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

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Introduction

Understanding the energetic electron environment below 6 Earth radii has long been an area of scientific interest as well as practical concern. This information helps us to understand the radiation dosages that spacecraft at different orbits are likely to see over time, which in turn goes into the Total Ionizing Dose (TID) the spacecraft is designed to be tolerant to. The response of the radiation belts to solar input can elicit a variety of responses, complicating the calculation of how much radiation a given spacecraft has actually been exposed to so far. In order for spacecraft industries to track the predicted remaining lifetimes of all their satellites, it would be useful to have some real measure of how many energetic electrons were in Earth's radiation belts at any given time. This is especially useful for the many satellites that do not have energetic particle detectors to measure their received radiation dose. Even with detectors, existing satellites can give only single point *in situ* measurements of the electron distribution from a stable orbit. Measurements of the global synchrotron emission could yield a view of the bigger picture by providing a proxy measurement of the global electron distribution, providing useful constraints for space weather forecasting models and TID calculations. An array capable of such measurements would also be able to localize auroral transient events with high precision, providing local, small scale electron data in addition to global data.

Objectives

- **Formulate a Noise Budget of expected noise sources for an array on the Lunar Surface**
- **Get a physically motivated prediction of the Synchrotron Emission at Earth**
- **Design software pipeline to simulate response of radio array on Lunar Surface**
- **Determine the parameters of a Lunar Array that could recover the expected signal of Earth's Synchrotron Emission**

Understanding Noise Sources

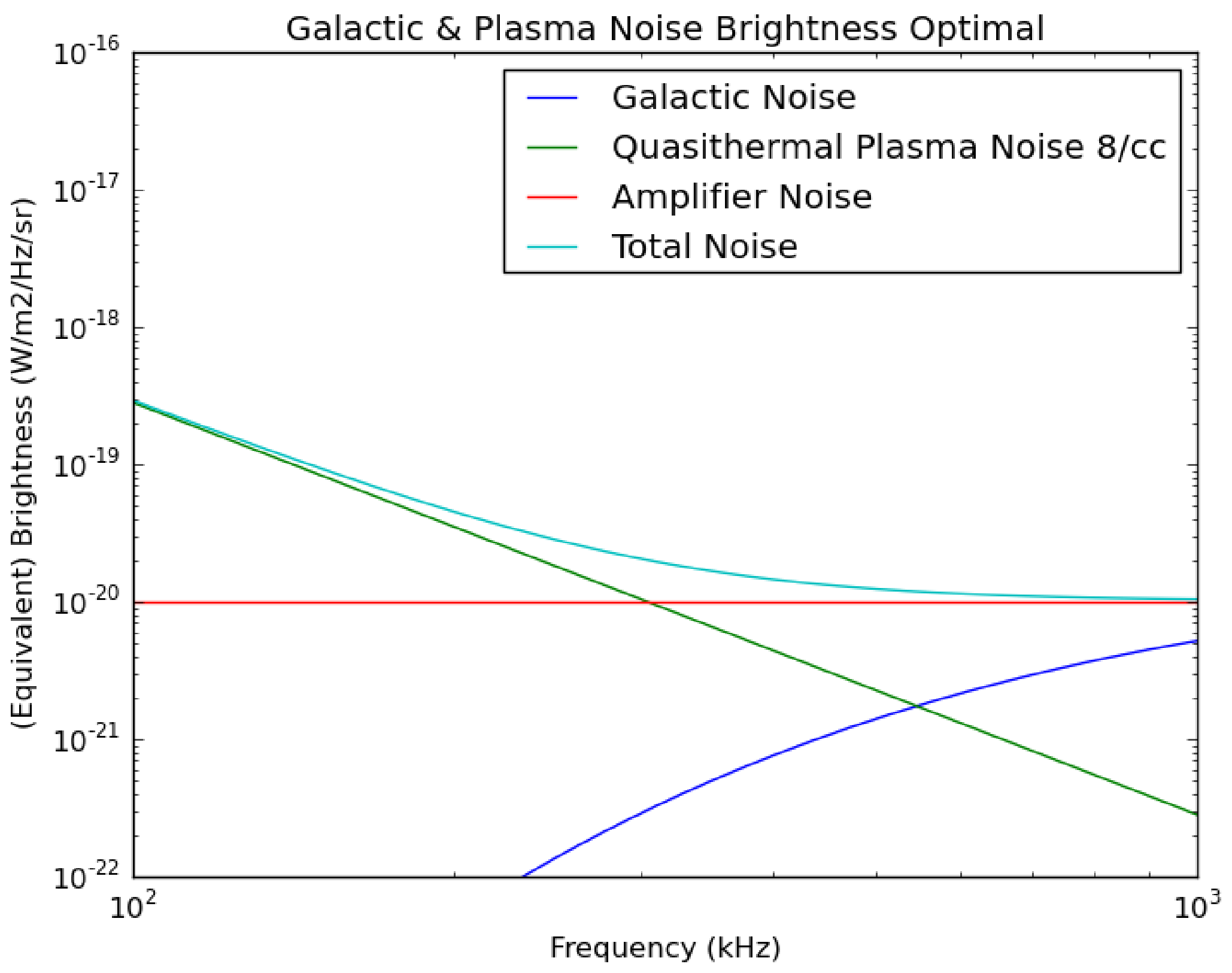
- We decide on a science bandwidth of 500-1000 kHz to avoid most of the transient auroral interference. Calculate Signal to Noise Ratio (SNR) with standard equations [1].

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

- Reduce the noise problem to amplifier noise and electron quasithermal noise [2]

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

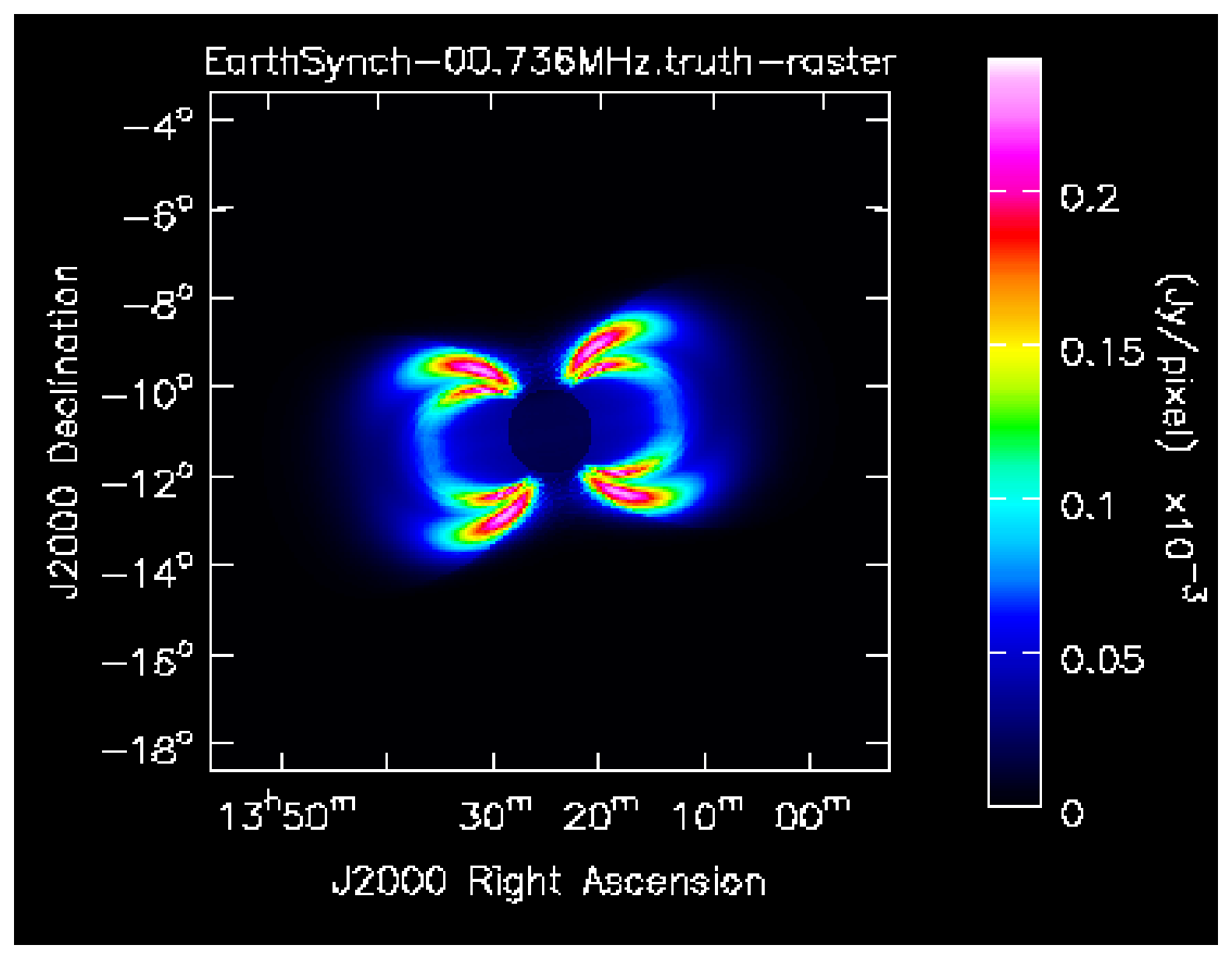
- We create an optimal, moderate, and conservative noise budget by varying the level of electron quasithermal noise, a function mainly of Solar Zenith Angle



Modeling Earth's Synchrotron Emission

The Salammbo code [3] solves the three-dimensional phase-space diffusion equation while modeling Coulomb collisions with neutral and plasma populations around Earth, wave-particle interactions, radial diffusion and magnetopause shadowing induced dropouts. This code uses the Time History of Events and Macroscale Interactions during Substorms/Solid State Telescope (THEMIS-SST) data set of electron distributions up to several hundred keV as a boundary condition. The model also takes Kp as an input, which parameterizes radial diffusion strength and plasmapause position. The output then is analyzed to provide realistic predictions of the brightness of the synchrotron emission up to 1 MHz.

Synchrotron Model Inputs
THEMIS-SST Electron Distributions
Earth's Magnetic Field
Kp – Plasmapause Position



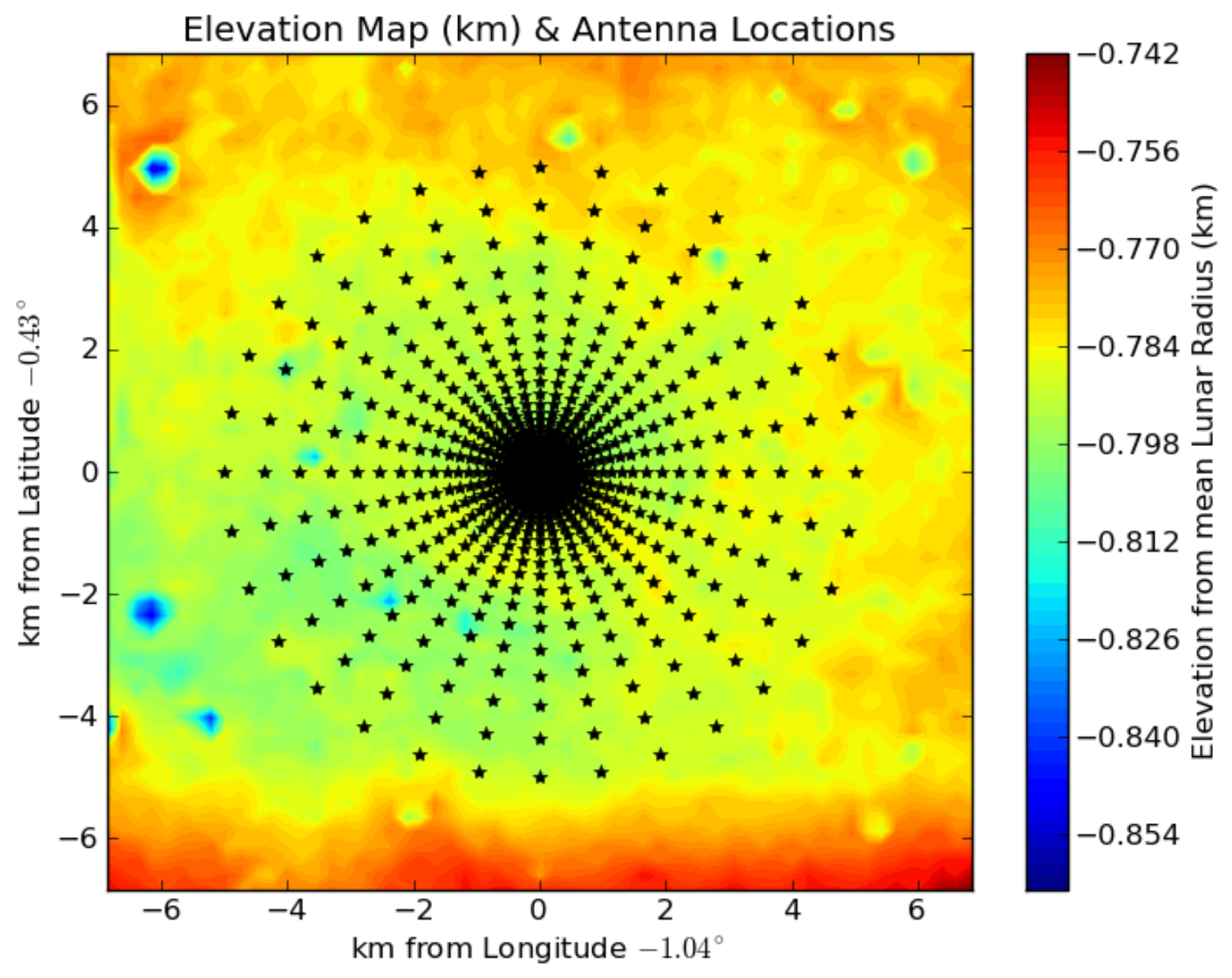
Simulated Synchrotron Brightness of Earth's Radiation Belts from Lunar Distances at 736 kHz

Creating Array Simulation Pipeline

Using Digital Elevation Models from Lunar Reconnaissance Orbiter (LRO) Lunar Orbiter Laser Altimeter (LOLA) data [4], we select a set of locations near the Lunar sub-Earth point with minimum elevation variation over various sized patches where we simulate radio receivers to create a synthetic aperture. We assume that we are using 5 m dual-polarization dipole antennas for all our receivers, and that there is a minimum distance of 15 m between receivers. We use SPICE [5] to align the Moon ME frame to the celestial sky in order to track its relative position with the Sun and Earth. We then use a custom CASA [6] code to image and process the data from our defined array.

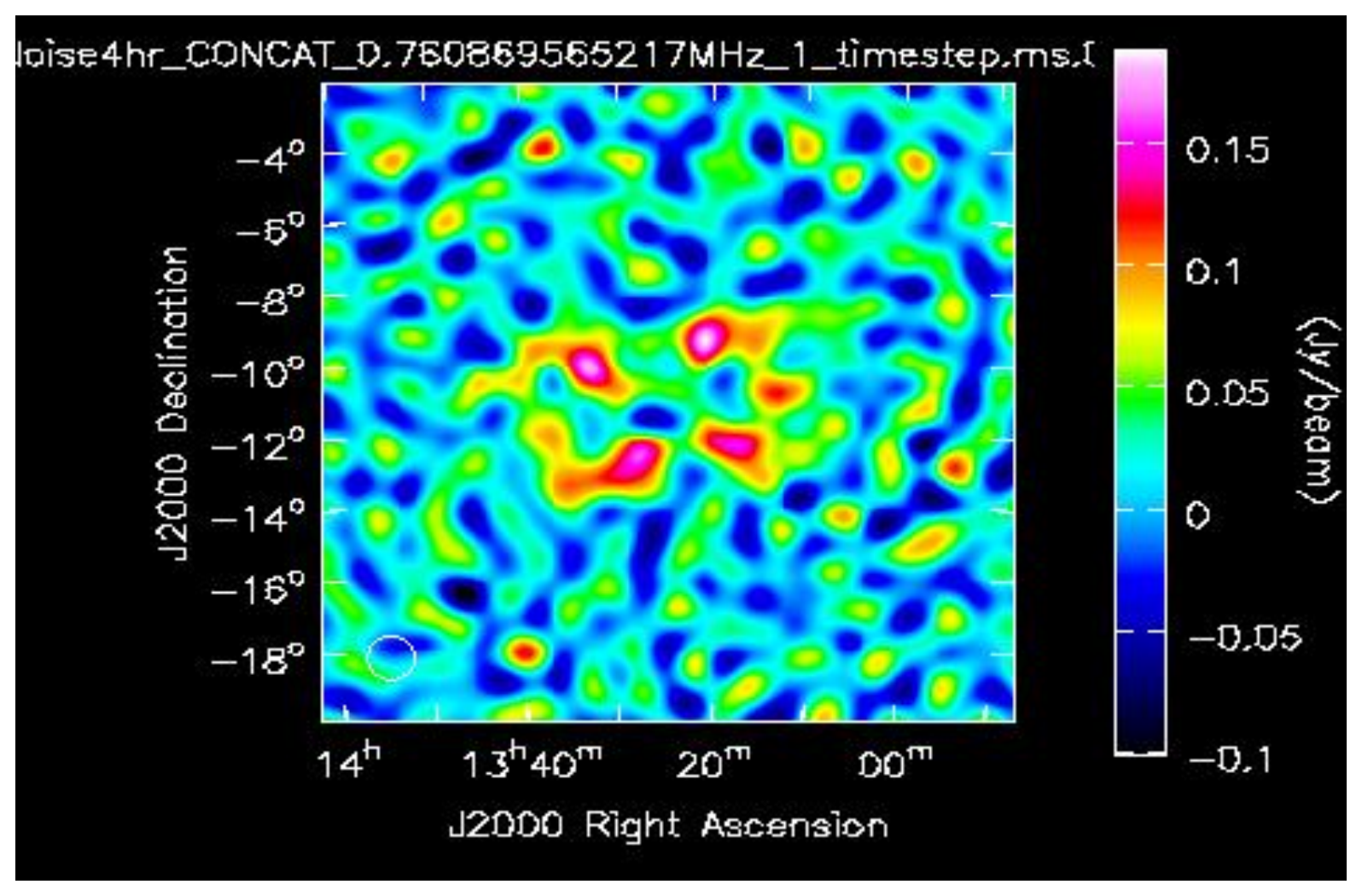
Simulated Array Inputs
LRO LOLA Lunar Surface Maps
SPICE Ephemeris of Moon & Earth

CASA Array Response Simulation
Calculate Baselines & Visibilities
Noiseless Response
Noisy Response
Imaging & Analysis

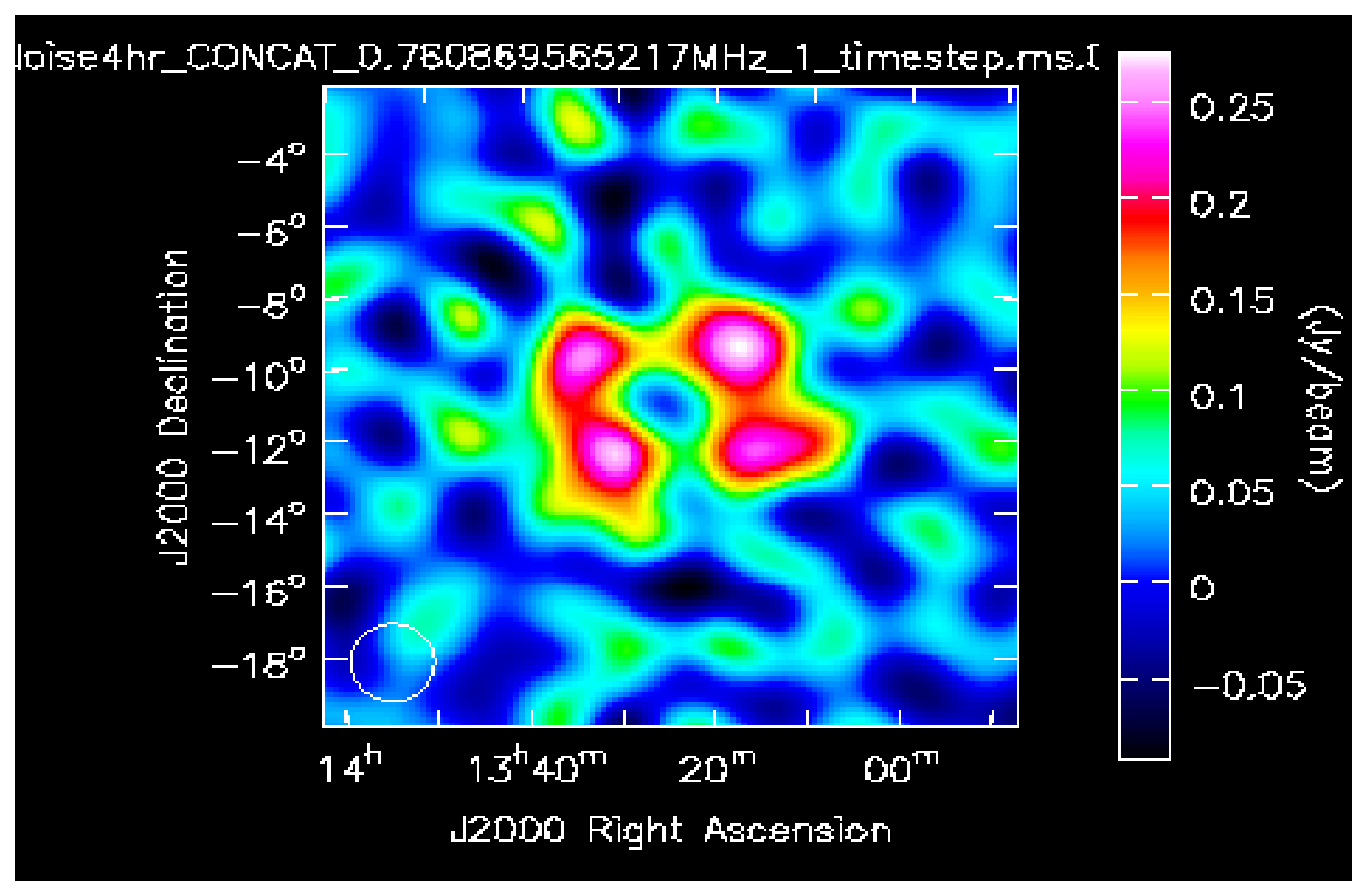


Configuration for 10 km Array, Logarithmically Spaced Circles at Flattest Place Near Lunar Sub-Earth Point

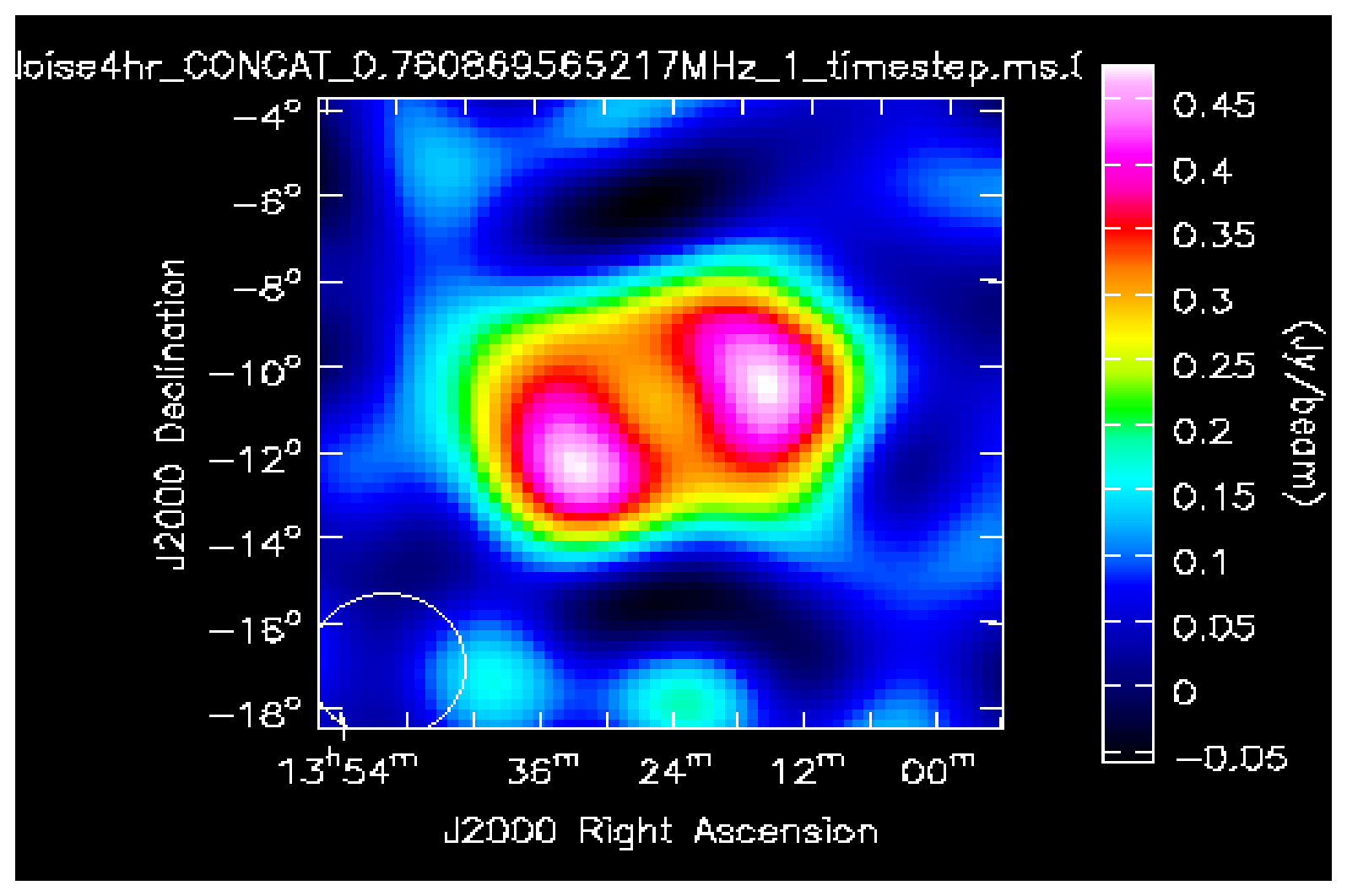
Recovered Images & Conclusions



Recovered Image 1
20 km Array Diameter, 4 hours integration
Optimal Noise Budget, 16k antenna,
Jy/beam rms = .0318 => 3.93 SNR
=> 2-4 hours for a 3 σ detection



Recovered Image 2
10 km Array Diameter, 4 hours integration
Optimal Noise Budget, 16k antenna,
Jy/beam rms = .041 => 5.85 SNR
=> 1-2 hours for a 3 σ detection



Recovered Image 3
6 km Array Diameter, 4 hour integration,
Optimal Noise Budget, 16k antenna,
Jy/beam rms = .073 => 6.44 SNR
=> 0.85 – 1.8 hours for a 3 σ detection

We find that for a moderate lunar surface electron density of 250/cm^3, **the radiation belts may be detected in 1-2 times a day with a 16384 element array over a 10 km diameter circle**. Lunar surface electron densities in the 1000s mean there will be too much quasithermal noise to observe the radiation belts in a reasonable time frame. Such high densities are only theoretically possible at low Solar Zenith Angles, and would fall off towards the night side. **If functional at Lunar night/dusk, such an array could make a snapshot of Earth's radiation belts 10-20 times a day.**

References

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Acknowledgments

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