Measuring Synchrotron Emission from the Radiation Belts with a Lunar Near Side Radio Array

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Key Non-Polar Destinations Across the Moon to Address Decadal-level Science Objectives with Human Explorers: Panel on Heliophysics, Physics, and Physical Science

Outline

- Synchrotron Emission
- State of the Art Understanding & Measurements
- Lunar Array Potential
- Sensitivity Requirements
- Array Layout
- Base Logarithmic Array vs FarView
- Simulated Images
- Conclusions & Future Work

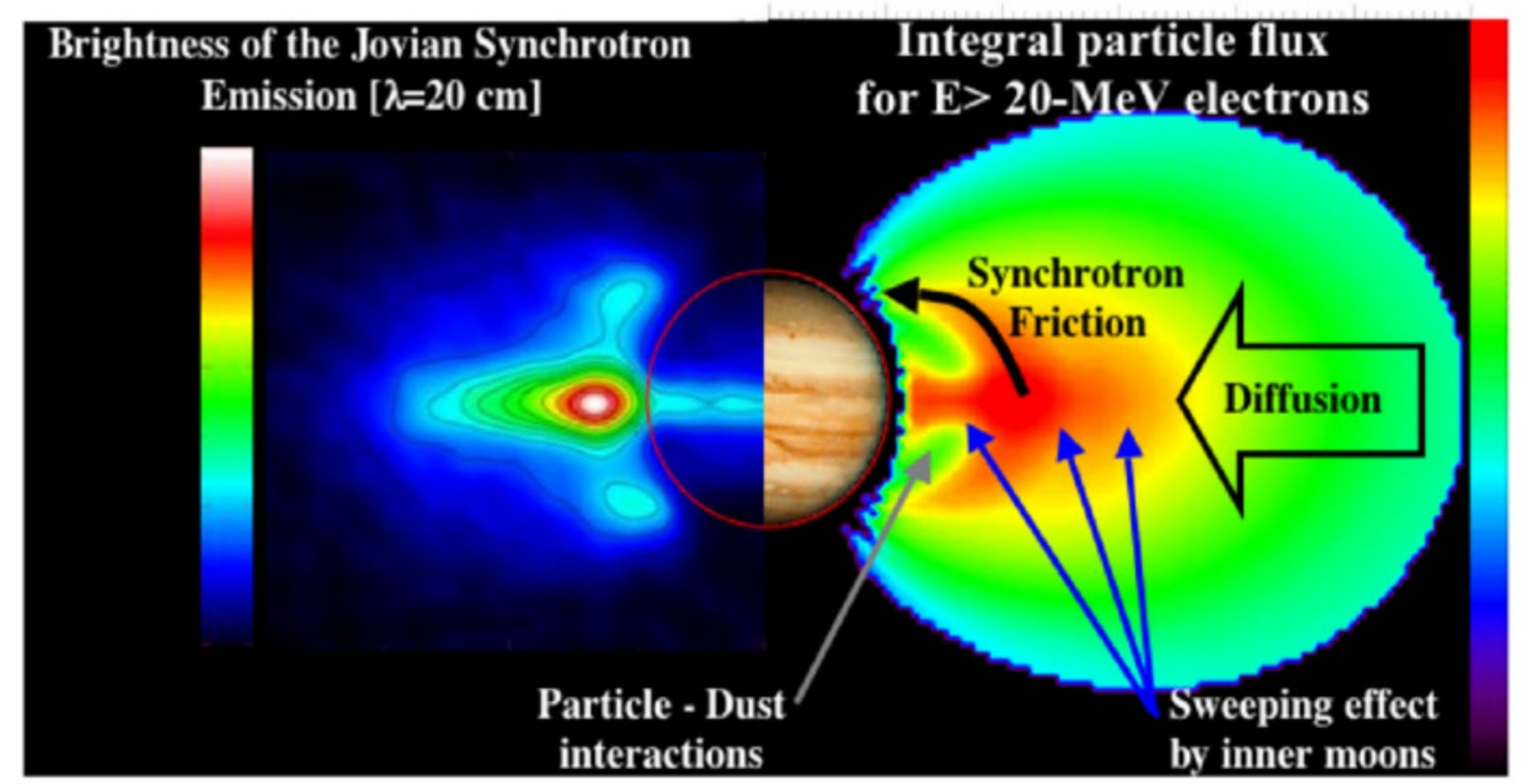
Synchrotron Emission

- The high kinetic energy electrons that populate the Earth's radiation belts emit synchrotron emissions because of their interaction with the planetary magnetic field.
- Emission provides near real time measure of how the radiation belts are globally responding to the current solar input
- E in Mega electron-volts (MeV) and pitch angle α, planetary magnetic field B Gauss

$$f_c = \frac{qB}{2\pi m} \qquad f_{peak} \approx 4.8 E^2 B \sin\alpha$$

Jovian Synchrotron Emission

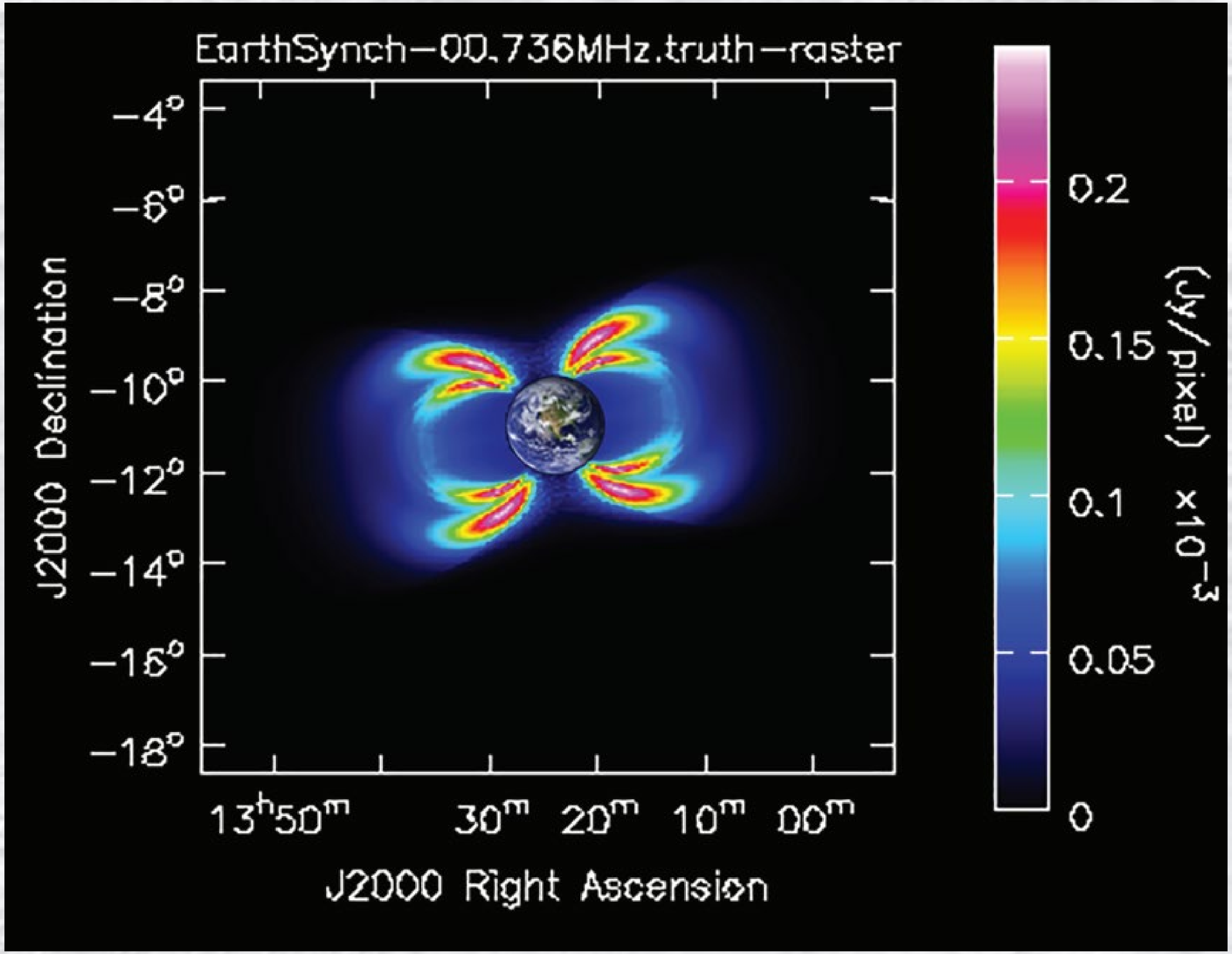
- 100s of MHz
- Magnetic moment of Jupiter is $1.59 \cdot 10^{30}$ G/cm^3
- ≥1-MeV electrons of 10^8 electrons per cm^2/s
- Peaks at 9.5 Jovian radii, energies above 1,000 MeV



D. Santos-Costa, S.J. Bolton / Planetary and Space Science 56 (2008) 326–345

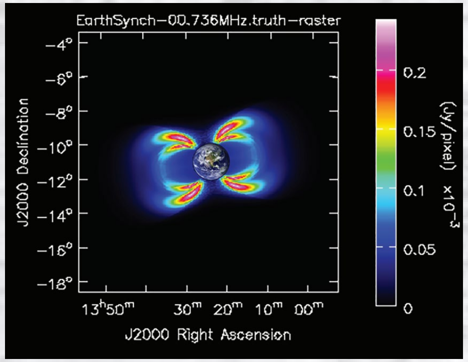
Earth's Synchrotron Emission

- 100s of kHz
- Magnetic moment of Earth's is $2.10 \cdot 10^{25}$ G/cm^3
- Earth has a peak flux of ≥1-MeV electrons of 10^7 electrons per cm^2/s
- Peak energies in Earth's magnetosphere at 6 Earth radii below 10 MeV



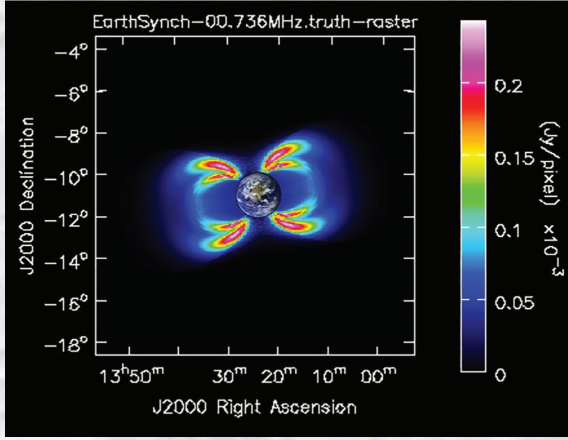
State of the Art Understanding & Measurements

- Salammbô code models solves the three-dimensional phase-space diffusion equation of electrons in magnetosphere
  - Models Coulomb collisions with neutral and plasma populations
  - Wave-particle interactions,
  - Radial diffusion
  - Magnetopause shadowing induced dropouts
  - Models L-shells 1-10 Earth radii
  - Uses THEMIS-SST electron distribution measurements as boundary condition
  - Kalman Filter for Data Assimilation of Kp plasmapause
  - Modeled Calm and Storm time as seen from the Moon

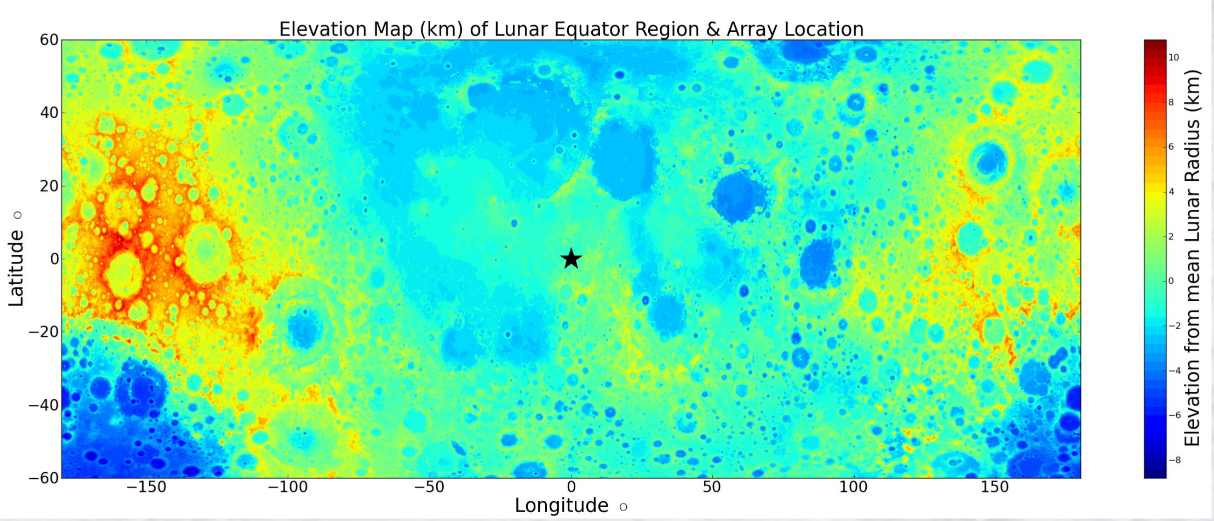


Maget, V., et al. "Improved outer boundary conditions for outer radiation belt data assimilation using THEMIS-SST data and the salammbo-enkf code" (2015)

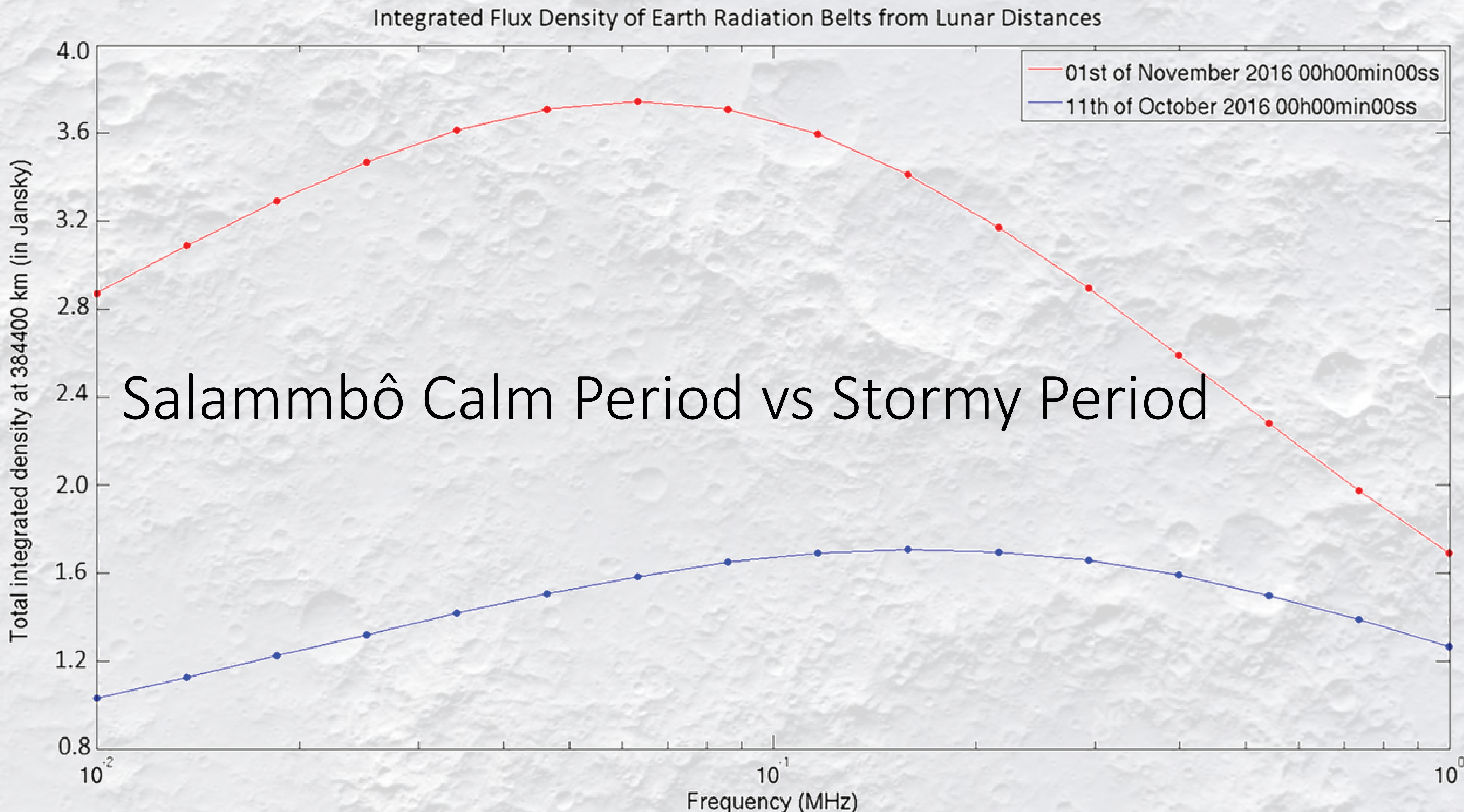
Why go to the Moon?



- Ionospheric Cutoff restricts observation from the ground
- Earth satellites can sample local electron distributions (THEMIS-SST)
- Moon is stable vantage point to spread out large telescope
- Lunar L1 is only ~16% closer, large satellite clusters still difficult
- Gets a global picture across 500-1000 kHz, infers global electron distribution
- Earth is 1.9 degrees from the Moon, matching possible resolution
- Potential in situ resource utilization (ISRU) reduces launch mass



Salammbô Calm Period vs Stormy Period



Noise Sources/Additional Science Targets: *Transients*

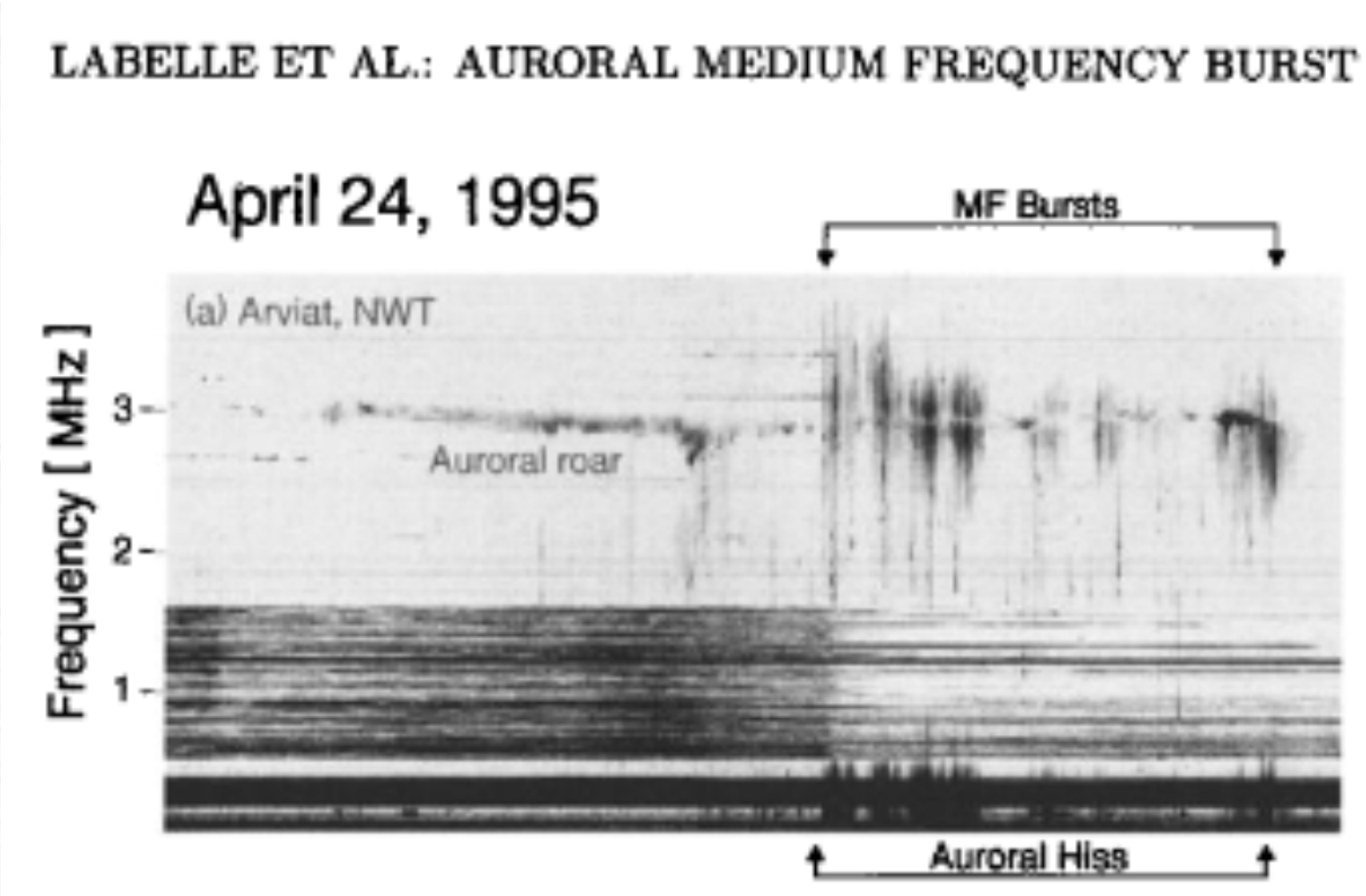
Primary Synchrotron Science Band

0.5 – 1.0 MHz

Marginal Science Band

1.0-1.5 MHz

Avoids most transients

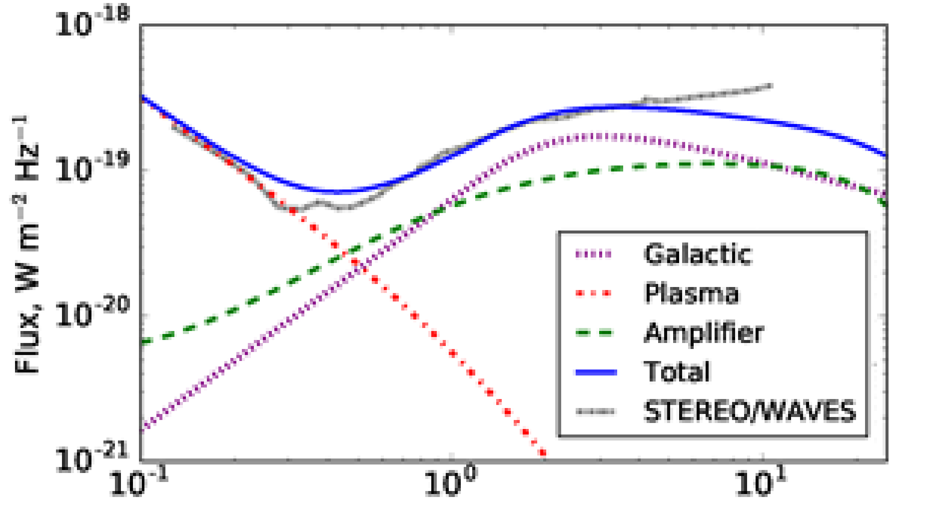


Noise Sources/Additional Science Targets: *Transients*

Transient Source	Frequency Range	Lunar 1 MHz Flux Density	Occurrence Rate	10 km Overresolution
Auroral Kilometric Radiation	50-800 kHz	10^{10} Jy	50% of night	0.2-0.4 deg at 500 kHz, 10x better
Earth Continuum Emission	30-200 kHz	10^{5} Jy	60% total, highest near midnight	N/A, low frequency
Medium Frequency Bursts	1.5-4.3 MHz	10^{6} Jy	every 6-20 hours Kp correlation Beamed	0.7 deg at 3 MHz
Auroral Hiss	Continuous 0-30 kHz Impulsive 100-600 kHz	$6.1*10^{8}$ Jy	MF correlation	0.3 deg at 500 kHz
Auroral Roar	2.8-3.0 MHz	10^{6} Jy	1 every 3-5 hours Kp correlation	0.7 deg at 3 MHz
Solar Radio Bursts	100s kHz – 100s MHz	10^{6} Jy - 10^{8} Jy	Solar cycle dependent	N/A bursts scatter over time

Noise Sources/Additional Science Targets: *Constants*

Unavoidable Noise	Lunar 1 MHz Flux Density	Notes
Galactic Brightness	$5*10^6$ Jy	Acts like correlated noise
Amplifier Noise	10^7 Jy	Comparable to Wind & SunRISE
Electron QTN Optimal	$3*10^5$ Jy	$n_e = 8/cm^3$
Electron QTN Moderate	10^7 Jy	$n_e = 250/cm^3$
Electron QTN Conservative	$6*10^7$ Jy	$n_e = 1000/cm^3$



$$\sigma = \frac{2\,k_B\,T_{sys}}{\eta_s\,A_{eff}\,\sqrt{N(N-1)(N_{IF}\,\Delta T\,\Delta\nu)}}$$

$$V^2_{QTN} \simeq 5.10^{-5}\frac{n_e T_e}{f^3 L},$$

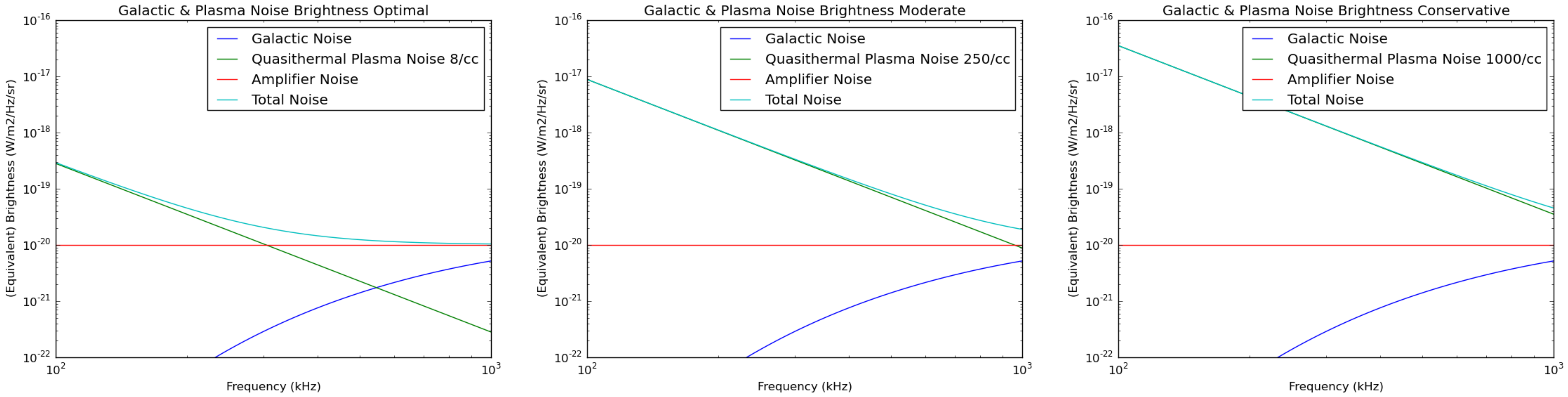
Constant Noise Budgets

Average noise taken over 500-1000kHz

Average = 1.1e-20 W = 1.1e6 Jy
8/cc electron density, solar wind

Average = 3.66e-20 W = 3.66e6 Jy
250/cc electron density, moderate

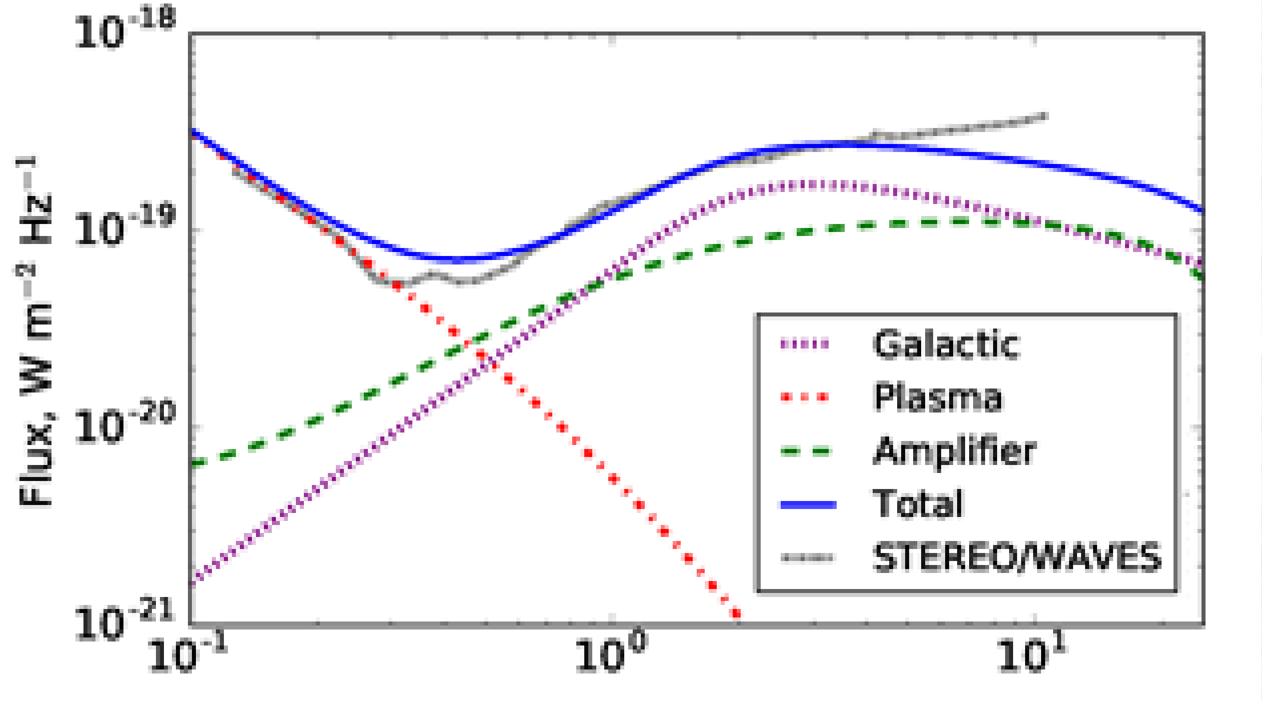
Average = 1.16e-19 W = 1.16e7 Jy
1000/cc electron density, conservative



Signal to Noise Calculation

- Dominant 750 kHz background sources:
  - Galactic Emission
  - Amplifier Noise
  - Quasi-thermal Electron Noise

- QTN driven by electron density, can change over lunar day
  - Photoionization of lunar dust
  - Highest at lunar noon

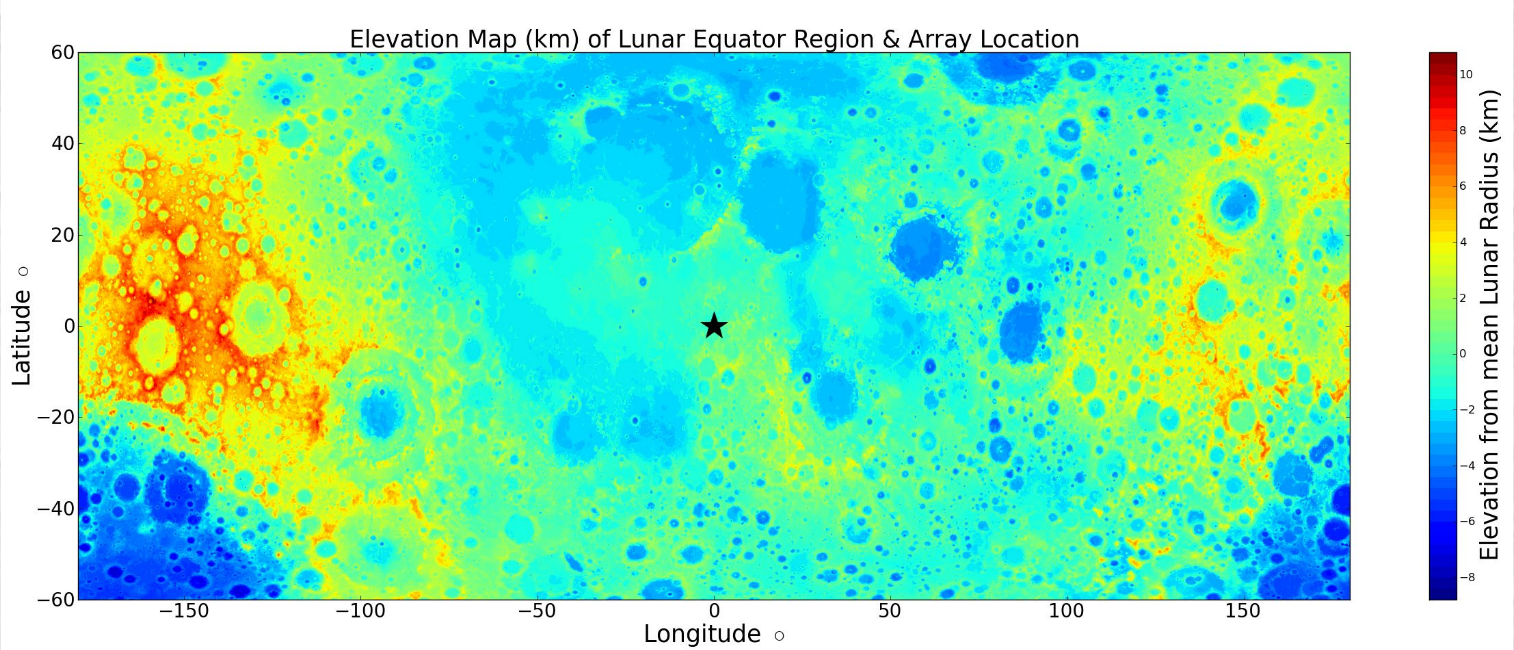


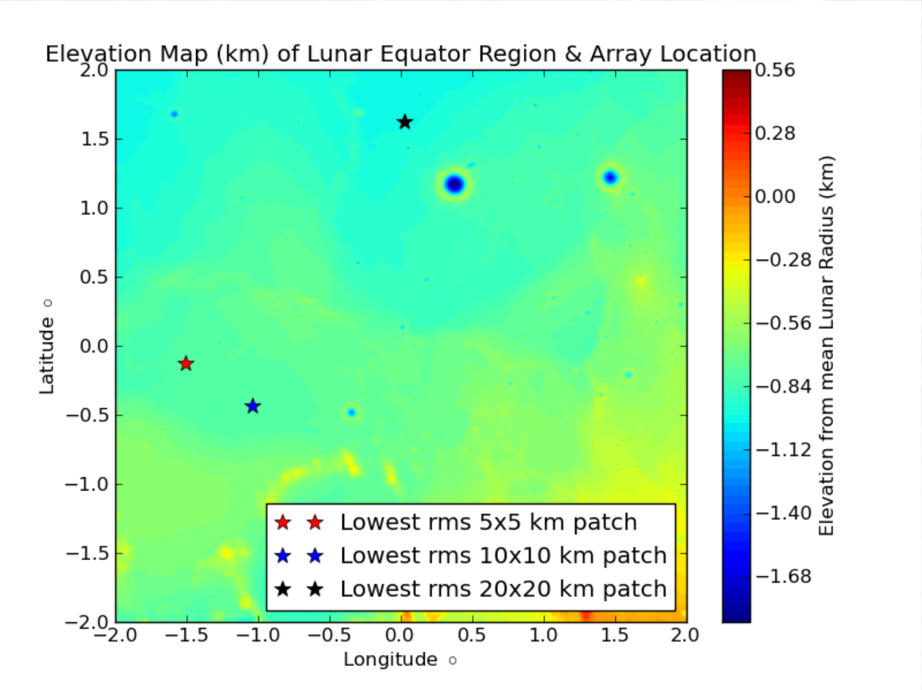
Taken from SunRISE CSR

$$\sigma = \frac{2\,k_B\,T_{sys}}{\eta_s\,A_{eff}\,\sqrt{N(N-1)(N_{IF}\,\Delta T\,\Delta\nu)}}$$

Creating Lunar Arrays

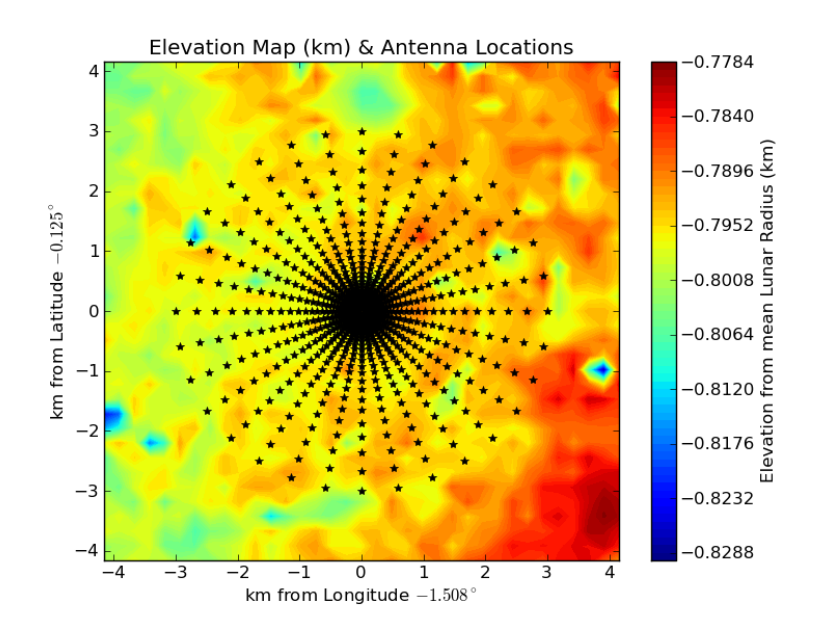
- LRO Laser Altimeter Data for Topography
- SPICE for orientation of Lunar coordinates with Sky and Earth
- CASA to handle simulated interferometric data
- Focused on sub-Earth point, but many near side locations would be ok

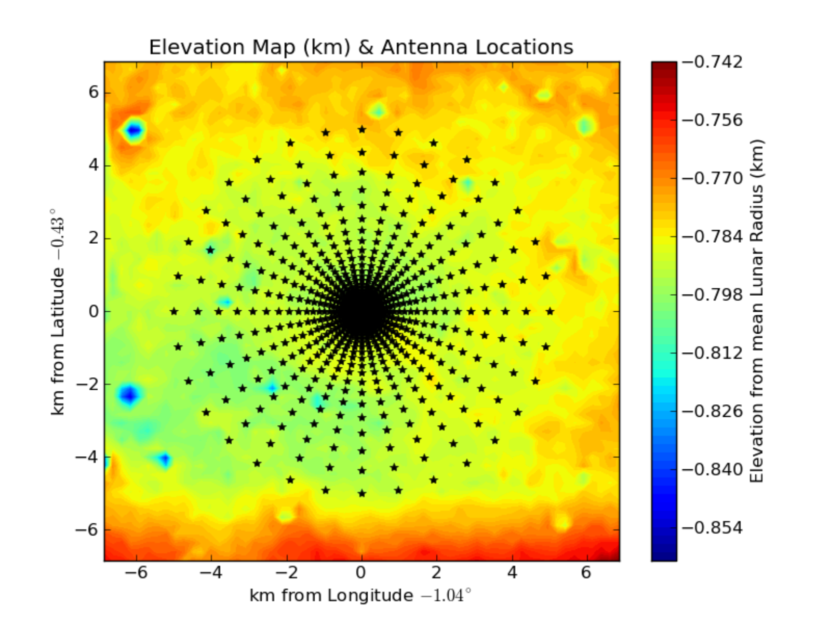


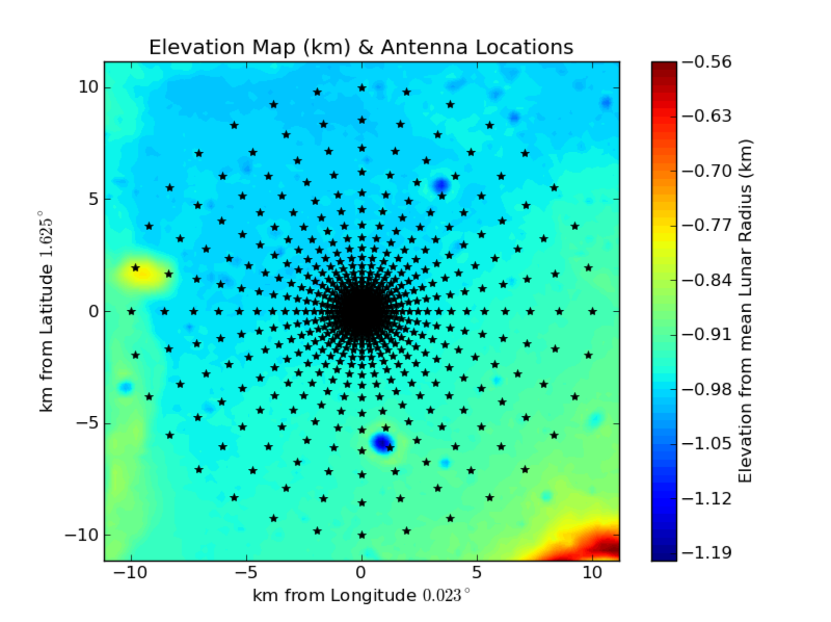


Creating Lunar Arrays

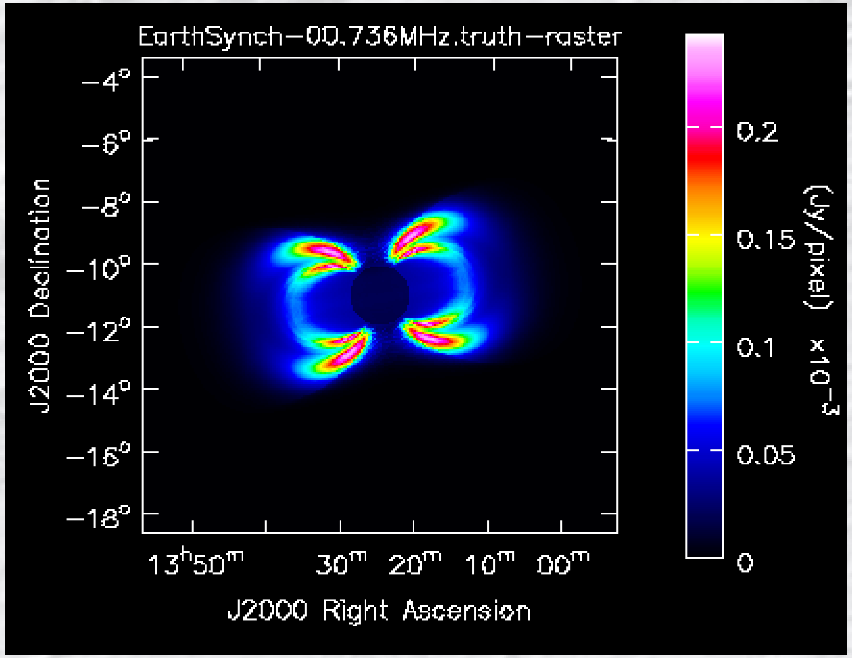
- Simulate 6, 10, and 20 km diameter arrays
- Best if on region of large crustal thickness to reduce intensity of subsurface echoes
- Minimal surface elevation rms preferable

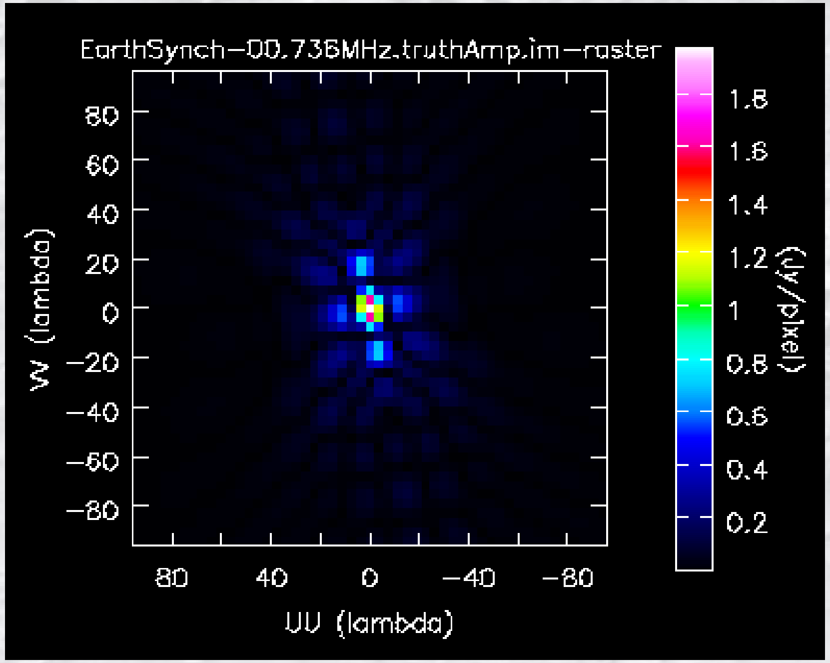


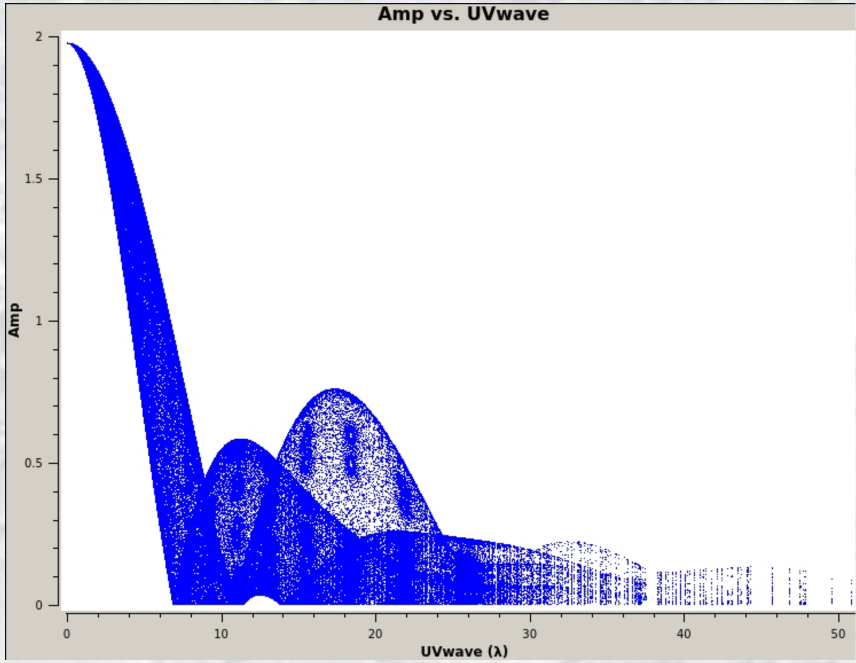




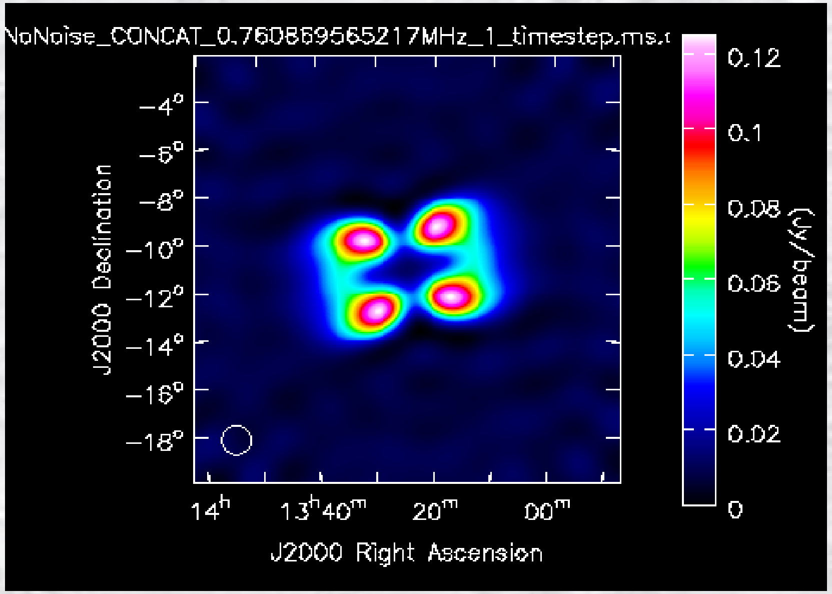
Salammbô Output as Ground Truth

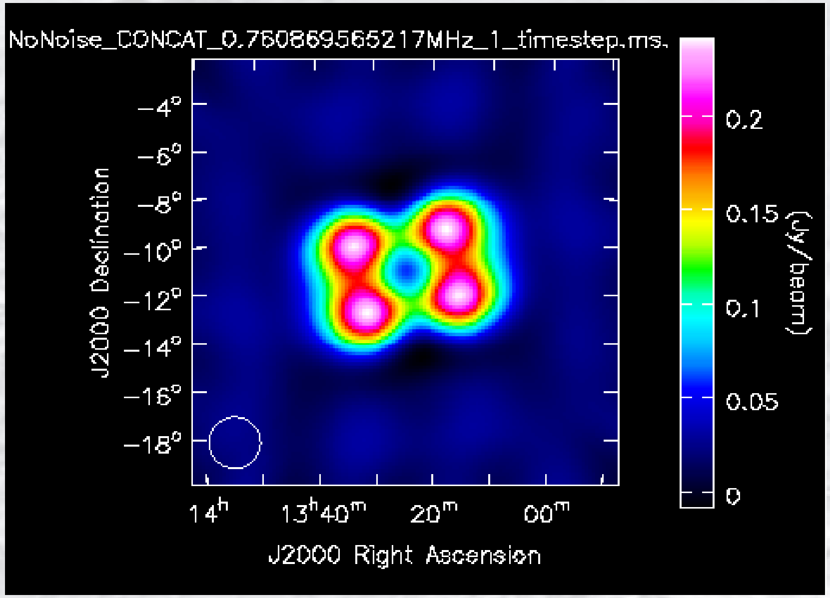


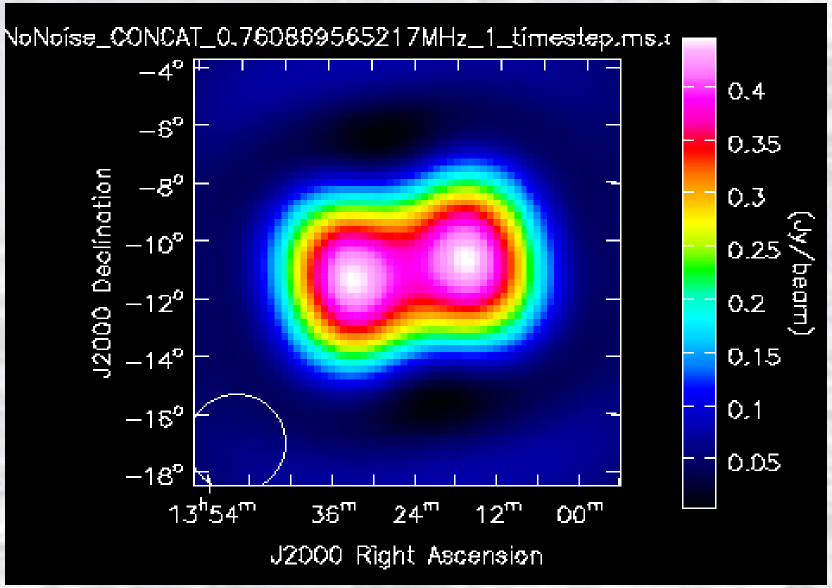




- Most power/information comes from
- baselines ≤ 30 λ long (12 km) to 10 % max power
- baselines ≤ 6 λ long (2.4 km) to 50 % max power



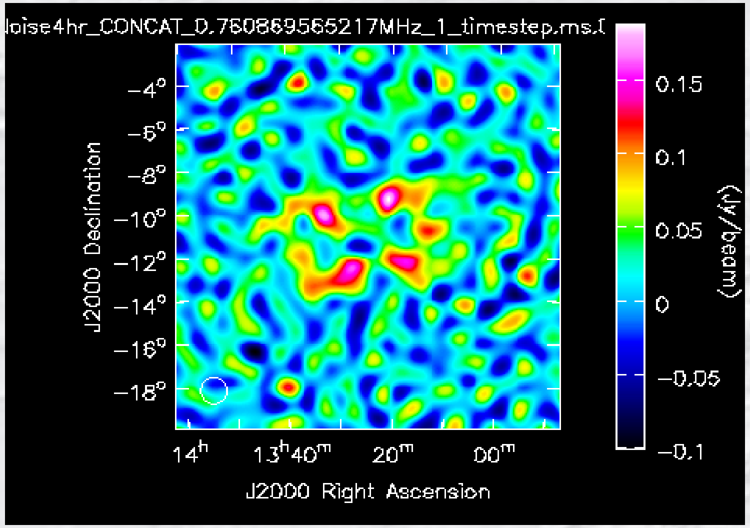


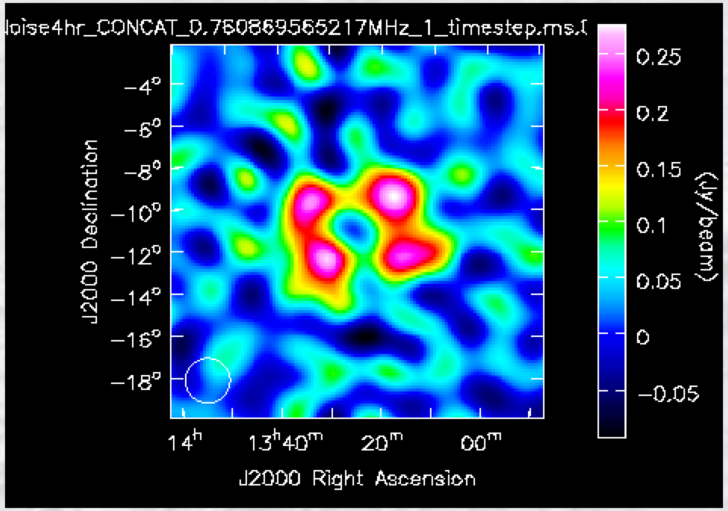


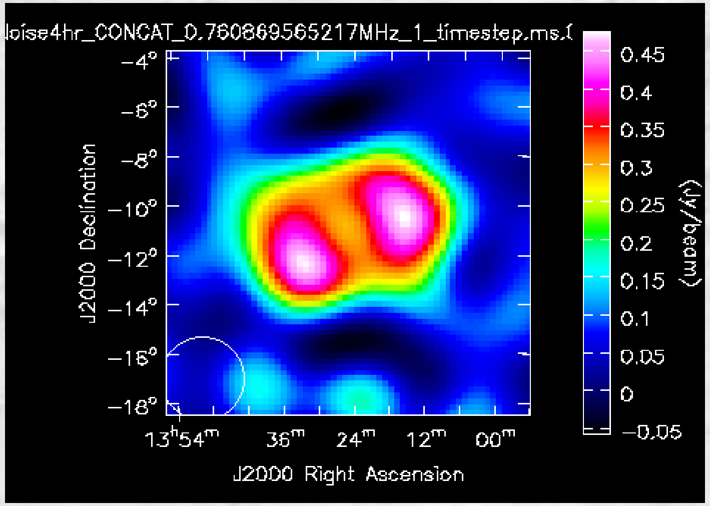
20 km, 4 hours integration
optimal noise 16k antenna,
image rms = .0318, 3.93 SNR

10 km, 4 hours integration
optimal noise 16K antenna,
image rms = .041, 5.85 SNR

6 km, 4 hour integration,
optimal noise 16K antenna,
image rms = .073, 6.44 SNR

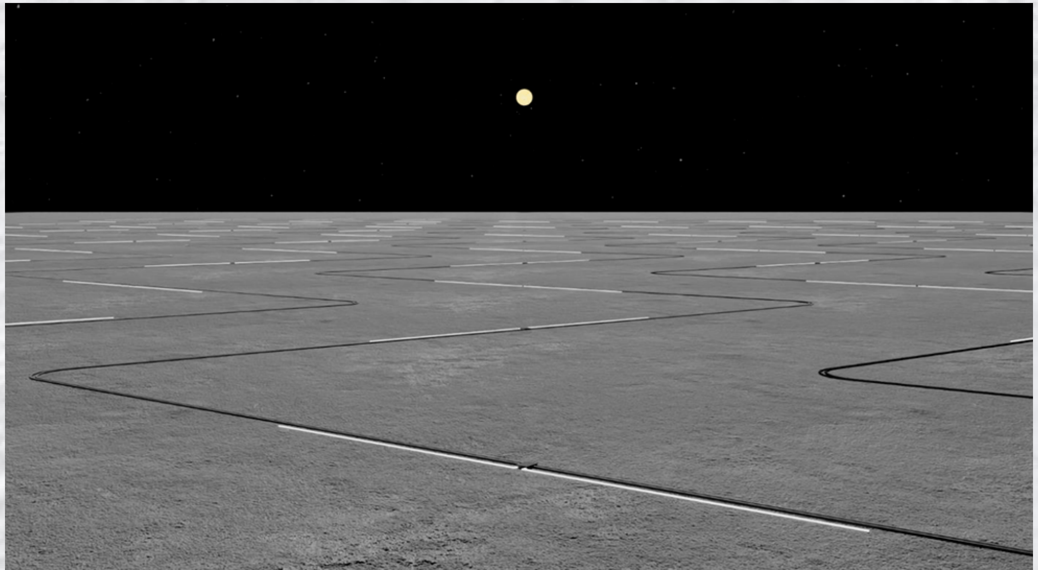




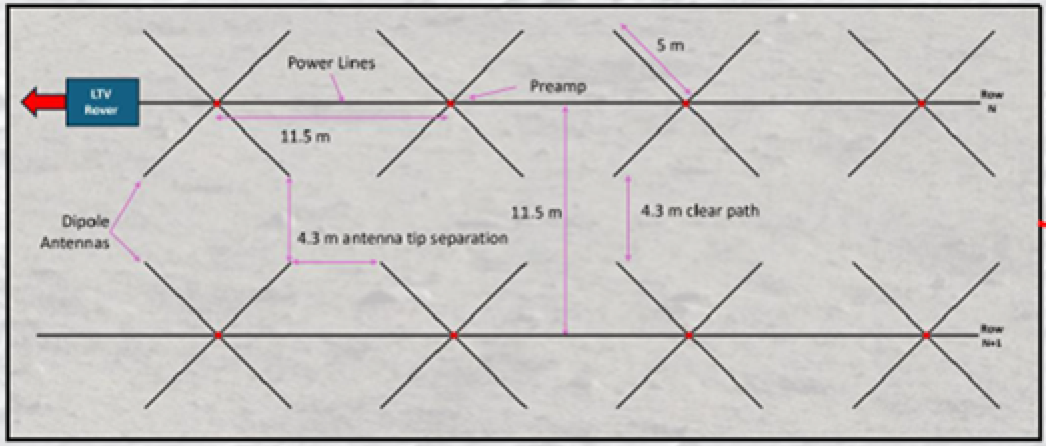


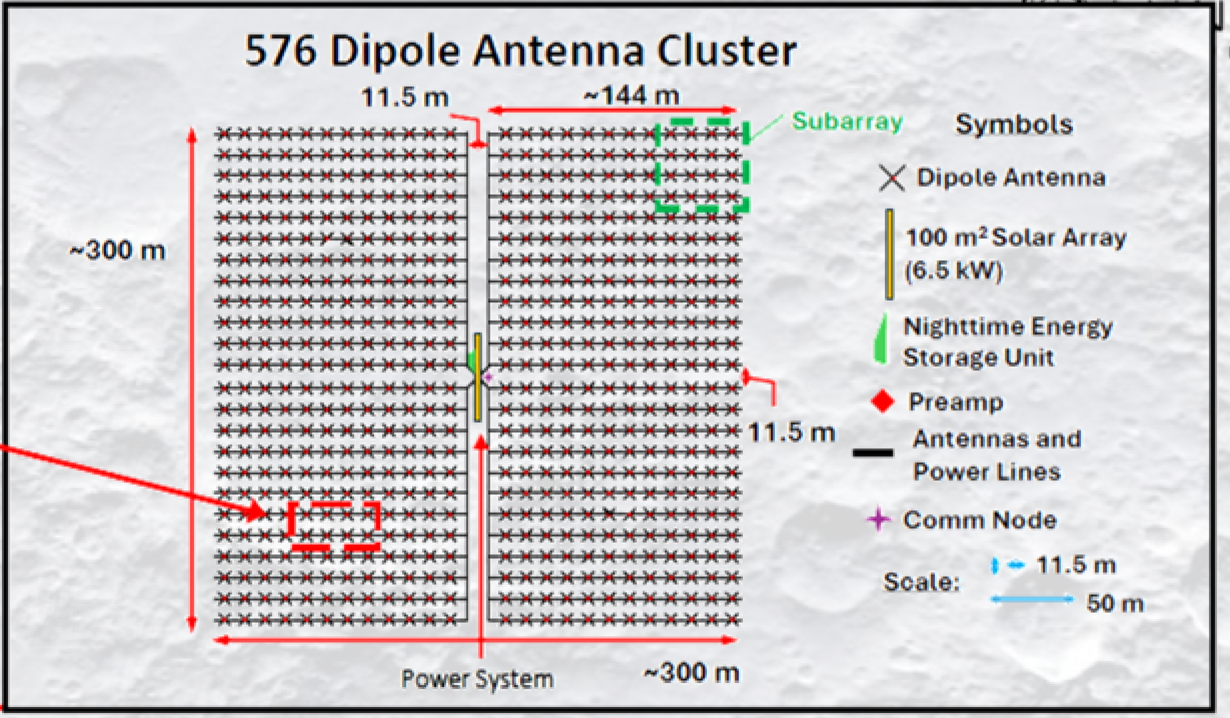
Modernized approach

- FarView uses NASA funded technology using in situ resource utilization (ISRU) to print ~100K cross dipole antenna from the lunar regolith
- Primary science is from radio quiet zone on the far side, but same technology applicable on the near side
- ISRU enables scale needed for sensitive measurements
- Just finished NIAC Phase II Study
- 21-cm early universe cosmology
- Rovers do most the work, humans could provide robustness



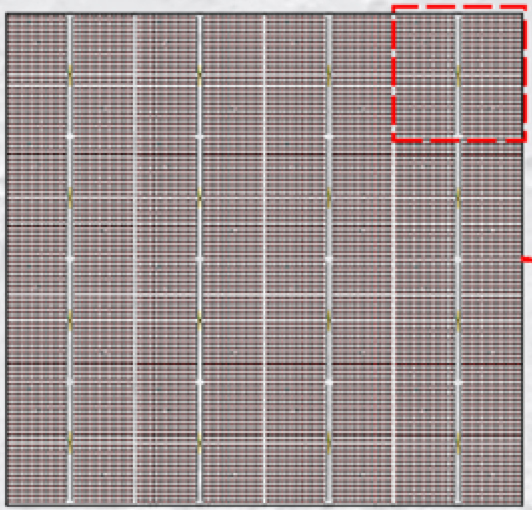
FarView Architecture

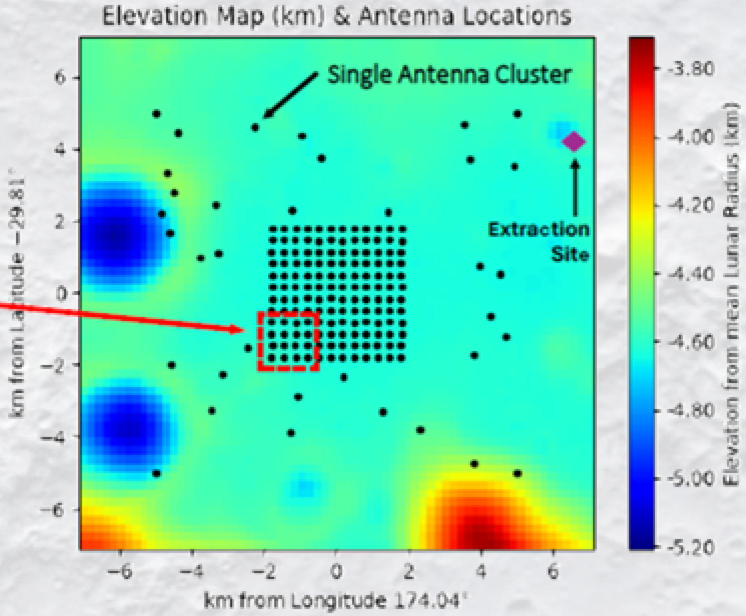




16 Antenna Clusters
(1/9th of the core)

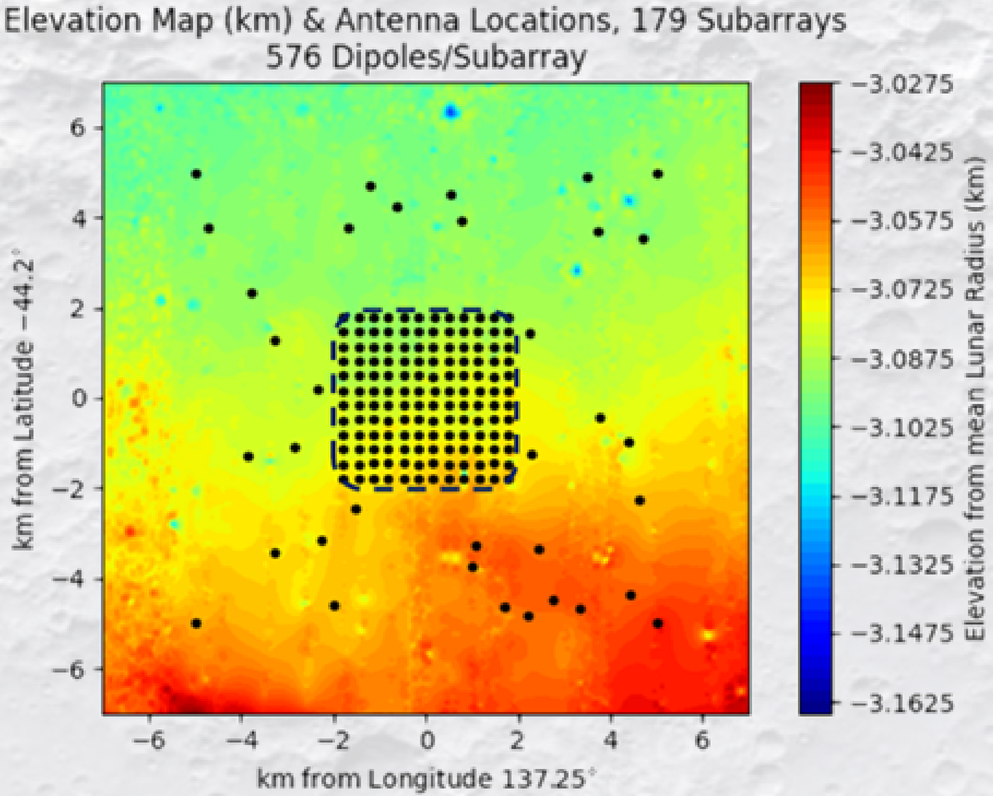
Each Antenna Cluster is separated from adjacent Antenna Clusters by 11.5 meters.



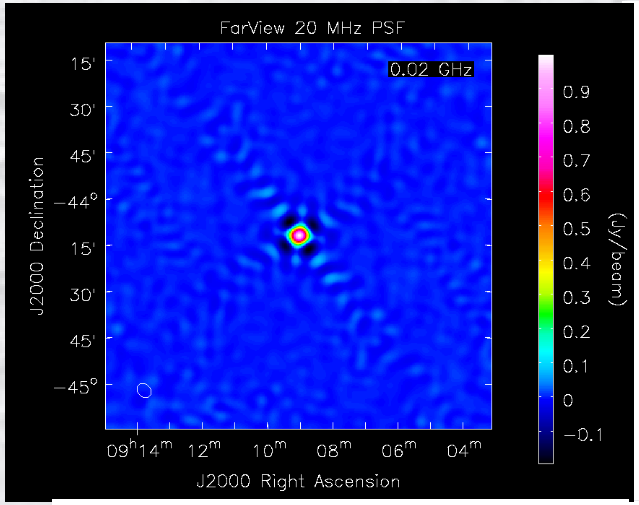


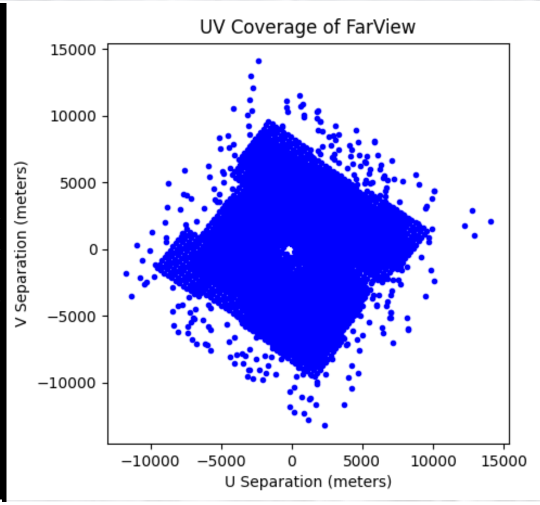
FarView's Antenna Cluster distribution (all 179) and the extraction site shown in an elevation map of Birkeland crater.

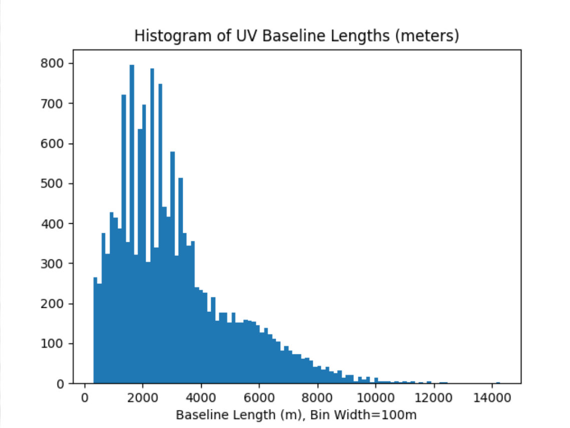
FarView Simulations

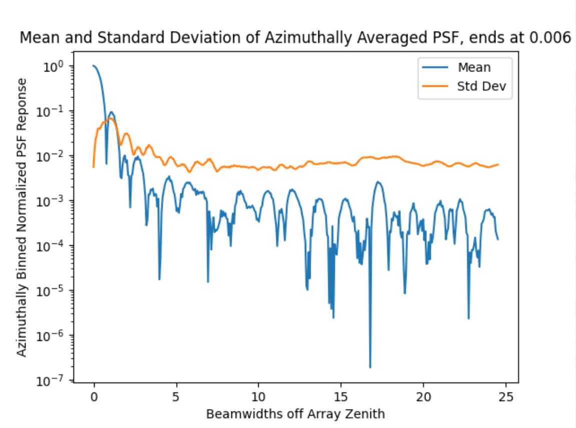


~6 km core, ~14 km diameter halo.
80-20 split in core-outriggers (82,944 – 20,160)
Each subarray shares power, 576 dipoles/subarray
Each subarray is 36x16-dipole beamforming units
6444 total beamforming units





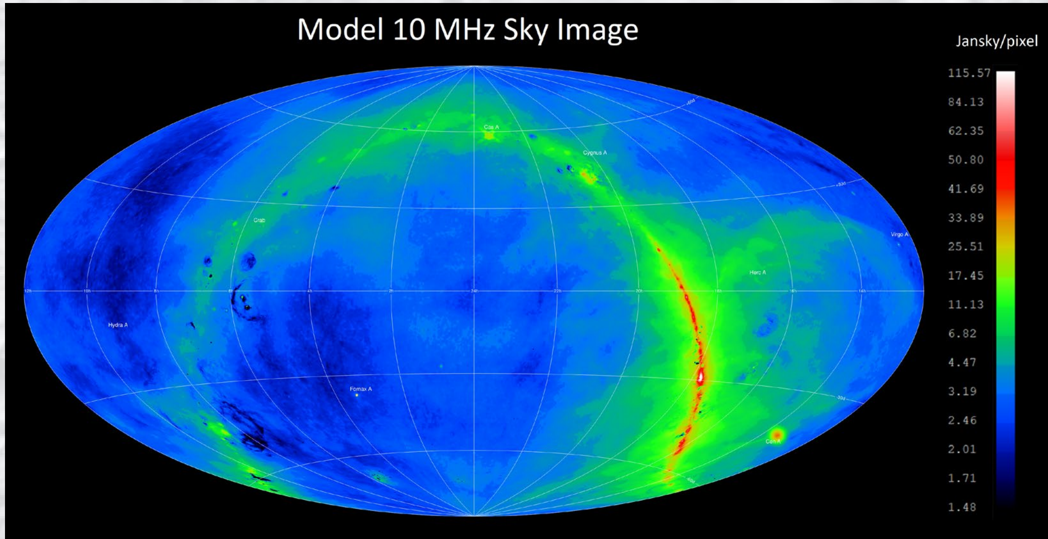




Point spread function from *FarView's* 179 subarrays from the left. This simulated observation uses a snapshot of from instantaneous uv-coverage. Achieves sub 1% sidelobes.

Bootstrapping Low Frequency Sky Maps

- Constraining a Model of the Radio Sky below 6 MHz Using the Parker Solar Probe/ FIELDS Instrument in Preparation for Upcoming Lunar-based Experiments
- SunRISE launching soon with 6 CubeSats in this frequency range
- ROLSES-1 of CLPS gave a small sample of data from the Moon
- LuSEE Night coming soon with radio measurements on the lunar surface
- Characterization of galaxy will help more sensitive observations of other targets
  - Like 21-cm early universe cosmology



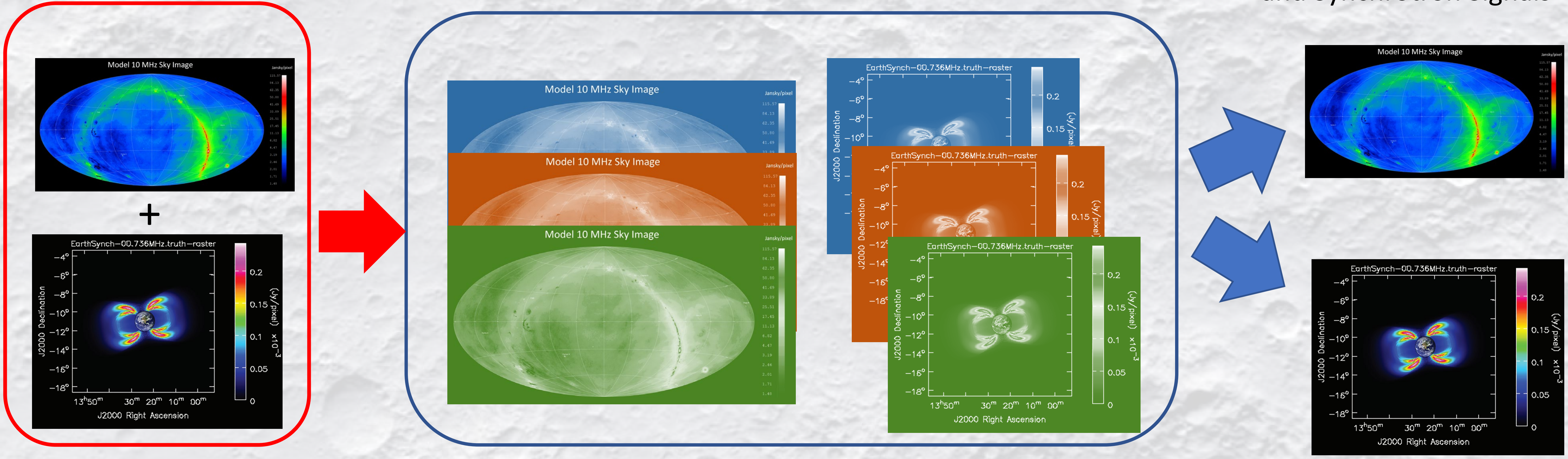
Plans for pylinex analysis

eg Tauscher et al. 2018 “Global 21 cm Signal Extraction from Foreground and Instrumental Effects. I. Pattern Recognition Framework for Separation Using Training Sets“ ApJ

Input: Observed GSM + Synchrotron

Trained pylinex model from many variations of separate data

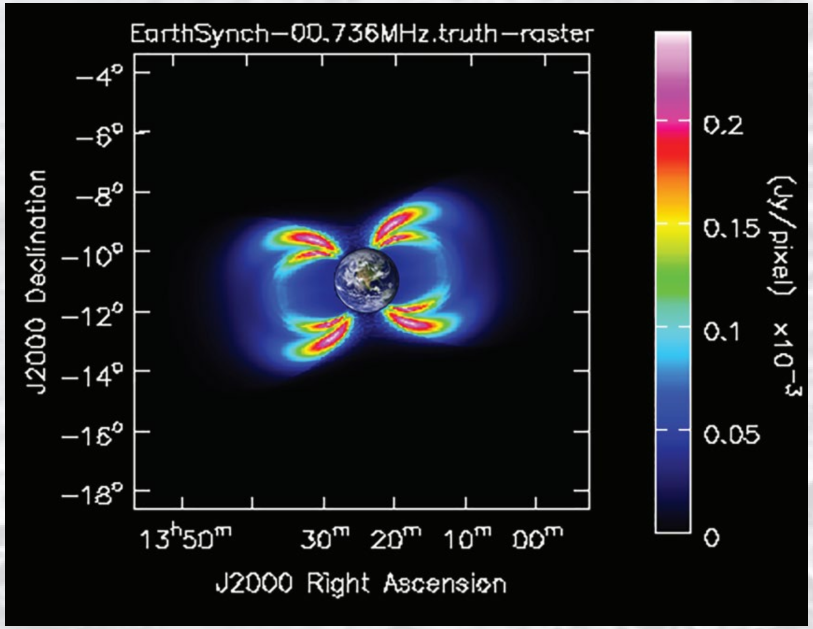
Output: Separated GSM and Synchrotron Signals

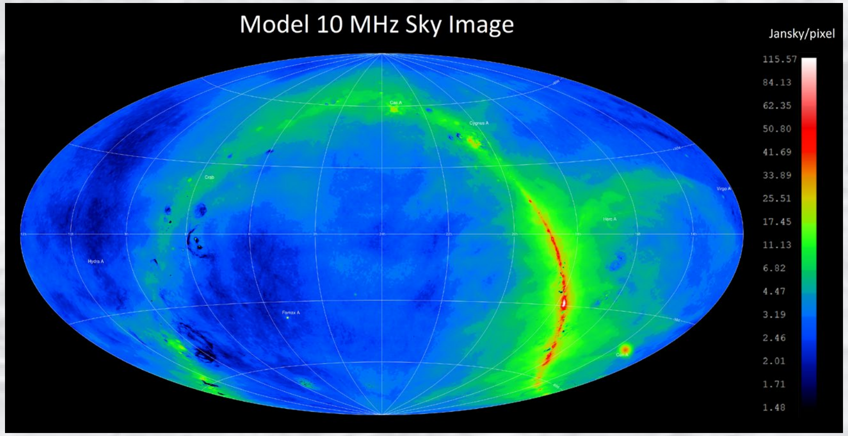


End Goal: Trained model to separate all instrumental effects and competing signals

Conclusions & Future Work

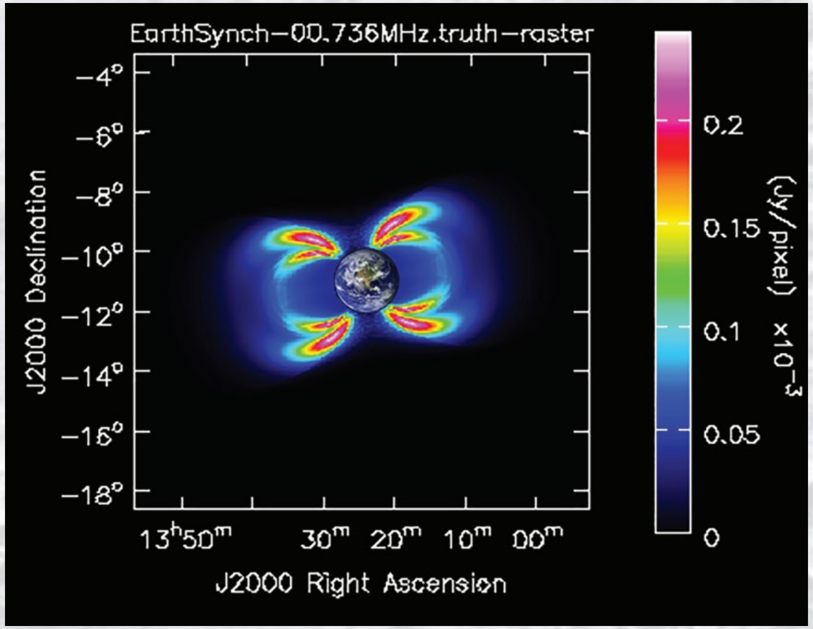
- Near side of the Moon provides a unique vantage point for observing Earth's space weather
- For a moderate lunar surface electron density of 250/cm^3, radiation belts might be detectable ~daily
- 10x harder or easier depending on local electron noise / Lunar time of day
- Output images allow analysis of global and local electron distributions around Earth

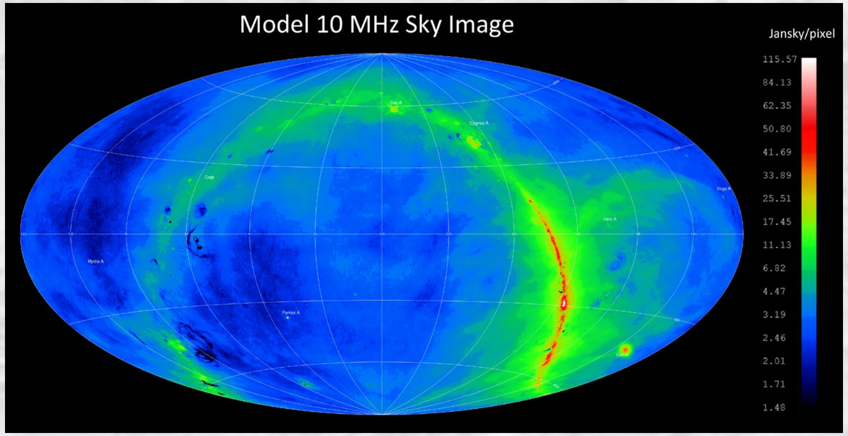




Conclusions & **Future Work**

- Next: Bootstrap Sky Maps with future missions like LuSEE Night and SunRISE
- Next: Foreground Modeling of Galaxy over whole Field of View
- Next: Study possible effects of mutual coupling on array sensitivity
- Next: Modeling Antenna Beam, Systematics, and signal combined w/ pylinex





Acknowledgements & Citations

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D. Santos-Costa, S.J. Bolton "Discussing the processes constraining the Jovian synchrotron radio emission's features" *Planetary and Space Science 56 (2008) 326–345*

Polidan, R. et al." FarView: An in-situ manufactured lunar far side radio array concept for 21-cm Dark Ages cosmology" Advances in Space Research, 74:1 (2024).

Hegedus, A.M. et al., 2020. Measuring the Earth's synchrotron emission from radiation belts with a lunar near side radio array. Radio Sci. 55. https://doi.org/10.1029/2019RS006891

LaBelle, J., Shepherd, S. G., & Trimpi, M. L. (1997). Observations of auroral medium frequency bursts. Journal of Geophysical Research, 102, 22,221–22,232. https://doi.org/10.1029/97JA01905

Offringa et al., WSCLEAN: an implementation of a fast, generic wide-field imager for radio astronomy. MNRAS Volume 444, Number 1, 606-619. (2014). 10.1093/mnras/stu1368

McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, Astronomical Data Analysis Software and Systems XVI (ASP Conf. Ser. 376), ed. R. A. Shaw, F. Hill, & D. J. Bell (San Francisco, CA: ASP), 127

Barker, M., et al. A new lunar digital elevation model from the Lunar Orbiter Laser Altimeter and SELENE Terrain Camera. Icarus. 273, 346 – 355 (2016).

Acton, C. H. Ancillary data services of NASA's Navigation and Ancillary Information Facility. Planetary and Space Science. 44, 65–70 (1996).

Astropy Collaboration et al. Astropy: A community Python package for astronomy. Astronomy & Astrophysics, Volume 558, id.A33, 9 pp (2013).

Astropy Collaboration et al. The Astropy Project: Building an Open-science Project and Status of the v2.0 Core Package. The Astronomical Journal, Volume 156, Issue 3, article id. 123, 19 pp. (2018).

Maget, V., et al. (2015). Improved outer boundary conditions for outer radiation belt data assimilation using THEMIS-SST data and the salammbo-enkf code. Journal of Geophysical Research: Space Physics, 120, 5608–5622. https://doi.org/10.1002/2015JA021001

Tauscher et al. 2018 "Global 21 cm Signal Extraction from Foreground and Instrumental Effects. I. Pattern Recognition Framework for Separation Using Training Sets" ApJ.