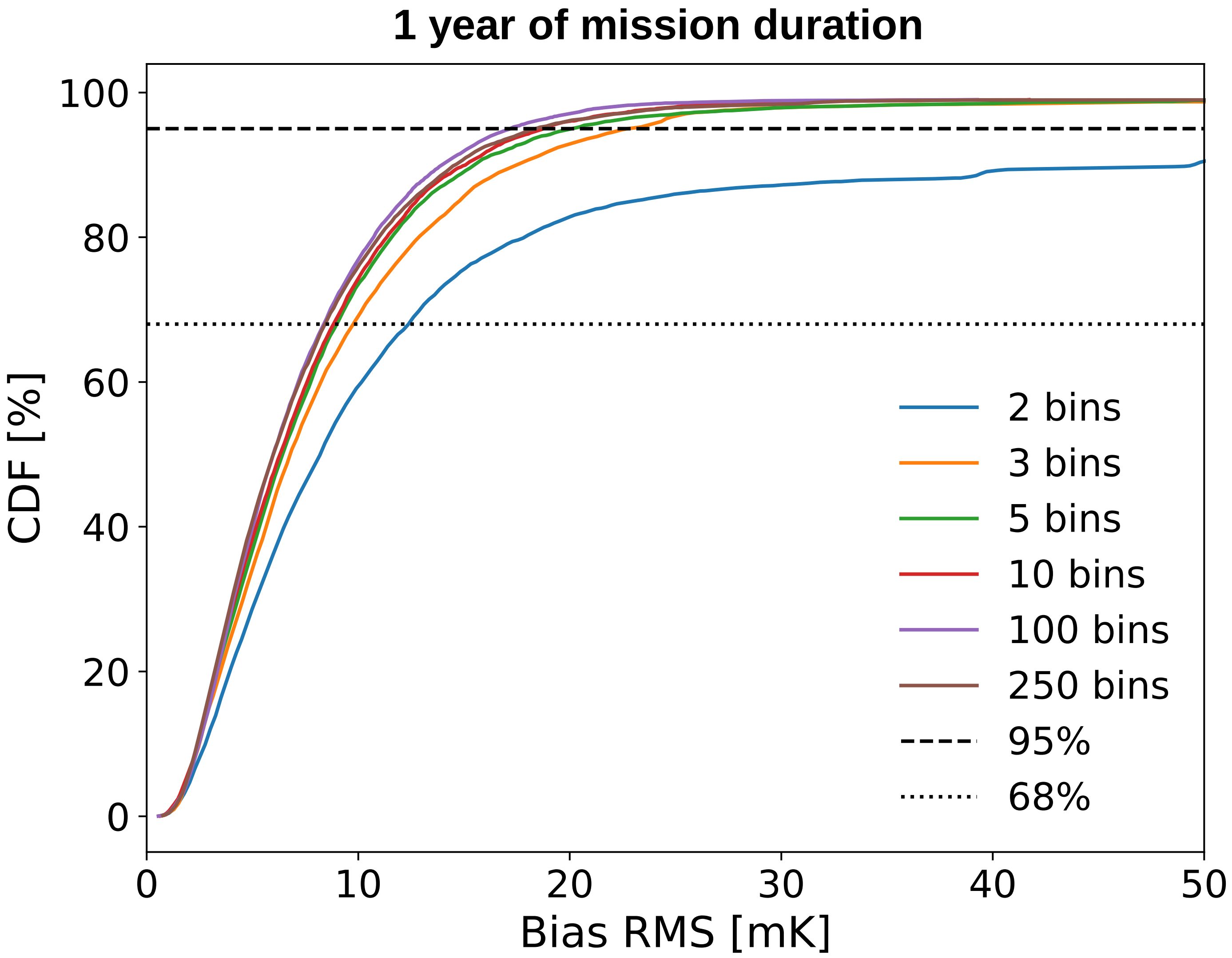


Effect of Mission Duration



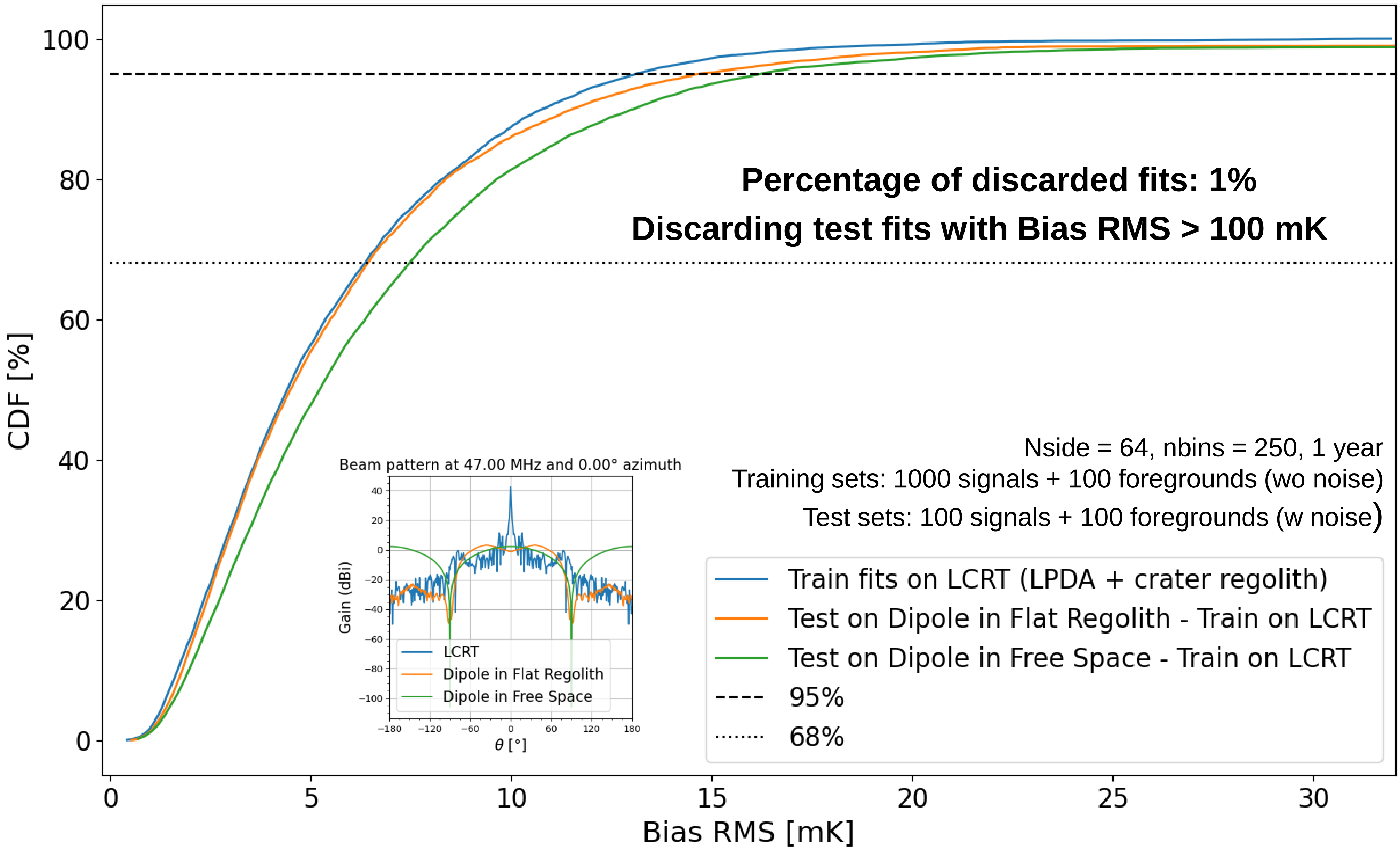
Mission duration (years)	68% (mK)	95% (mK)
1	8.4	18.4
2	7.2	16.8
5	5.9	12.6
10	4.3	9.3
20	3.7	8.2

Effect of Number of Time Bins

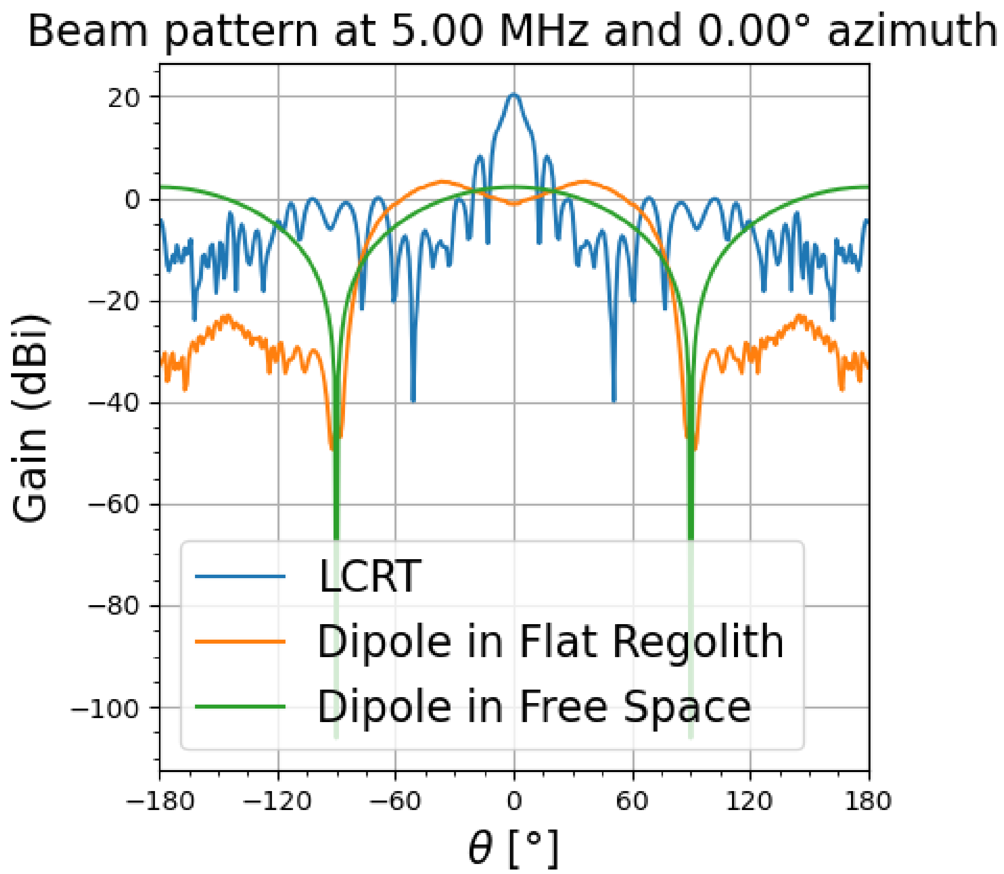


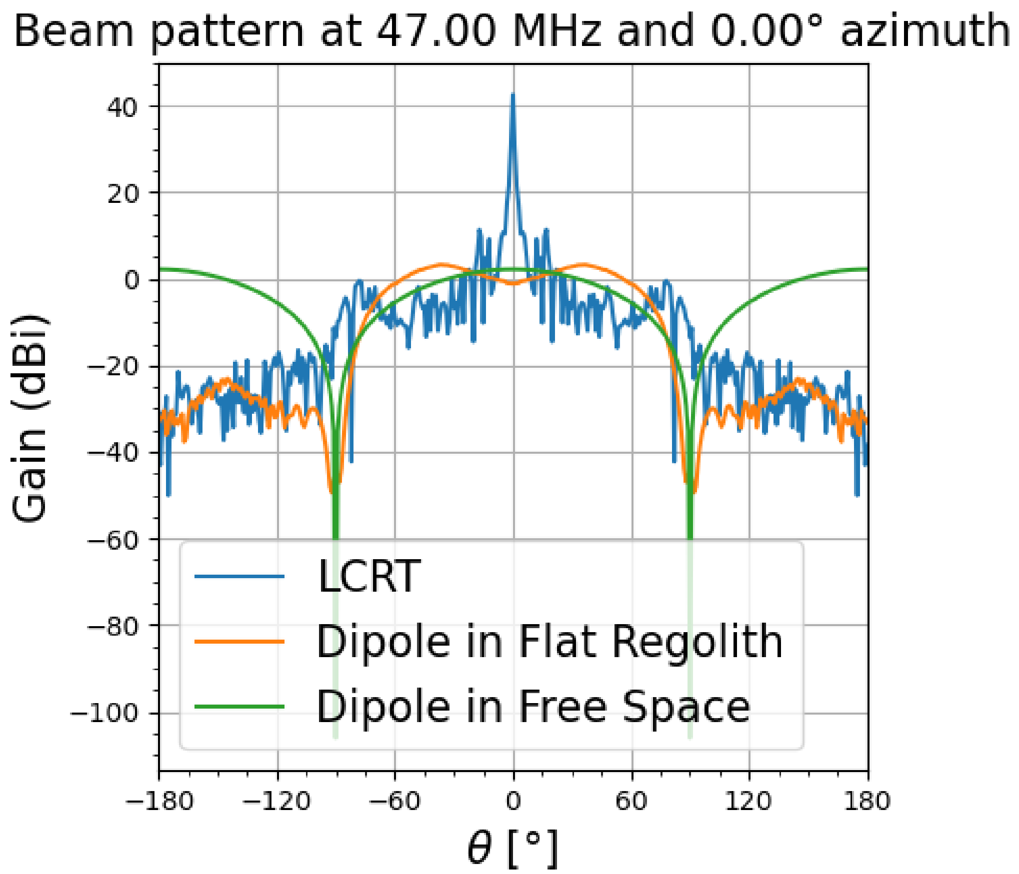
Bins	68% (mK)	95% (mK)
2	12.4	/
3	9.8	22.7
5	9.0	20.1
10	8.8	18.8
100	8.4	17.2
250	8.4	18.4

Train on LCRT Antenna – Test on Dipoles

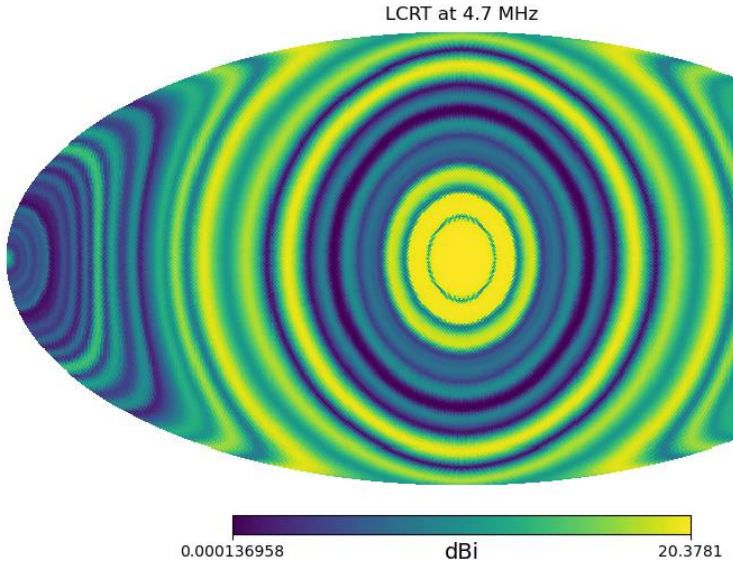


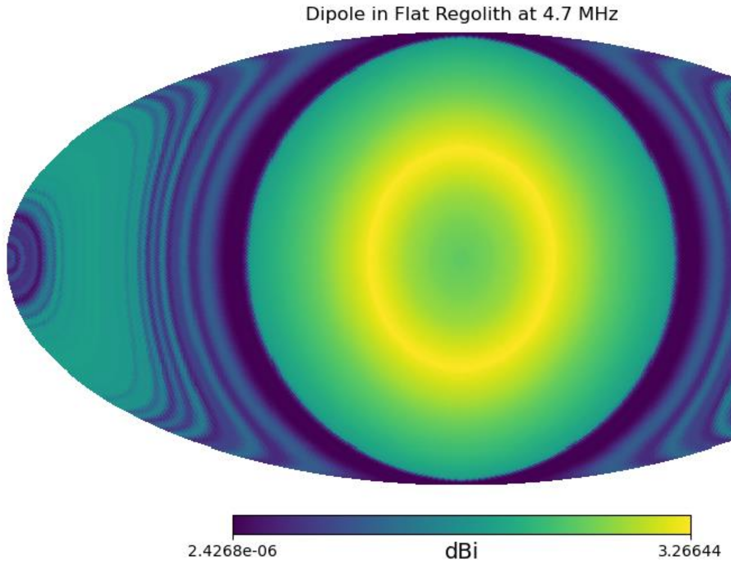
Radiation Patterns

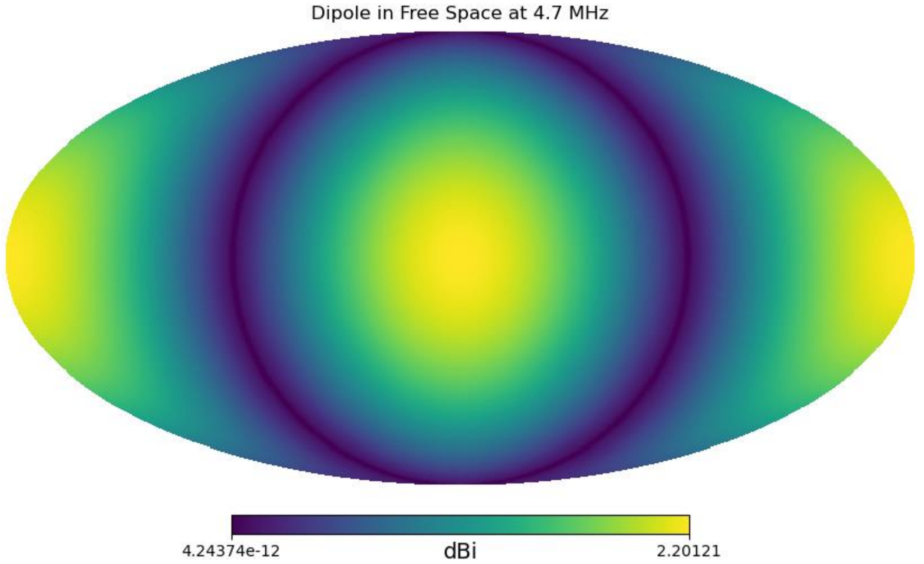




Radiation Patterns – 2D maps at 4.7 MHz







Radiation Patterns – 2D maps at 47 MHz