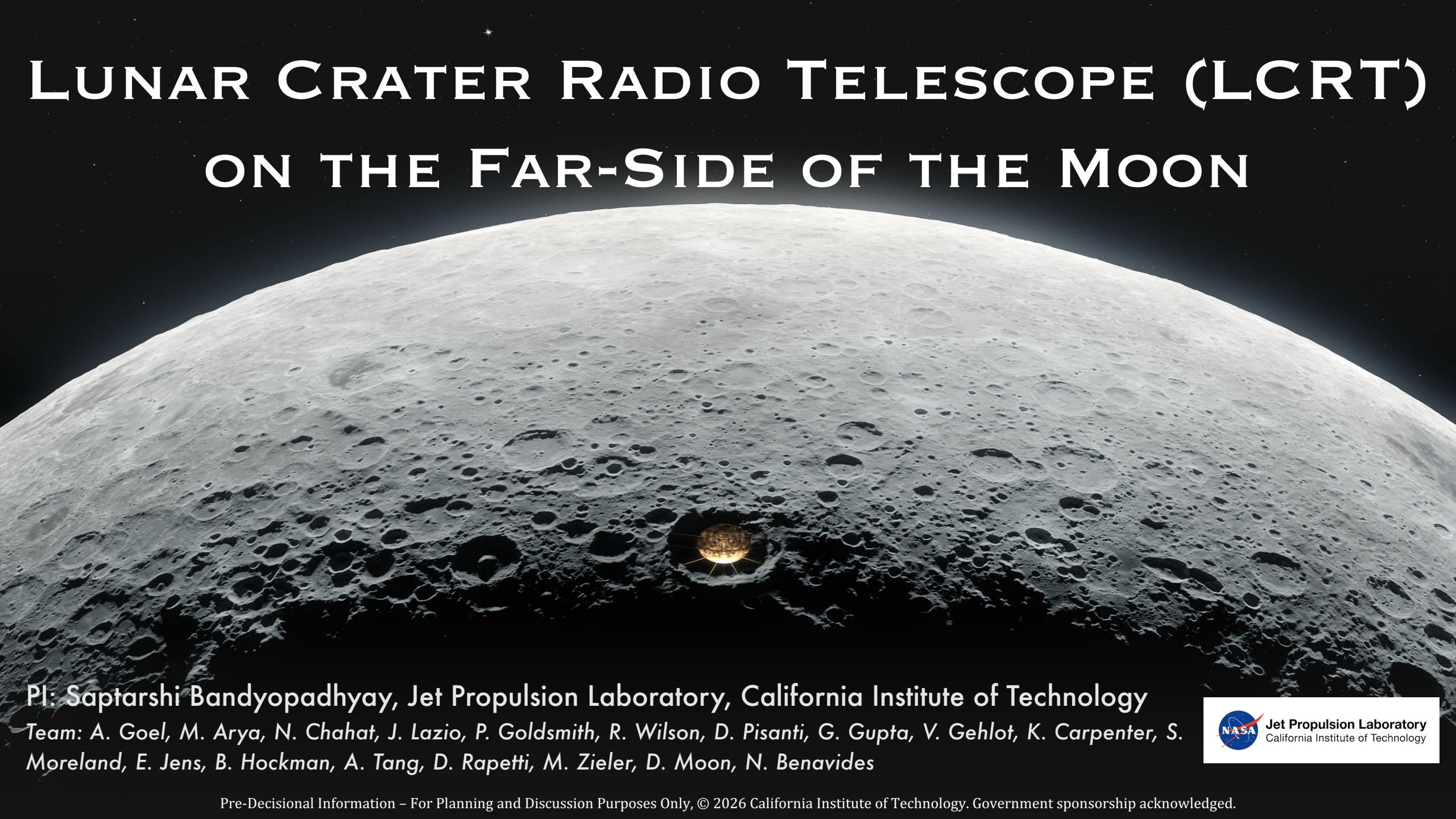
Lunar Crater Radio Telescope (LCRT) on the Far-Side of the Moon



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

Team: A. Goel, M. Arya, N. Chahat, J. Lazio, P. Goldsmith, R. Wilson, D. Pisanti, G. Gupta, V. Gehlot, K. Carpenter, S. Moreland, E. Jens, B. Hockman, A. Tang, D. Rapetti, M. Zieler, D. Moon, N. Benavides

Jet Propulsion Laboratory
California Institute of Technology

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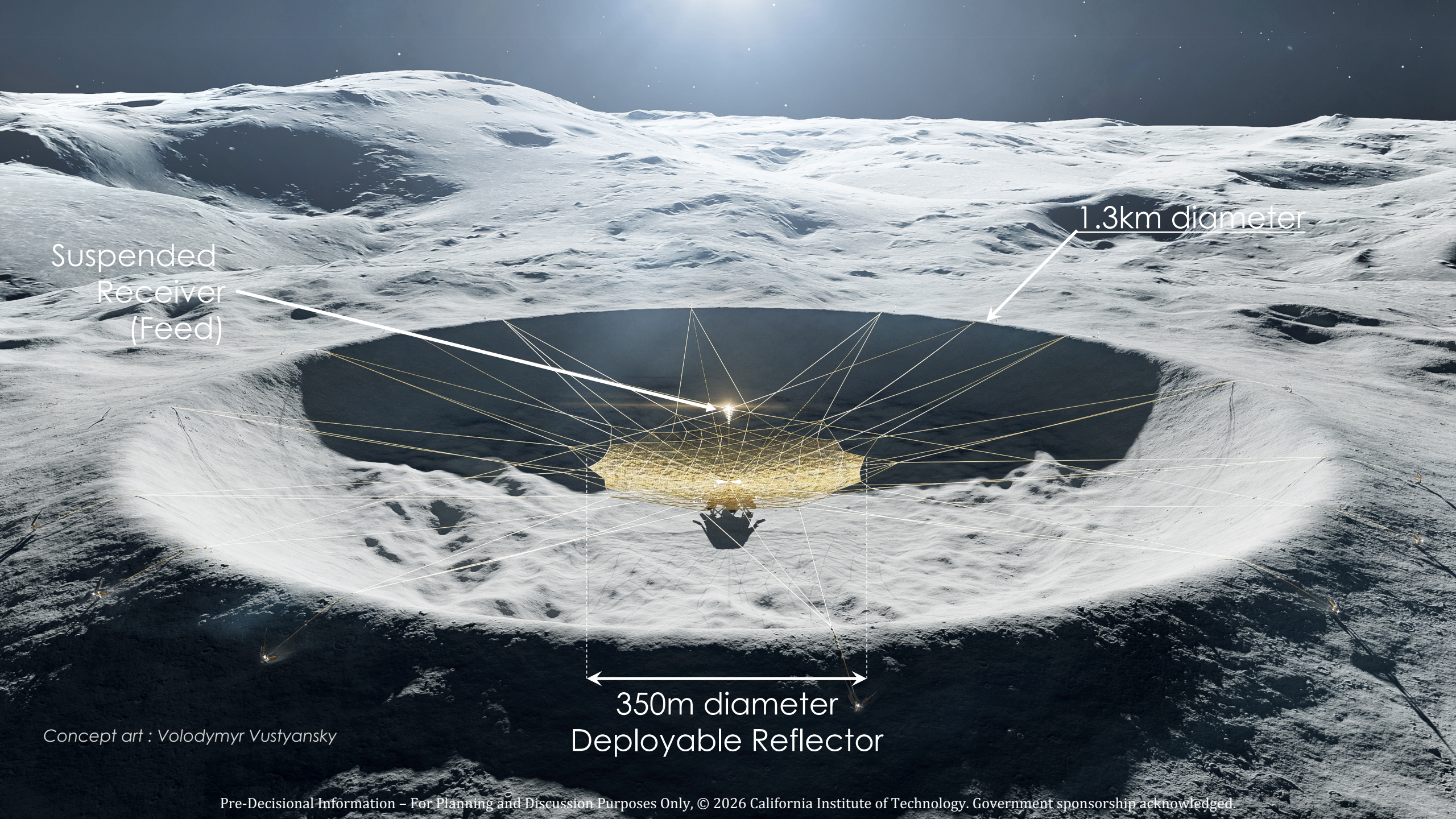

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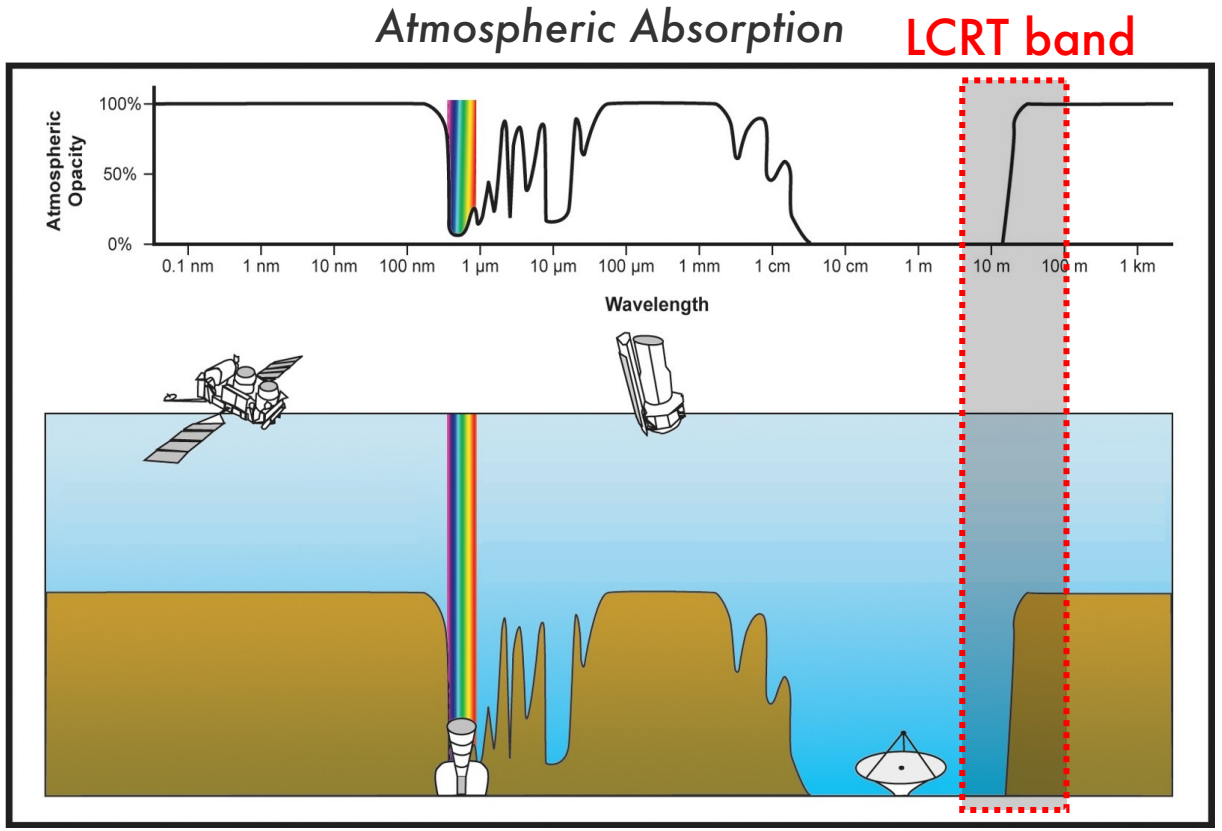
Science Motivation

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



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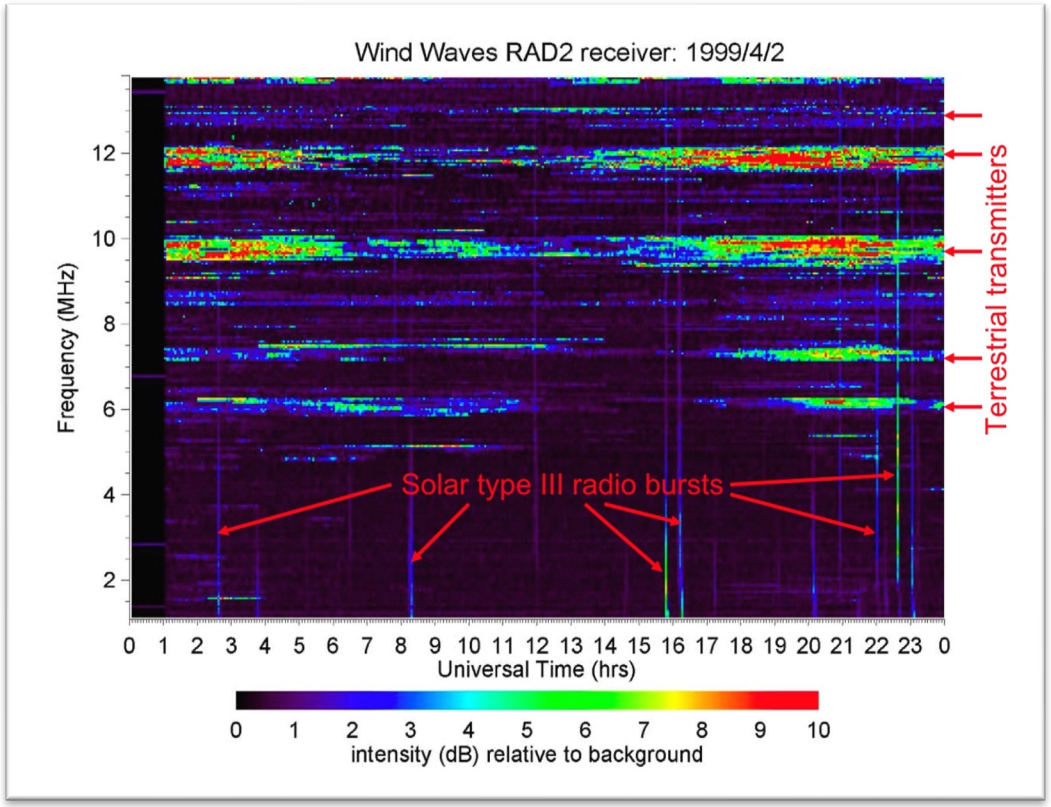
Science Motivation

Challenging Noise Sources :

- Earth
- Sun
- Jupiter + Saturn
- Galactic foreground
- Lunar Regolith and bedrock

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



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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!

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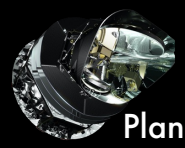
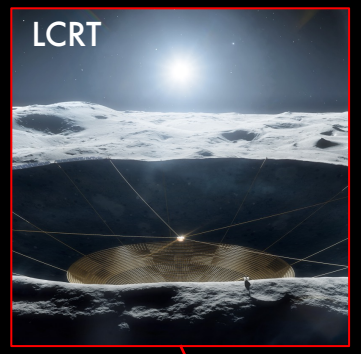
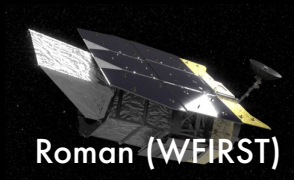
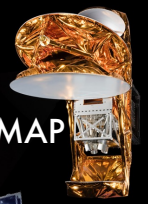
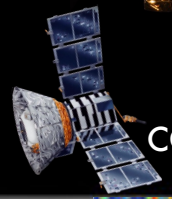
Evolution of the Universe


Planck

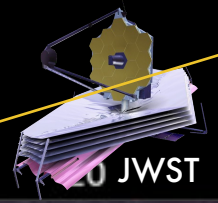


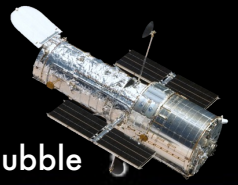

Roman (WFIRST)

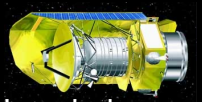

WMAP


COBE

No data on this region of the Universe!


JWST


Hubble


Herschel

1,000 12 Redshift (z) 0

Cosmic Dark Ages
$z > 15–30?$
$t < 100–270$ Myr

Reionization
$z \approx 6–15?$
$t < 1$ Gyr

IGM mostly ionized
$z = 0–6$, $t > 1$ Gyr

Recombination/ CBR emitted
$t \approx 370{,}000$ years
$z \approx 1{,}100$

Rare sources form ionized bubbles

First stars ($z \approx 15–30?$)

Neutral IGM

Ionized bubbles overlap

Modern galaxies form

First galaxies ($z \approx 10–30?$)

Dense, neutral pockets

Present day, $z \approx 0$
$t = 13.75$ Gyr

13.7 LCRT band 13.5 13.4 13.0 Billions of Years Ago 0

Big Bang

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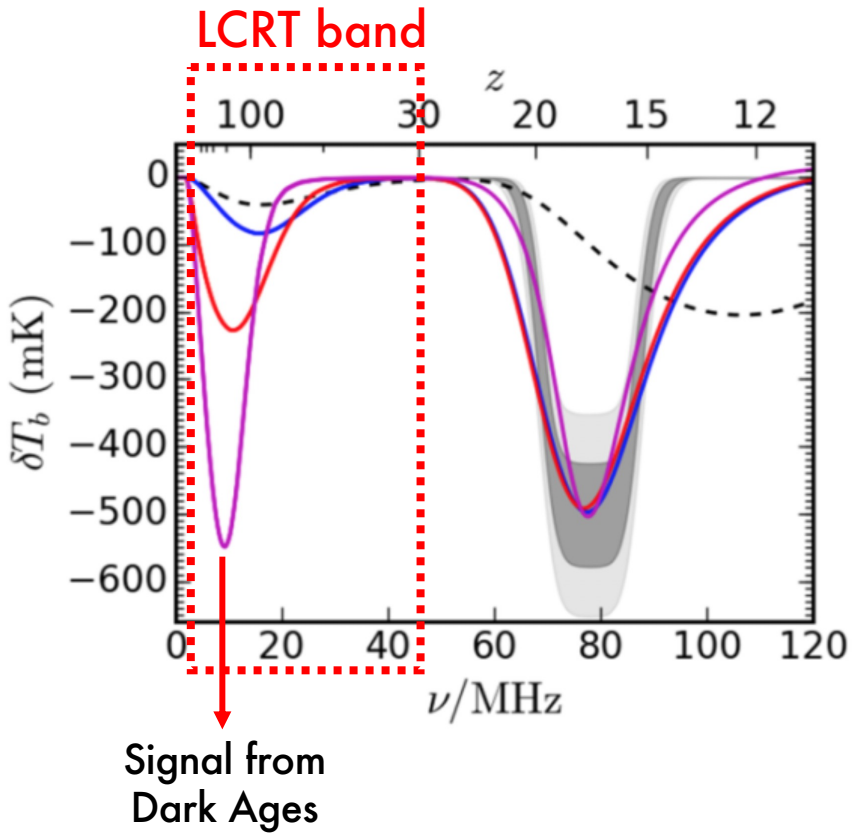
What is this Signal?

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

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.

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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 $< 0.5\Omega/m$ - 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: $20° \pm 20°$N - Longitude: $180° \pm 45°$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** $\approx$ 1 year [Bandyopadhyay et al., 2021, Rapetti et al., 2020]

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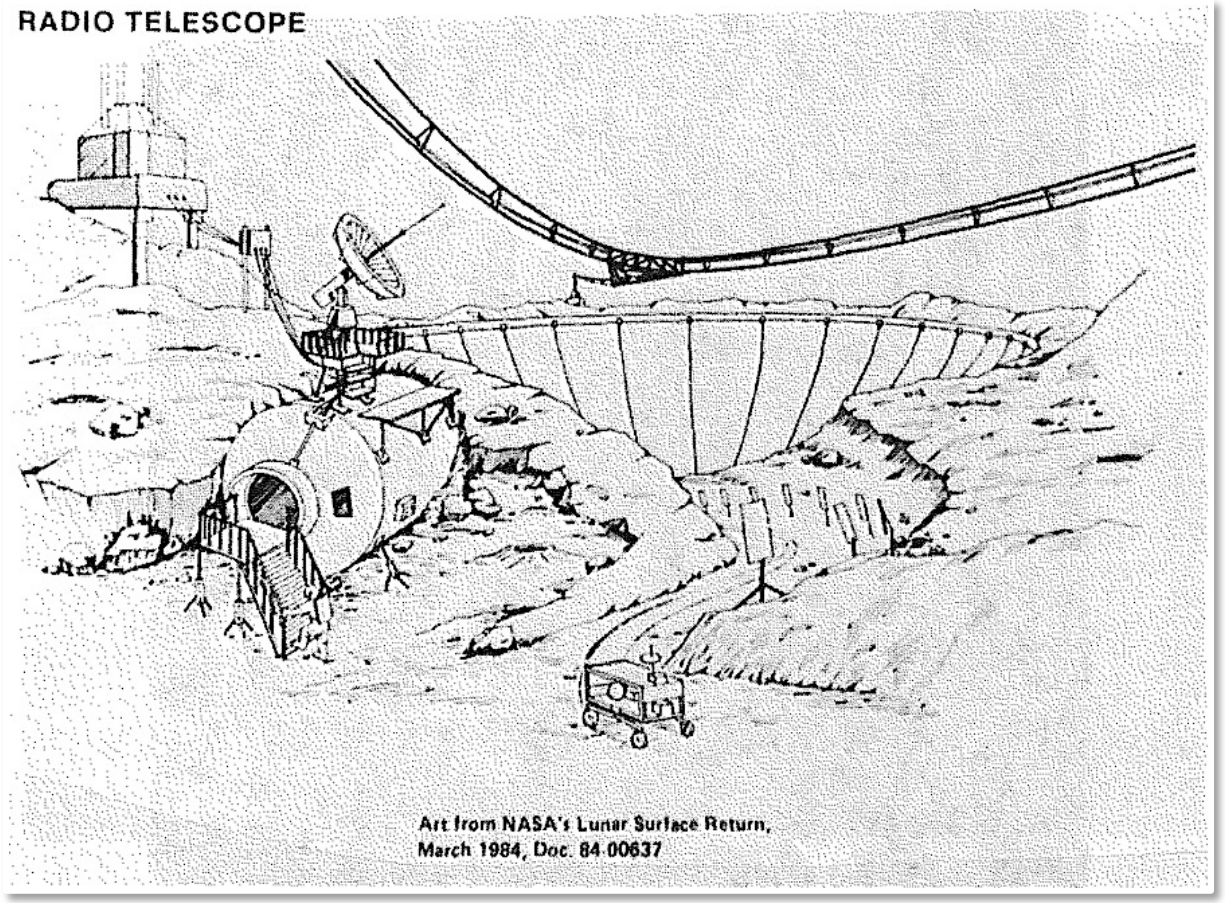
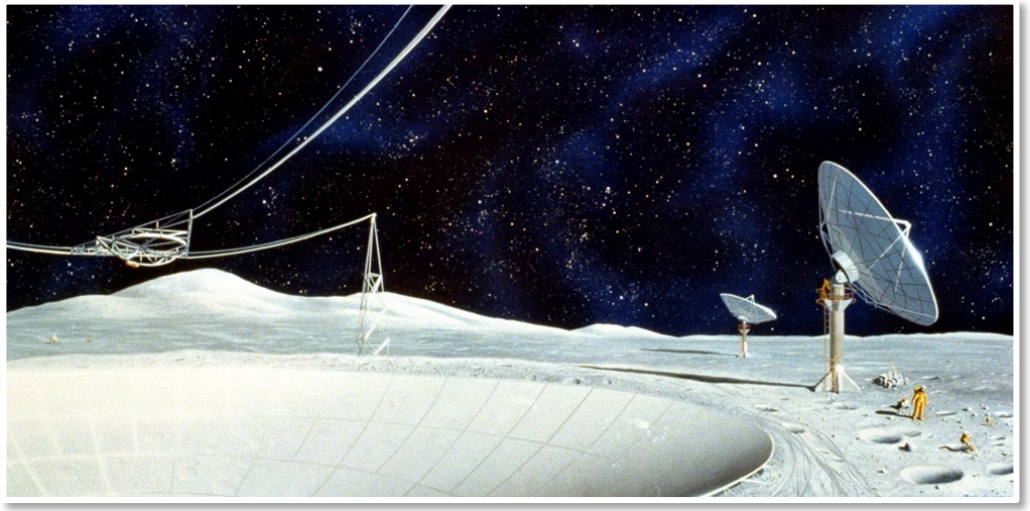
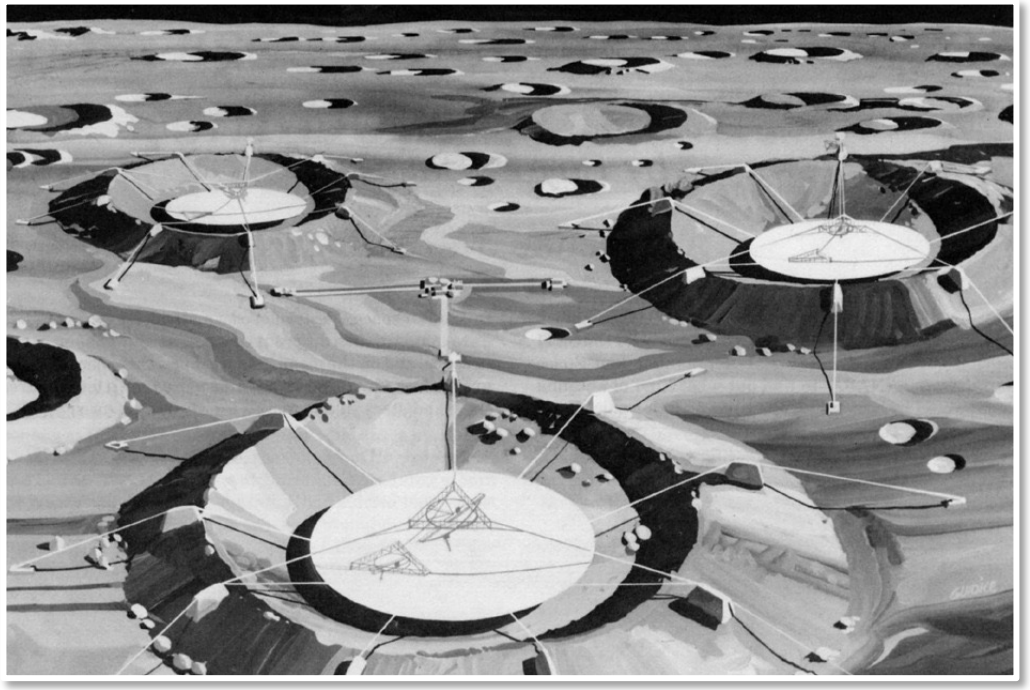
Lunar Arecibo-type Concept







[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.

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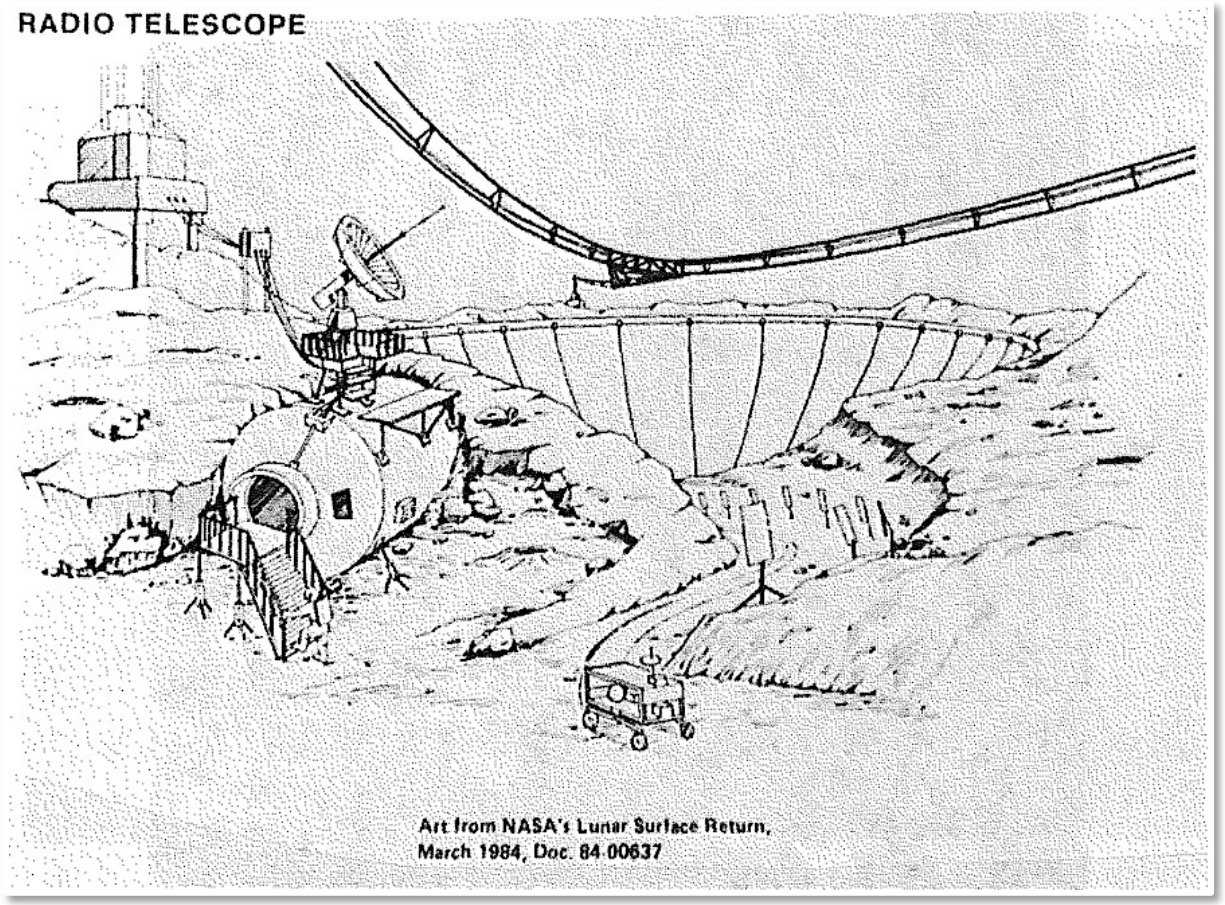
Lunar Arecibo-type Concept



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.

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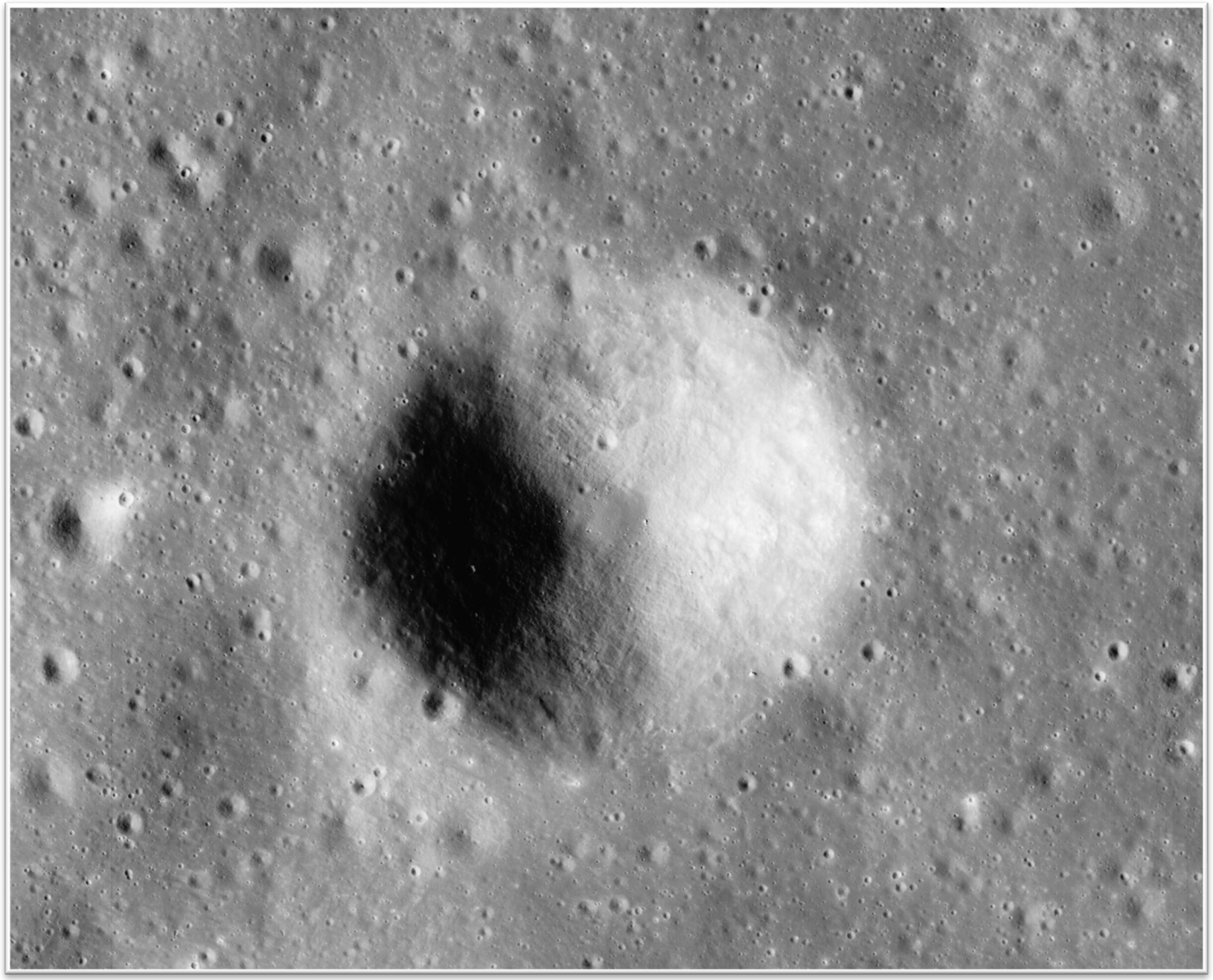
Selected Lunar Crater

Selected Crater

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



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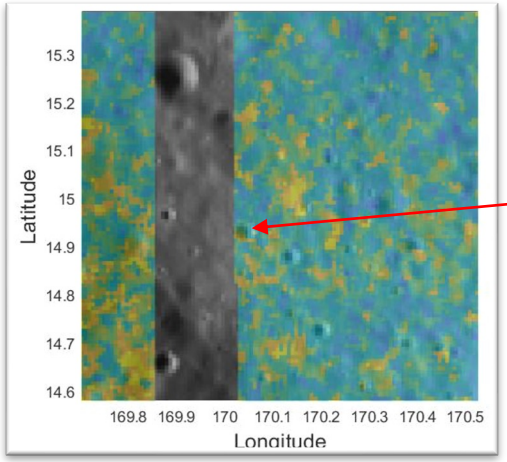
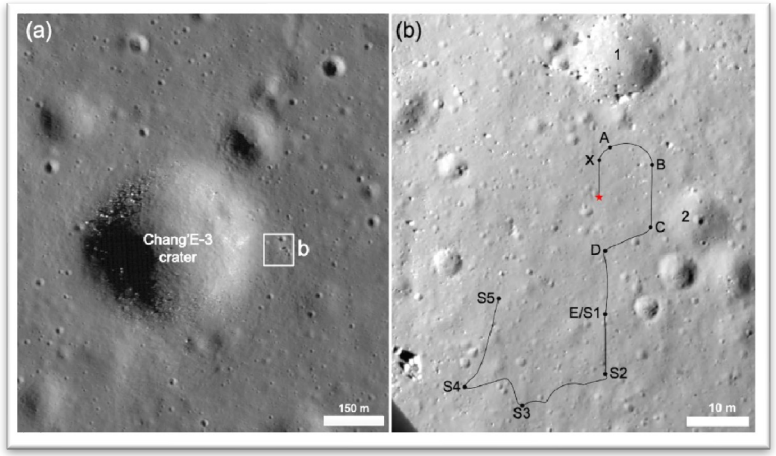
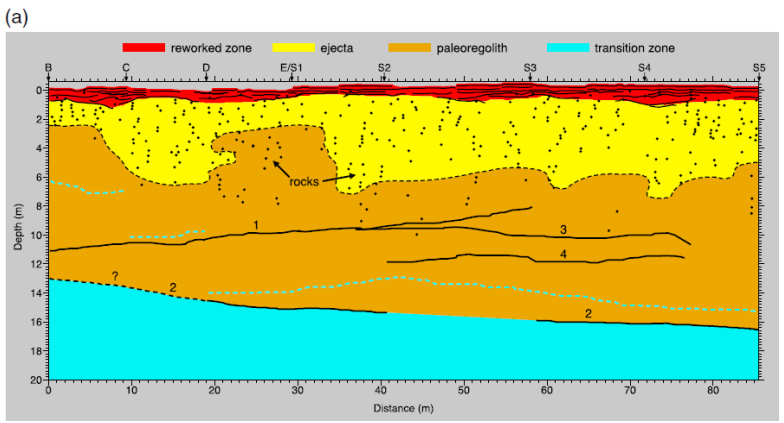
Subsurface Properties

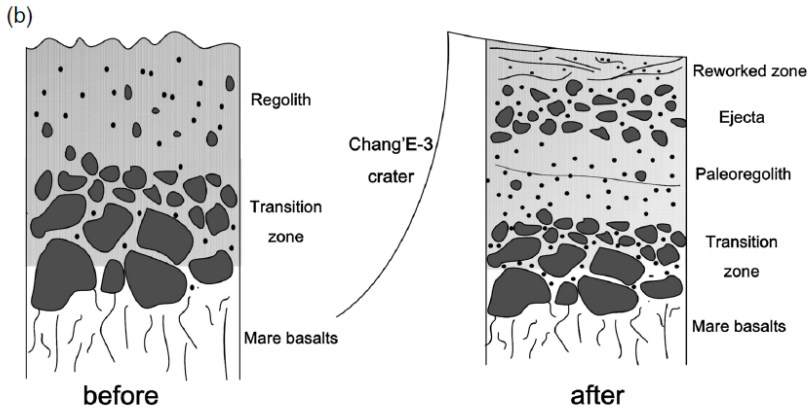
- Circular Polarization Ratio (CPR) from Mini-RF instrument on LRO Spacecraft
- Interpretation from Chang'E 3 Lunar Penetrating Radar data (500 MHz)





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.

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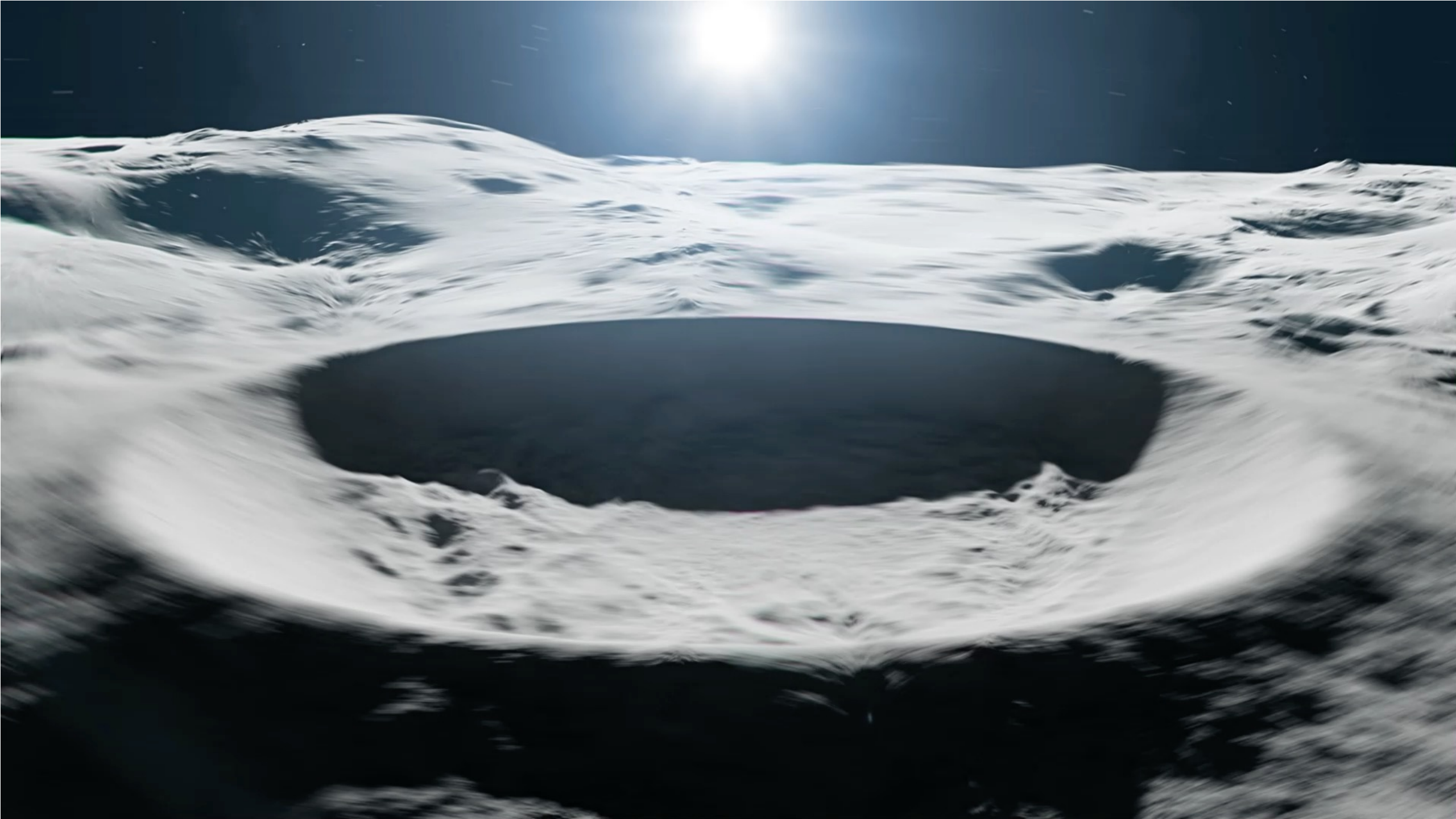
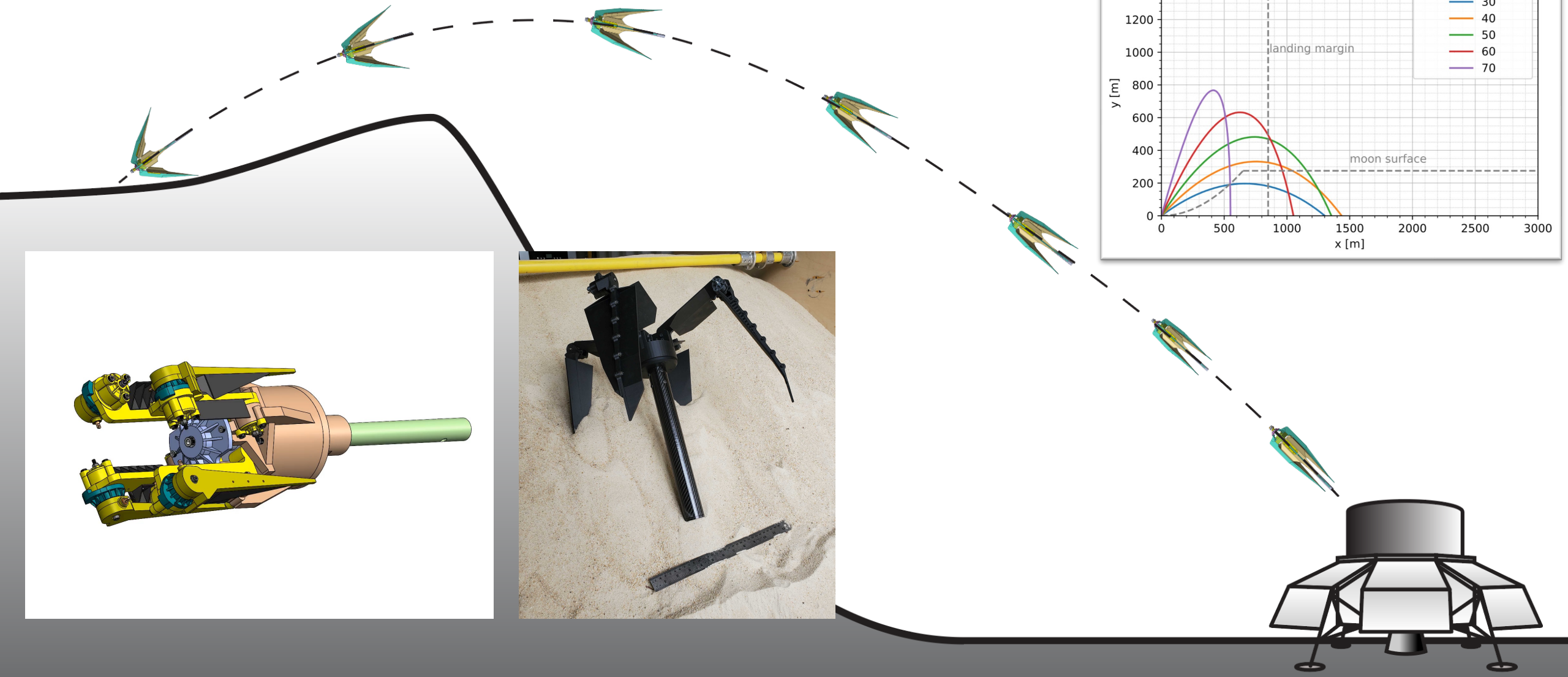


ConOps Step 2: Fire Anchors



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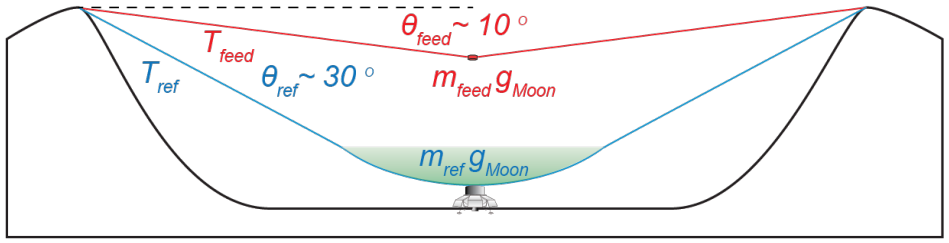
Testing of Plow Anchors



$T_{ref} = 321$ N, $T_{feed} = 317$ 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.

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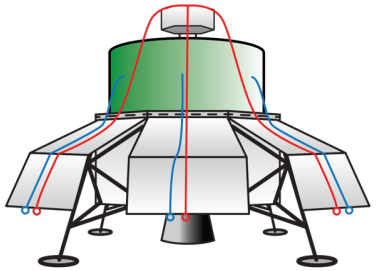
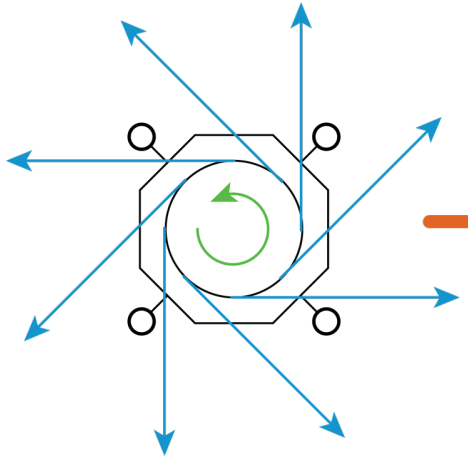
ConOps Step 5: Deploy Reflector

Rotating Disk with embedded antenna
(blue deployment wires)

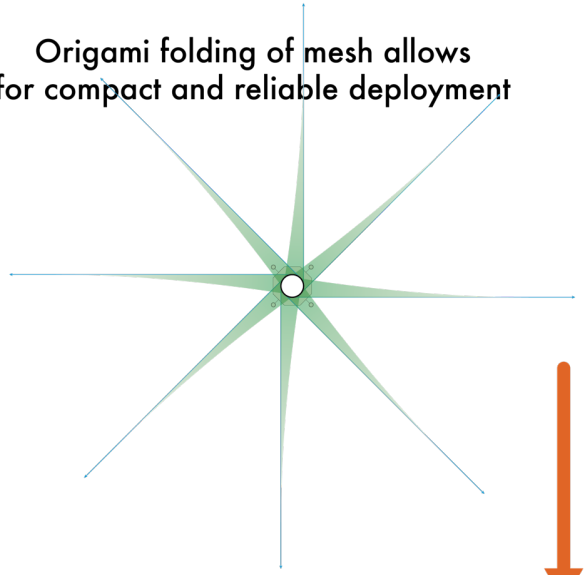


Red Wire for receiver deploy first
(not as complex simple lift)

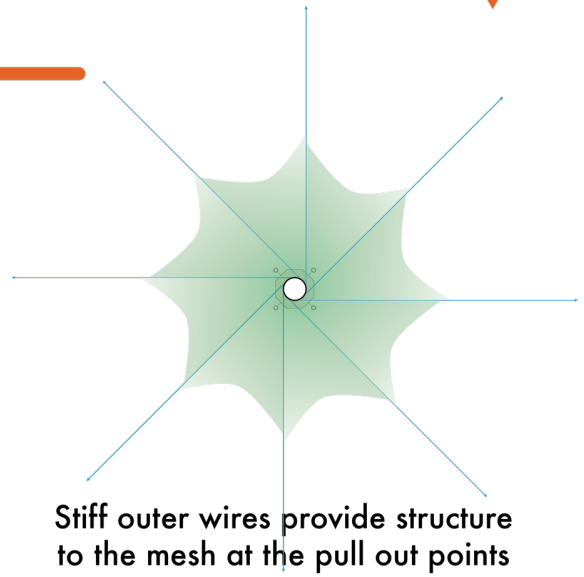


Pulled guide wire spins the
disc, releasing constraints

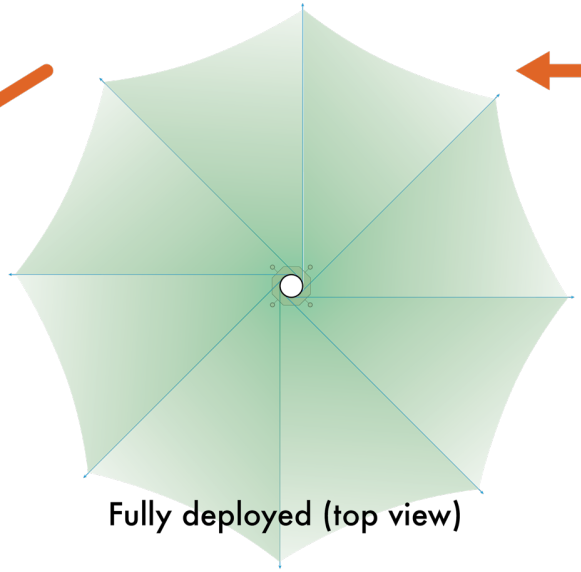
Origami folding of mesh allows
for compact and reliable deployment



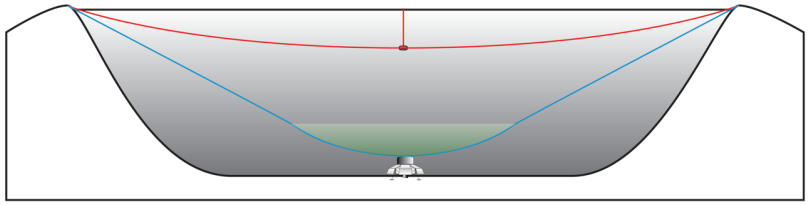
Height of stack depends
of number of folds
h = 2πr / folds



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

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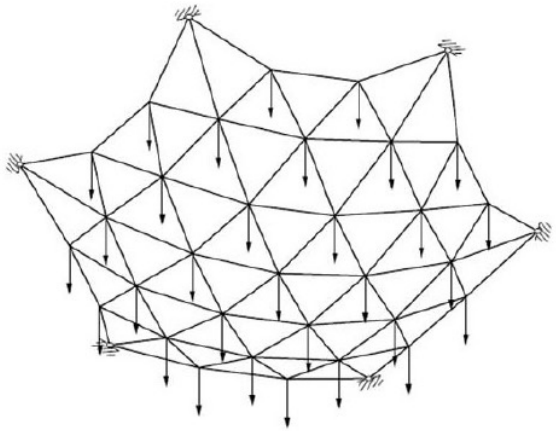
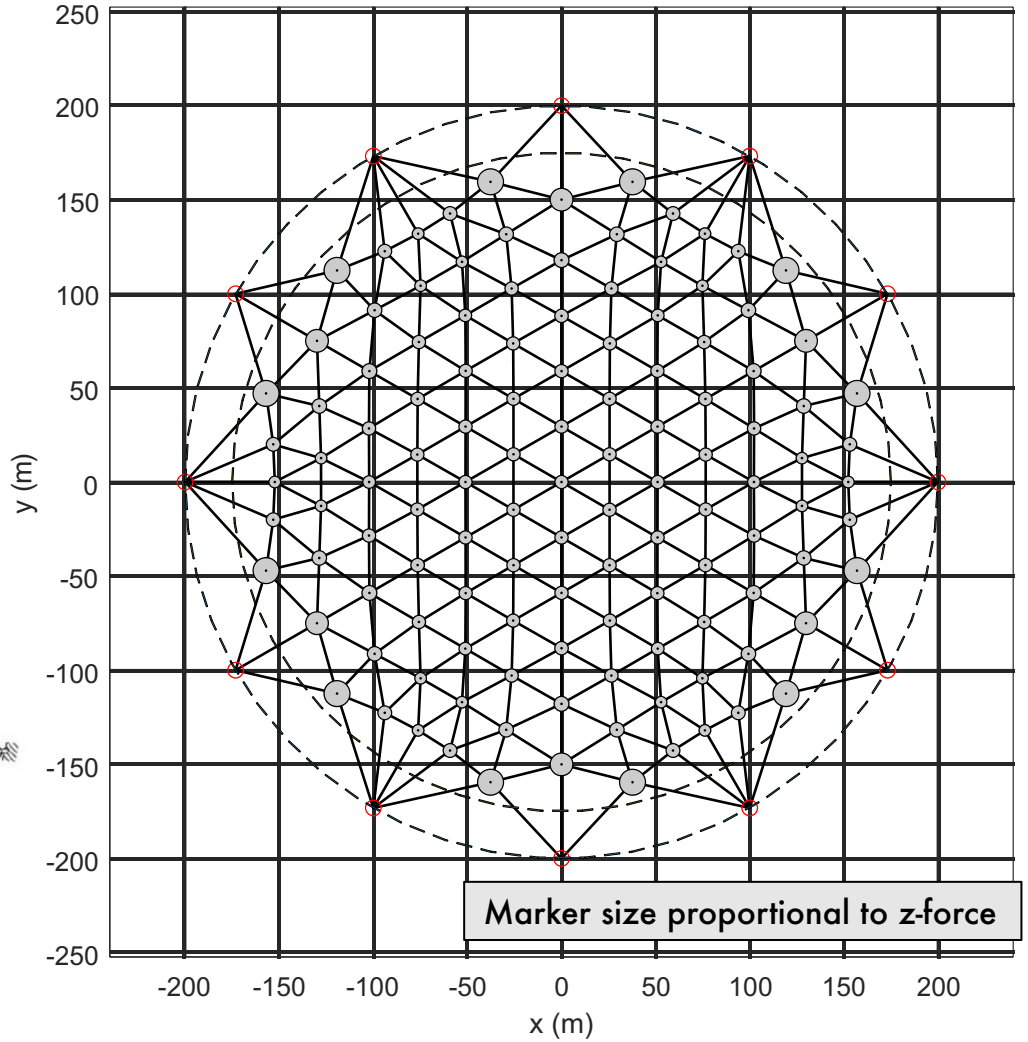
Design of the Reflector

- 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.

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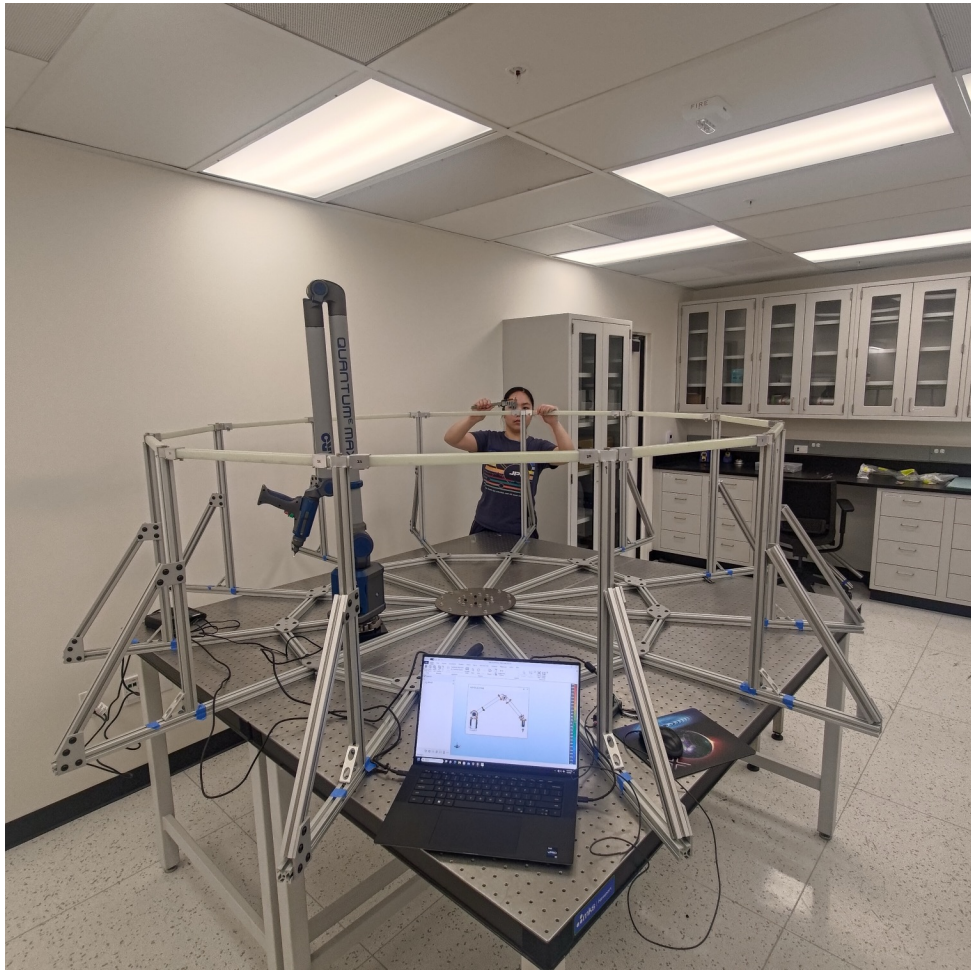
Subscale Reflector Prototype

1/200 scale (2 meter) reflector prototype in crater for RF testing:



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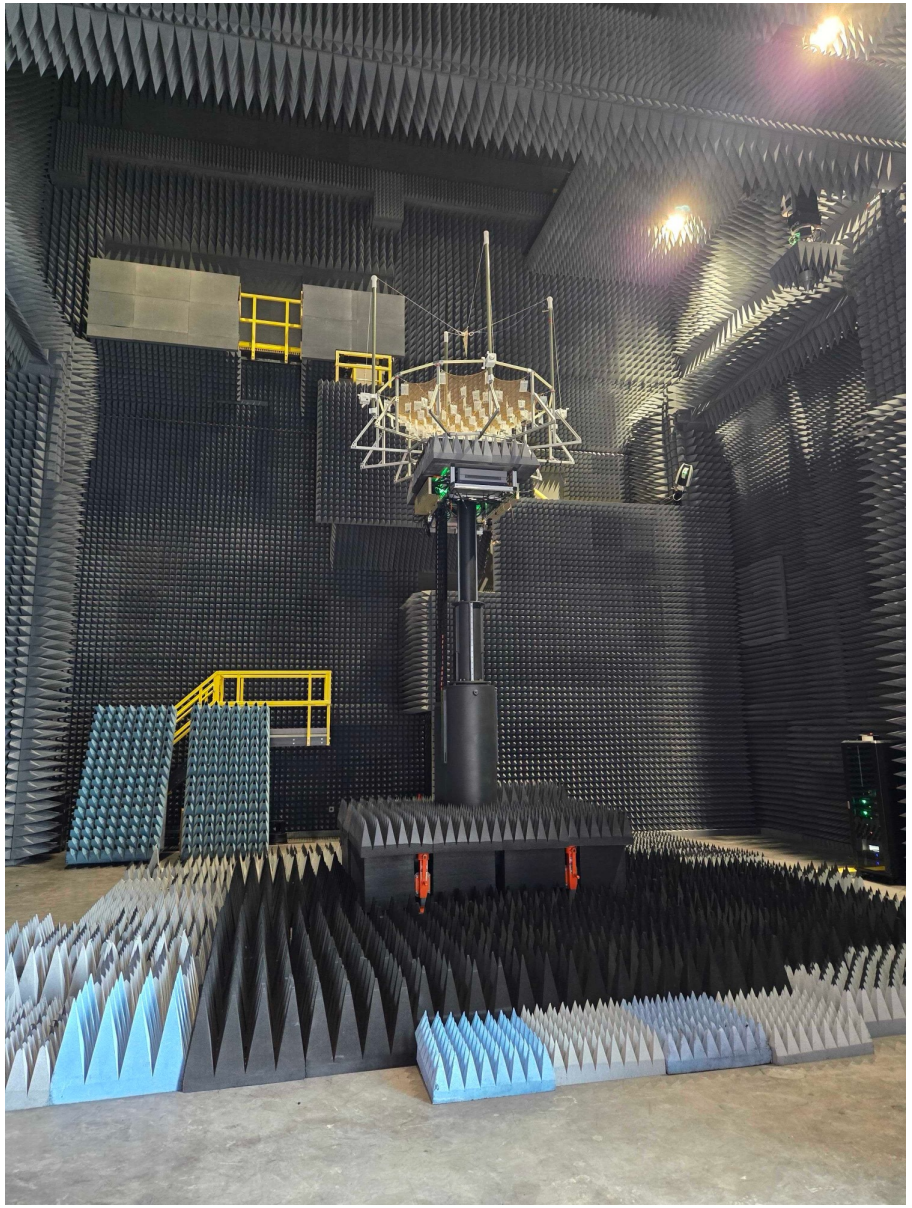
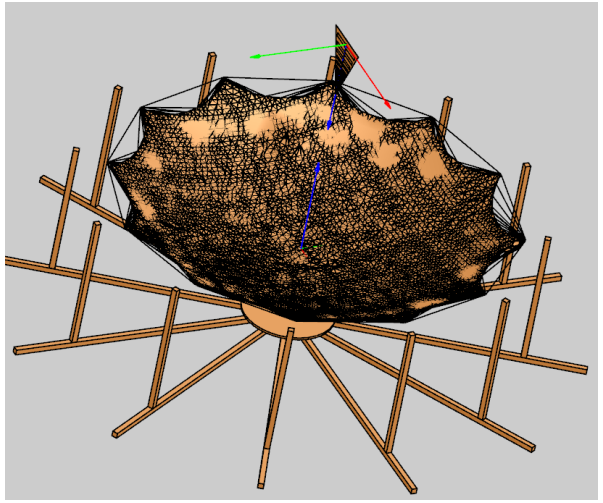
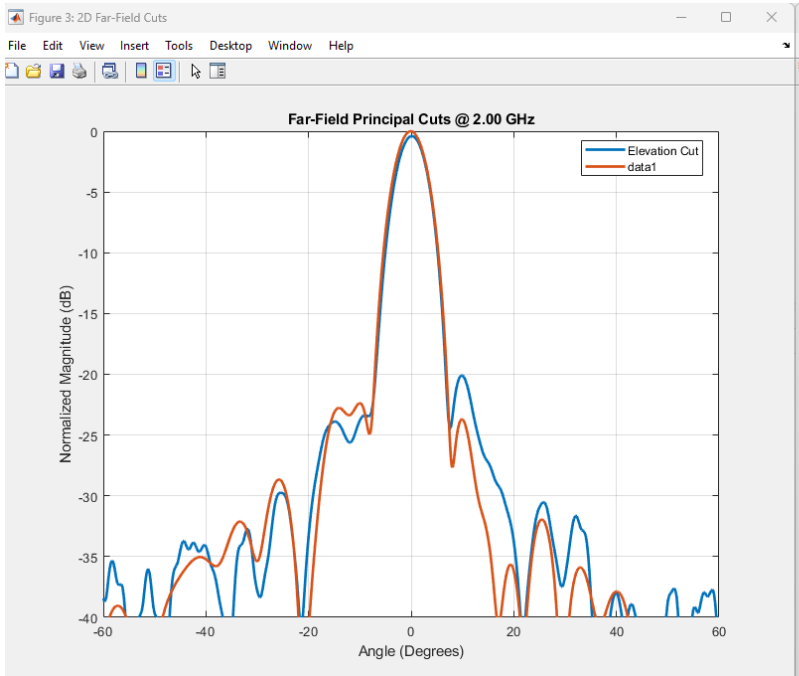
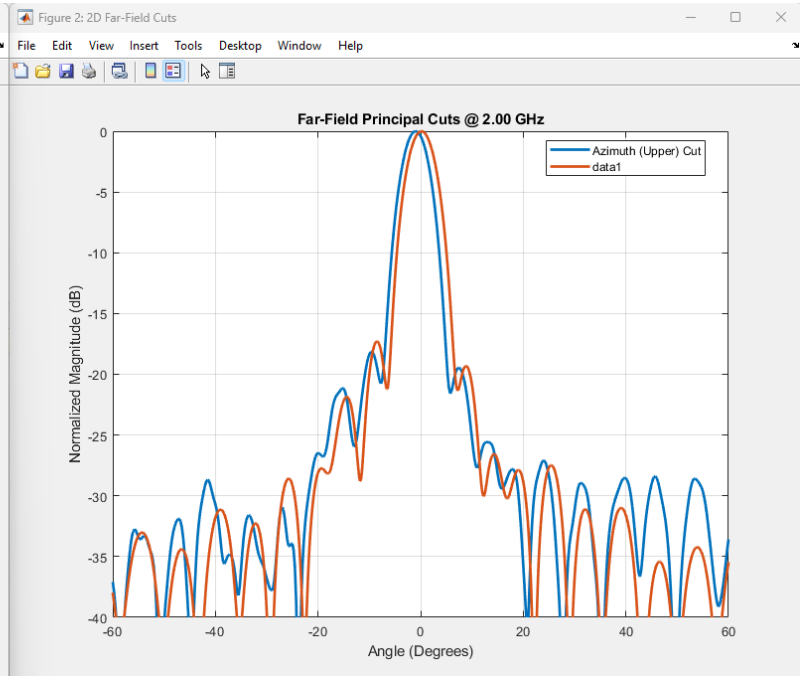
RF testing at NASA Glenn





Simulated vs Real RF Data





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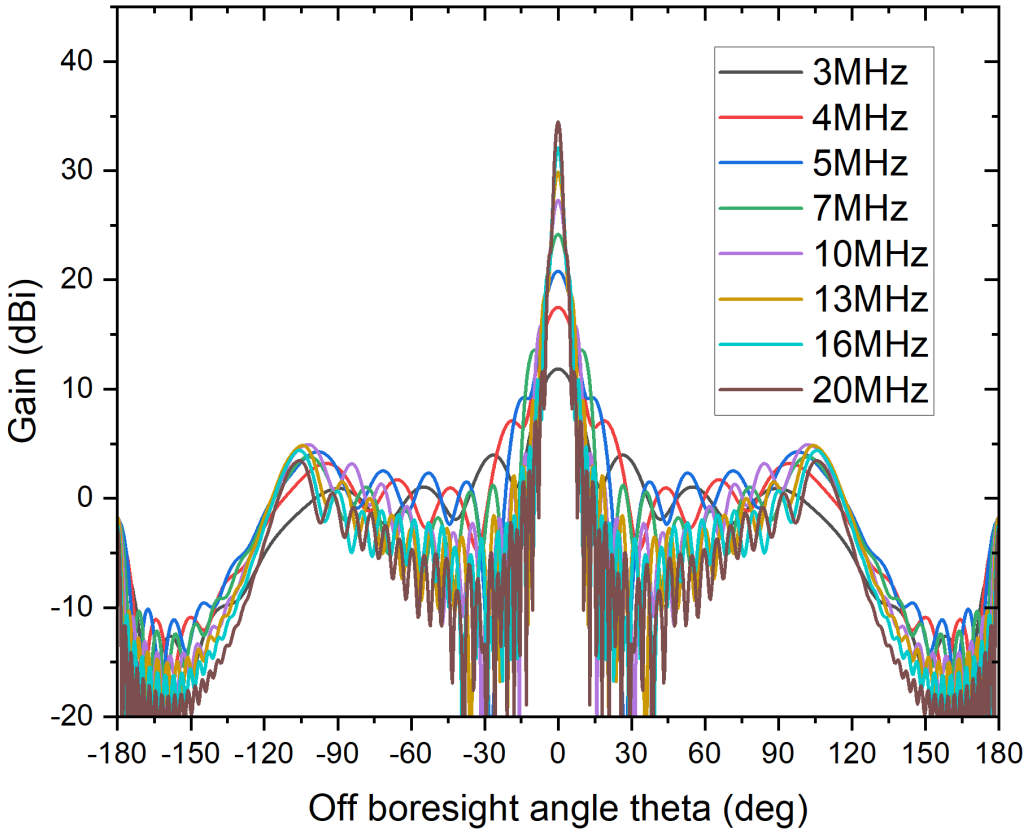
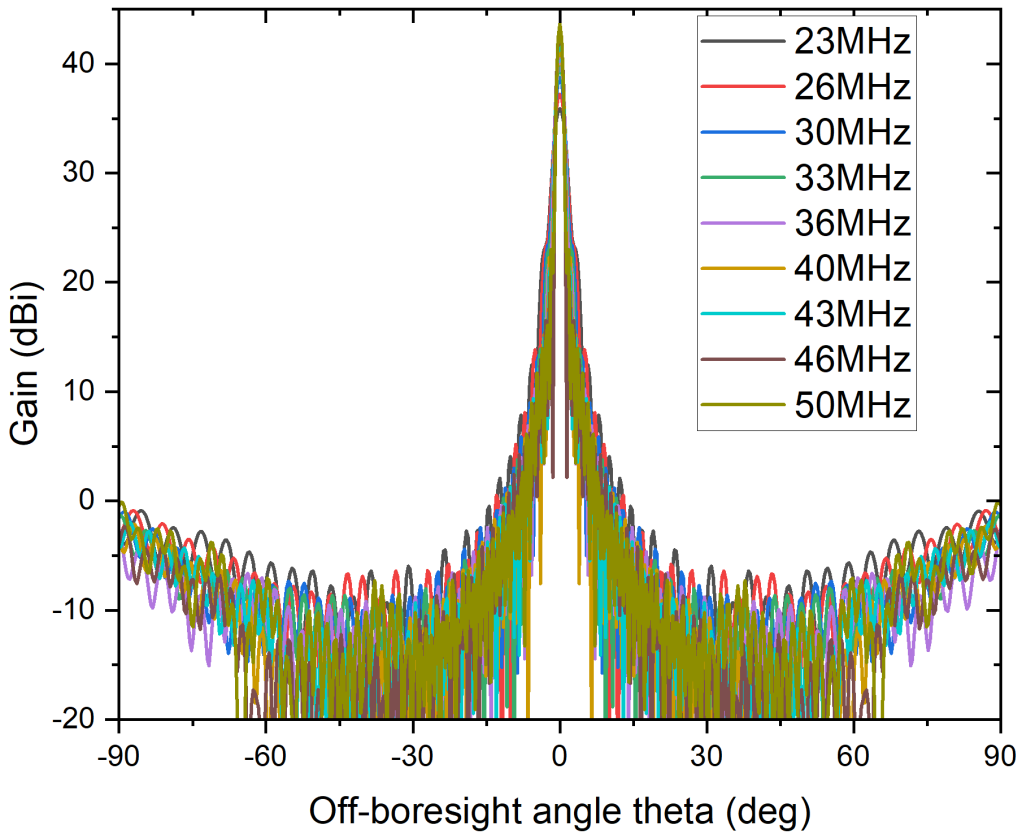
RF Performance of LCRT

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

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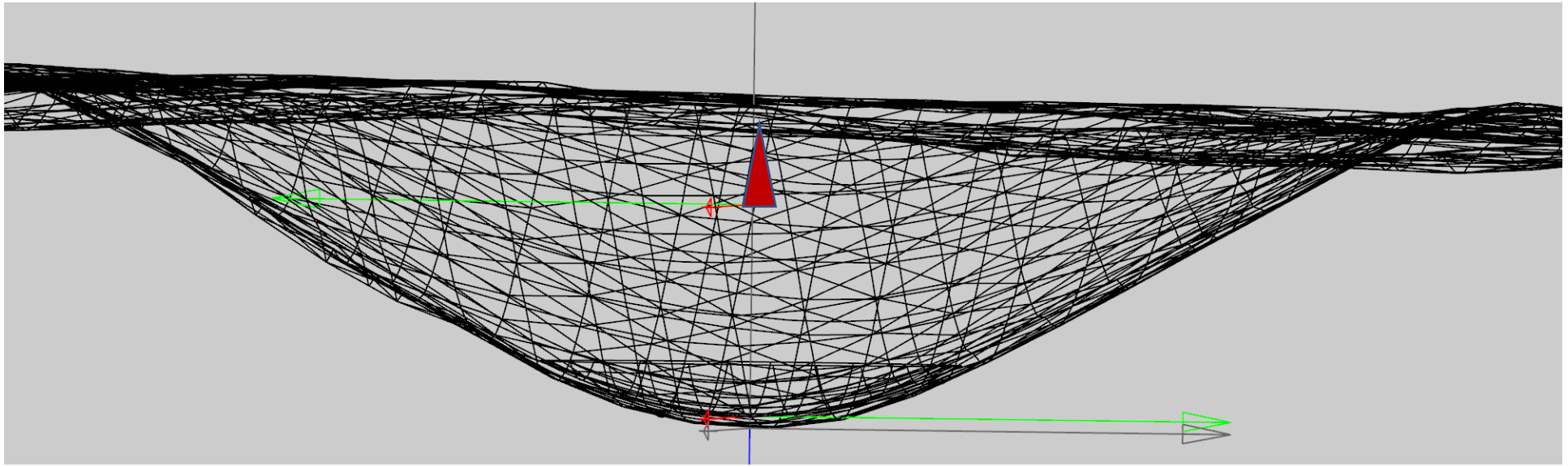
RF Performance with Subsurface



	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

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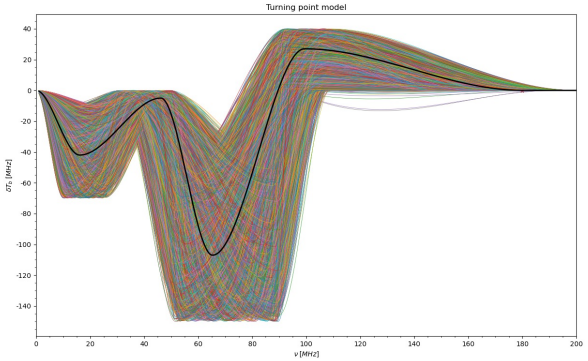
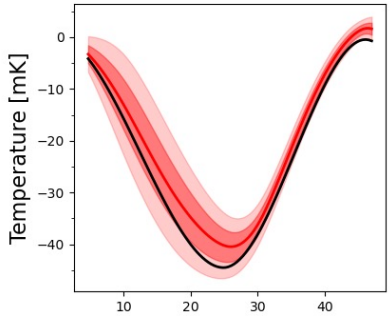
Proving the STM



LCRT's Measurements at Moon



Dark Ages Signal

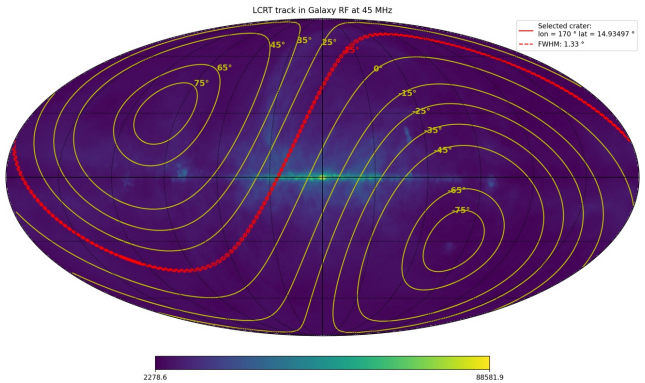
Galactic Foreground

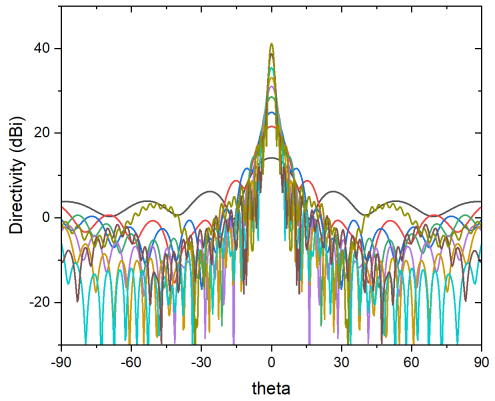
Instrument Model

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.

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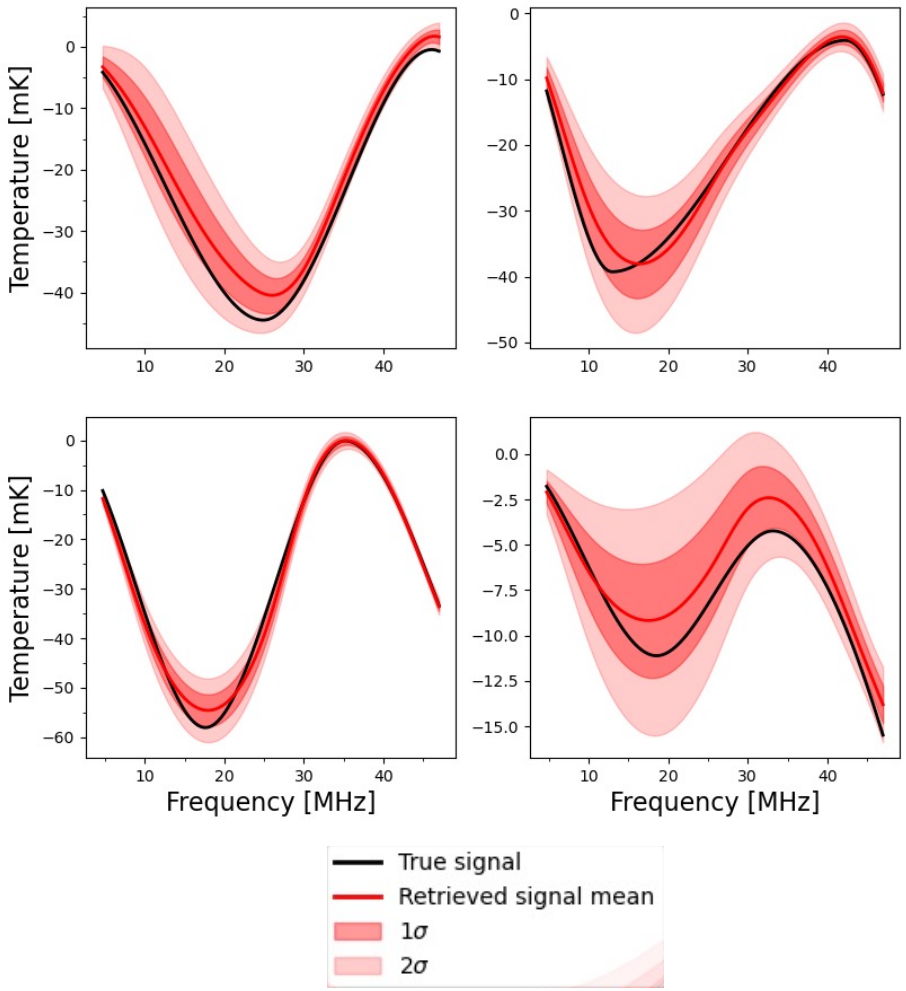
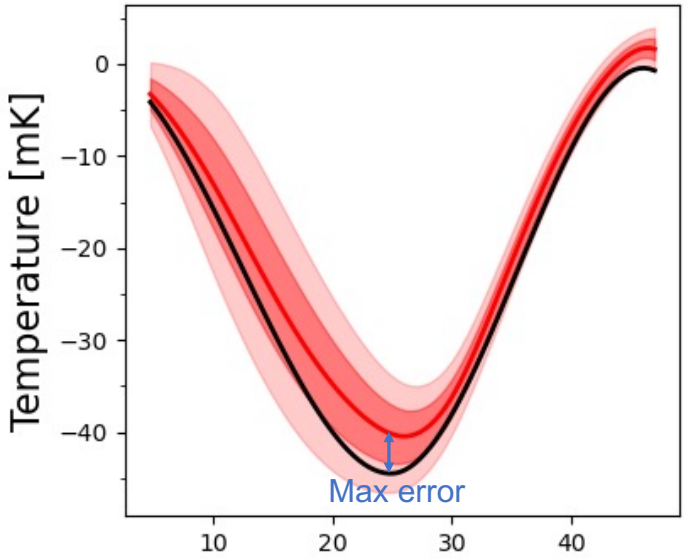
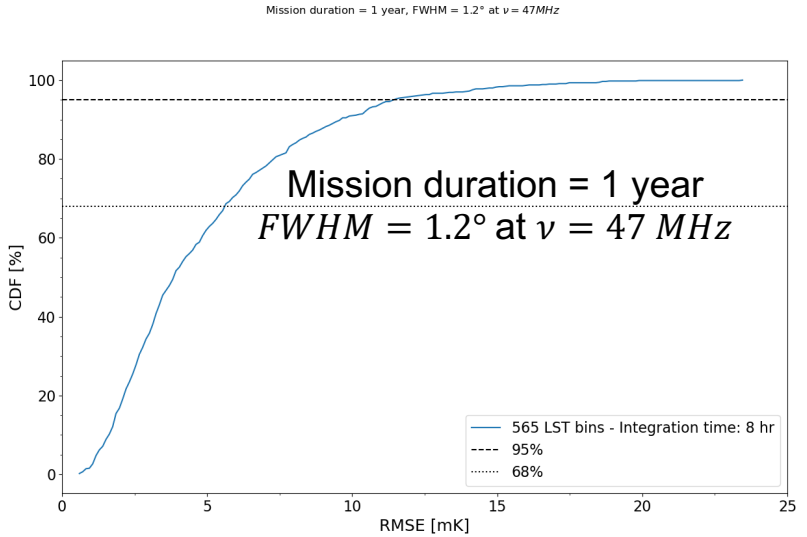
Preliminary Results

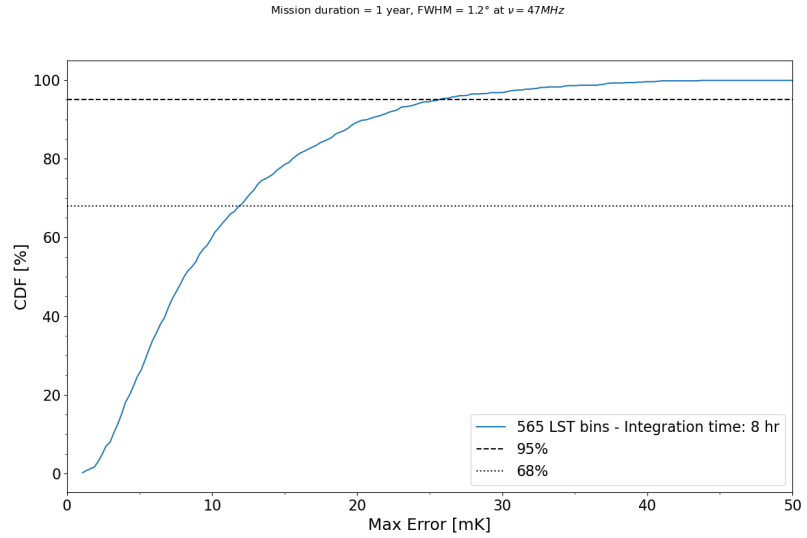
Sample retrievals





Error Statistics





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

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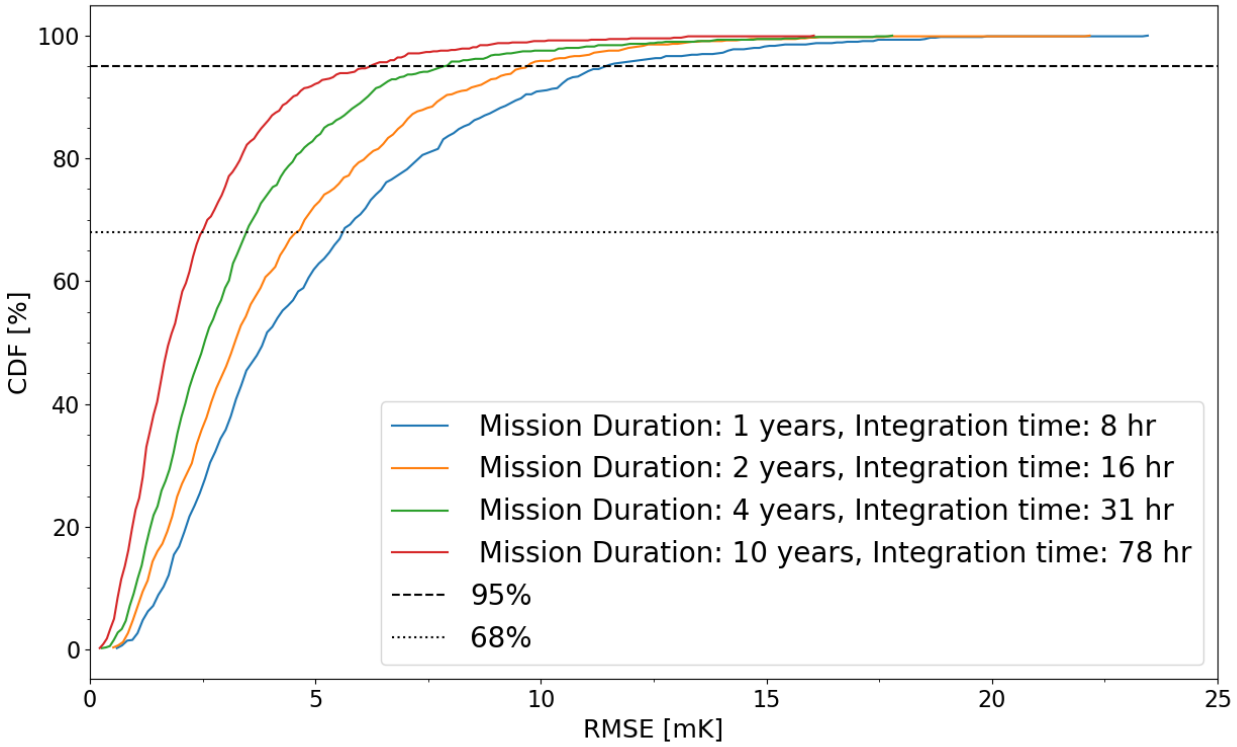
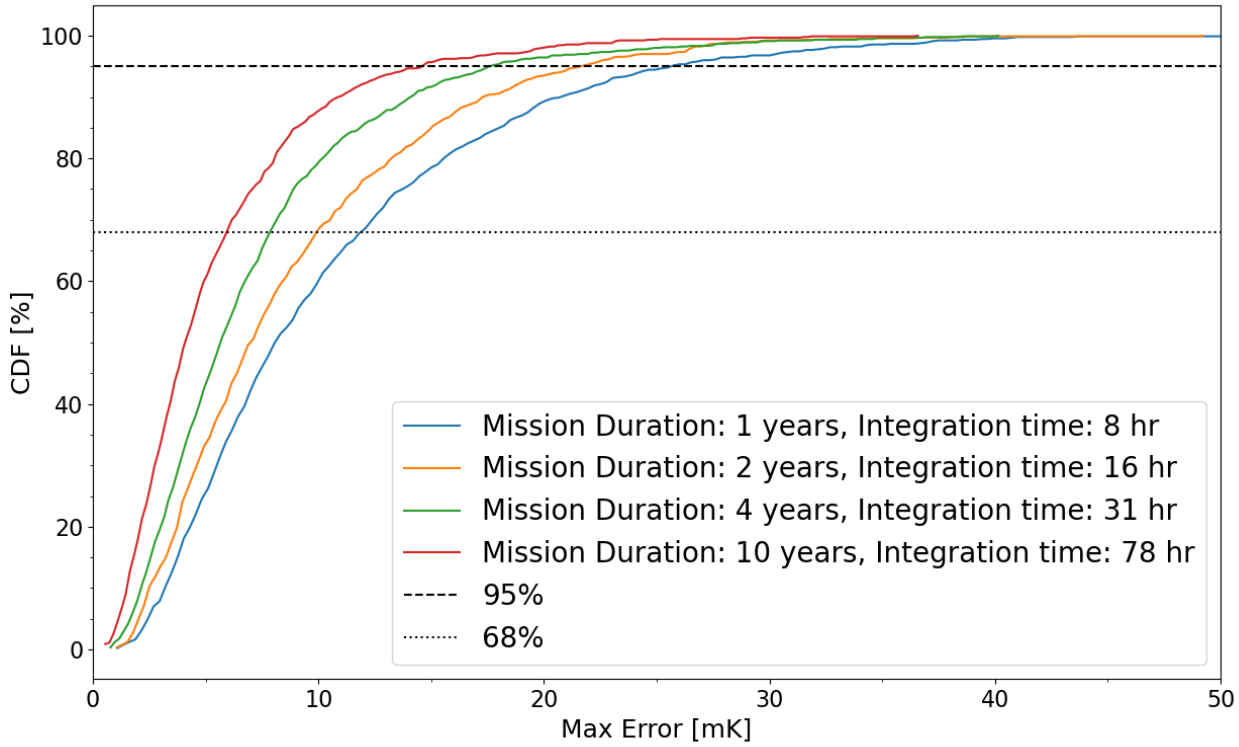
Varying Mission Duration

- $FWHM = 1.2°$ 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.

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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!

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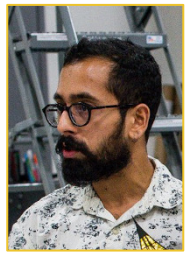
LCRT Team

Saptarshi B. (JPL)

Ashish Goel (JPL)

Kalind Carpenter (JPL)

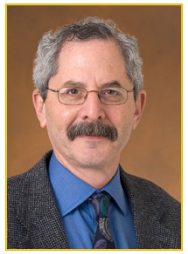
Dario Pisanti (Ex-JPL)


Manan Arya (Stanford)

Gaurangi Gupta (JPL)

Benjamin Byron (UCF)

Joseph Lazio (Ex-JPL)


Paul Goldsmith (JPL)

Jedrzej Cader (JPL, ETH Zurich)

Adrian Stoica (Ex-JPL)

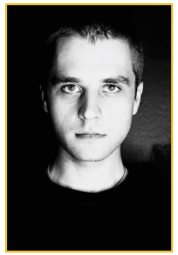
Issa Nesnas (JPL)

Nacer Chahat (JPL)

Rebecca Wang (JPL, Stanford)

Kenneth Jenks
(Ex-NASA JSC)

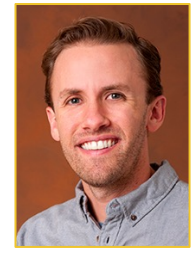
Ron Wilson
(Ret. Brig. Gen. USAF)


Vladimir Vustyansky
(CG Artist)

Gregg Hallinan (Caltech)

Robert Miller (JPL)

Vinod Gehlot (JPL)


Patrick McGarey (Ex-JPL)

Deaho Moon
(JPL, UC Berkely)

Nathan Benavides
(JPL, EPFL)

Elizabeth Jens (JPL)

Benjamin Hockman (JPL)

Adrian Tang (JPL)

David Rapetti
(NASA Ames)

Martin Zieler
(JPL, ETH Zurich)

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Making LCRT a Reality...

Concept art : Volodymyr Vustyansky

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Thank You!

ACKNOWLEDGMENT

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Jet Propulsion Laboratory
California Institute of Technology

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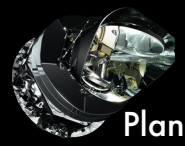
Backup Slides

Evolution of the Universe


Planck

LOFAR

SKA

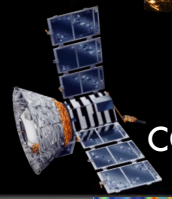
ALMA

Roman (WFIRST)

HERA

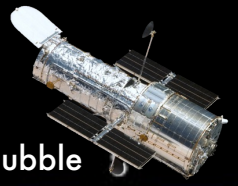
VLA

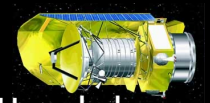
WMAP


COBE

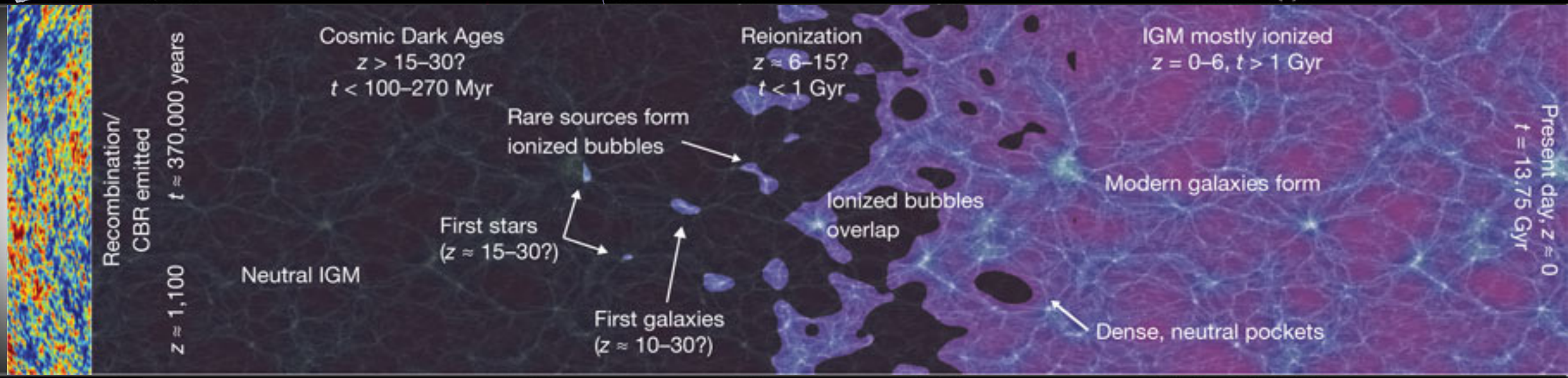
No data on this region of the Universe!

JWST


Hubble


Herschel

1,000 12 Redshift (z) 0



13.7 13.5 13.4 13.0 Billions of Years Ago 0

Big Bang

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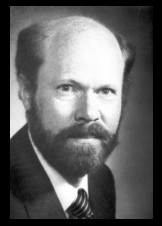
Nobel Prizes in Cosmology

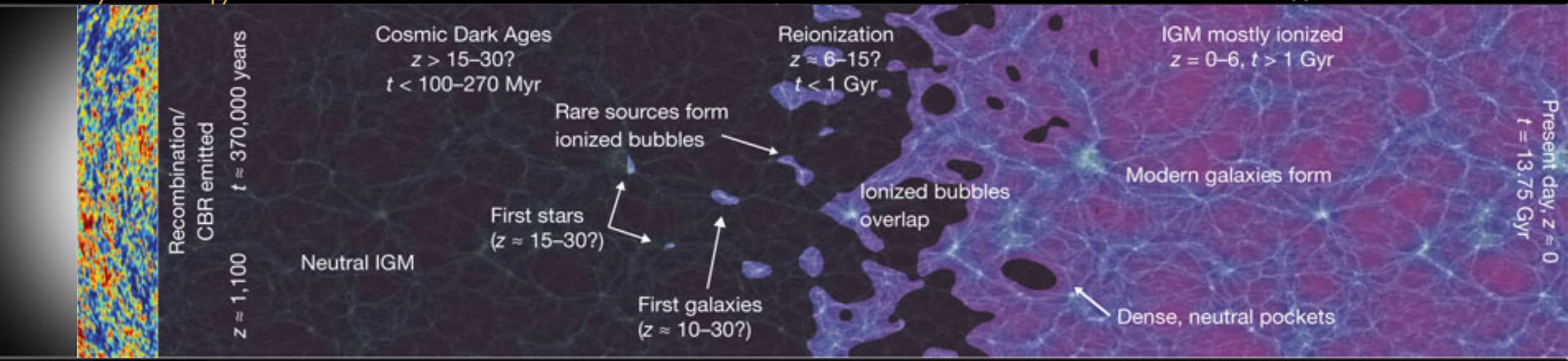


A. Penzias, R. Wilson (1978)
"Discovery of CMBR"

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"



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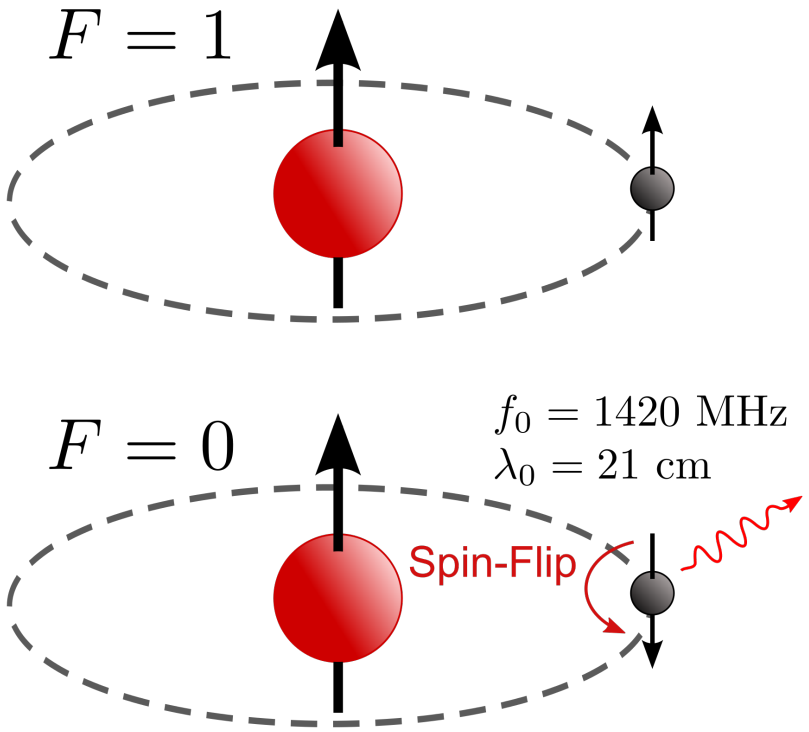
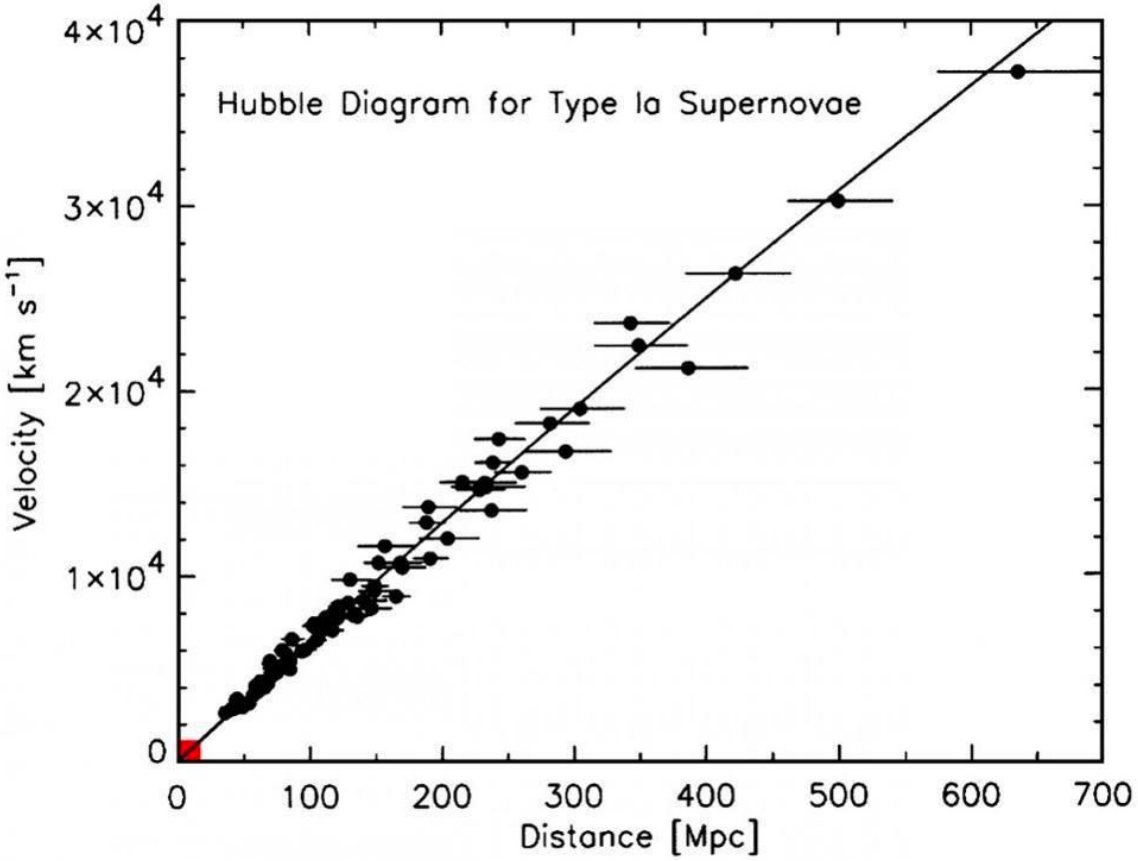
What is this Signal?

Neutral Hydrogen Hyperfine Transition



Cosmological Redshift due to Expanding Universe



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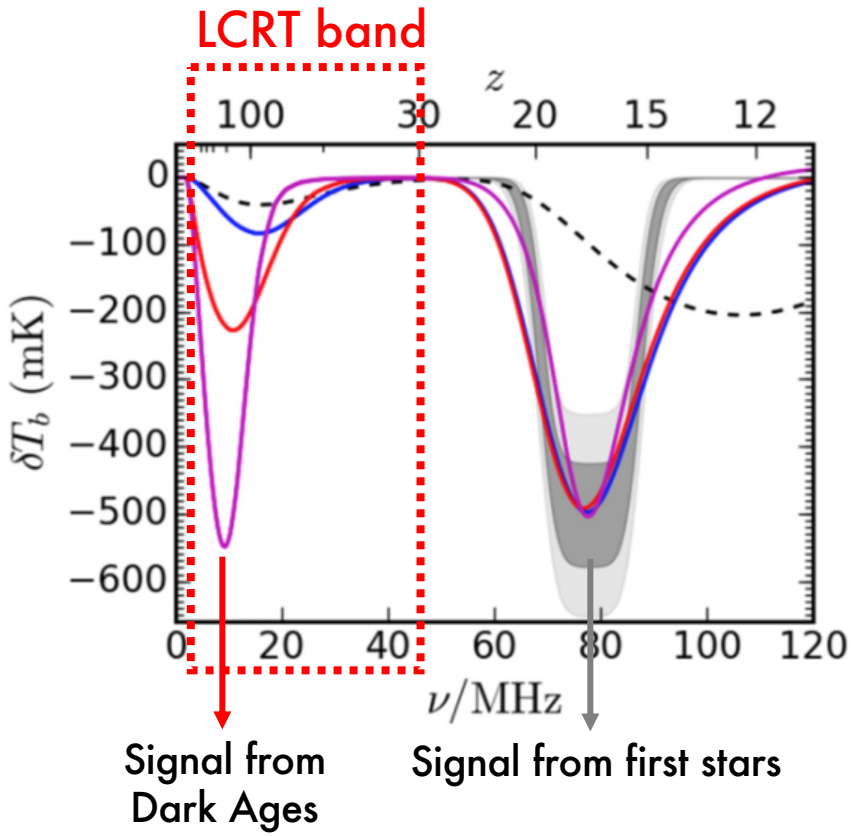
What is this Signal?

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

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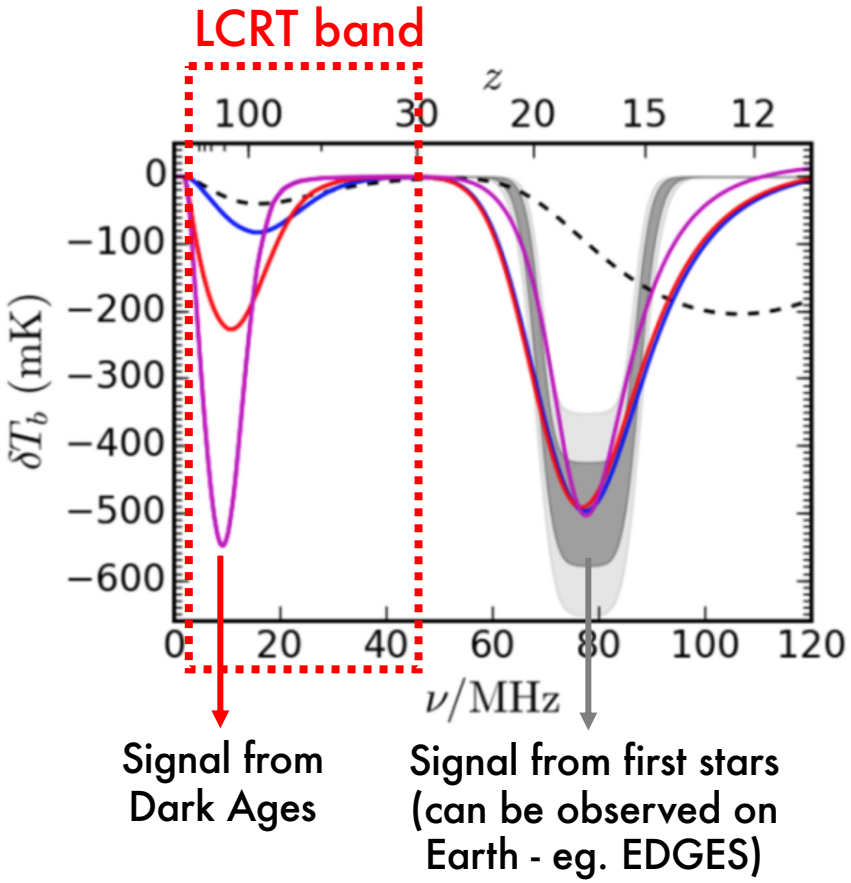
What is this Signal?

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)

EDGES (Experiment to Detect the Global EoR Signature) measurements

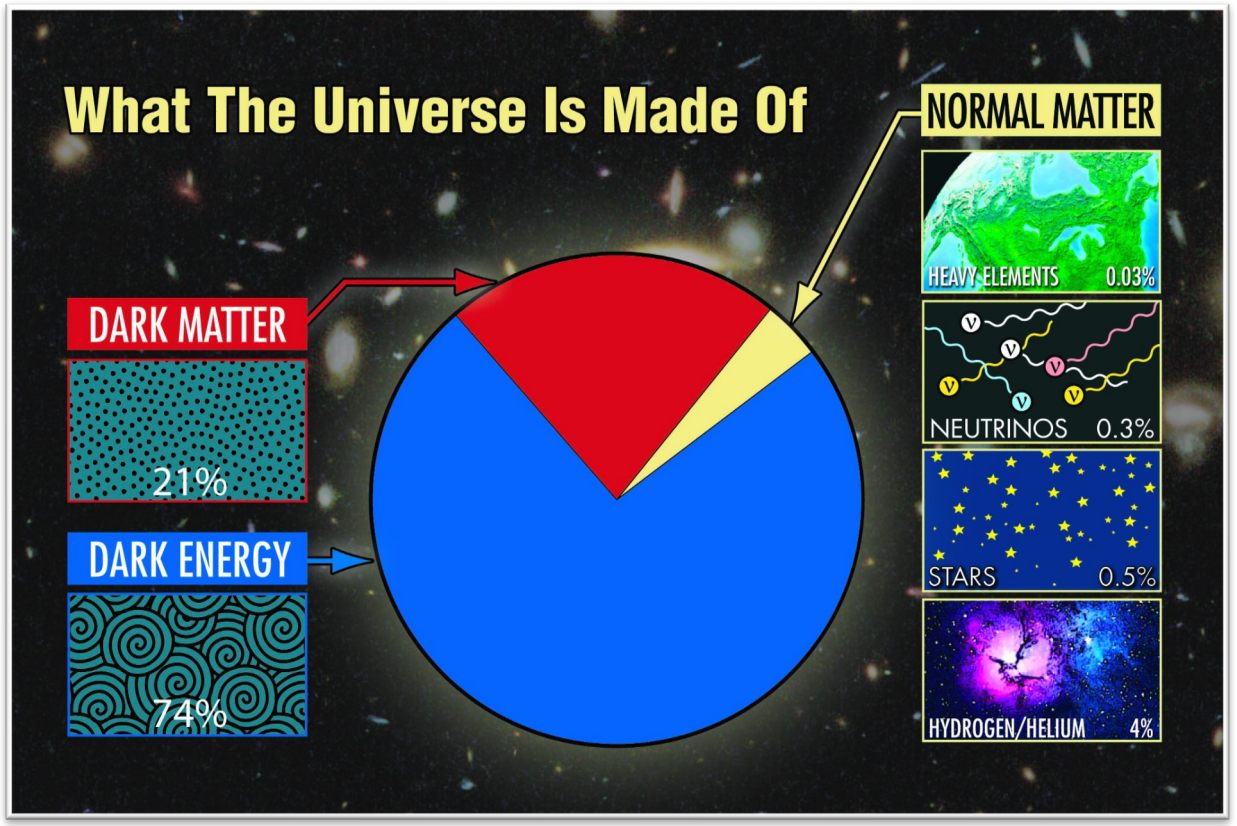


[1] S. R. Furlanetto et. al., "A er: I ges with 21-cm Line Fluctuations "
[2] Mirocha, Jordan, and St es t n tell us about early galaxies?."
Monthly Notices of the Roy .

Pre-De l Disc echnology. Government sponsorship acknowledged.

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

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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.

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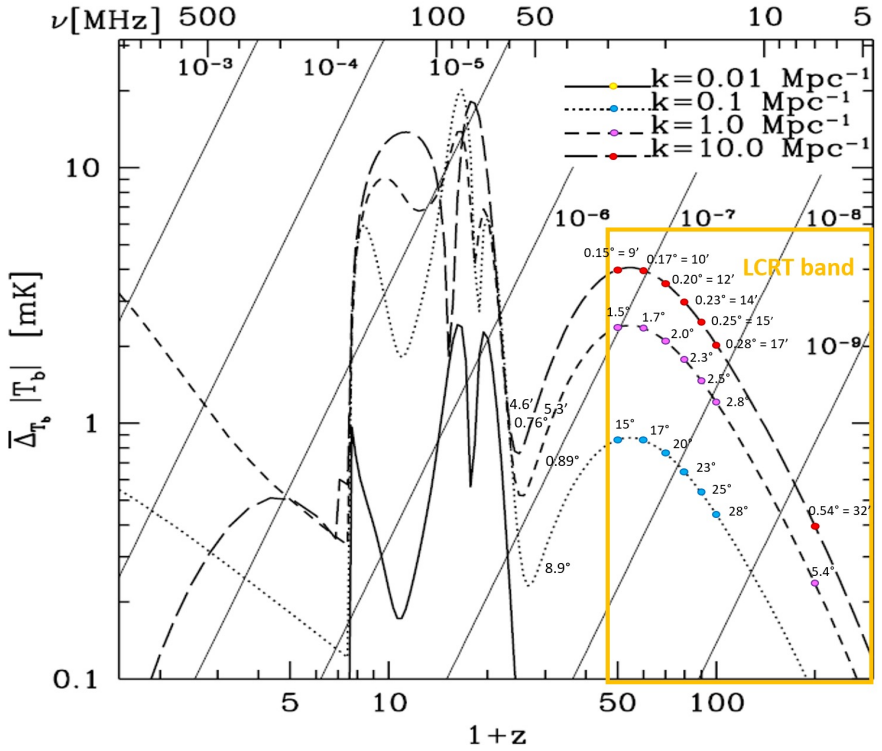
Why 350-m Diameter Size?

- LCRT can observe only the global 21cm signal, not the spatial frequencies in the global signal

- RF performance of 350m diameter telescope is deemed sufficient for science objective

	Reflector Diameter 1000 m		Reflector Diameter 350 m		Reflector Diameter 200 m	
Frequency	SLL supp. (dB)	Ang. Res. (°)	SLL supp. (dB)	Ang. Res. (°)	SLL supp. (dB)	Ang. Res. (°)
3 MHz	-19.7	5.94°	-9.3	15.1°	-5.57	32.6°
5 MHz	-26.59	4.14°	-17.3	10.1°	-11.5	17.3°
10 MHz	-34.42	1.8°	-24.2	5.94°	-19.3	8.82°
20 MHz	-40.94	1°	-30.7	2.52°	-25.8	4.32°
30 MHz	-44.74	0.72°	-34.6	1.8°	-29.7	3.06°
40 MHz	-47.22	0.42°	-37.1	1.26°	-32.2	2.2°
50 MHz	-48.9	0.36°	-38.8	1.08°	-34.9	1.8°



Anticipated power spectrum of the 21 cm signal

[1] J. R. Pritchard and A. Loeb, "21 cm cosmology in the 21st century," Reports on Progress in Physics, 2012.

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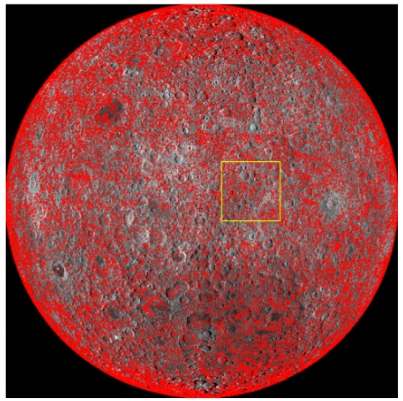
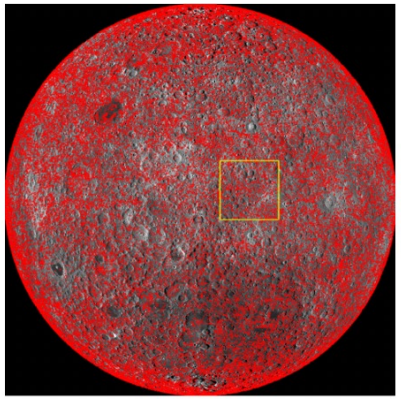
Lunar Crater Selection

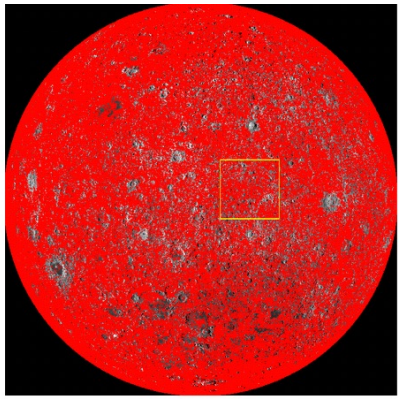
Lunar Reconnaissance Orbiter Camera (LROC) database



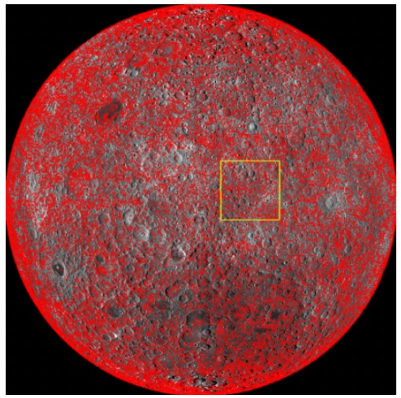
70K craters
(1 - 1.1 km)



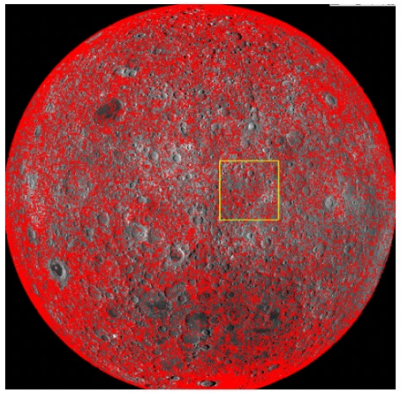
66K craters
(1.1 - 1.2 km)



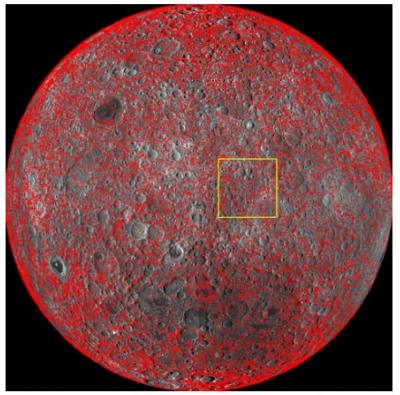
324K craters
(1.2 - 2 km)



140K craters
(2 - 3 km)



82K craters
(3 - 5 km)



39K craters
(5 - 10 km)

LRO Spacecraft

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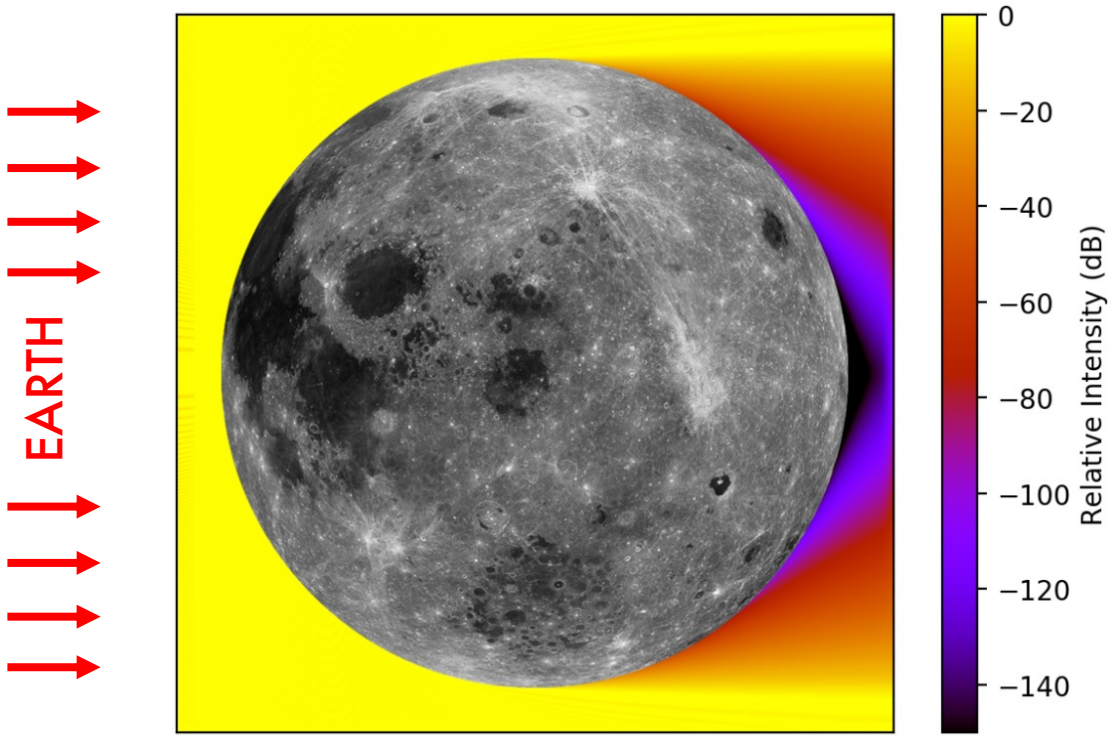
Lunar Crater Selection

Crater Requirements

- Diameter: 1-2 km
- Minimum Depth: 200 m
- Location: 20°N, 180±45°E
- 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

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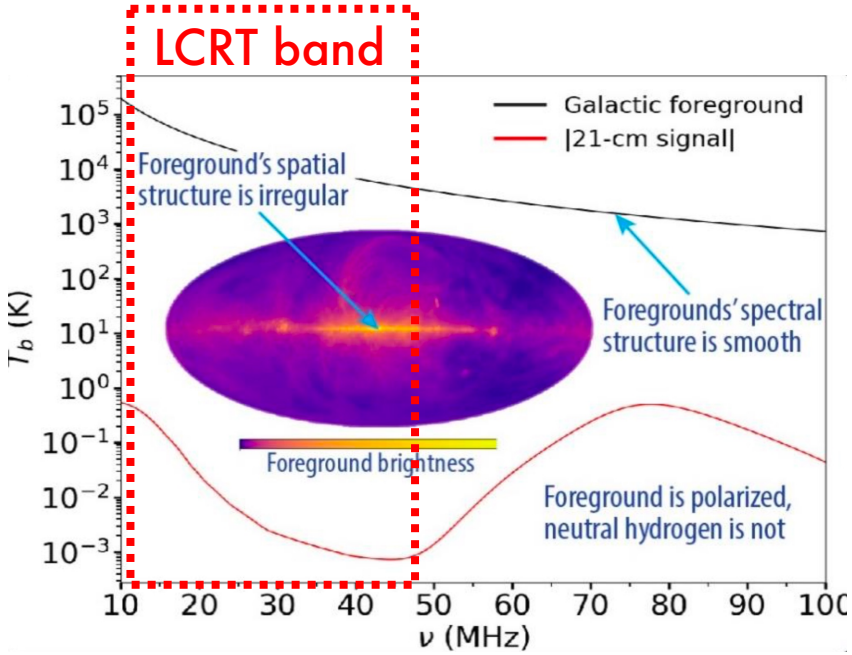
Galactic Foreground

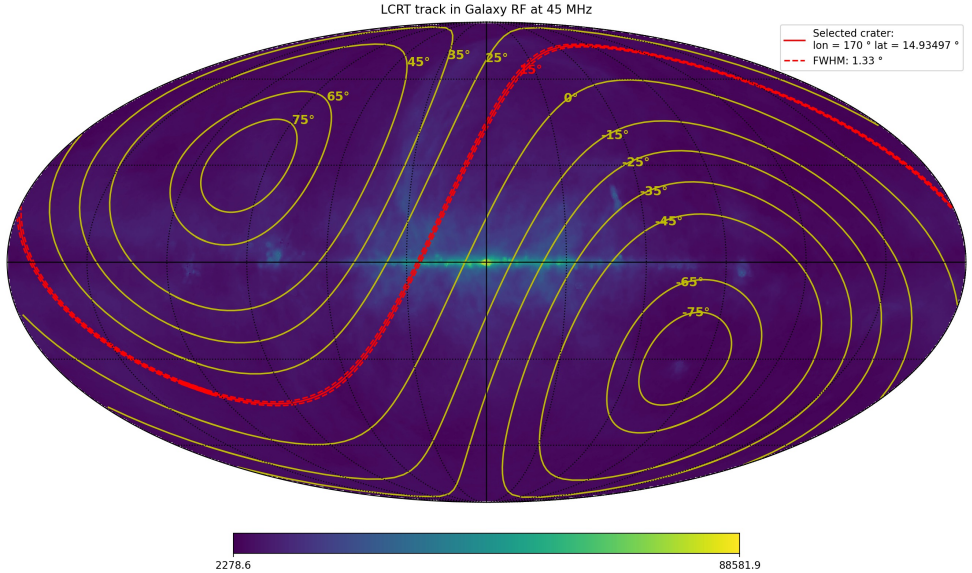
- Challenge :

  Galactic foreground several orders of magnitude stronger than signal



(Adapted from Prof. Jack Burns' slides)

- Variation of galactic signal with lunar latitude



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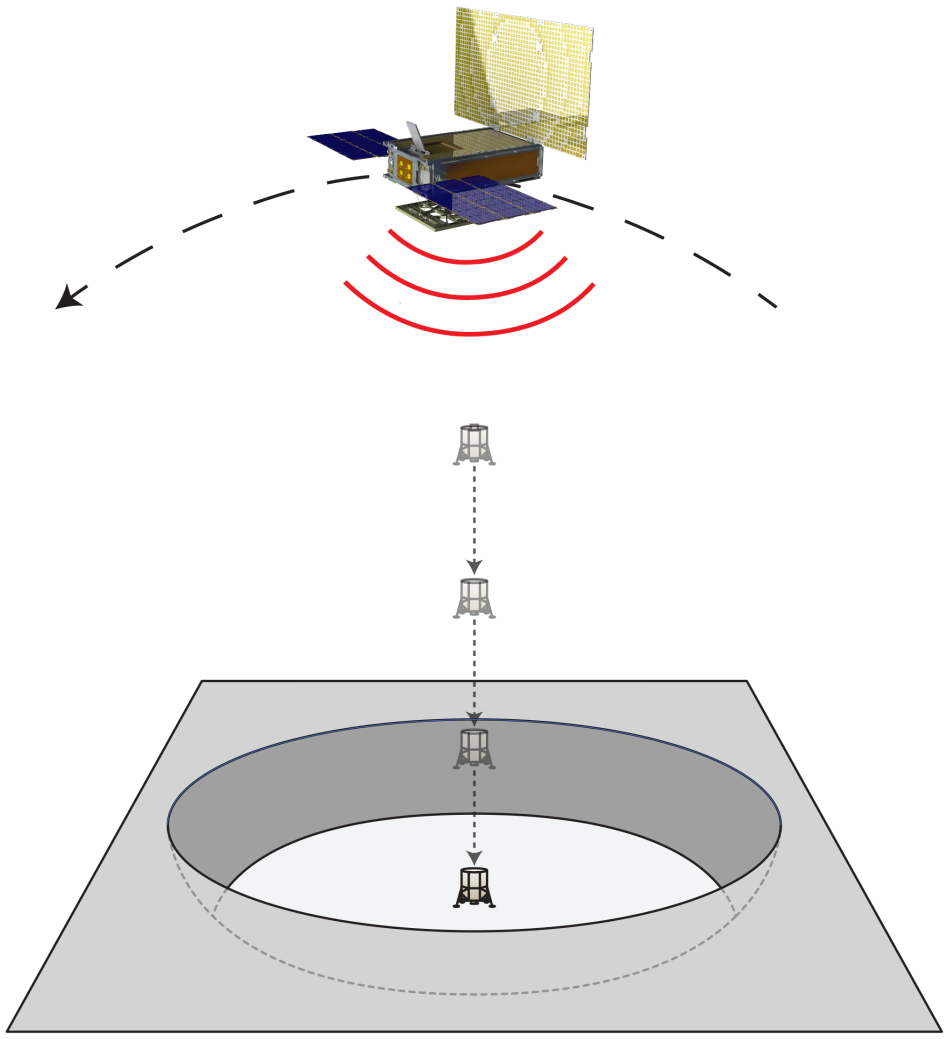
ConOps Step 1: Land in Crater



	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**

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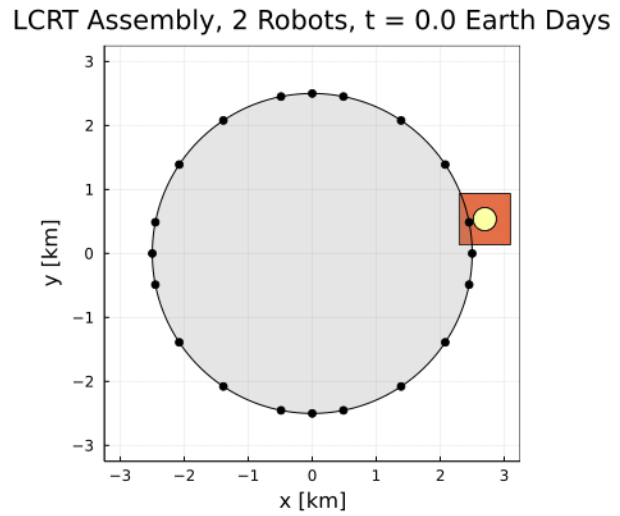
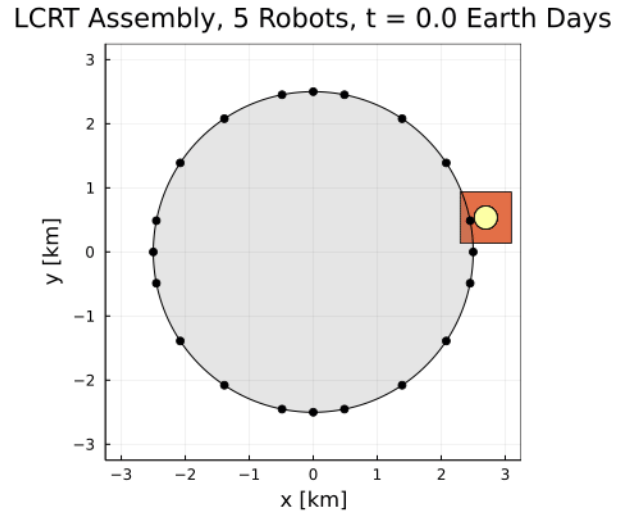
Why Projectile-based Deployment?

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.

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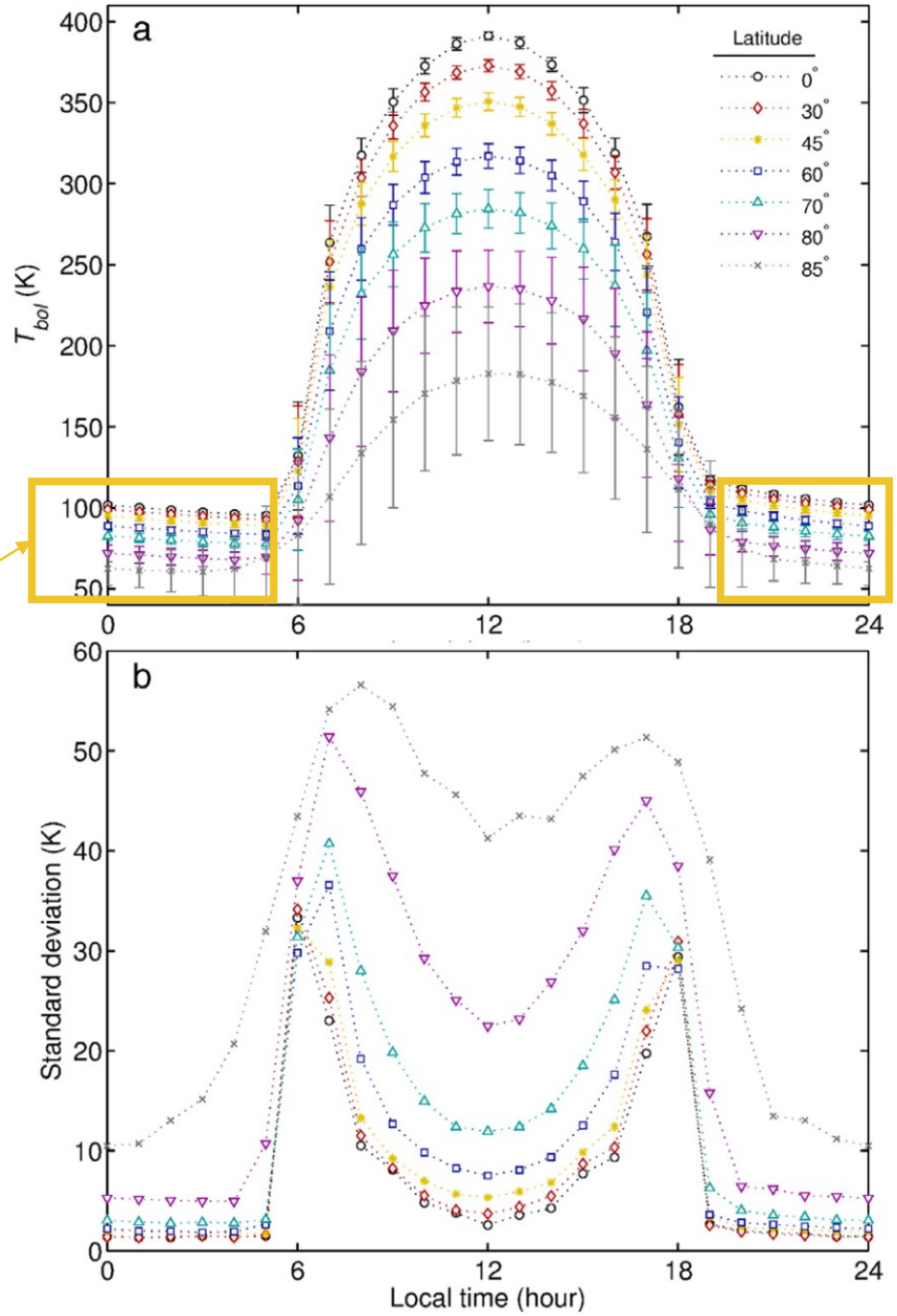
Temperature during Lunar Night

- 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.

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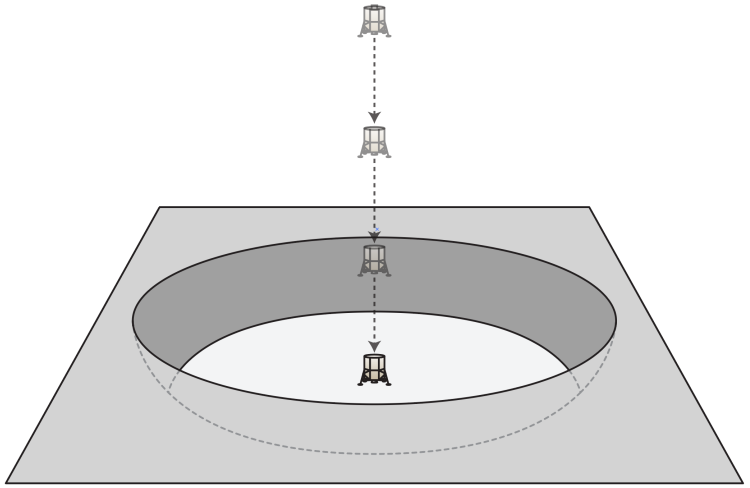
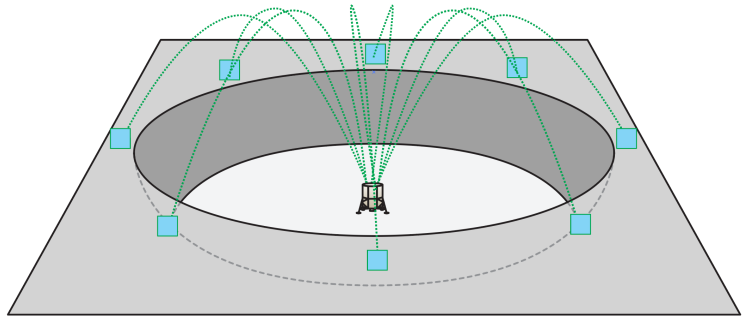
Concept of Operations

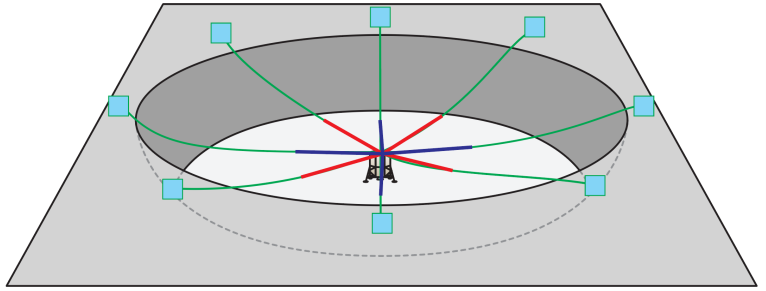
Step 1: Land in Crater



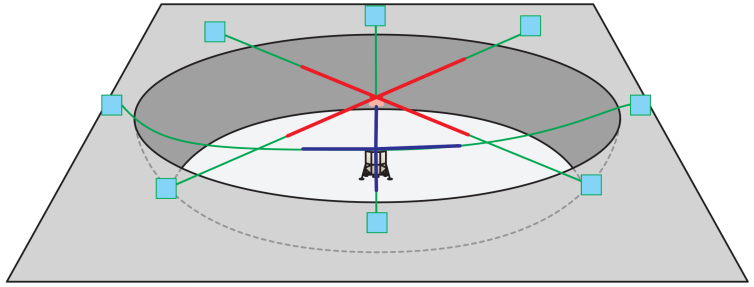
Step 2: Fire Anchors to Crater Rim



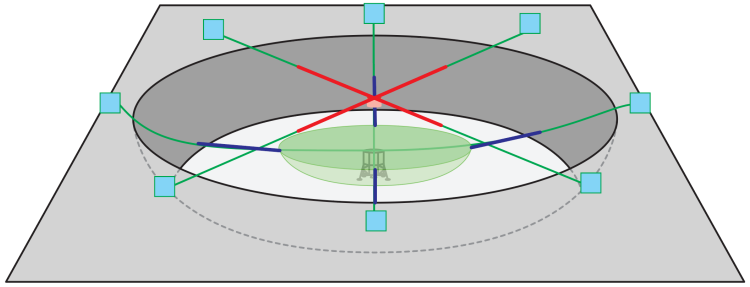
Step 3: Tension Lift Wires



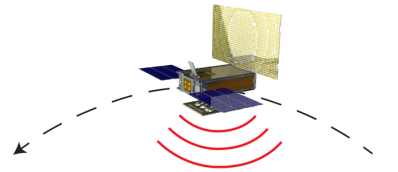
Step 4: Deploy Feed

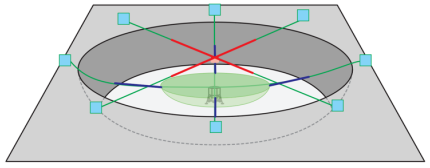


Step 5: Deploy Reflector



Step 6: Calibrate LCRT





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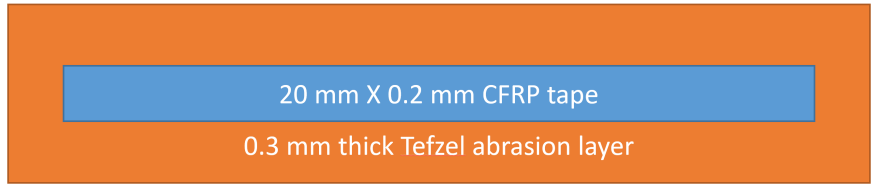
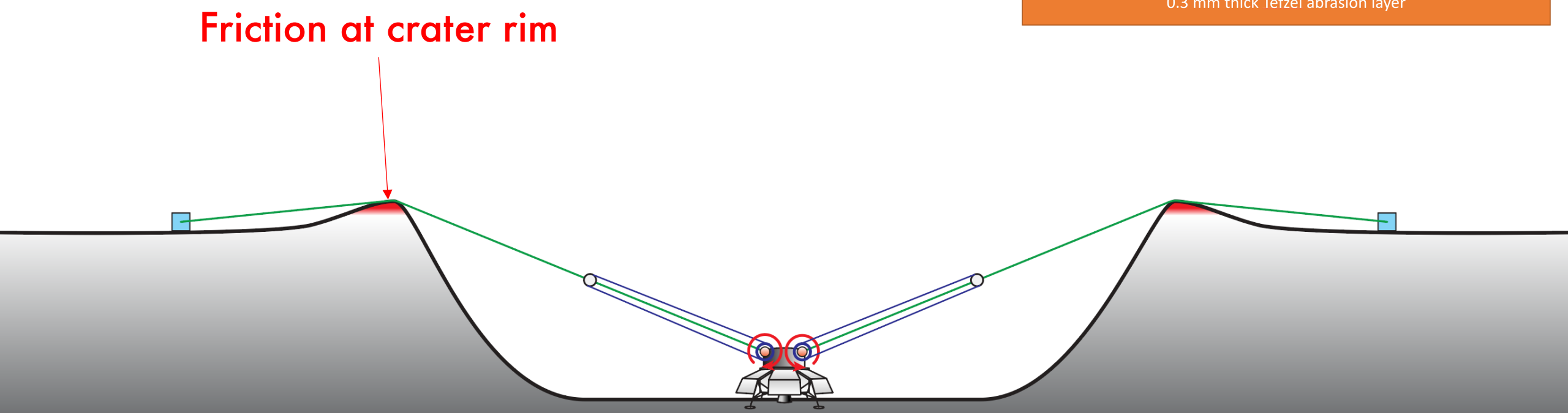
ConOps Step 3: Tension Lift Wires

Lift wire cross-section





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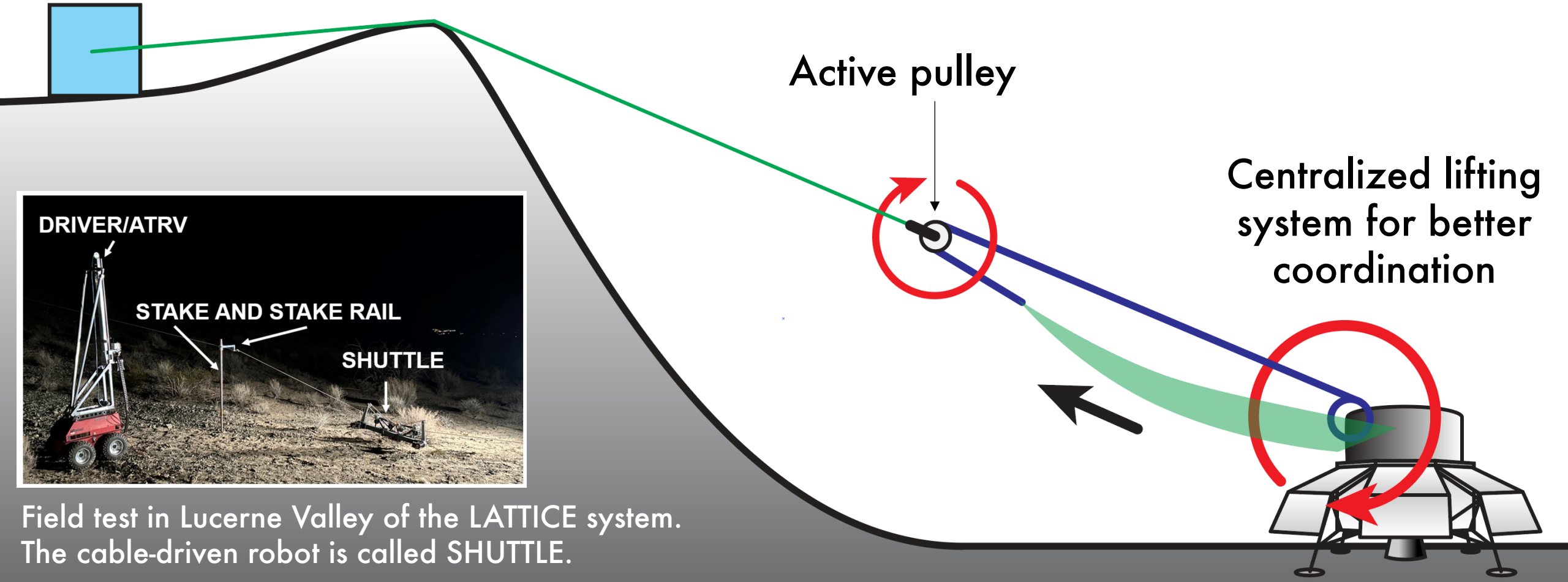
ConOps Step 4: Deploy Feed



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

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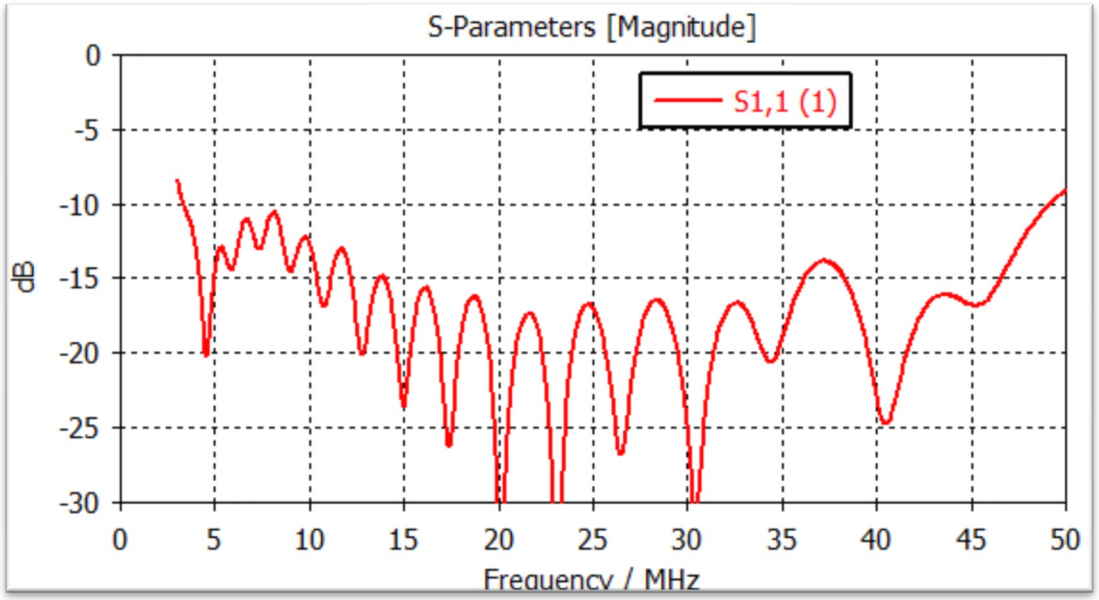
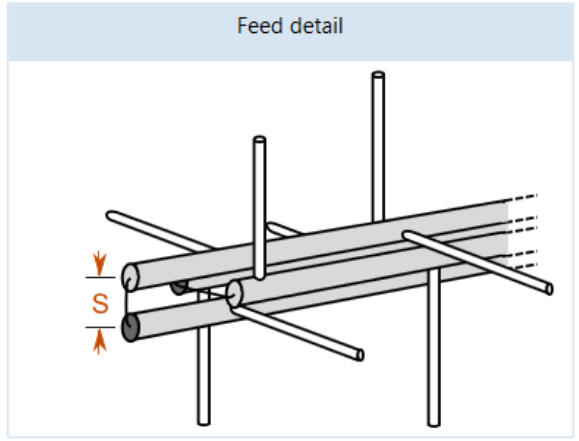
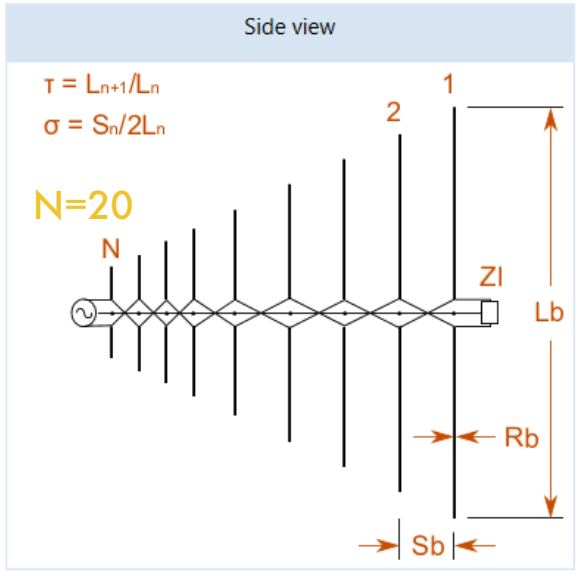
Design of the Feed

Log Periodic Antenna:

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







Lb = 37m

Sb = 2.3m

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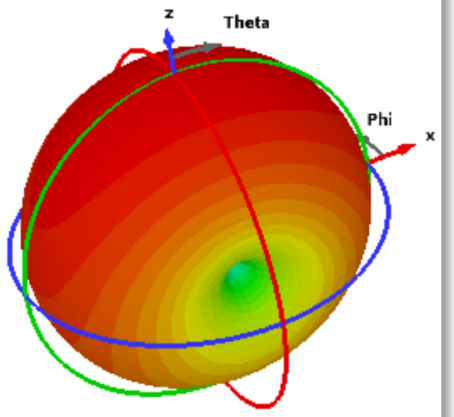
RF Performance of the Feed

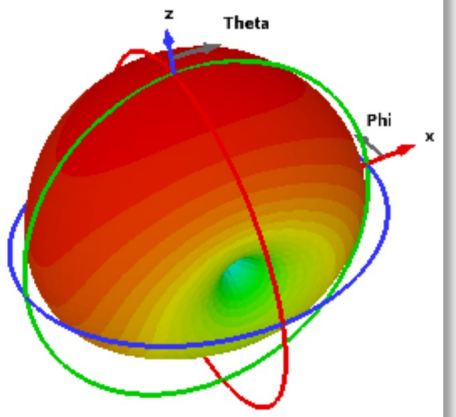
5 MHz



farfield (f=5) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Gain
Frequency	5 MHz
Rad. Effic.	-0.7099 dB
Tot. Effic.	-0.7700 dB
Gain	3.599 dBi

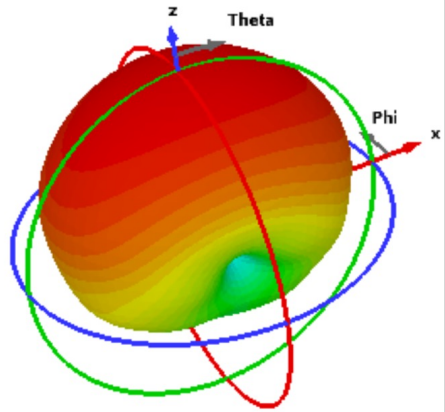
10 MHz



farfield (f=10) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Gain
Frequency	10 MHz
Rad. Effic.	-0.1618 dB
Tot. Effic.	-0.2608 dB
Gain	5.532 dBi

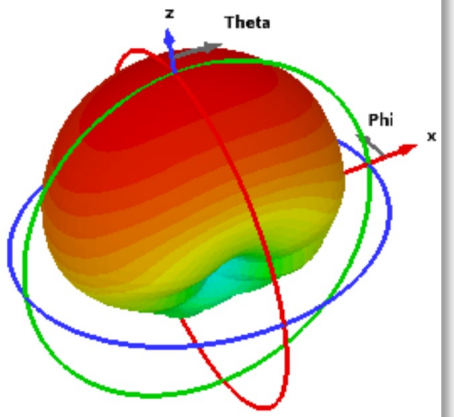
20 MHz



farfield (f=20) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Gain
Frequency	20 MHz
Rad. Effic.	0.003256 dB
Tot. Effic.	-0.006105 dB
Gain	7.043 dBi

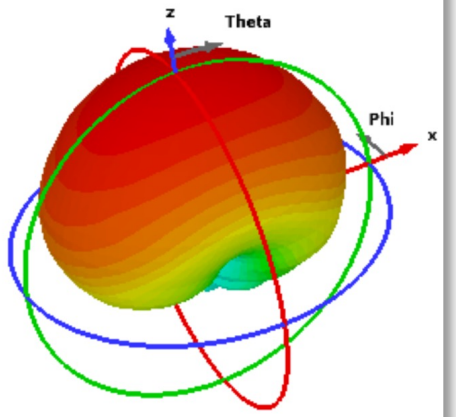
30 MHz



farfield (f=30) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Gain
Frequency	30 MHz
Rad. Effic.	-0.001076 dB
Tot. Effic.	-0.01135 dB
Gain	7.735 dBi

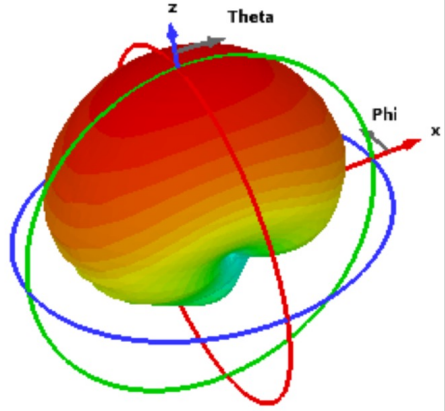
40 MHz



farfield (f=40) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Gain
Frequency	40 MHz
Rad. Effic.	-0.0004277 dB
Tot. Effic.	-0.01487 dB
Gain	7.554 dBi

46 MHz



farfield (f=46) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Gain
Frequency	46 MHz
Rad. Effic.	0.001990 dB
Tot. Effic.	-0.1274 dB
Gain	8.002 dBi

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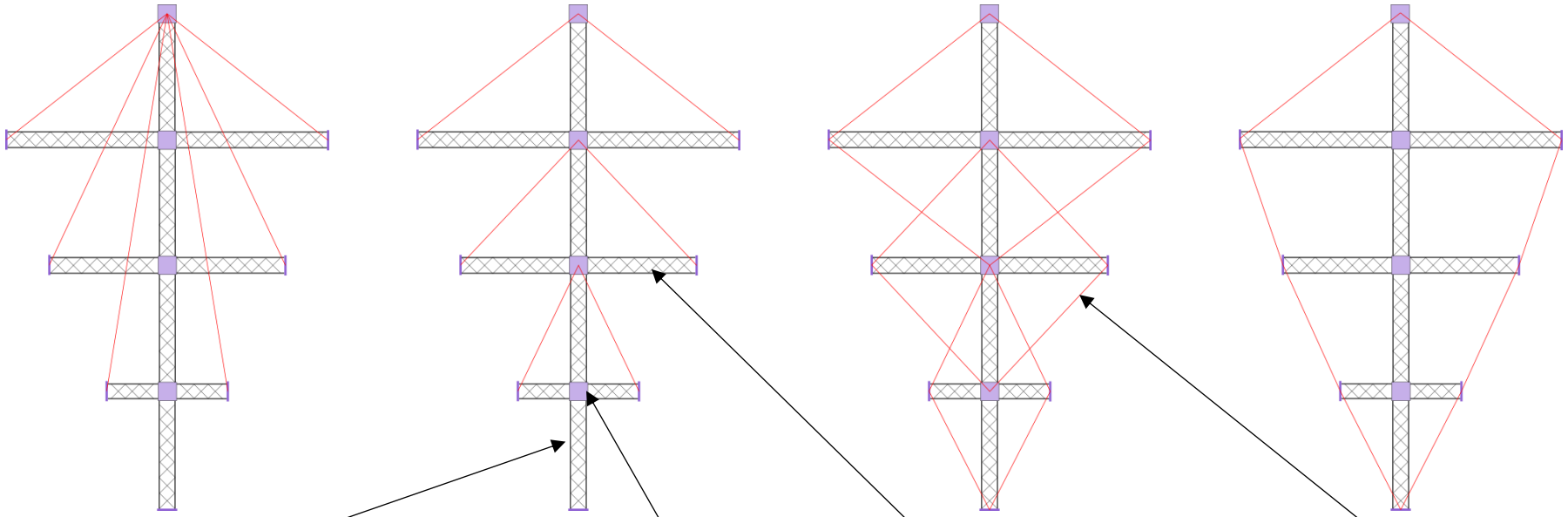
Deployment of the Feed

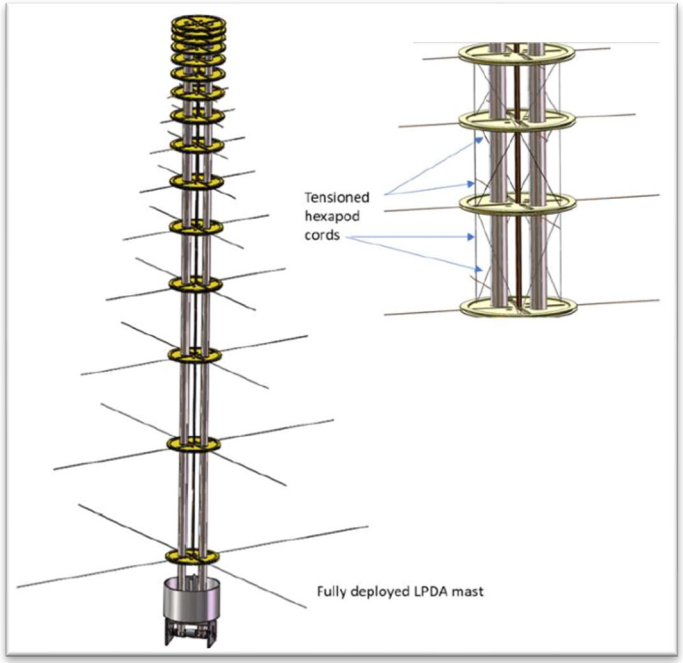


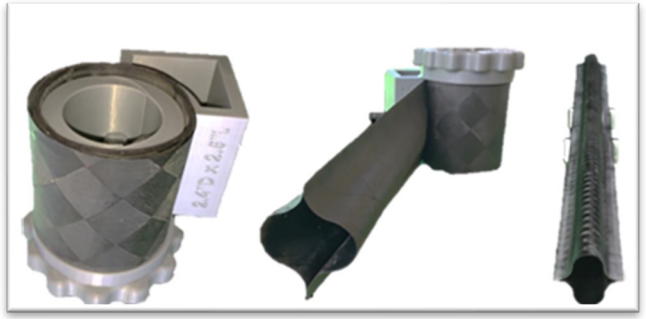
Central mast
AstroMast or
similar

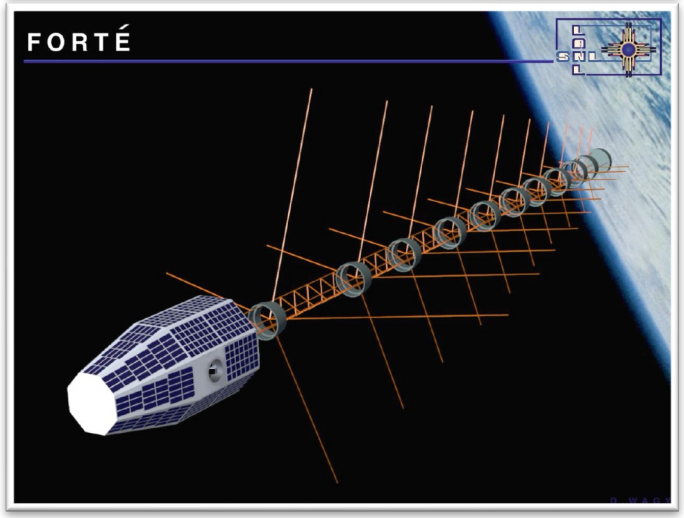
Non-
deployable
nodal structures

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

Tension cables







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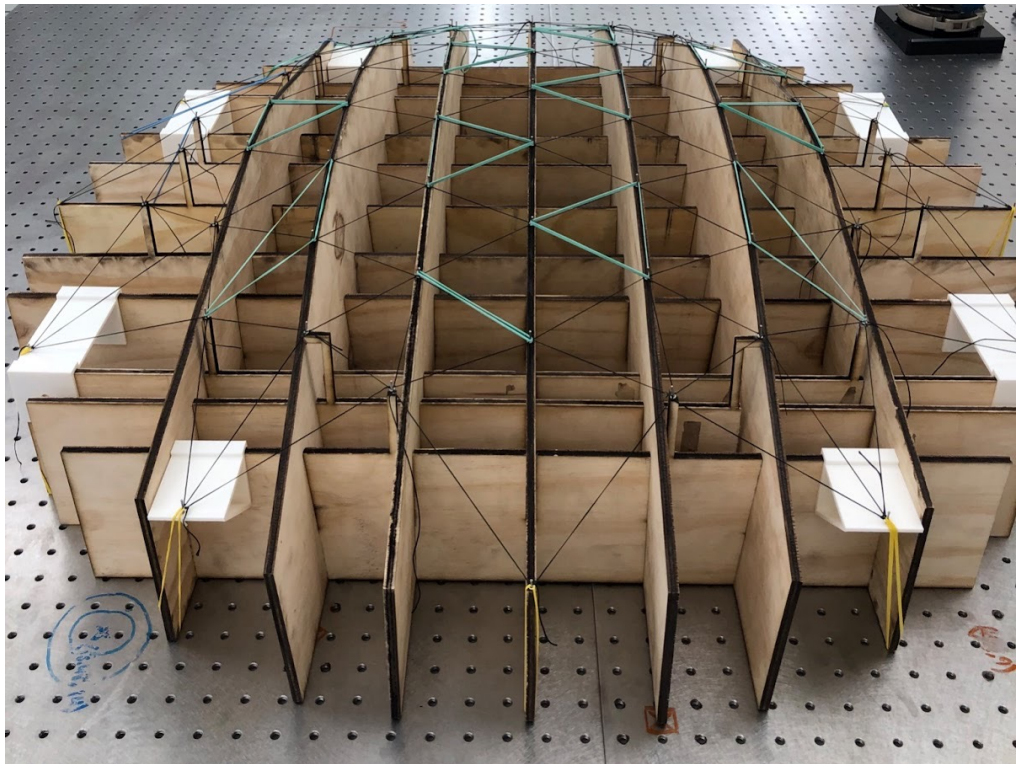
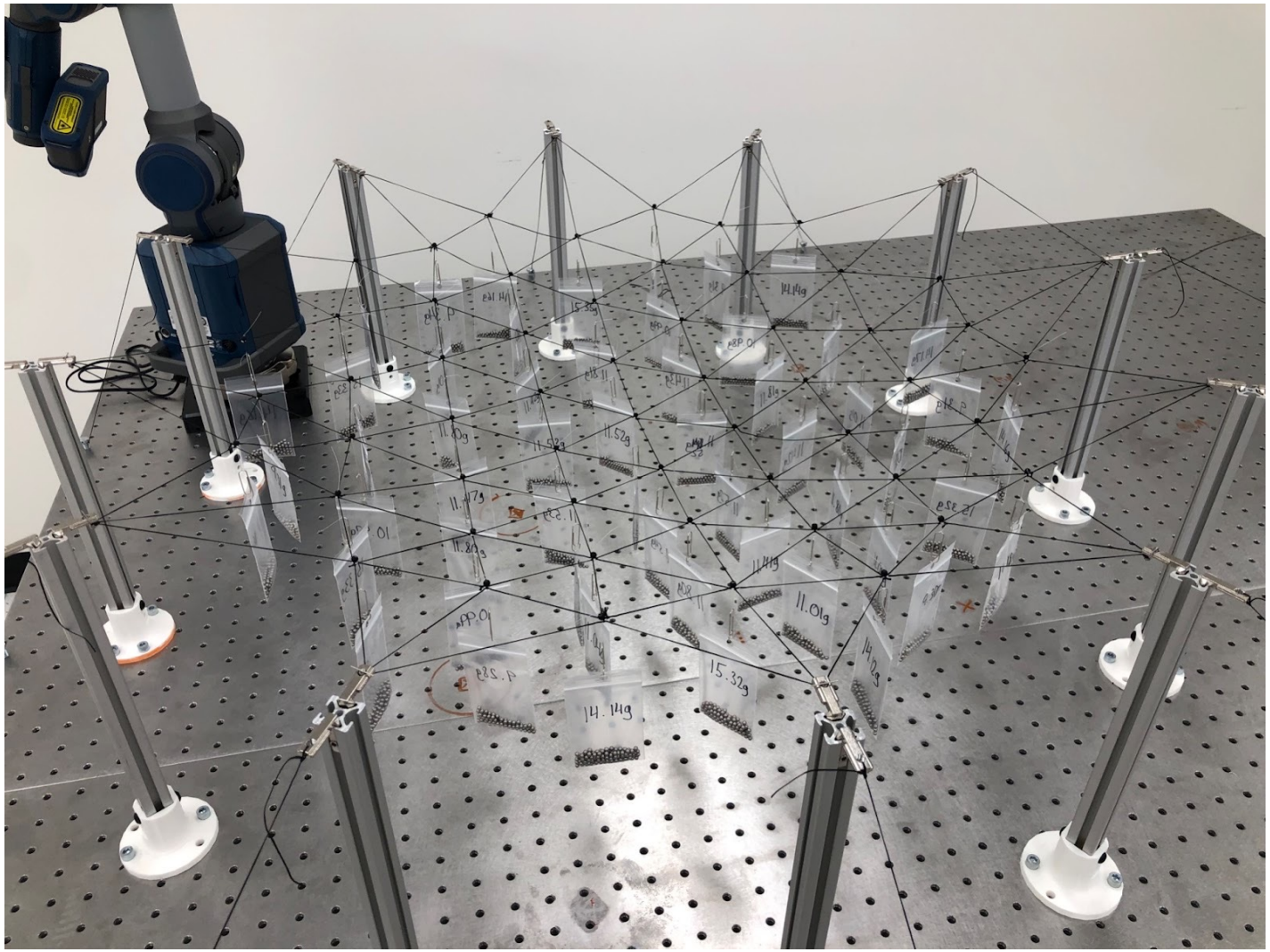
Subscale Reflector Prototype

~1 m-scale reflector prototype to check:

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





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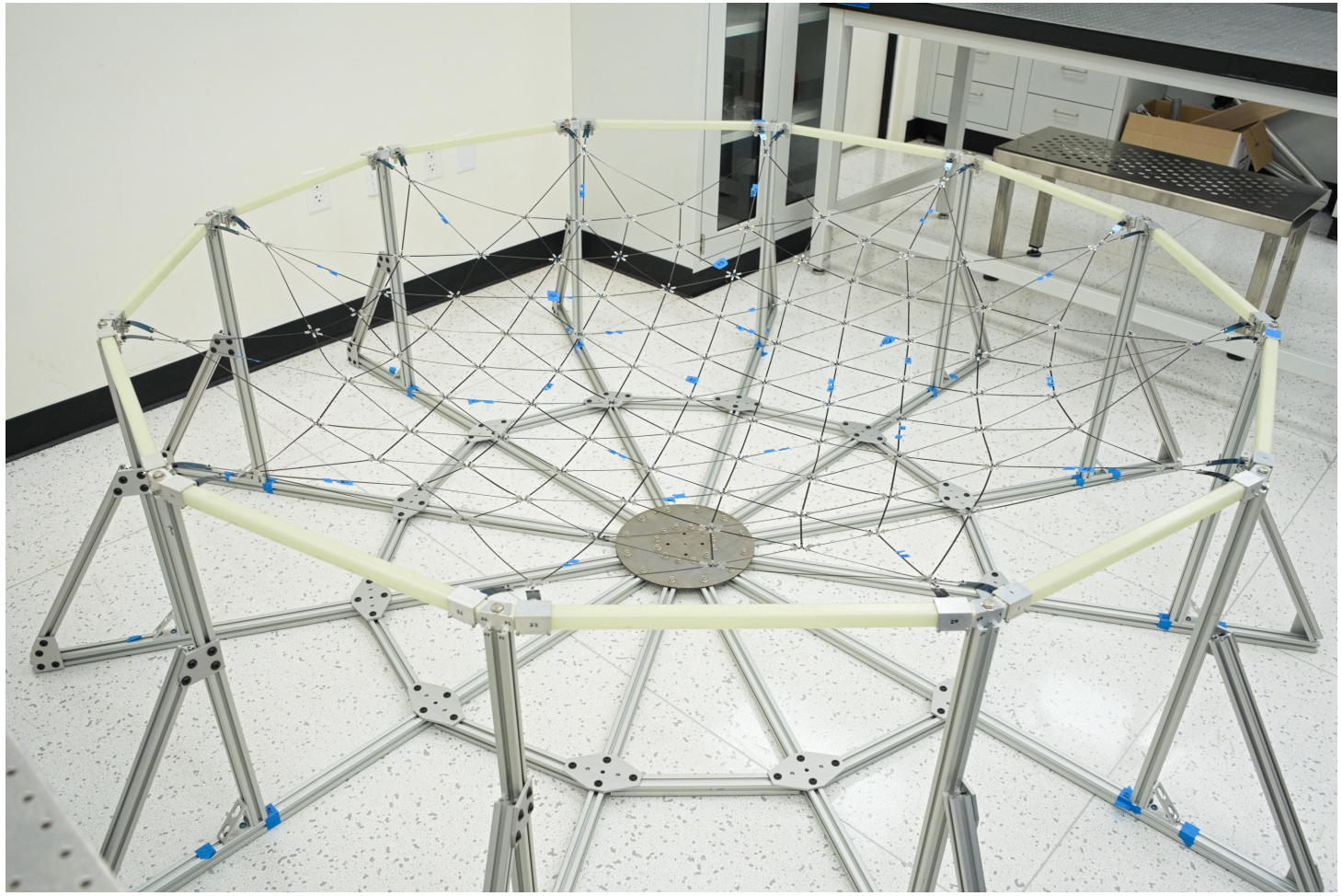
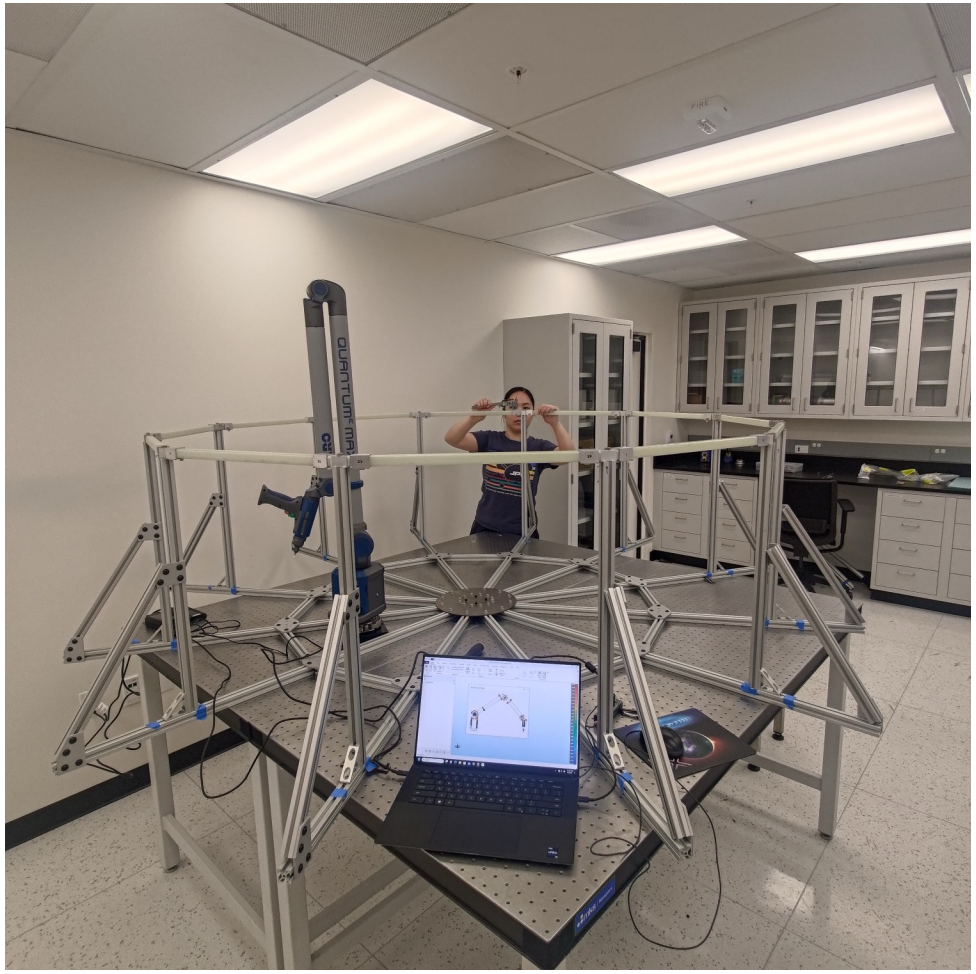
Subscale Reflector Prototype

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





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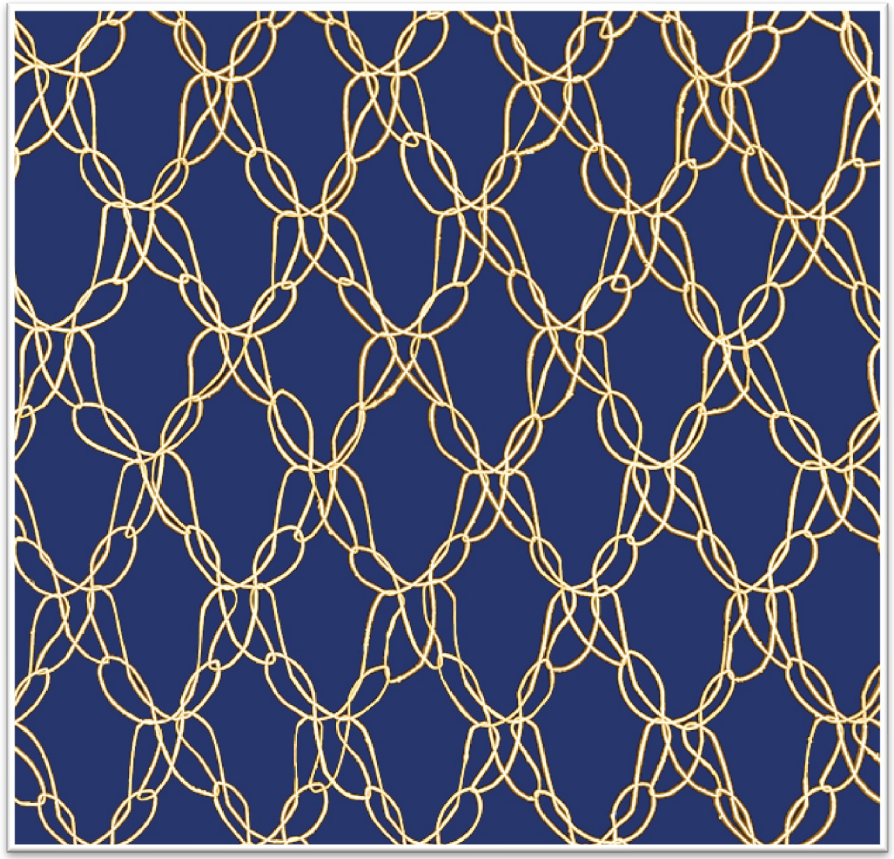
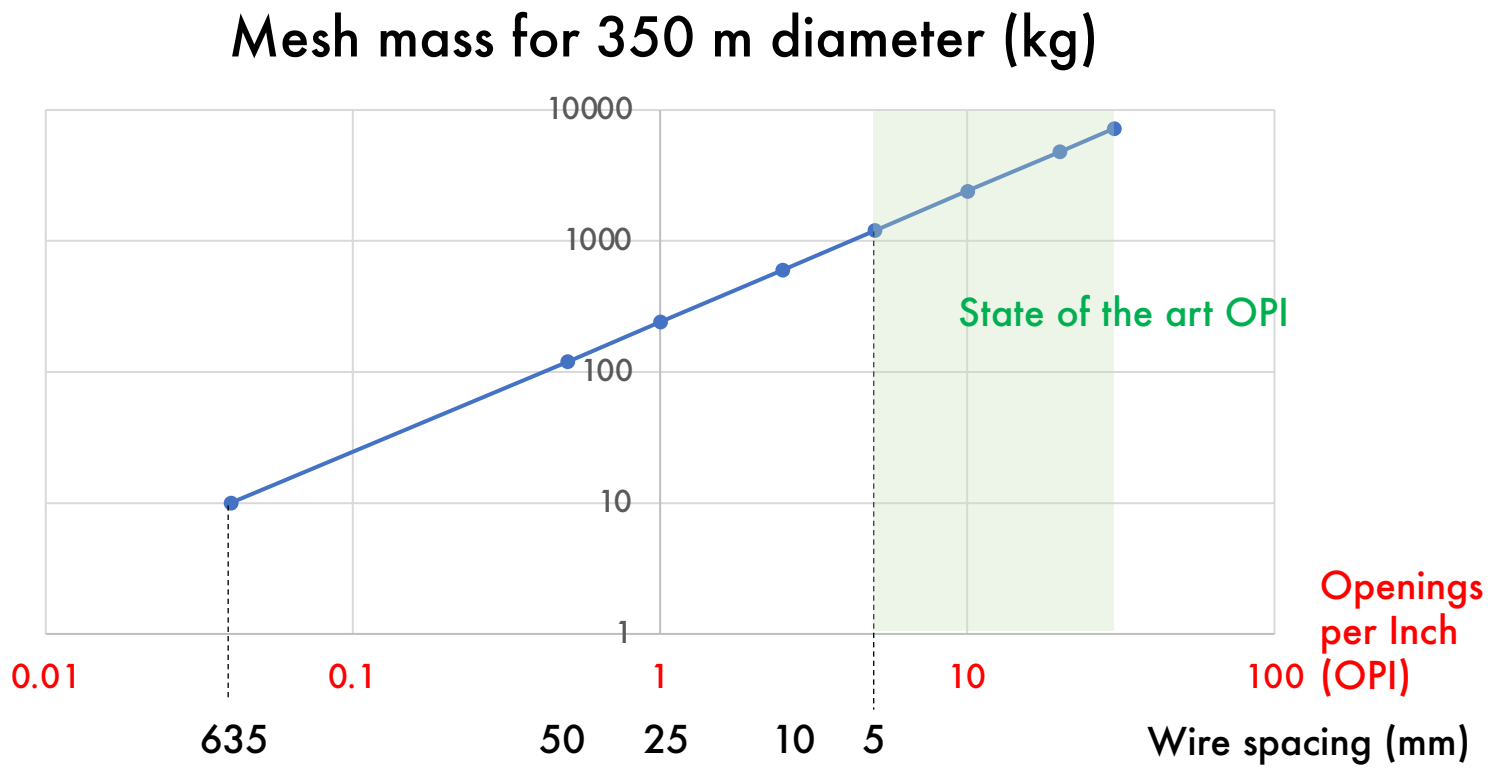
Design of the Reflector Mesh



Secant Group's Knit Gold Antenna Mesh



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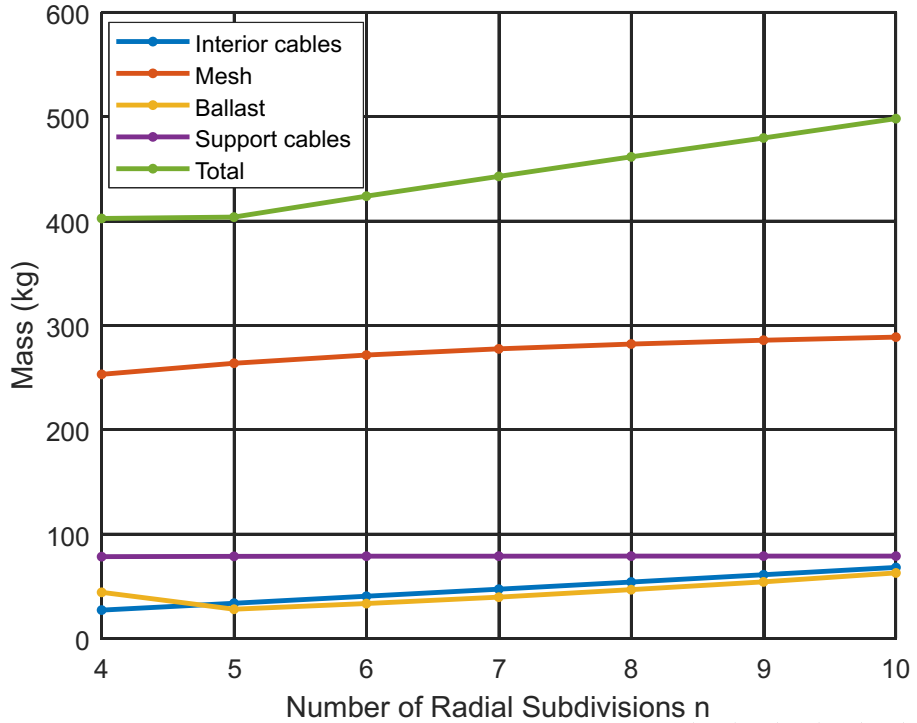
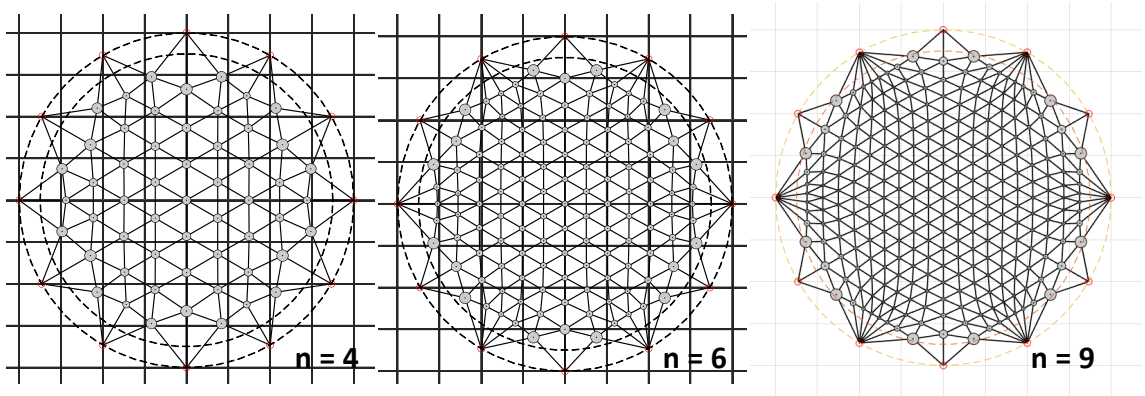
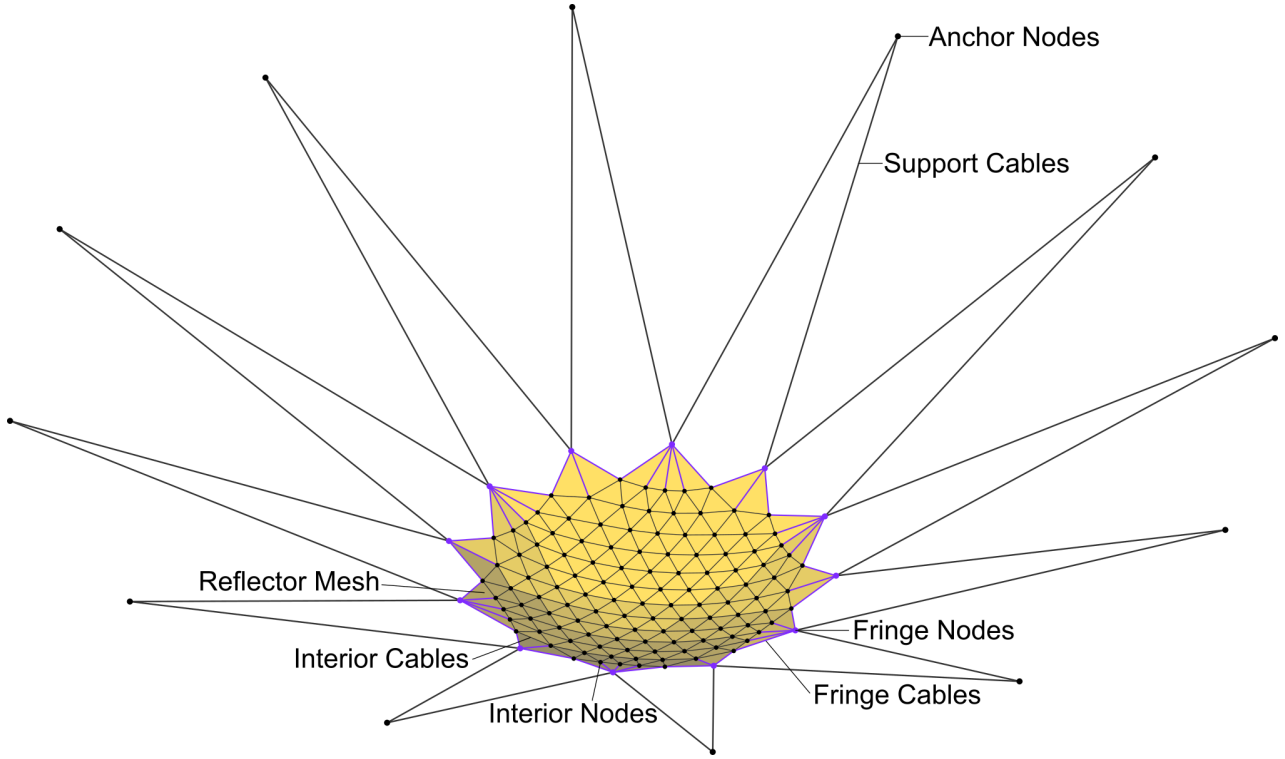
Design of the Reflector





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]**

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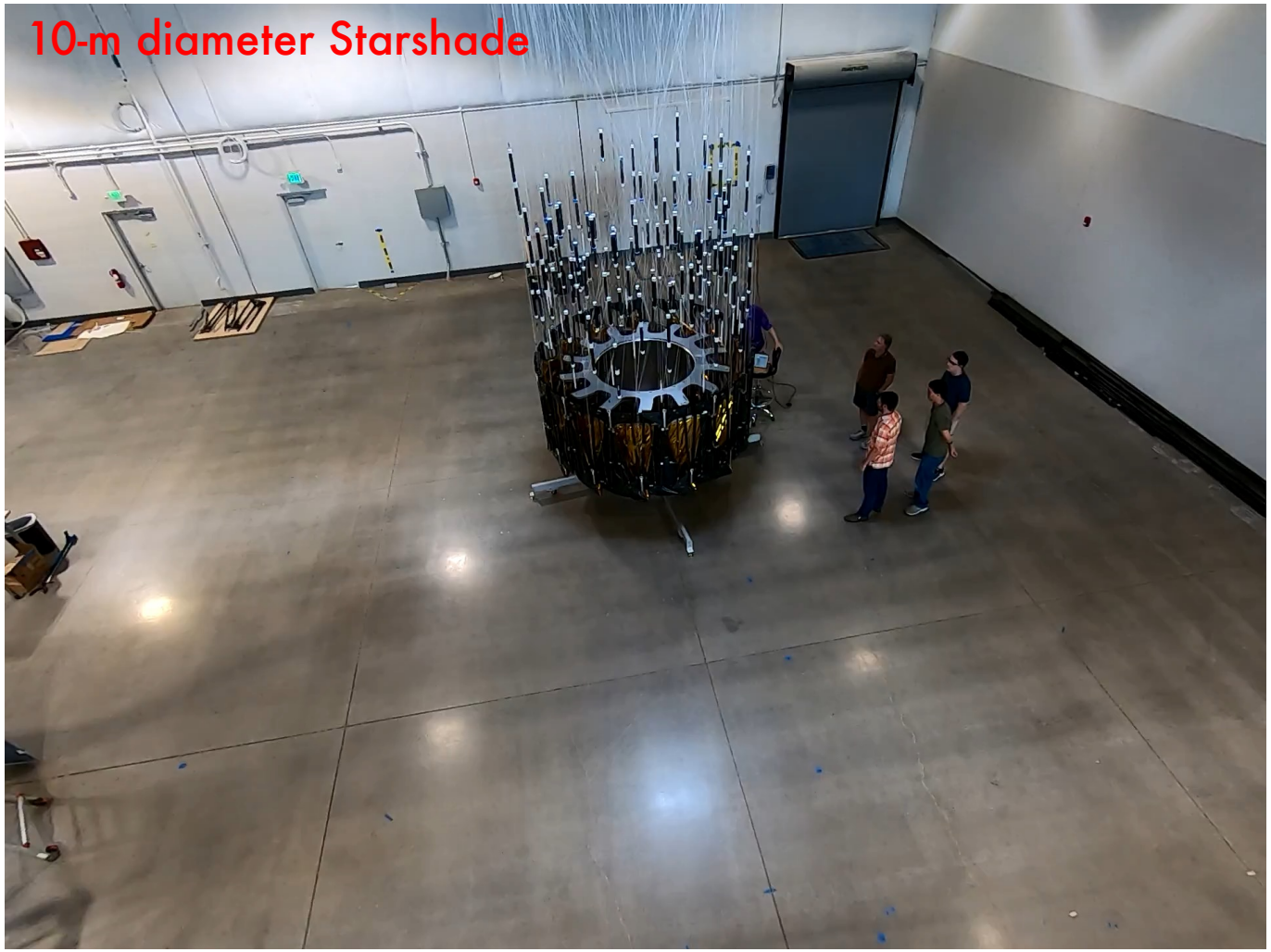
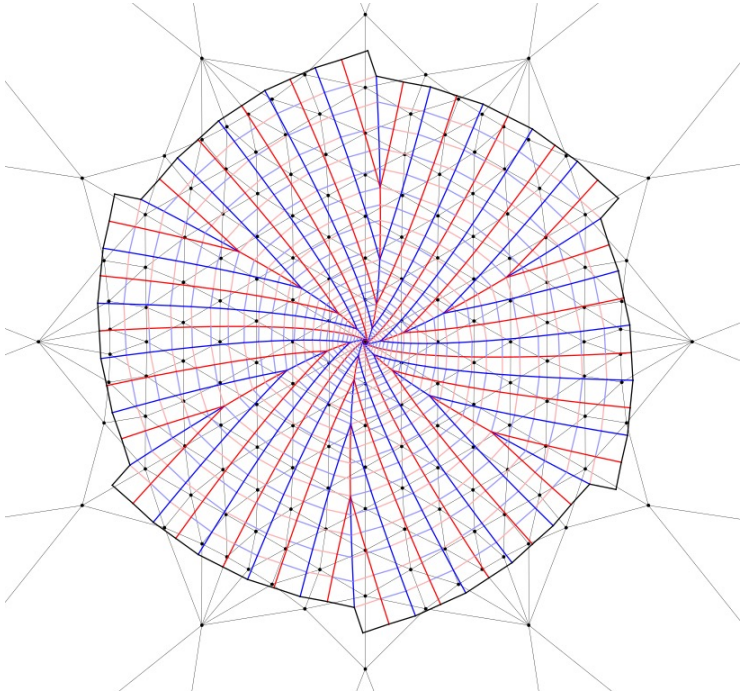
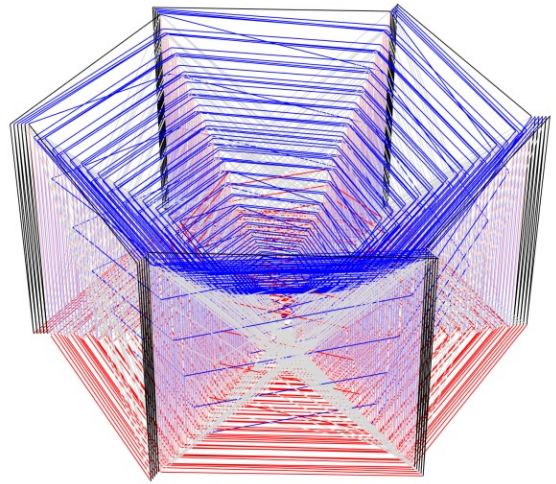
Deployment of the Reflector







[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).

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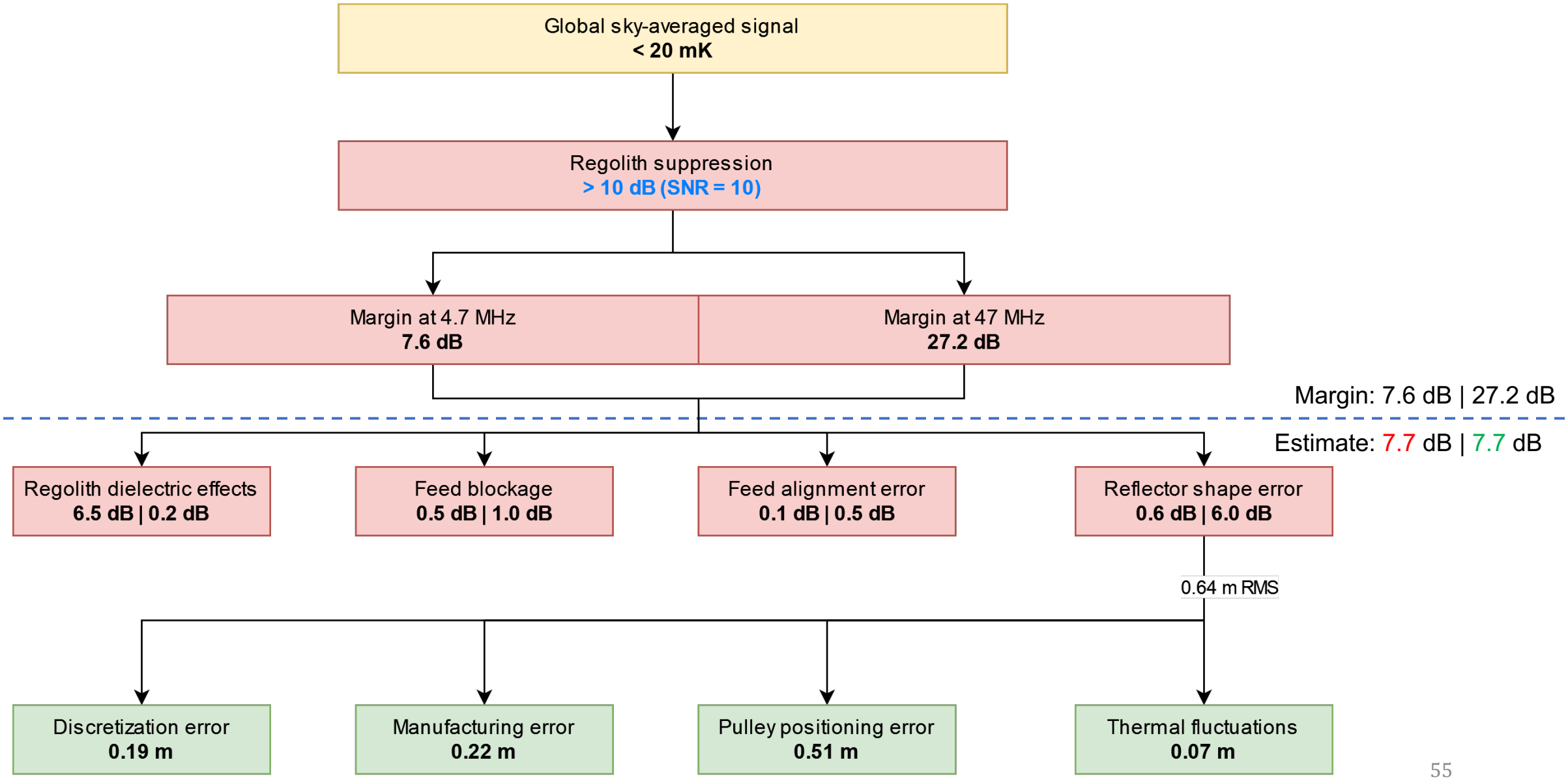
Telescope Error Budget



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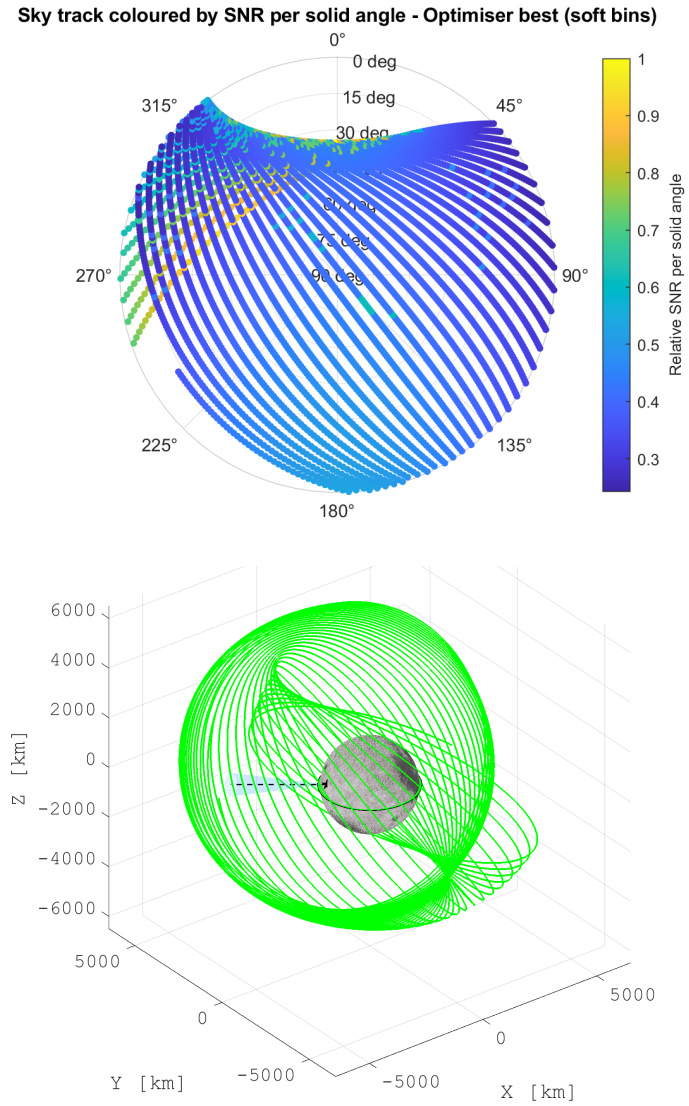
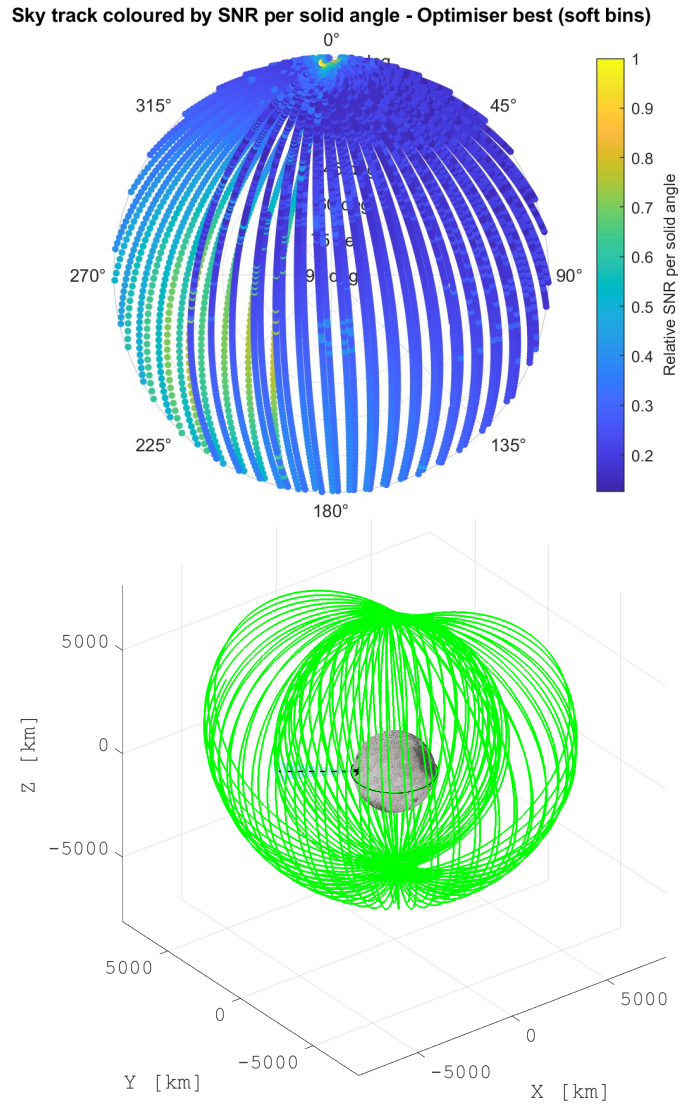
Calibrate LCRT from Orbit

Find optimized orbits such that a beacon spacecraft could calibrate LCRT within 1 lunar night, or 2 lunar nights.

1 lunar night



2 lunar nights



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