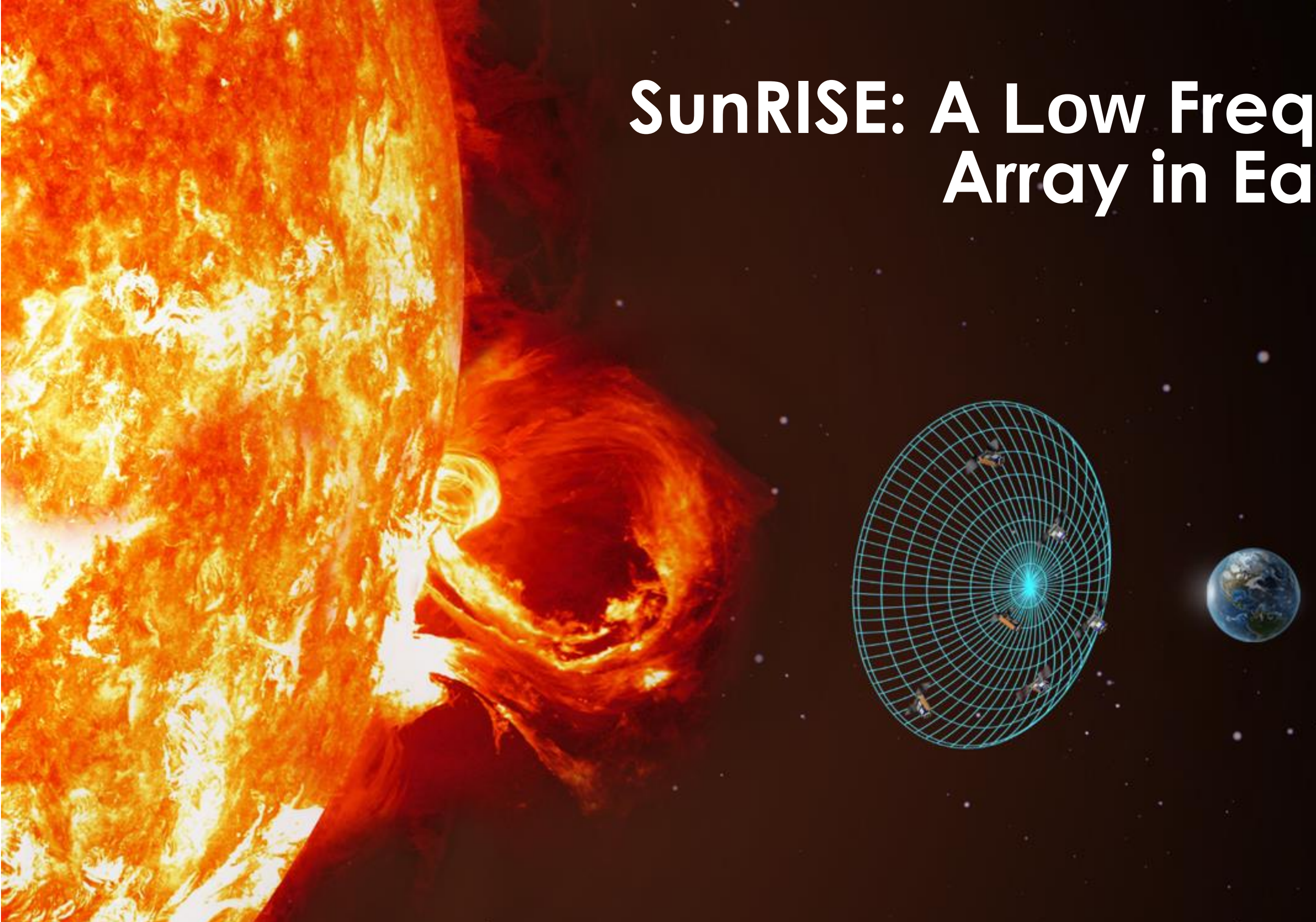
SunRISE: A Low Frequency Pathfinder Array in Earth Orbit



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SunRISE

Sun Radio Interferometer
Space Experiment

AAS 237, 1/13/21, Splinter Session 159: Low Frequency Radio Astronomy for Cosmic Origins

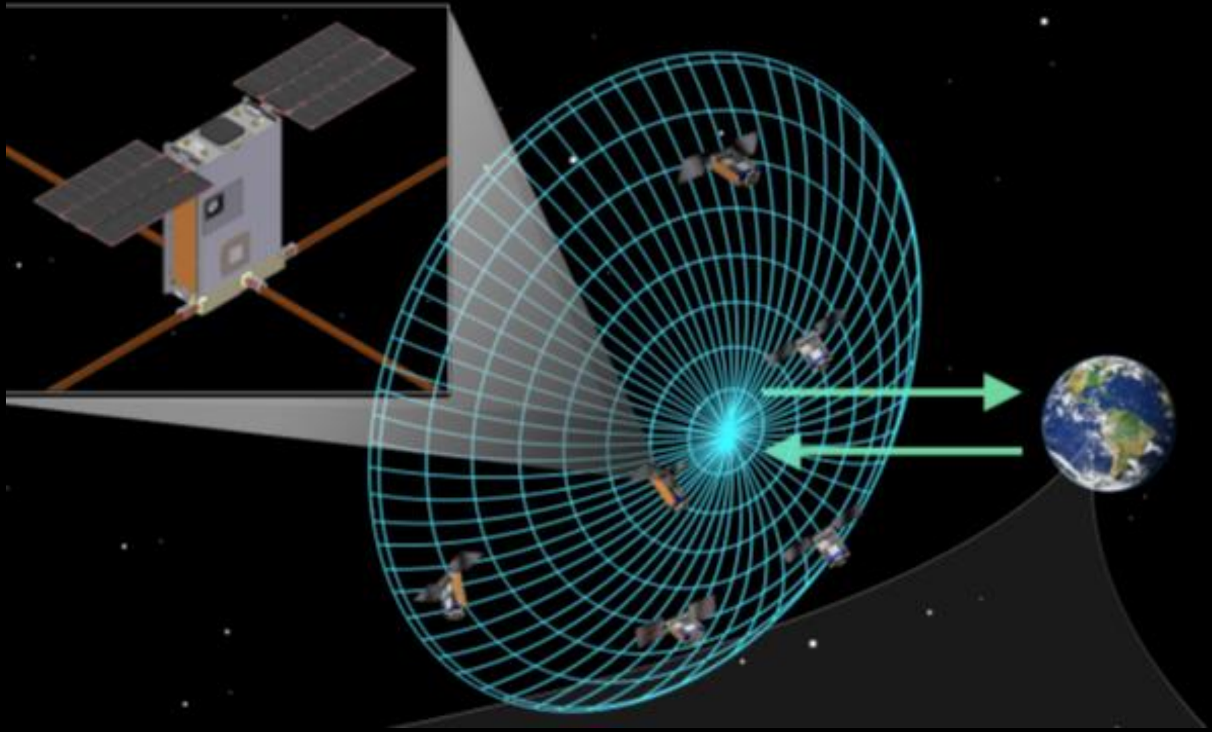
PRINCIPAL INVESTIGATOR: Justin C. Kasper (University of Michigan)

TALK OUTLINE

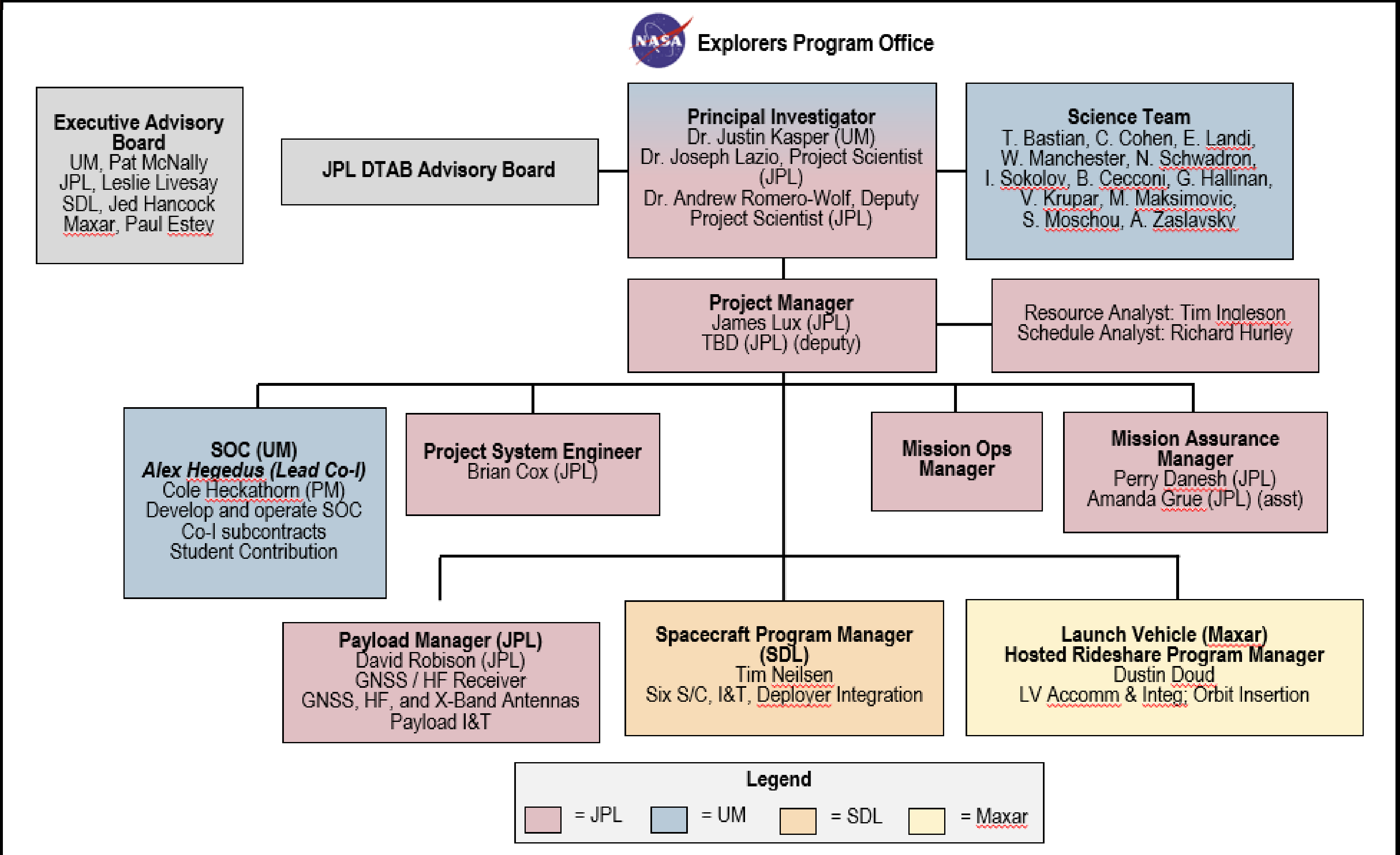
- Introduction to SunRISE
- Primary Science Objectives
- Science Operation Pipeline
- Coupling Radio Observations with MHD Simulations
- Preliminary Sky Maps
- Looking Ahead

SUNRISE INTRODUCTION

- SunRISE – Sun Radio Interferometer Space Experiment
- Heliophysics Explorers Mission of Opportunity ($55 M)
- Almost done with Phase B
- Will launch mid 2023
- 6 CubeSats in GEO
  Graveyard Orbit
- Can see below Ionospheric Cutoff
  0.1 – 25 MHz



SUNRISE ORG CHART



Explorers Program Office

Executive Advisory Board
UM, Pat McNally
JPL, Leslie Livesay
SDL, Jed Hancock
Maxar, Paul Estey

JPL DTAB Advisory Board

Principal Investigator
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Dr. Joseph Lazio, Project Scientist (JPL)
Dr. Andrew Romero-Wolf, Deputy Project Scientist (JPL)

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TBD (JPL) (deputy)

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Schedule Analyst: Richard Hurley

SOC (UM)
Alex Hegedus (Lead Co-I)
Cole Heckathorn (PM)
Develop and operate SOC
Co-I subcontracts
Student Contribution

Project System Engineer
Brian Cox (JPL)

Mission Ops Manager

Mission Assurance Manager
Perry Danesh (JPL)
Amanda Grue (JPL) (asst)

Payload Manager (JPL)
David Robison (JPL)
GNSS / HF Receiver
GNSS, HF, and X-Band Antennas
Payload I&T

Spacecraft Program Manager (SDL)
Tim Neilsen
Six S/C, I&T, Deployer Integration

Launch Vehicle (Maxar)
Hosted Rideshare Program Manager
Dustin Doud
LV Accomm & Integ; Orbit Insertion

Legend
🟥 = JPL 🟦 = UM 🟧 = SDL 🟨 = Maxar

UNIVERSITY OF MICHIGAN

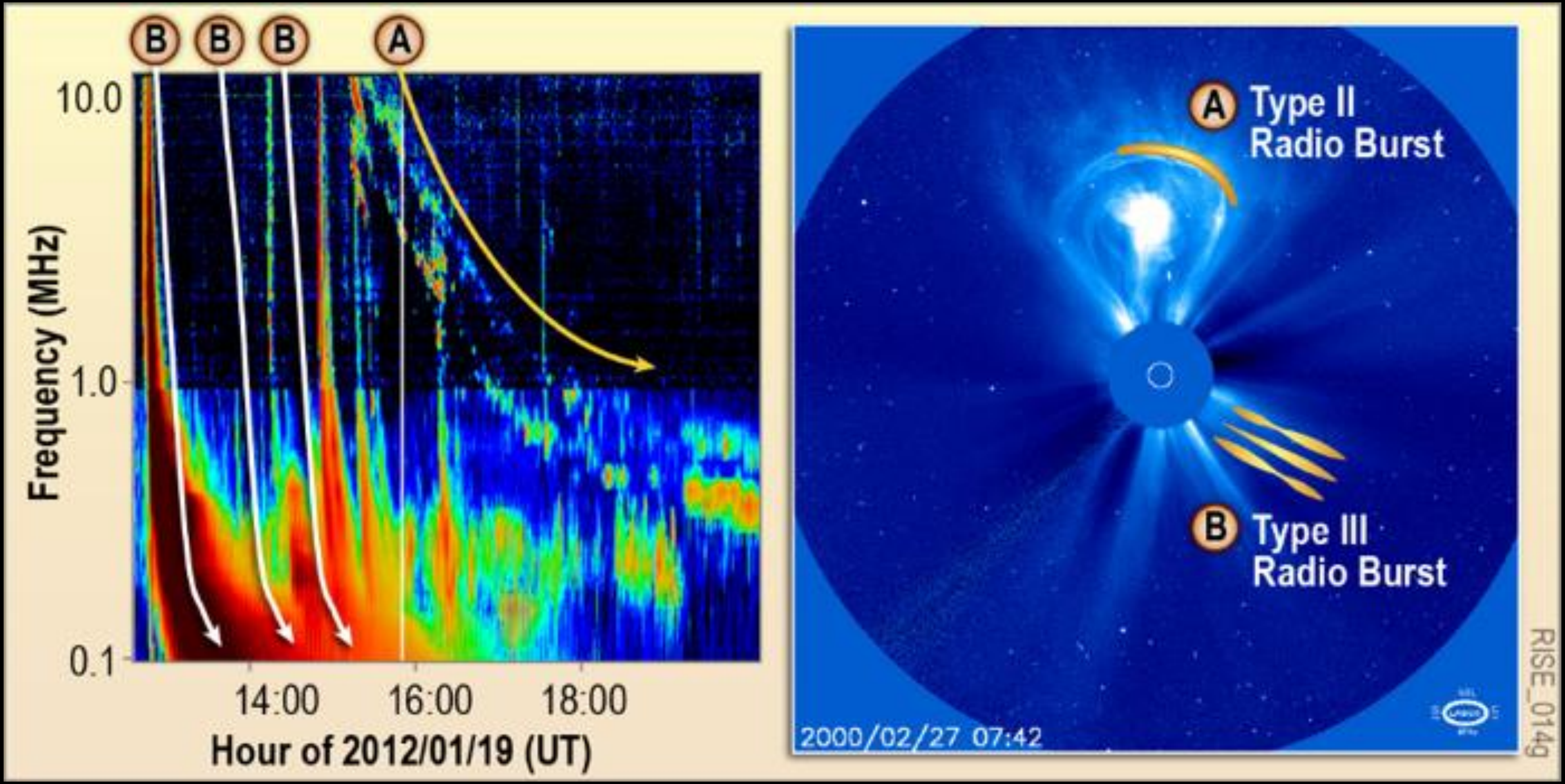
JPL
Jet Propulsion Laboratory
California Institute of Technology

SunRISE
Sun Radio Interferometer Space Experiment

SSL
A MAXAR COMPANY

Space Dynamics
LABORATORY
Utah State University Research Foundation

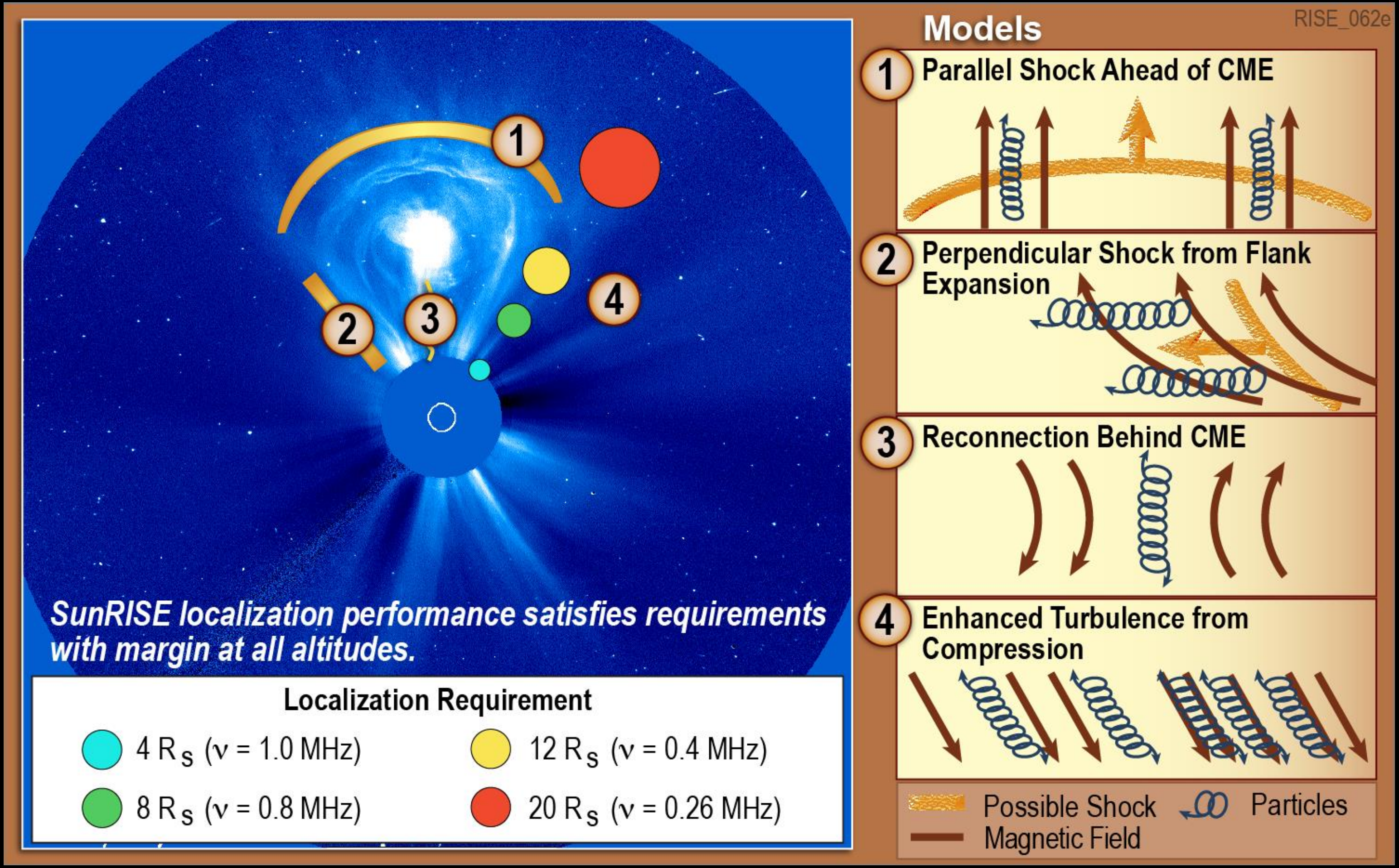
PRIMARY SCIENCE: SOLAR TYPE II & III BURSTS



CONNECT EVOLUTION OF RADIO BURST TO ONE OF FOUR MODELS

SunRISE Objective 1

Discriminate competing hypotheses for the source mechanism of CME-associated SEPs by measuring the location and distribution of Type II radio emission relative to expanding CMEs 2–20 Rs from the Sun, where the most intense acceleration occurs.



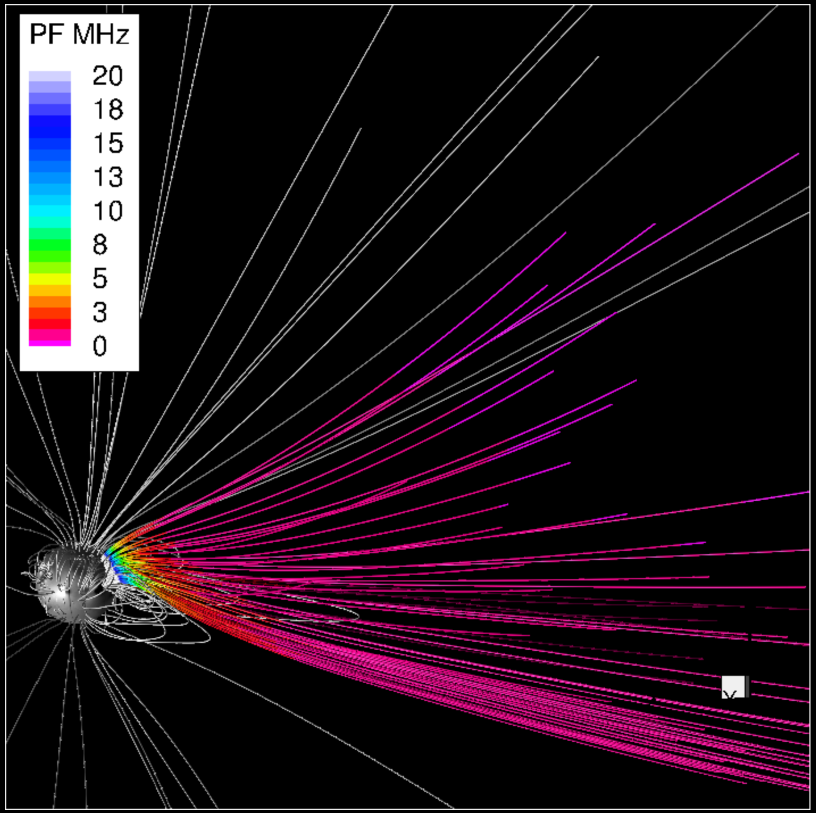
SunRISE localization performance satisfies requirements with margin at all altitudes.

MAPPING MAGNETIC FIELD LINES

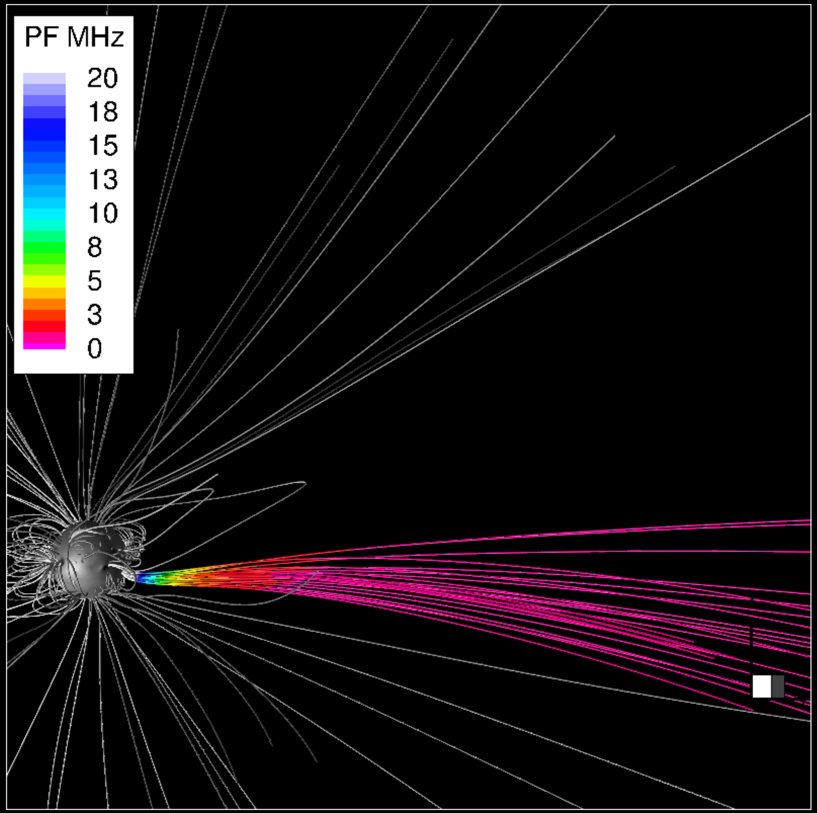
SunRISE Objective 2

Determine if a broad magnetic connection between active regions and interplanetary space is responsible for the wide longitudinal extent of some flare and CME SEPs by imaging the field lines traced by Type III bursts from 2–20 Rs.

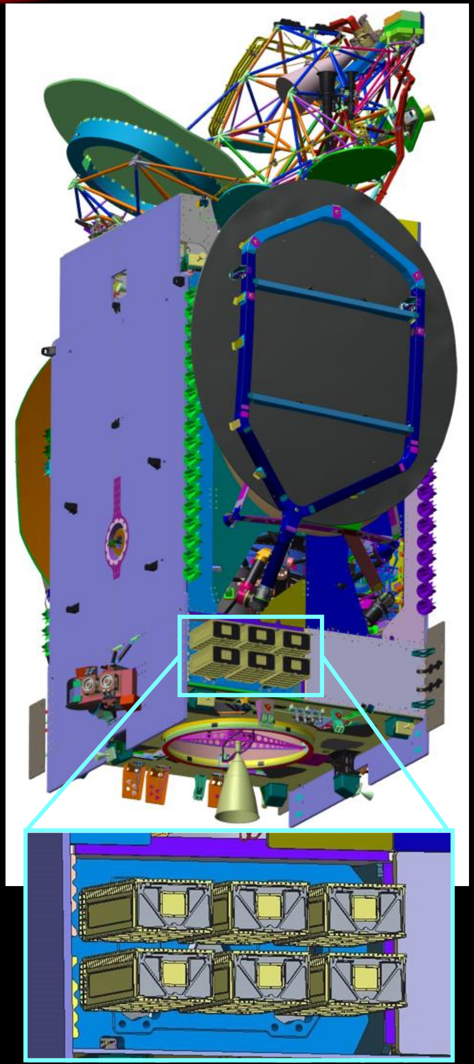
Separatrix-web Scenario (i)



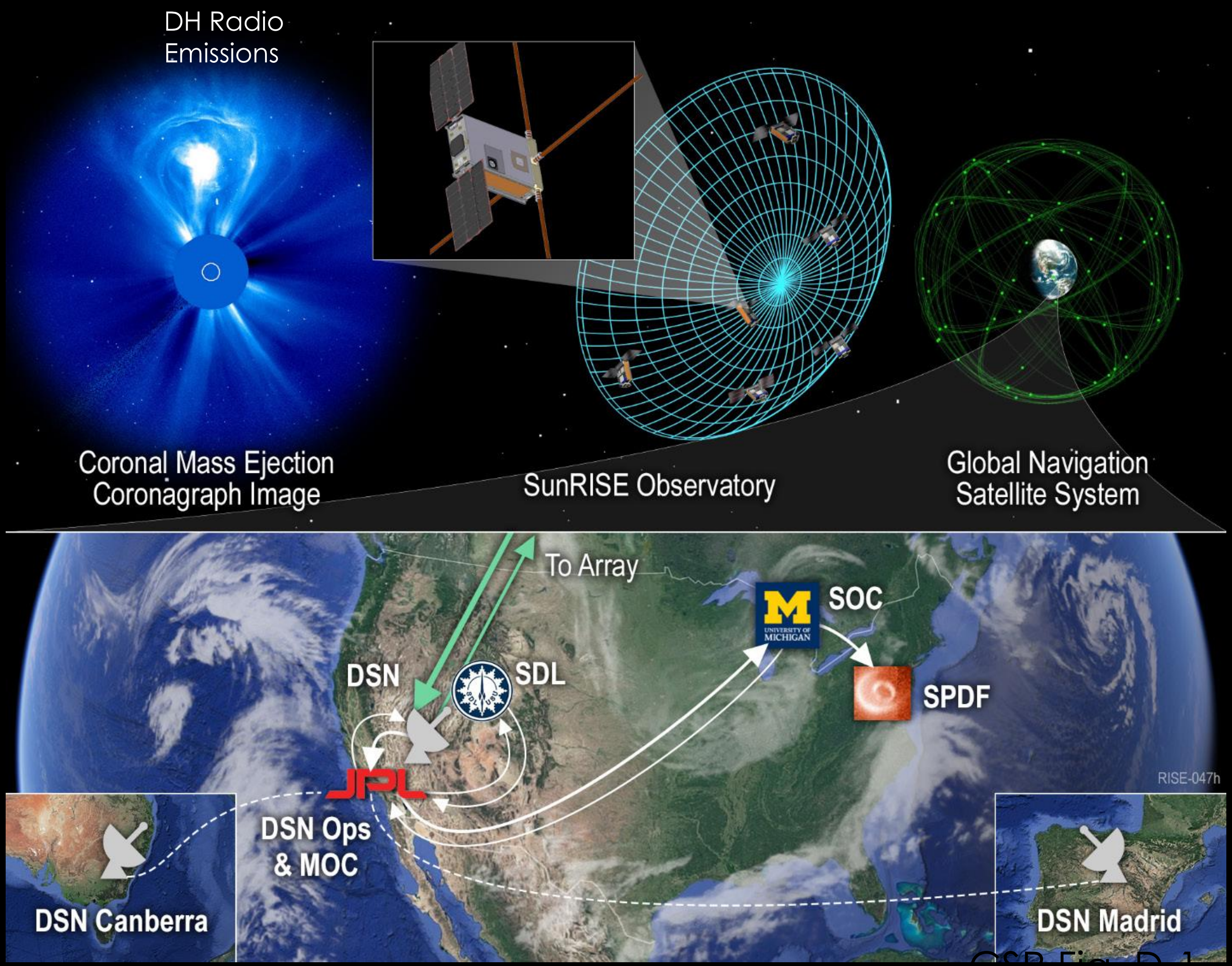
Random Walk Scenario (ii)

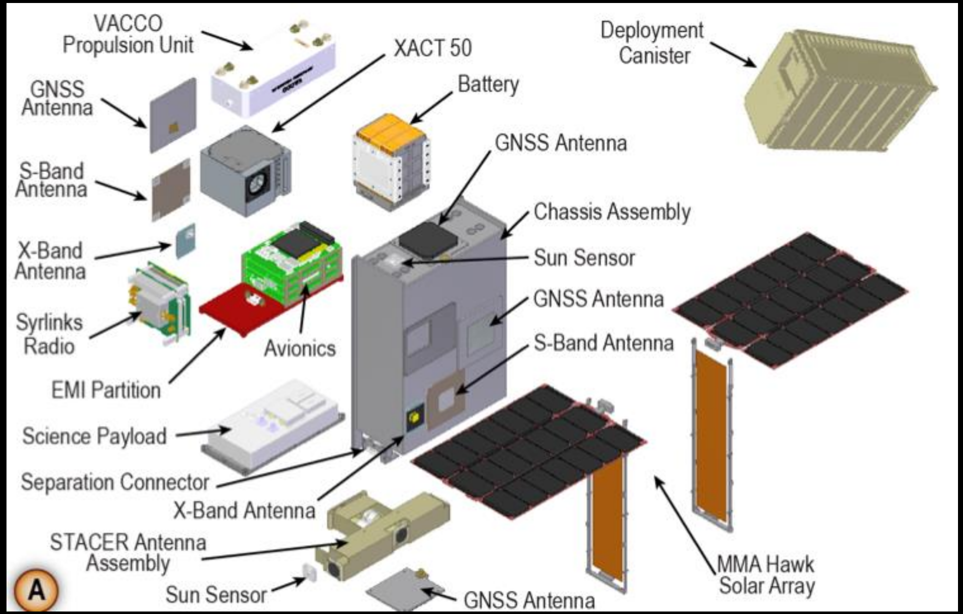


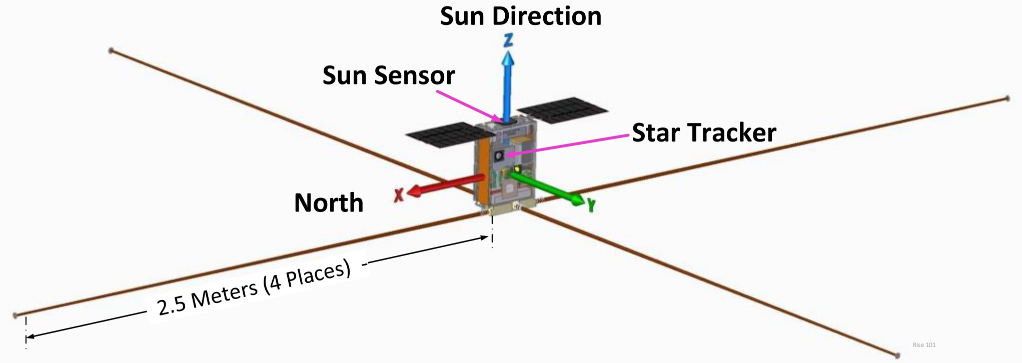
SUNRISE ORBITAL ACCESS & OPERATIONS



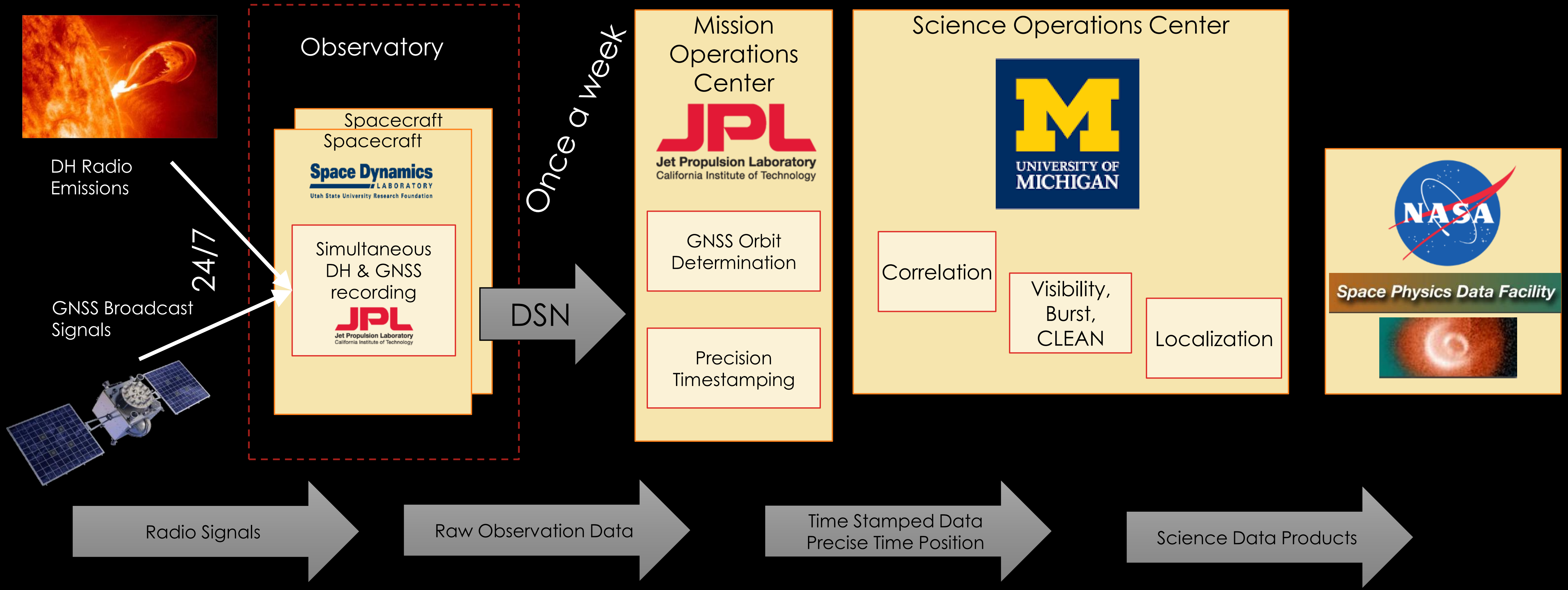
SUNRISE MISSION & SPACECRAFT







REGULAR AND ROUTINE SUNRISE OPERATIONS



DH Radio Emissions

GNSS Broadcast Signals

24/7

Observatory

Spacecraft

Spacecraft

Space Dynamics Laboratory
Utah State University Research Foundation

Simultaneous DH & GNSS recording

JPL
Jet Propulsion Laboratory
California Institute of Technology

DSN

Once a week

Mission Operations Center

JPL
Jet Propulsion Laboratory
California Institute of Technology

GNSS Orbit Determination

Precision Timestamping

Science Operations Center

University of Michigan

Correlation

Visibility, Burst, CLEAN

Localization

NASA

Space Physics Data Facility

Radio Signals

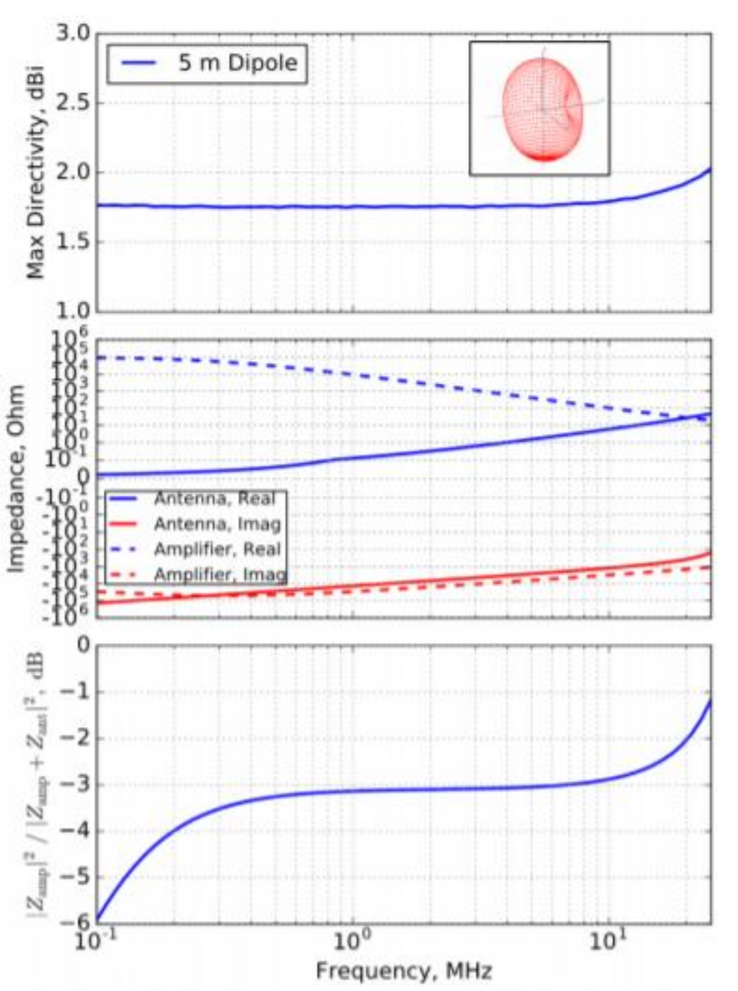
Raw Observation Data

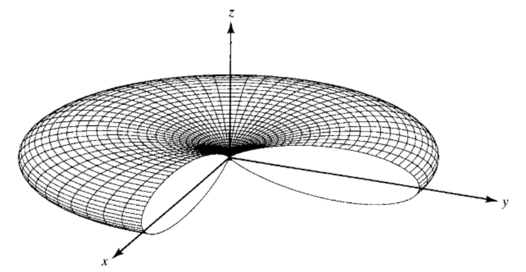
Time Stamped Data
Precise Time Position

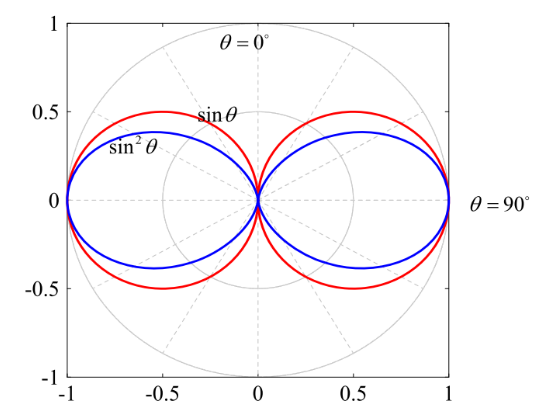
Science Data Products

ANTENNA PATTERNS

- Assume 5 m dual polarization isotropic dipoles (electrically short)
- Directivity of the Solar DH antenna as determined from a NEC2 simulation
- Directivity is 1.7 dBi, as expected from a short dipole
- Below, theoretical response for short dipole (red, sin(θ)), and a Half Wavelength dipole (blue, $\sin^2(\theta)$)

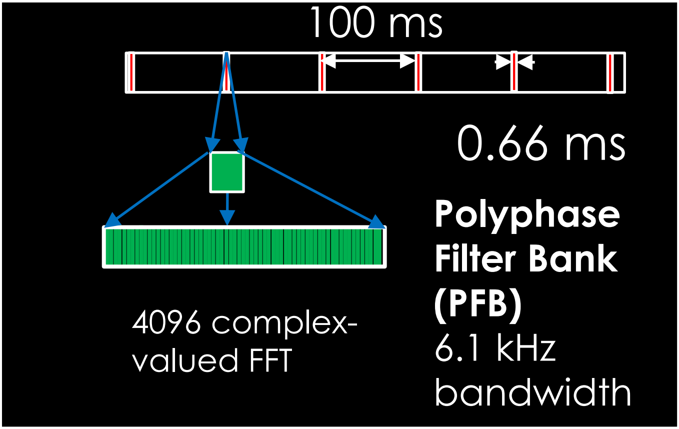






SIGNAL TO NOISE CALCULATION

- 4096 channel Polyphase Filter Bank, 0-25 MHz, 6100 Hz channels, 6.6 ms / sec integration, 0.1 sec cadence
- Type II Signals ≈ Galactic & Plasma Noise
- Array: 6 spacecraft, 2 polarizations improves the sensitivity by a factor of 8.5



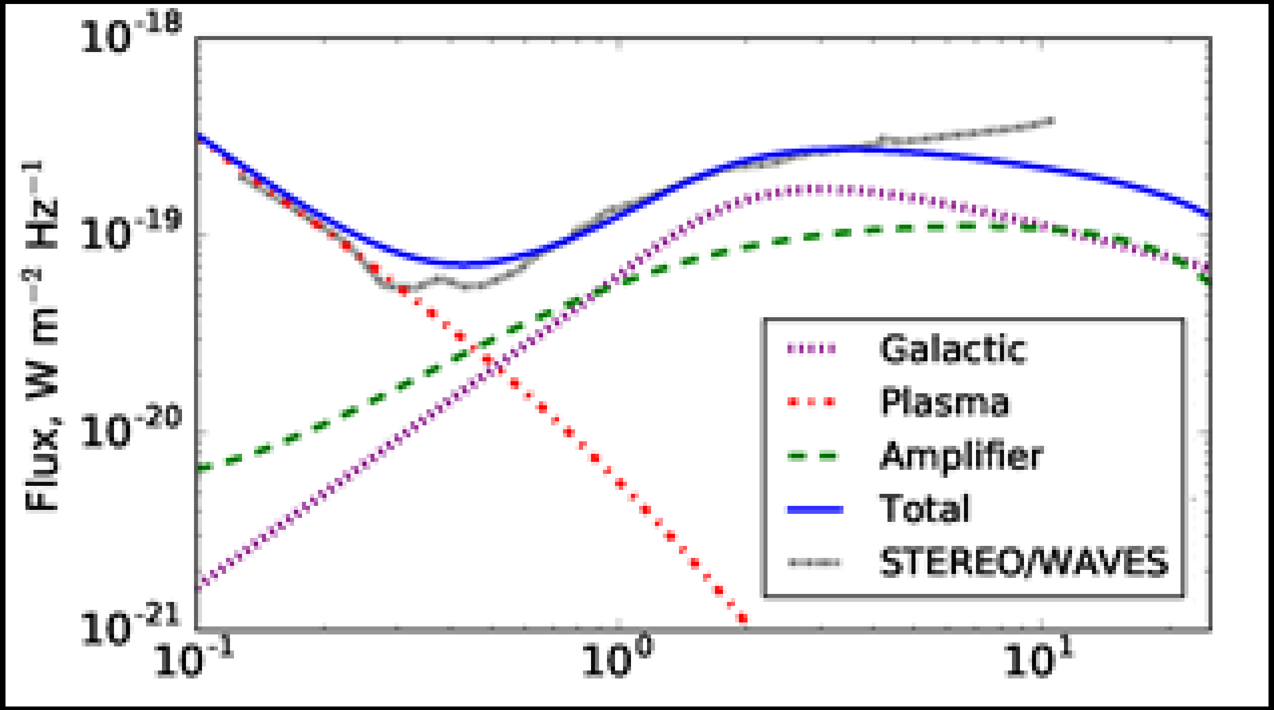
100 ms

0.66 ms

Polyphase Filter Bank (PFB)
6.1 kHz bandwidth

4096 complex-valued FFT

All spacecraft synchronized by GNSS



Taken from SunRISE CSR

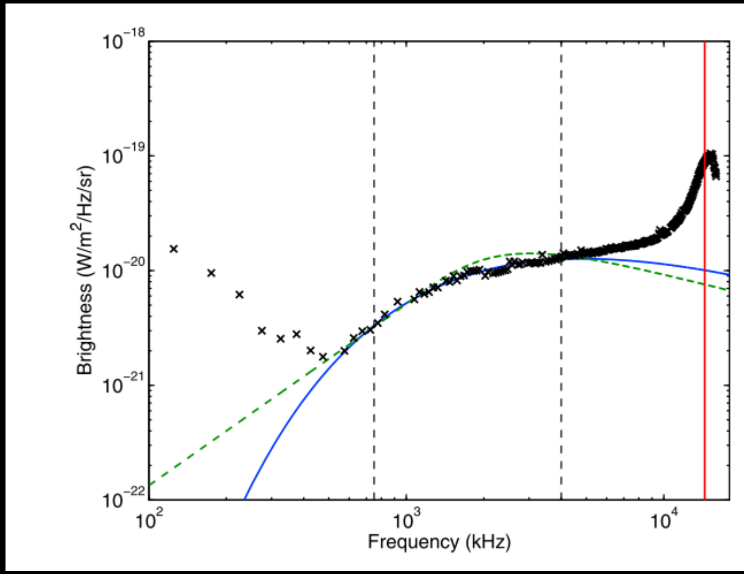
$$\sigma = \frac{2\,k_B\,T_{sys}}{\eta_s\,A_{eff}\,\sqrt{N(N-1)(N_{IF}\,\Delta T\,\Delta\nu)}}$$

CALIBRATING WITH GALACTIC BRIGHTNESS

- Mirror galactic calibration of STEREO antenna from Zaslavsky et al 2011
- Must understand Antenna and Stray impedance, goes into Γ^2

$$V_r^2 = V_{noise}^2 + \Gamma^2 V_{QTN}^2 + \frac{4\pi}{3} Z_0 \Gamma^2 l_{eff}^2 B_f .$$

- Choose middle range where galactic noise is dominant (Quasi Thermal Plasma Noise dominates at lowest freqs, short antenna approx. fails at higher freqs)
- Subtract off constant antenna noise to solve for effective antenna length
- Compare calibrated data (crosses) with Galactic brightness models Novacco and Brown [1978] (blue solid line) and Cane [1979] (green dashed line)



Zaslavsky et al. RADIO SCIENCE, VOL. 46, RS2008, doi:10.1029/2010RS004464, 2011

RADIO EQUATIONS

Reflection Coefficient/Voltage Divider from Impedance Mis-Matching

$$\Gamma = \left|\frac{Z_s}{Z_a+Z_s}\right|$$

General Spectral Antenna Voltage Equation

Brightness

dA Area

$$V_r^2 = V_{noise}^2 + \Gamma^2 2R_r \int_0^{2\pi}\int_0^{\pi} B(\theta,\phi)\frac{\lambda^2}{4\pi}G(\theta,\phi)\sin(\theta)d\theta d\phi$$

Effective Antenna Area

Resistance of Short Antenna

$$R_r = \frac{2\pi}{3}Z_0\left(\frac{l_{eff}}{\lambda}\right)^2$$

Gain of Short Antenna

$$G(\theta,\phi) = \frac{3}{2}\sin^2(\theta)$$

Electrically Short Antenna Simplified Voltage Equation

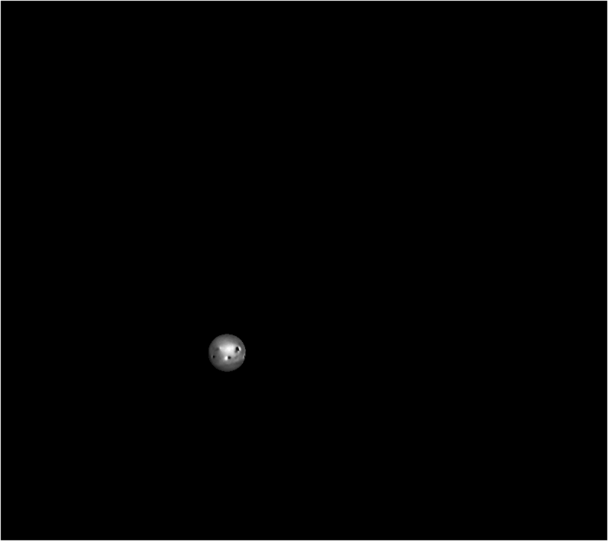
$$V_r^2 = V_{noise}^2 + \frac{4\pi}{3}Z_0\Gamma^2 l_{eff}^2 B_f$$

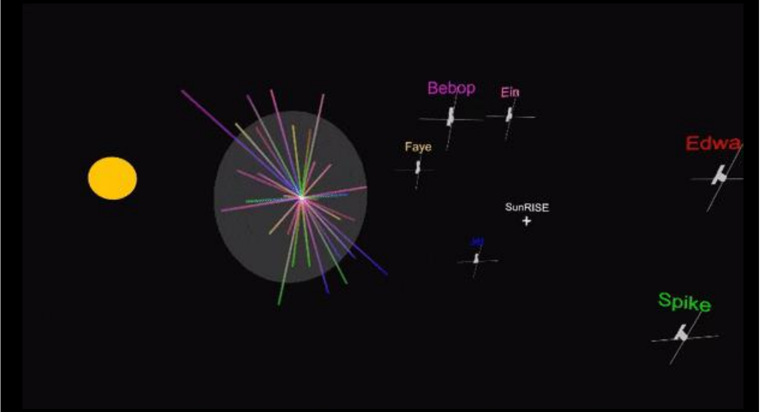
HIGH LEVEL PIPELINE TESTING OVERVIEW

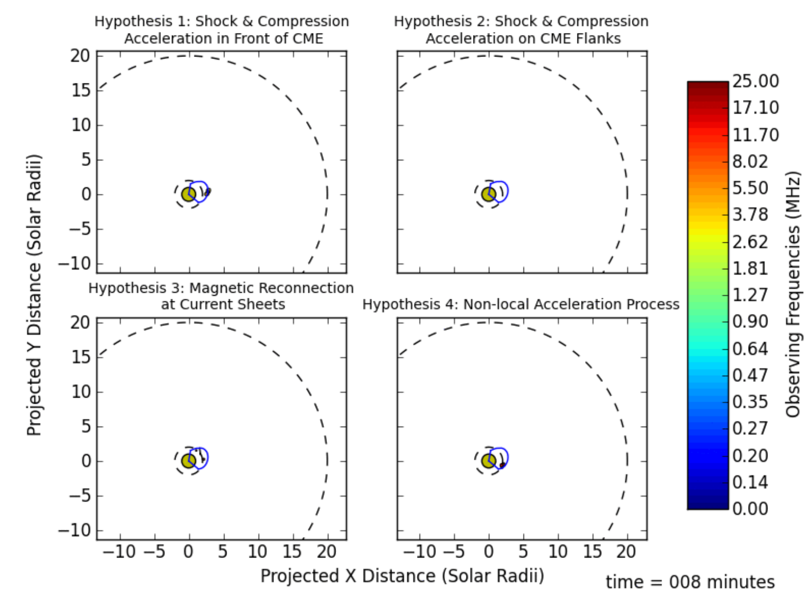
MHD CME Simulation

SunRISE Simulation

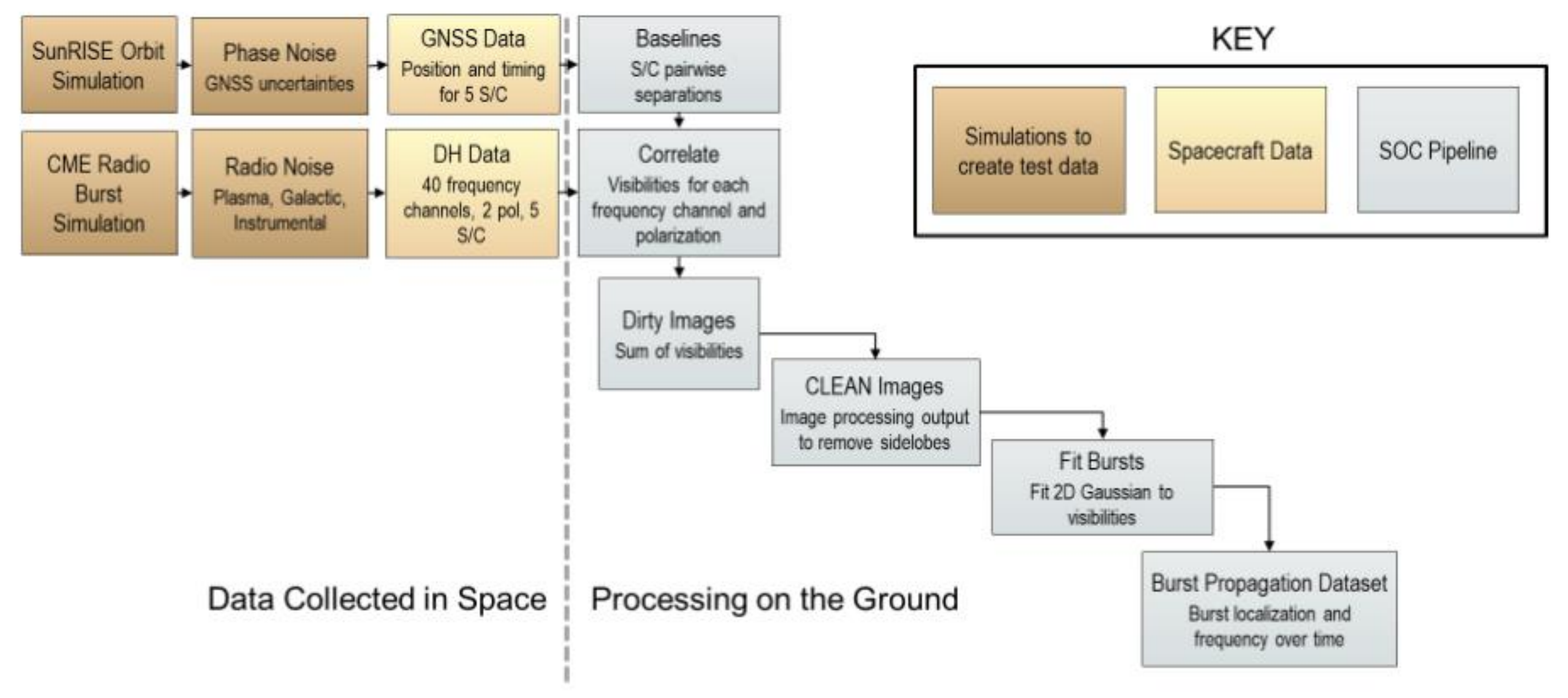
Science Operation Center Analysis Pipeline







PIPELINE OVERVIEW



SunRISE Orbit Simulation

Phase Noise
GNSS uncertainties

GNSS Data
Position and timing for 5 S/C

CME Radio Burst Simulation

Radio Noise
Plasma, Galactic, Instrumental

DH Data
40 frequency channels, 2 pol, 5 S/C

Baselines
S/C pairwise separations

Correlate
Visibilities for each frequency channel and polarization

Dirty Images
Sum of visibilities

CLEAN Images
Image processing output to remove sidelobes

Fit Bursts
Fit 2D Gaussian to visibilities

Burst Propagation Dataset
Burst localization and frequency over time

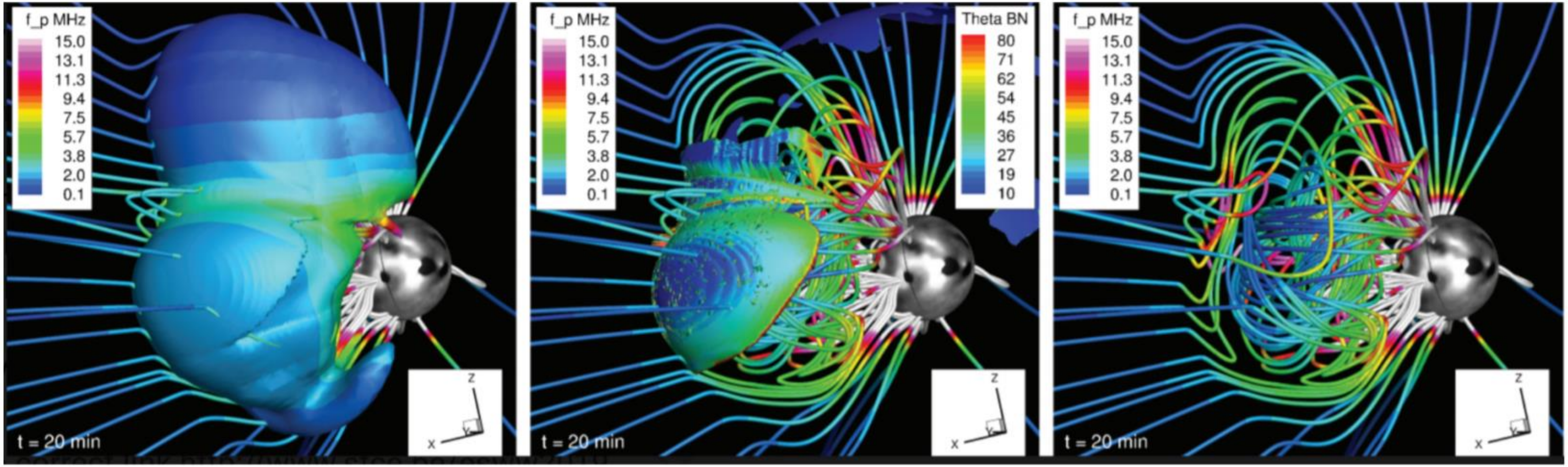
Data Collected in Space

Processing on the Ground

KEY

- Simulations to create test data
- Spacecraft Data
- SOC Pipeline

MHD CME SIMULATION



CME Density Enhancement

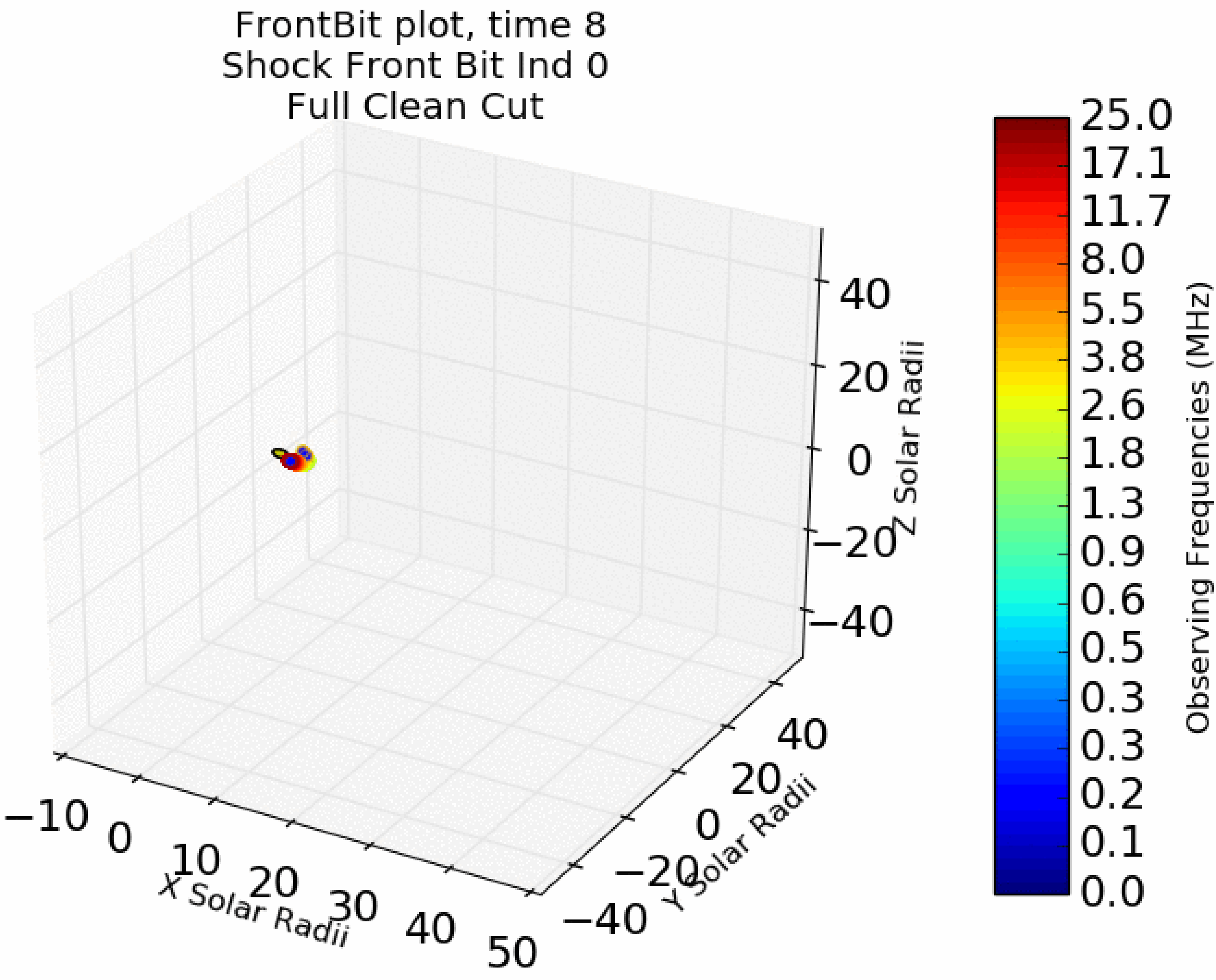
Entropy Derived Shock

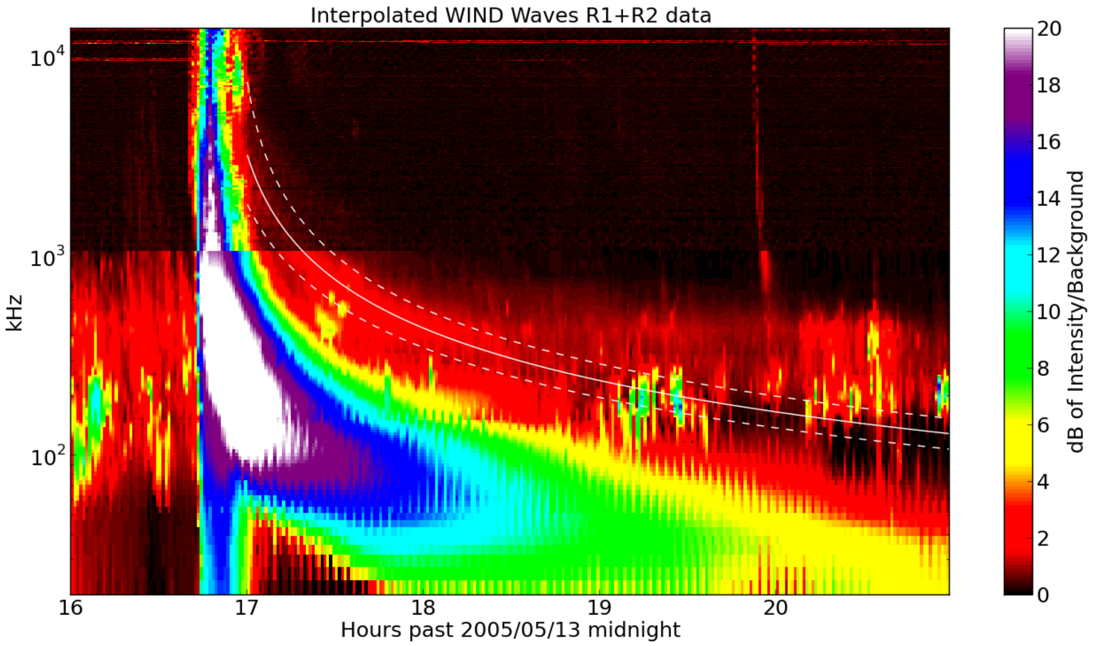
Magnetic Field

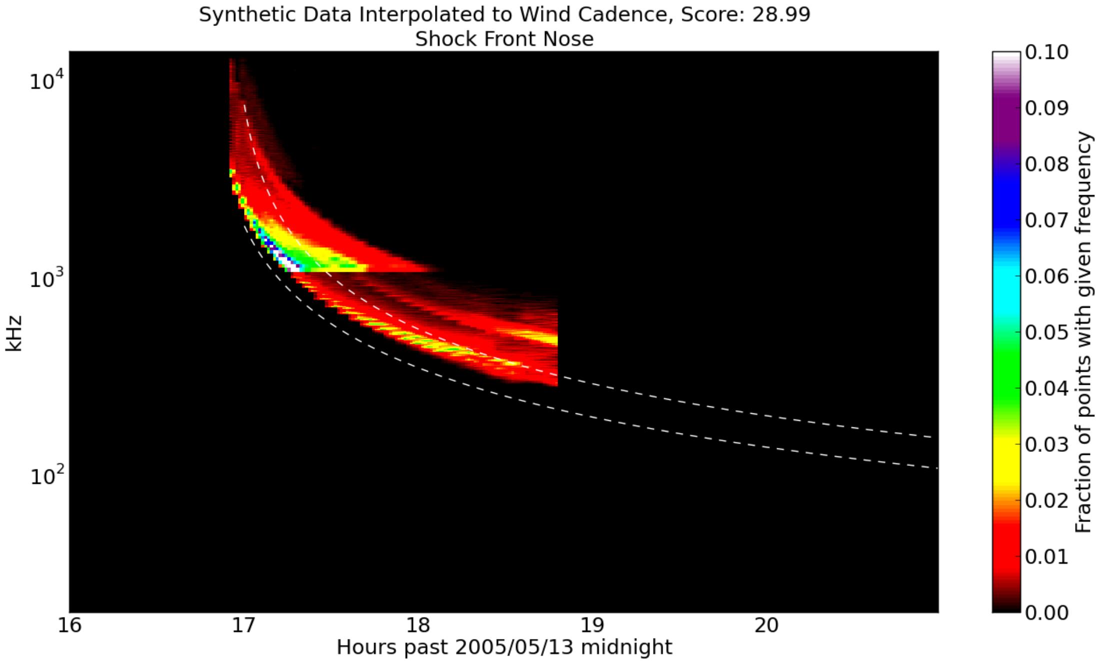
Snapshots from a AWSoM 2-Temperature MHD Simulation of a Radio-Loud CME on May 13, 2005

Manchester et al. 2014

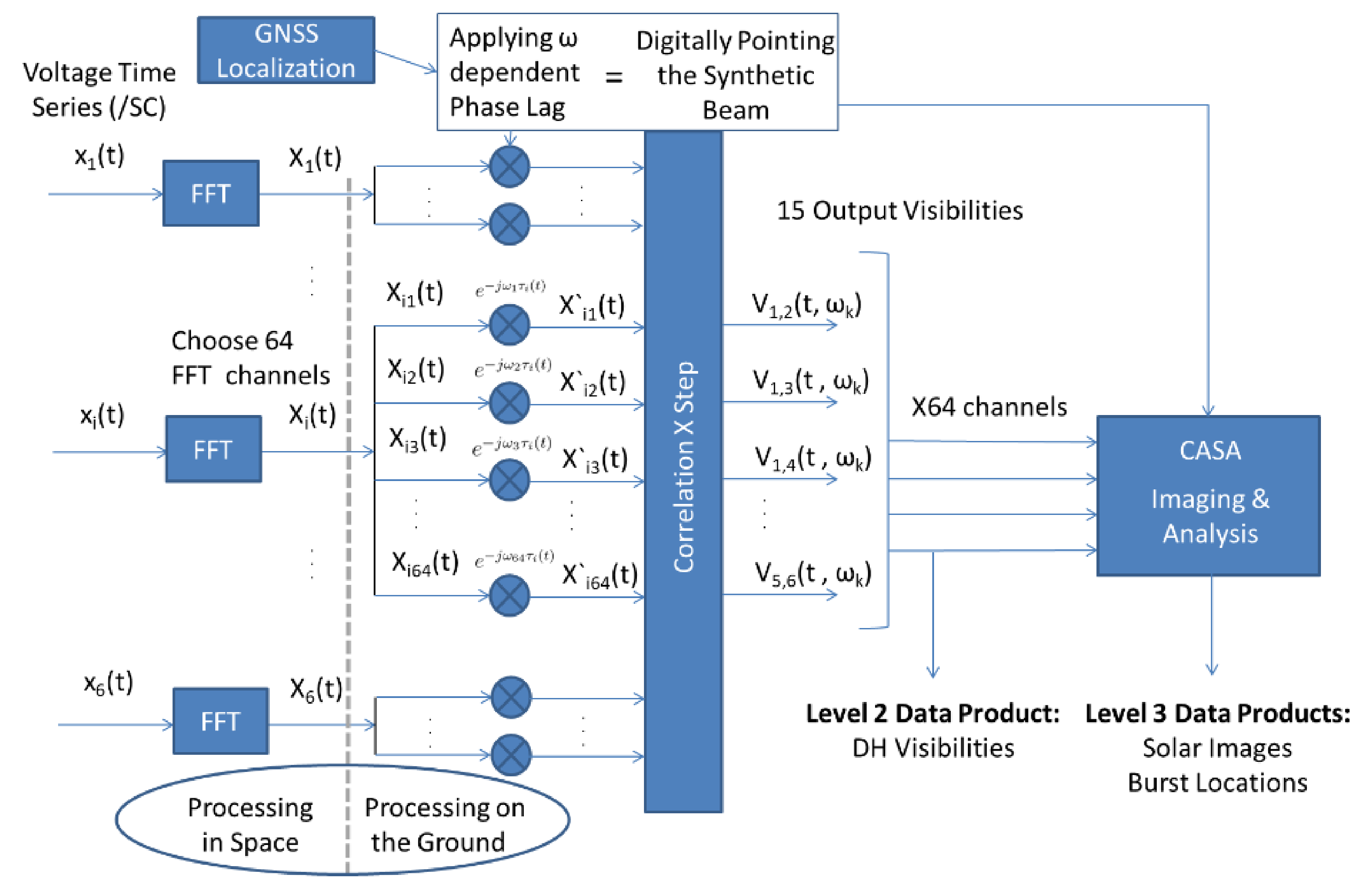
ZOOMING INTO ENTROPY SHOCK





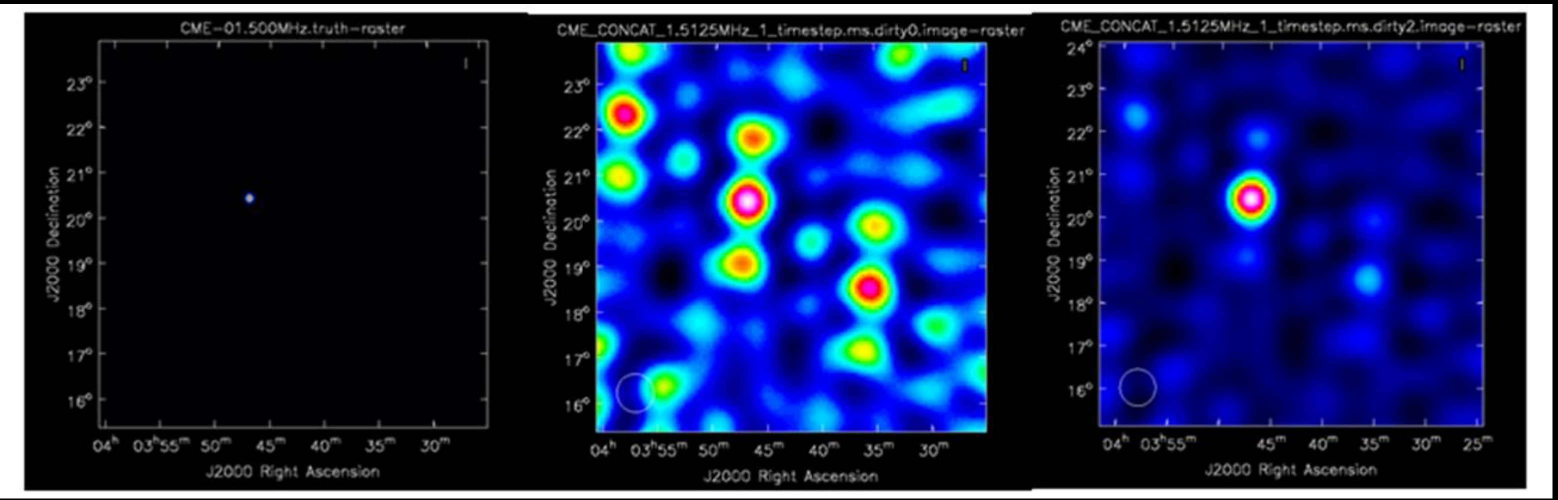


FX CORRELATION



IMAGING PIPELINE AT 1.5 MHZ

1 2 3



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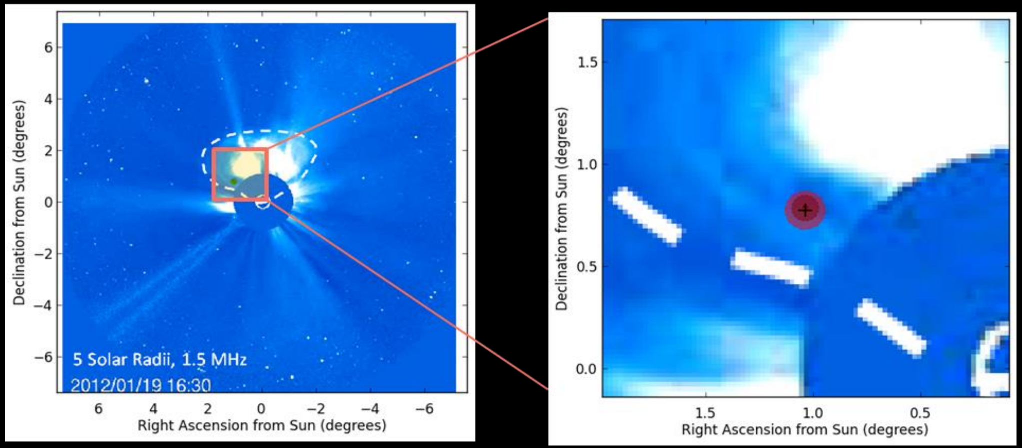
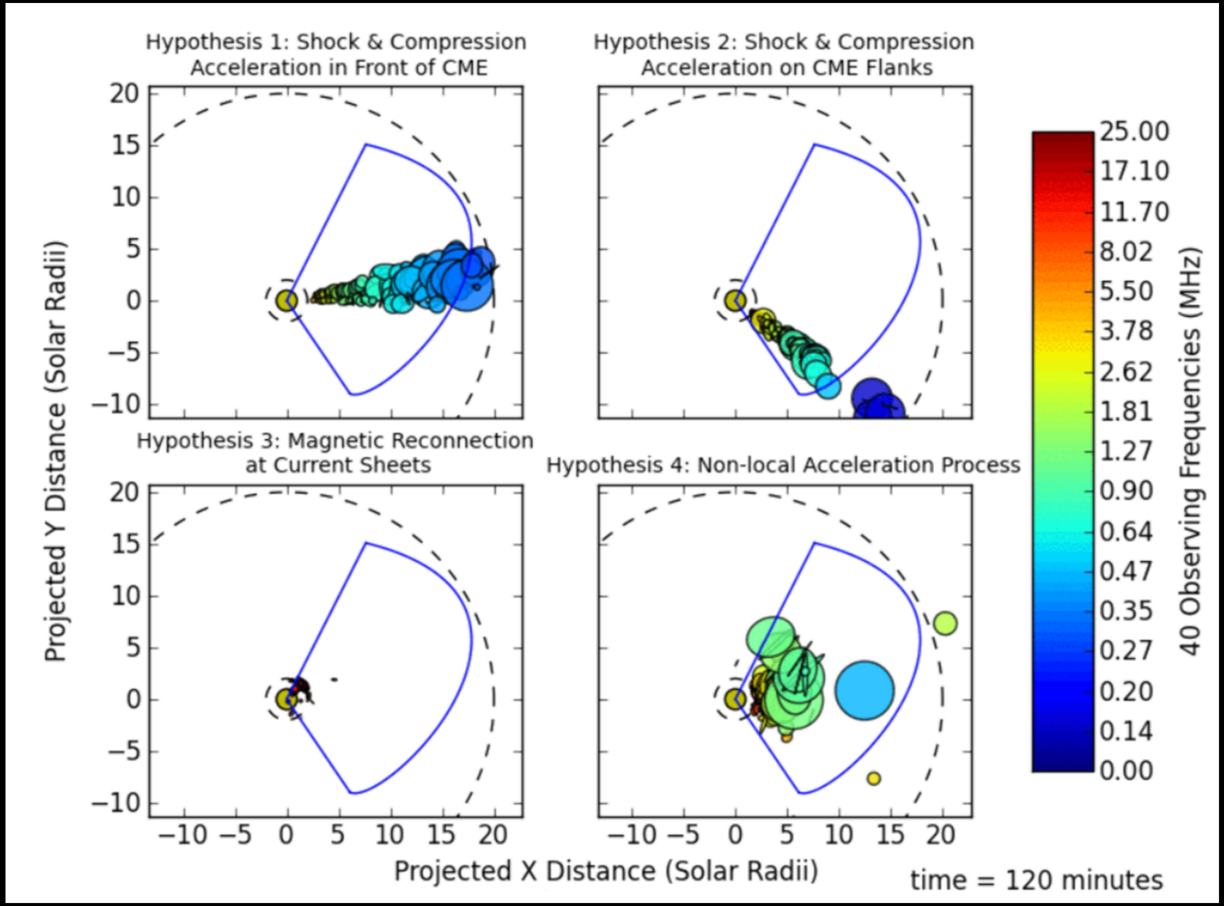
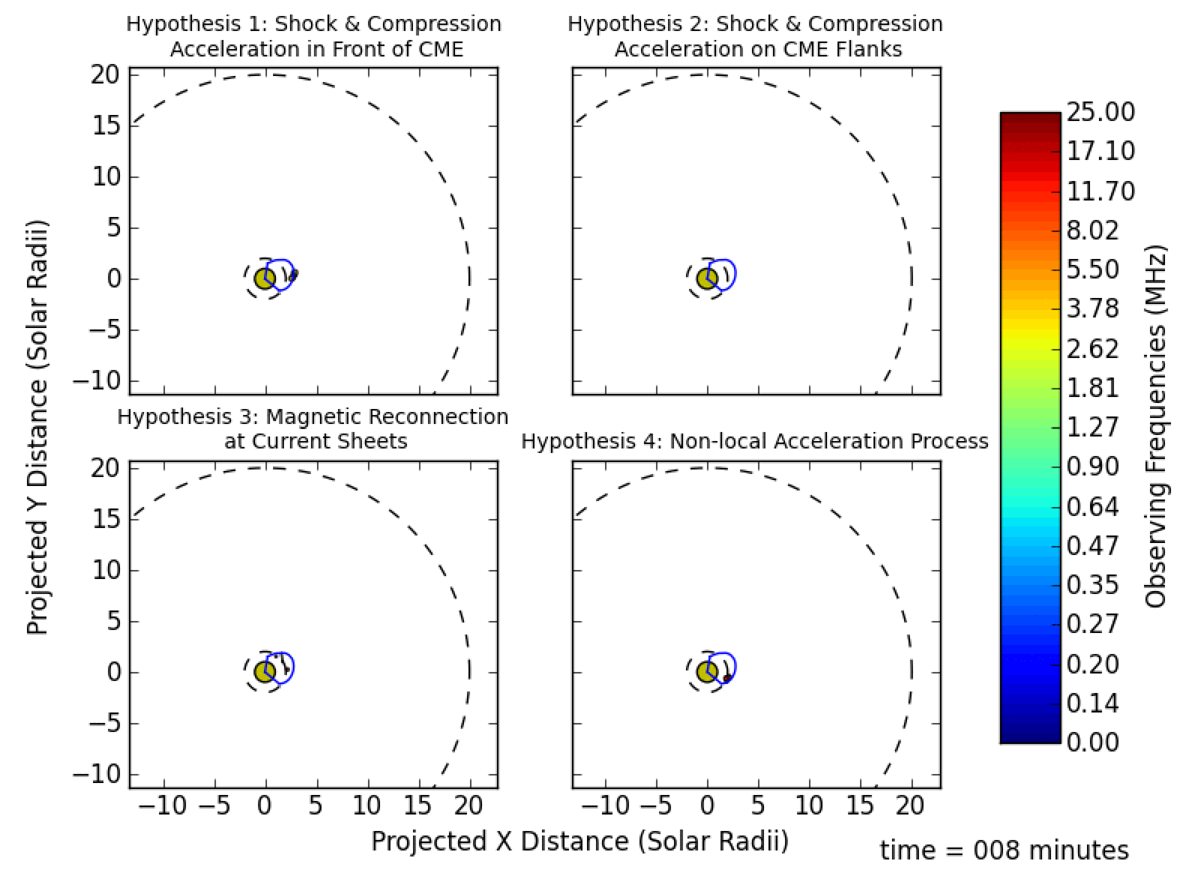


1. Simulation informed input emission distribution
2. Dirty Image with sidelobes
3. CLEANed Image with sidelobes removed
4. 2D Gaussian fit to data & put into context of CME Coronagraph Movie

SUNRISE RECOVERED RADIO EMISSION





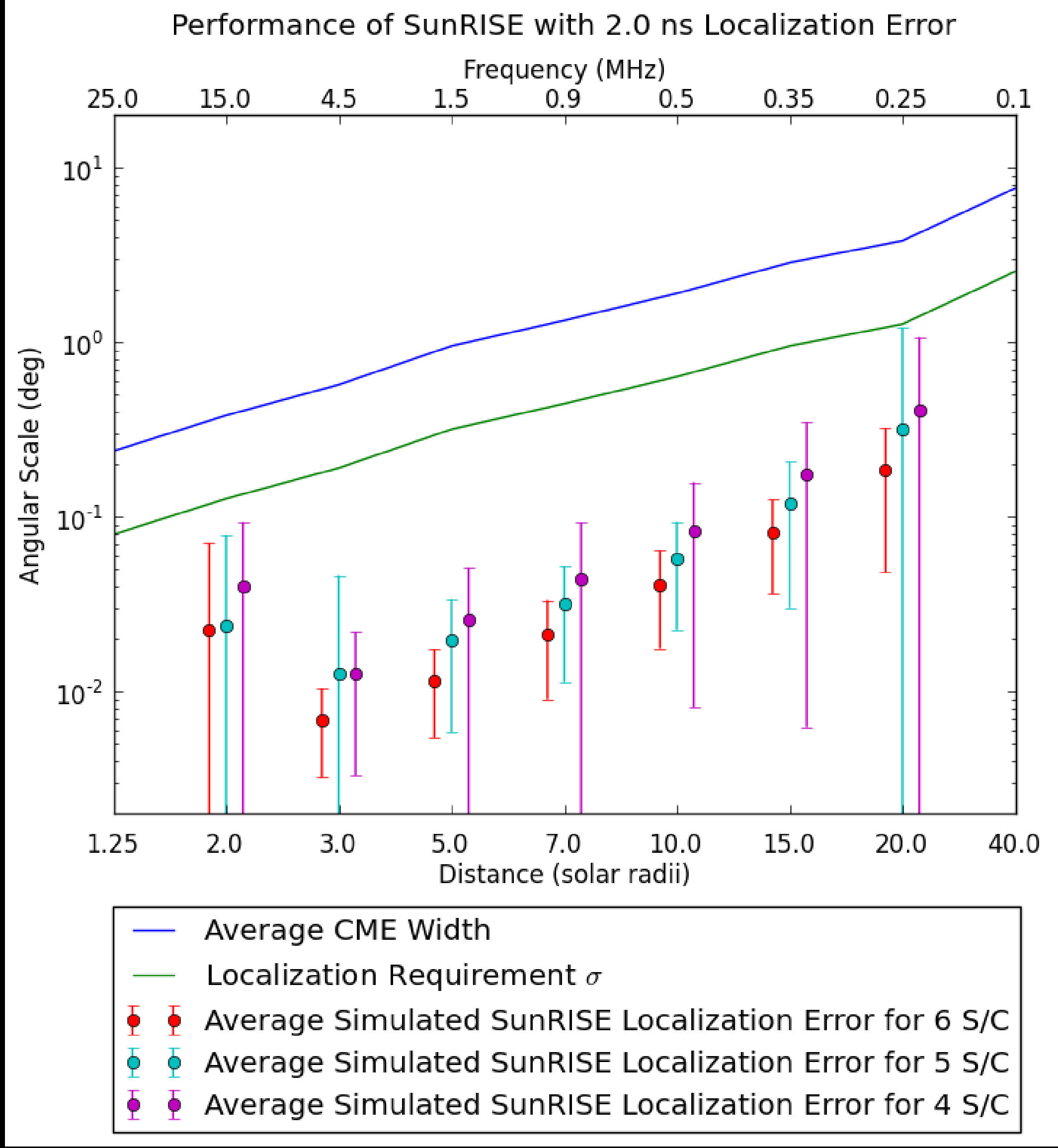
Simulated Pipelines turn Science Requirements into Engineering Requirements

Many knobs in mission may be tuned including

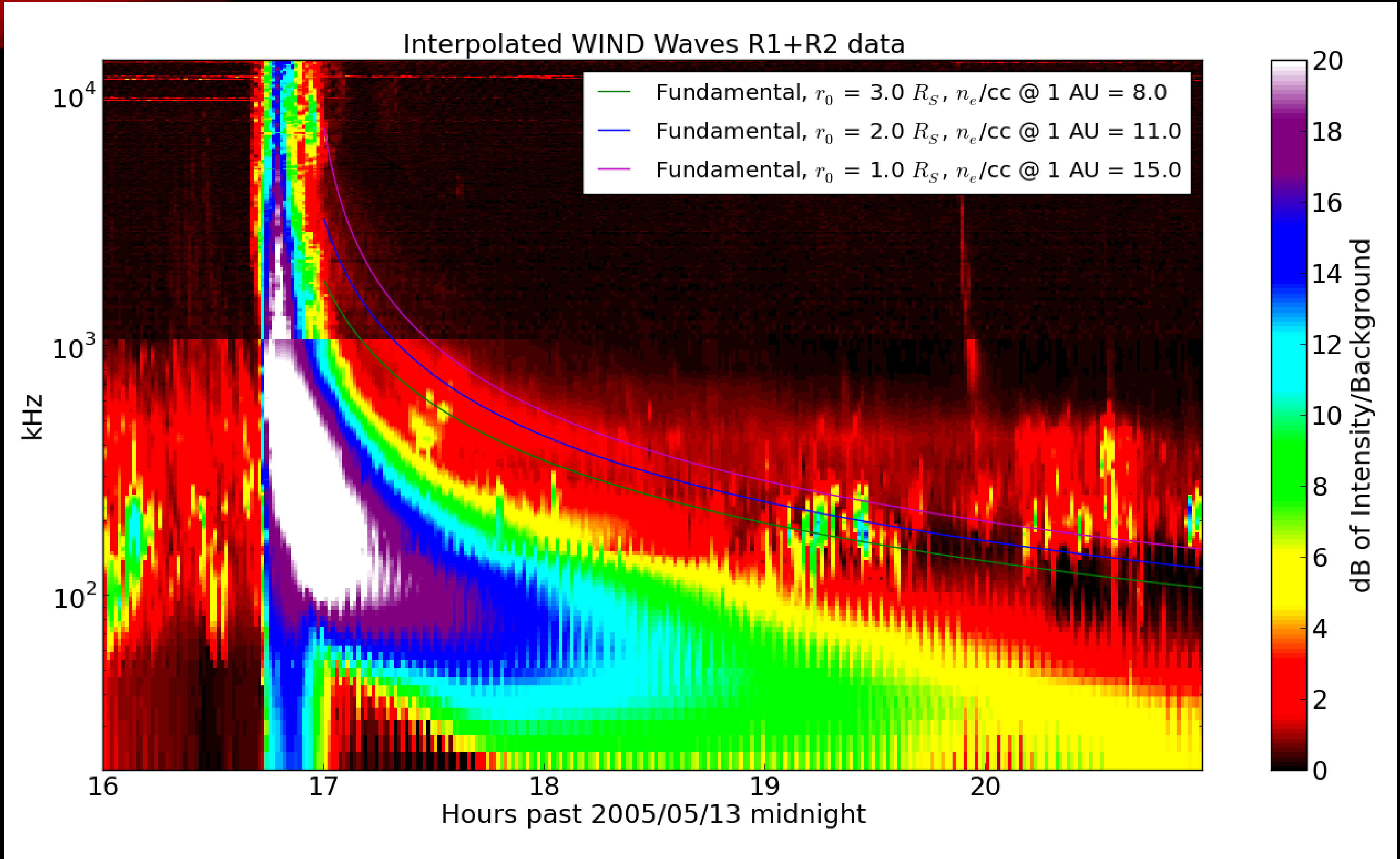
- Expected Signal Brightness
- Number of receivers/spacecraft
- Level of amplifier noise
- Level of positional uncertainty of receivers

Exploring the trade space in a mission specific manner is necessary to set requirements

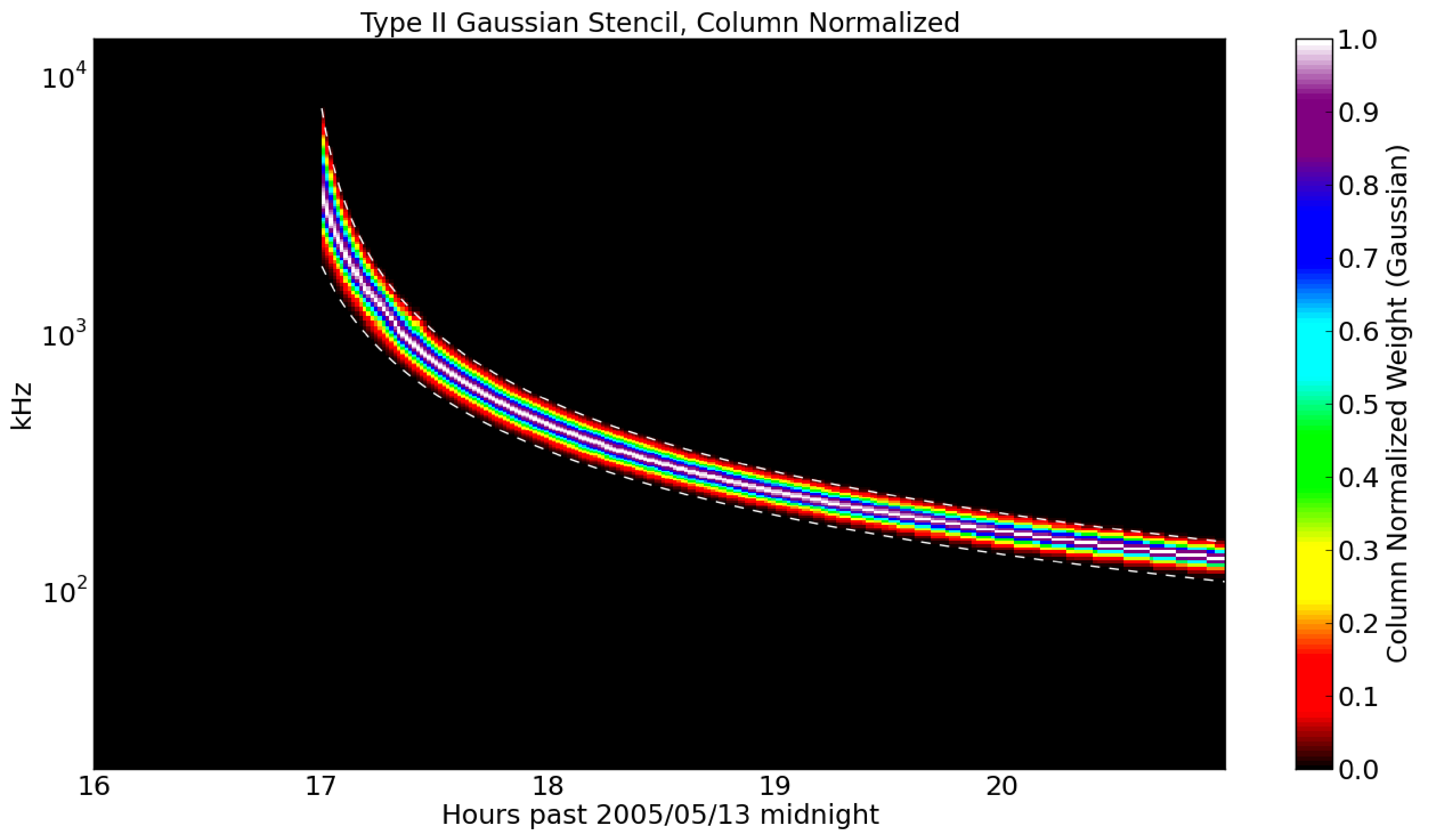
$$\sigma = \frac{2\, k_B\, T_{sys}}{\eta_s\, A_{eff}\, \sqrt{N(N-1)(N_{IF}\, \Delta T\, \Delta \nu)}}$$



CREATING AN ANALYTIC GAUSSIAN PROFILE



CREATING AN ANALYTIC GAUSSIAN PROFILE



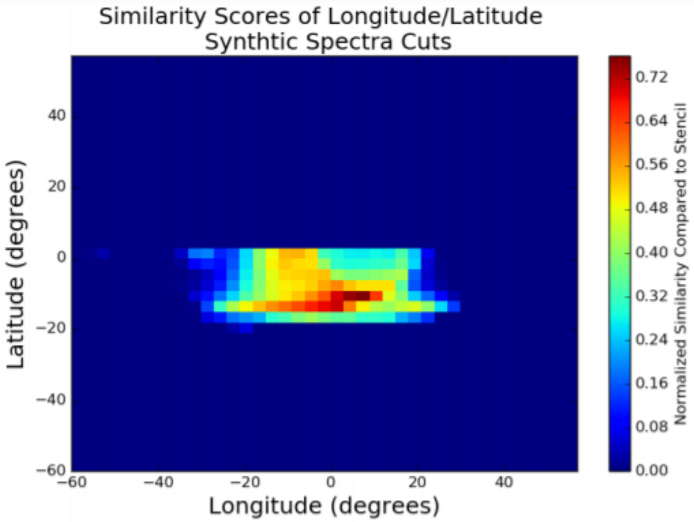
Yields “Scoring Stencil”

May be compared to synthetic spectra

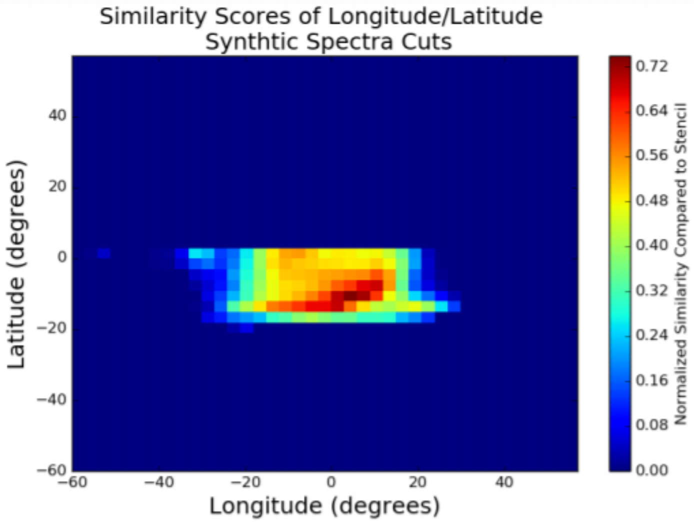
Normalized so 1 point/ timestep possible

Rewards spectra matching middle frequency

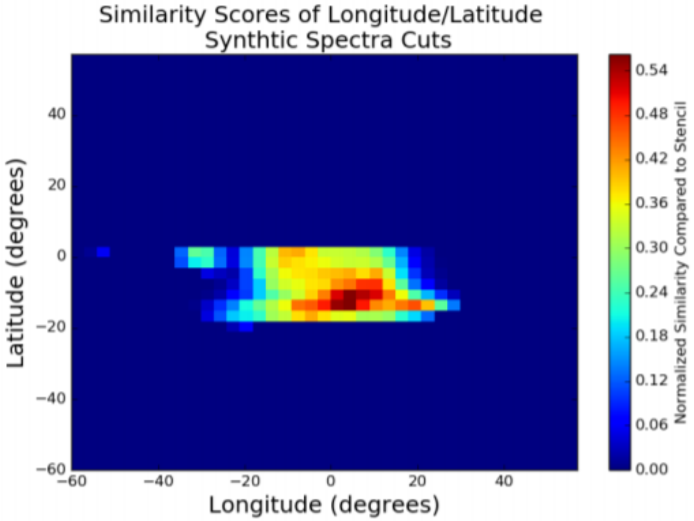
SCORING SPECTRA SIMILARITY OVER SHOCK GEOMETRY


Similarity Scores of Longitude/Latitude Synthtic Spectra Cuts

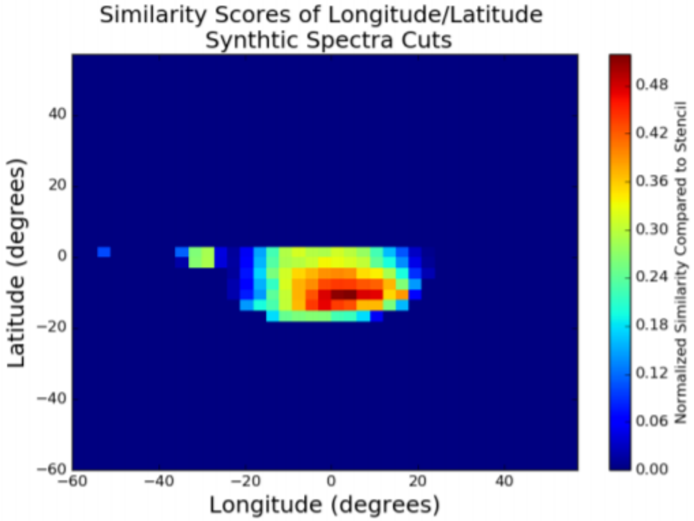
All (non-artifact) entropy enhanced data included


Similarity Scores of Longitude/Latitude Synthtic Spectra Cuts

Only data points with distance > 0.7*maxr included

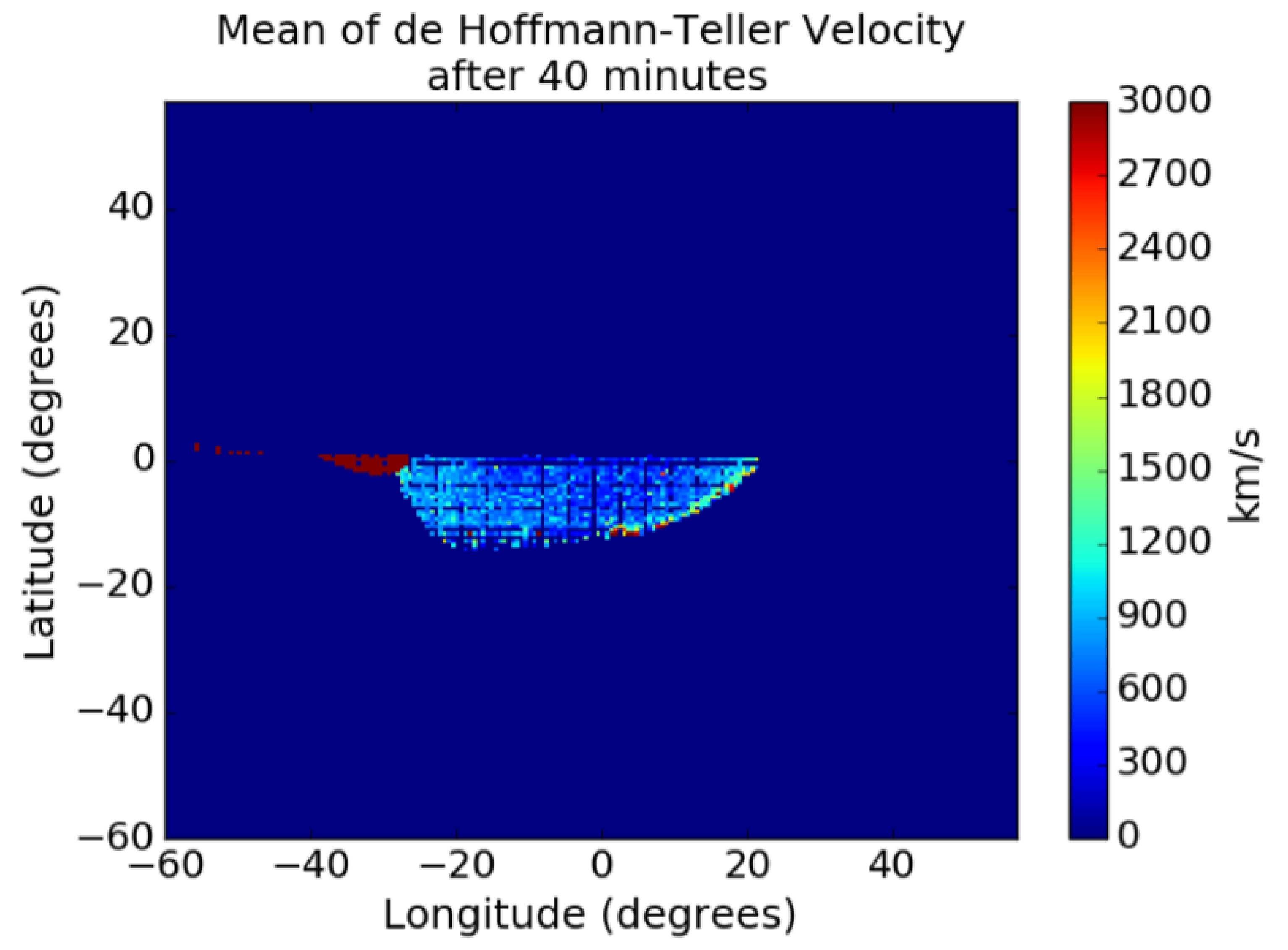

Similarity Scores of Longitude/Latitude Synthtic Spectra Cuts

Only data points with distance > 0.8*maxr included


Similarity Scores of Longitude/Latitude Synthtic Spectra Cuts

Only data points with distance > 0.9*maxr included

WHAT MATCHES THIS SIMILARITY STRUCTURE?



$$\mathbf{V}_{HT} = \frac{\hat{\mathbf{n}} \times (\mathbf{V_u} \times \mathbf{B_u})}{\mathbf{B_u} \cdot \hat{\mathbf{n}}}$$

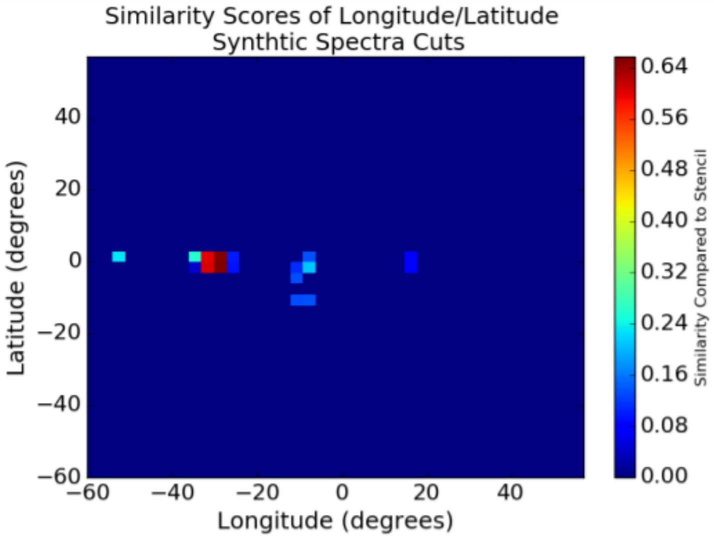
de Hoffmann-Teller frame velocity?

Frame where the convective electric field vanishes on both sides of the shock

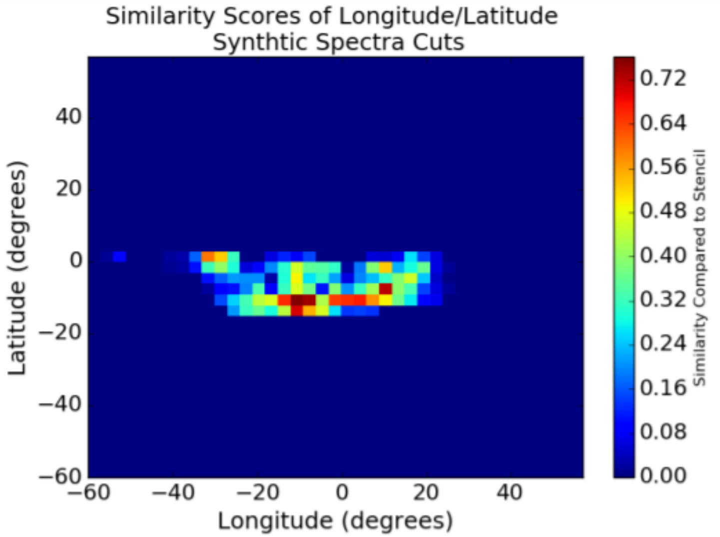
Highly correlated with in situ Langmuir Waves (Pulupa et al. 2010)

Features of this over shock surface matches similarity structure

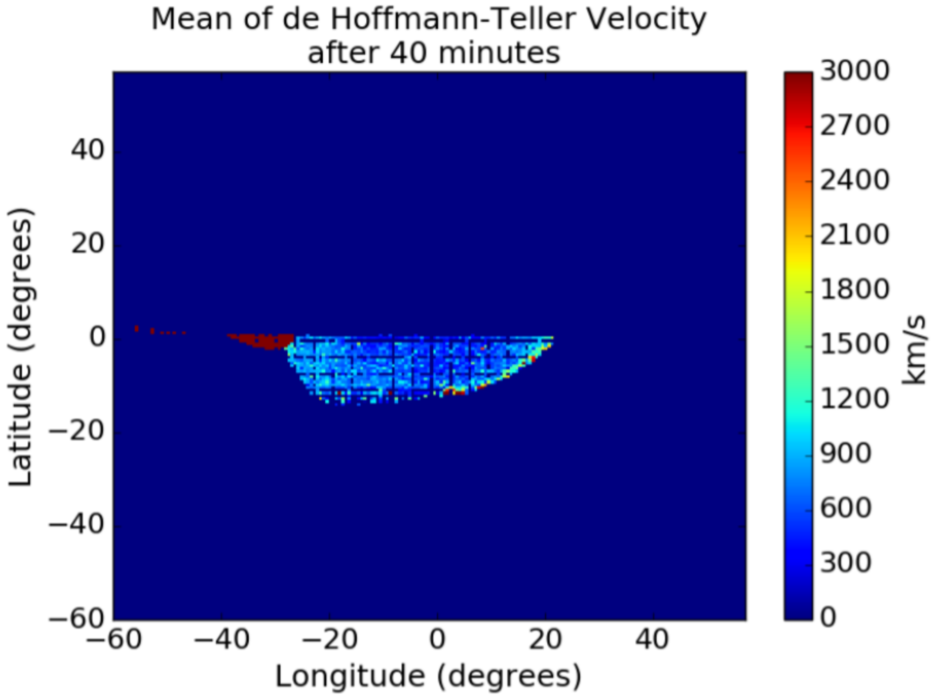
SIMILARITY SCORES WITH DE HOFFMANN-TELLER THRESHOLD

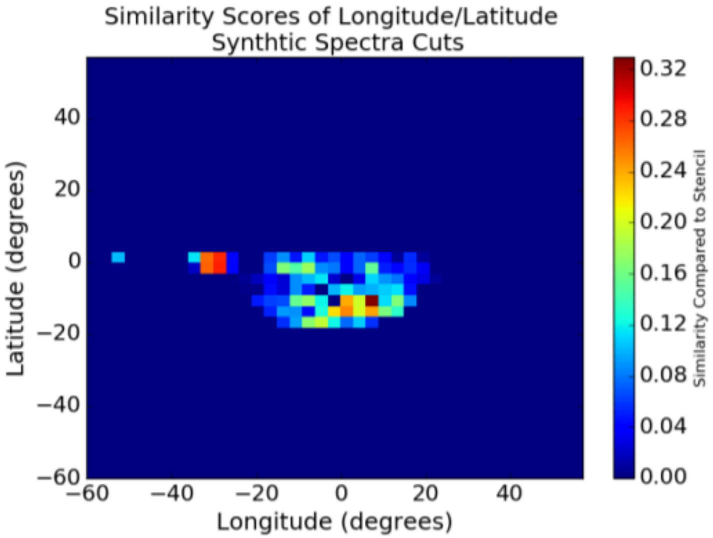


1 hour normalized, r > 0.9*maxr, $V_{HT} > 2000$ km/s

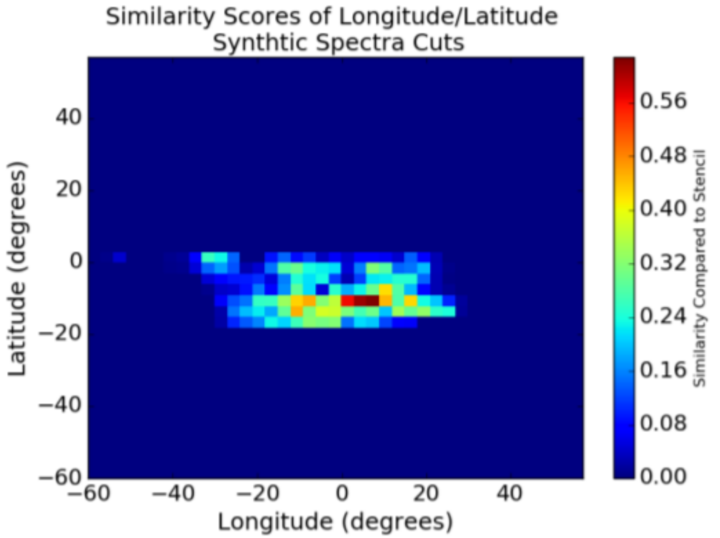


1 hour normalized, r > 0.7*maxr, $V_{HT} > 2000$ km/s



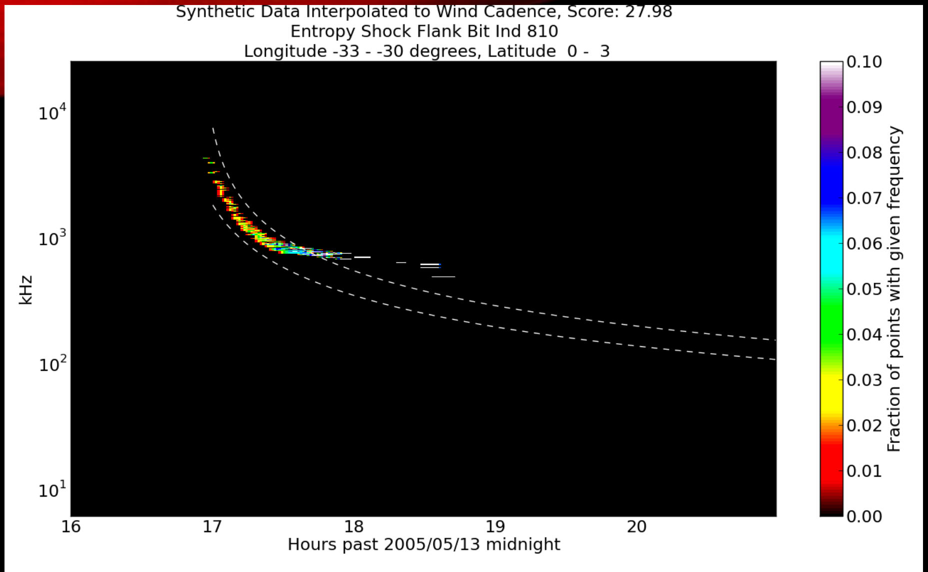


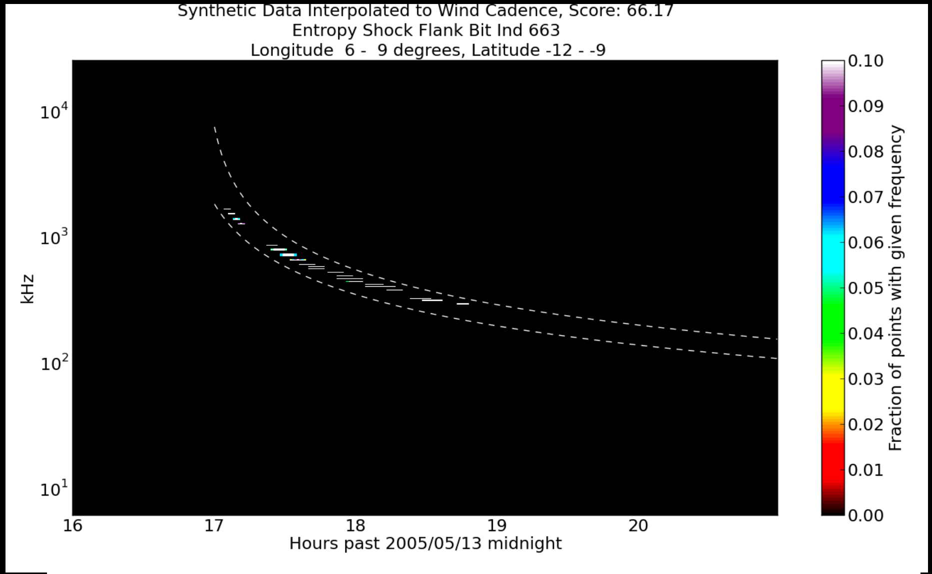
2 hour normalized, r > 0.9*maxr, $V_{HT} > 2000$ km/s

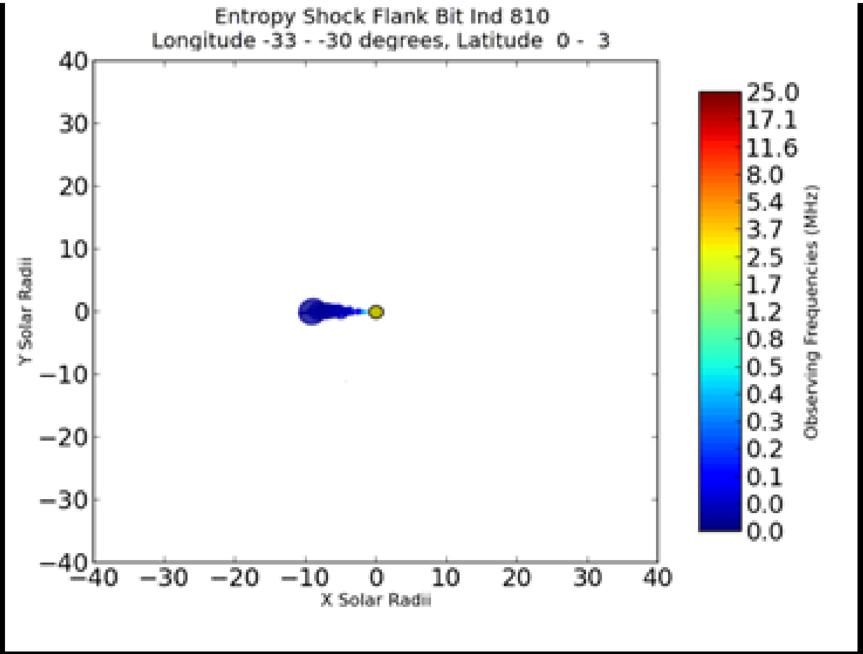


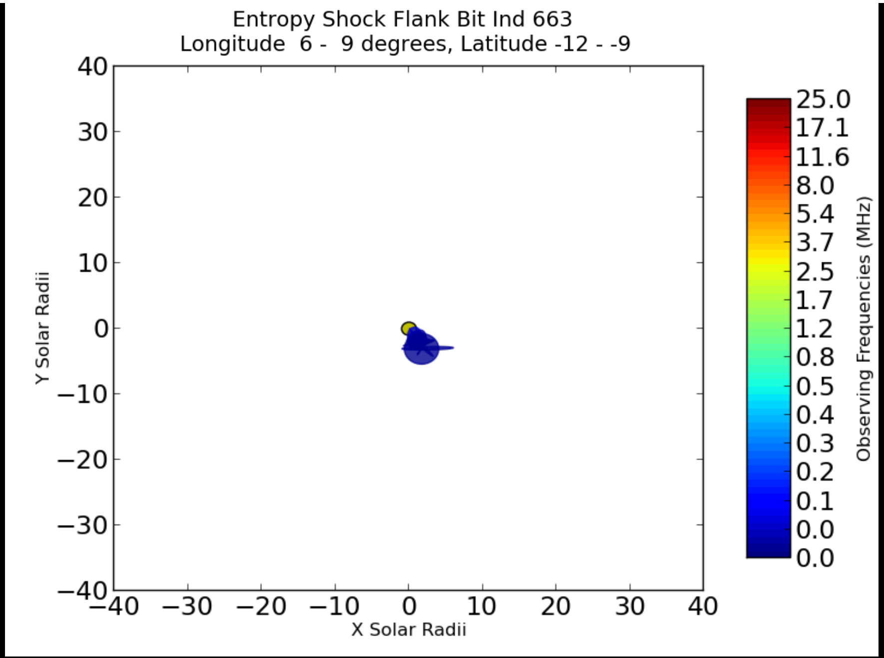
2 hour normalized, r > 0.7*maxr, $V_{HT} > 2000$ km/s

2 RECOVERED EMISSION SCENARIOS


Synthetic Data Interpolated to Wind Cadence, Score: 27.98
Entropy Shock Flank Bit Ind 810
Longitude -33 - -30 degrees, Latitude 0 - 3


Synthetic Data Interpolated to Wind Cadence, Score: 66.17
Entropy Shock Flank Bit Ind 663
Longitude 6 - 9 degrees, Latitude -12 - -9


Entropy Shock Flank Bit Ind 810
Longitude -33 - -30 degrees, Latitude 0 - 3

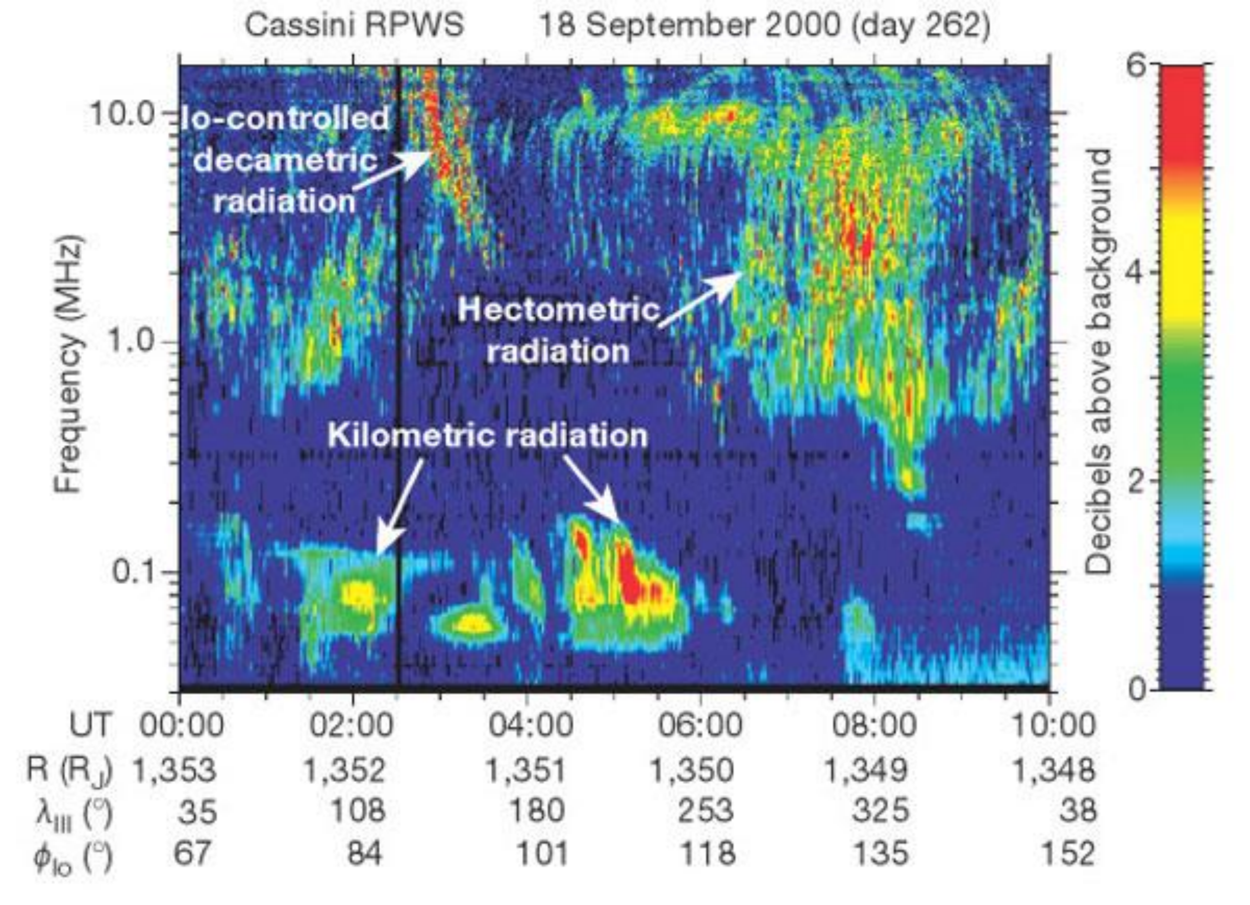

Entropy Shock Flank Bit Ind 663
Longitude 6 - 9 degrees, Latitude -12 - -9

LOOKING FOR PLANETARY EMISSION

May subtract out constant sky model to look for weaker transients

A Jovian Io burst (strongest and most predictable) will typically dwell on a frequency for > 1 hour.

Processing of searching for Jovian Emission mirrors that of extrasolar planetary emission



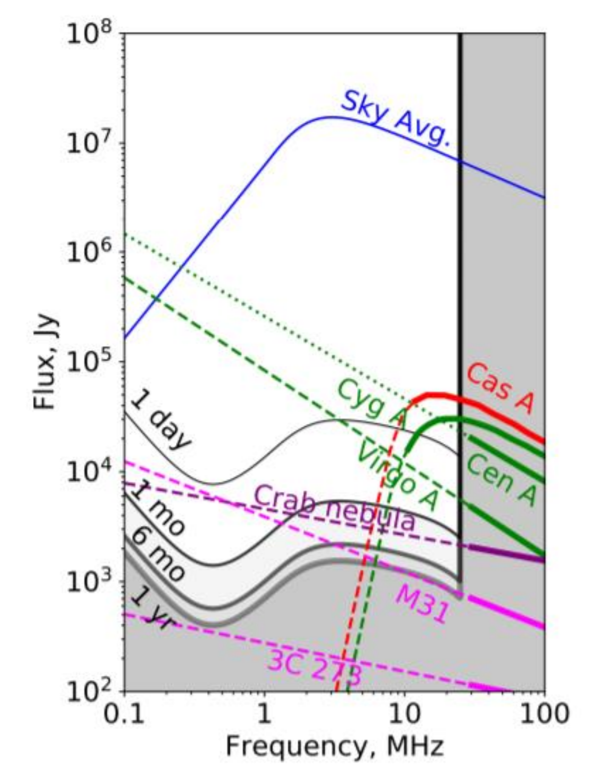
CALIBRATION / VALIDATION WITH JOVIAN BURSTS

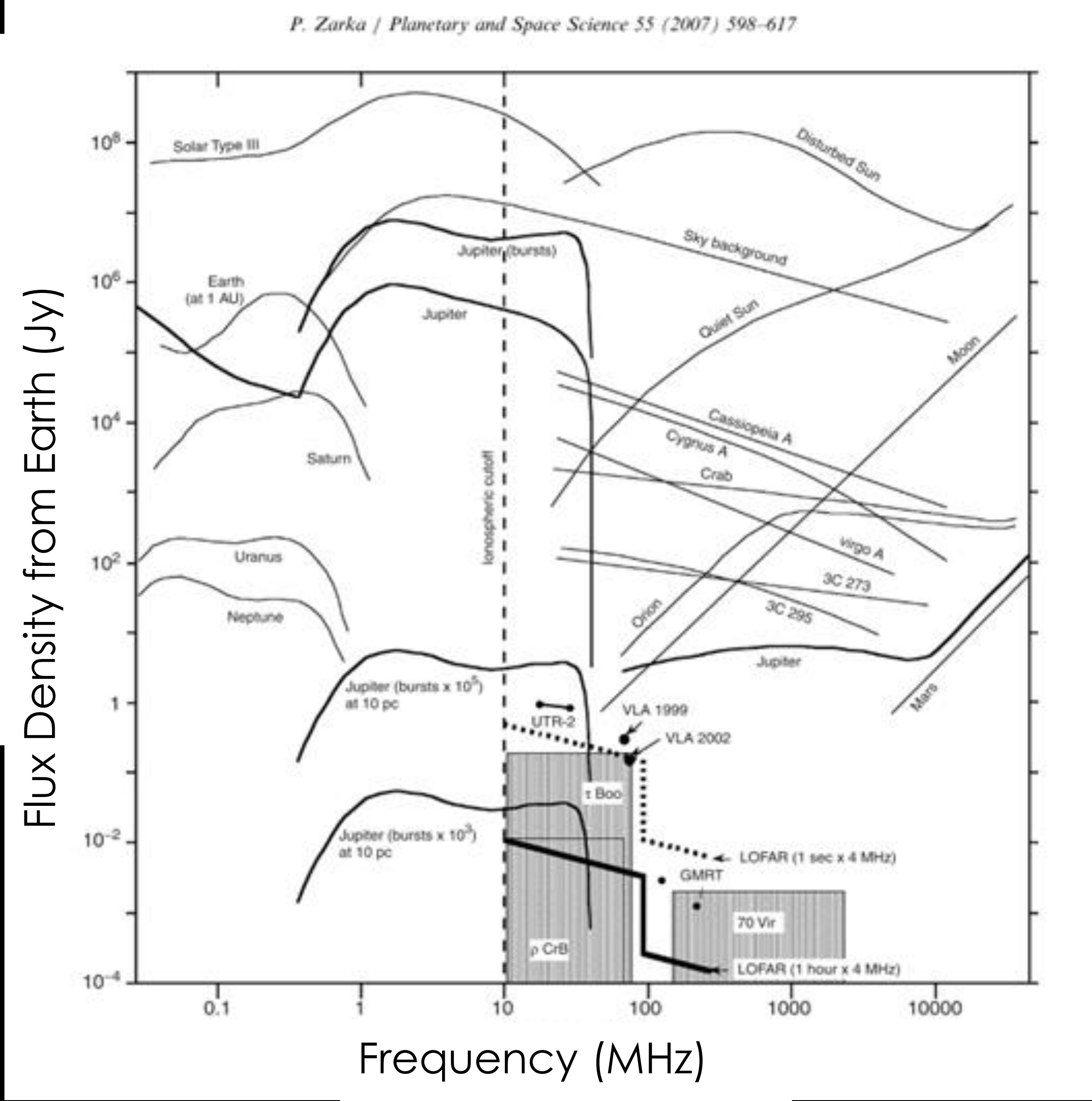
Jupiter’s Io Decametric Radiation as a Calibration Source

Property	Range	Notes
Frequency	$0.3\ \mathrm{MHz}\ - 35\ \mathrm{MHz}$	Significant overlap with SunRISE band.
Occurrence	$\sim$every couple of days	Predictable occurrence based on Io orbital phase and Jupiter’s longitudinal phase.
Duration	~ 2 hours	Equivalent ~72,000 snapshots with SunRISE
Flux Density	$10^{-20}\ to\ 10^{-19}\ \mathrm{W\ m^{-2}\ Hz^{-1}}$	Flux is variable but strong when active. Stereo/Waves sees them regularly.
Structure	Point source	Source size < 400 km at 4.4 AU from VLBI measurements.

NOTE: These data are gathered while in science mode. It does not interfere with regular operations.

THE LIMITS OF SUNRISE



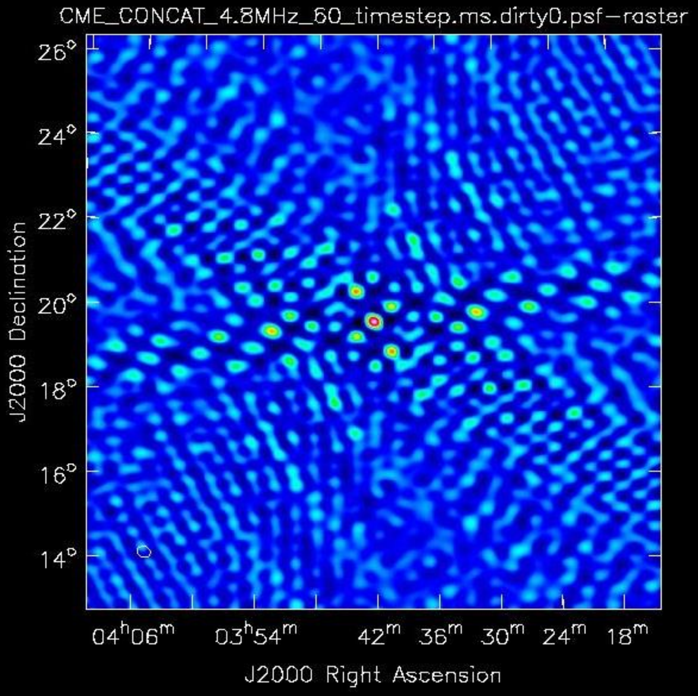


Small duty cycle ~0.1%
+ Limited lifetime
+ Few Spacecraft

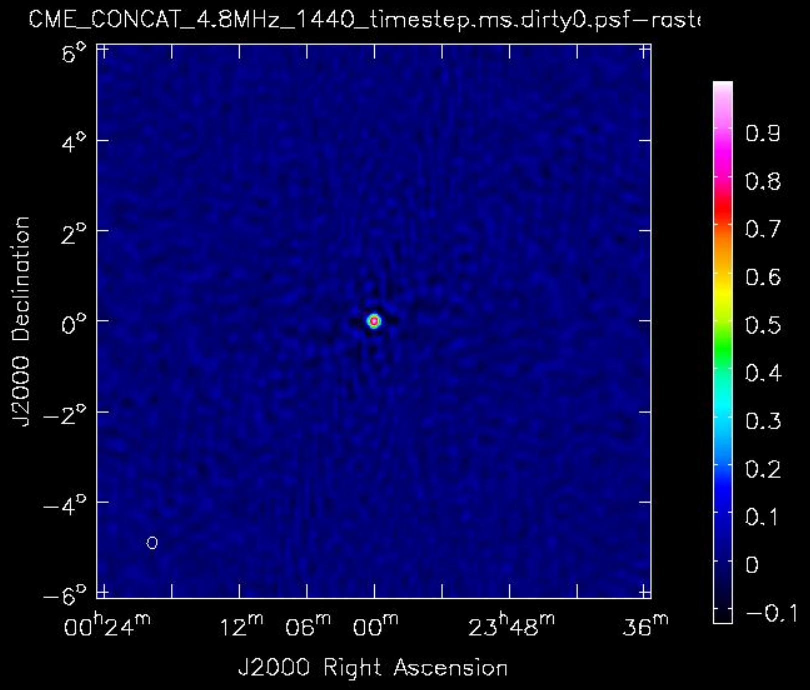
= Can only see brightest sources

INTEGRATING SUNRISE FOR STATIC IMAGING

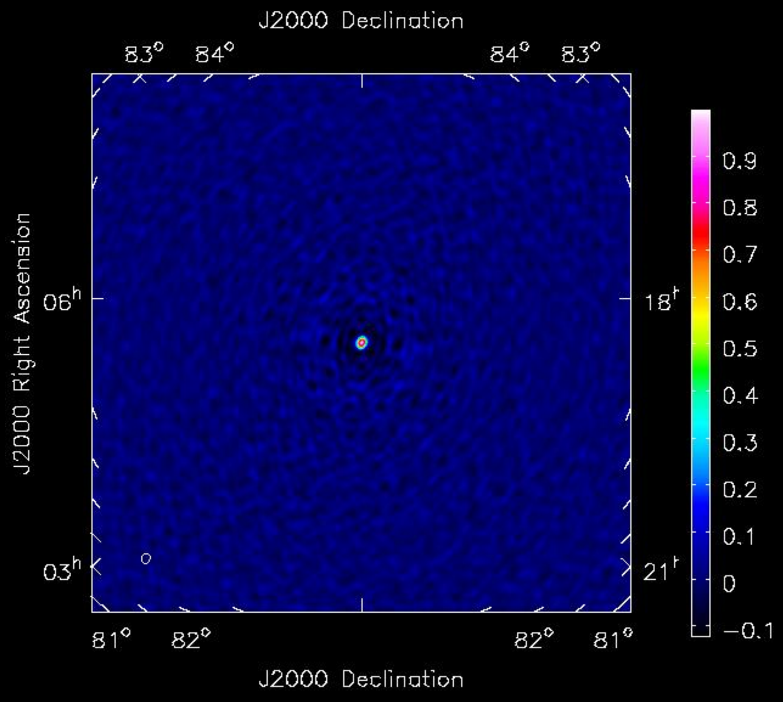
1 hour integrated beam



24 hour integrated beam

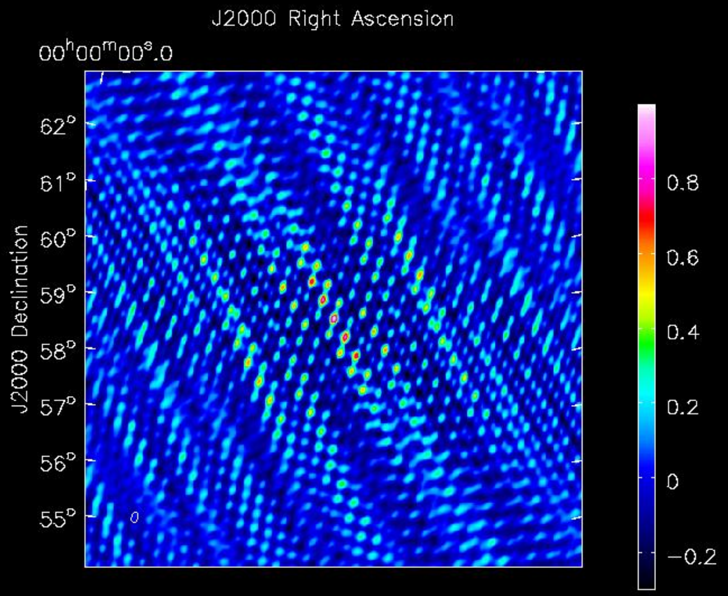


24 hour integrated beam
90° Declination

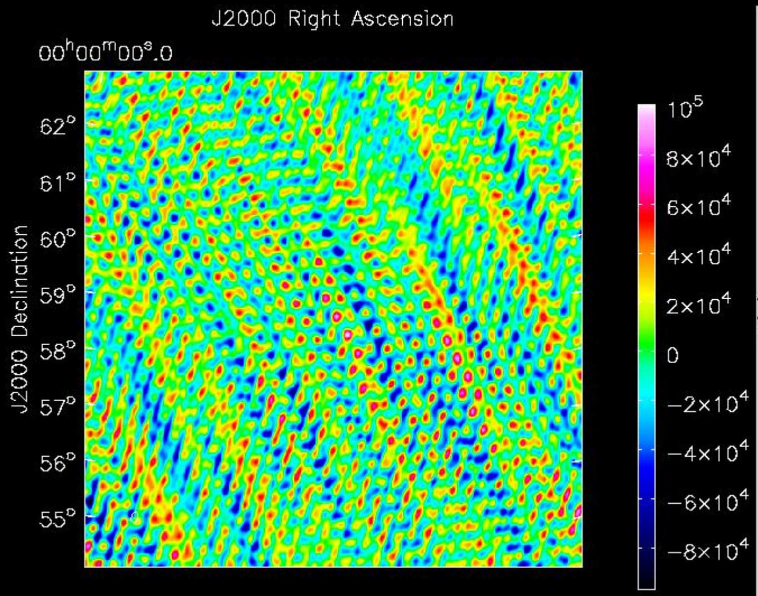


30 MINUTE INTEGRATION

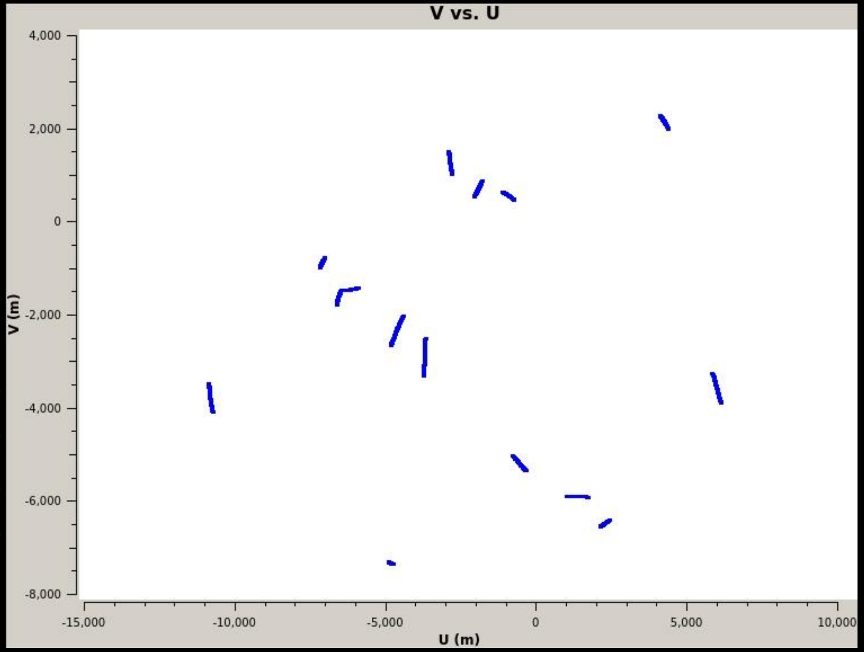
Dirty Beam



Noisy Cas A Image

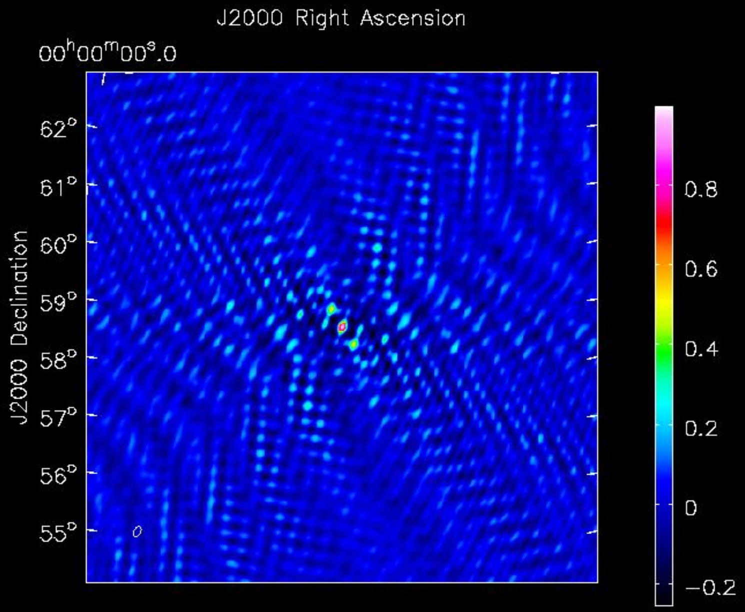


UV Coverage

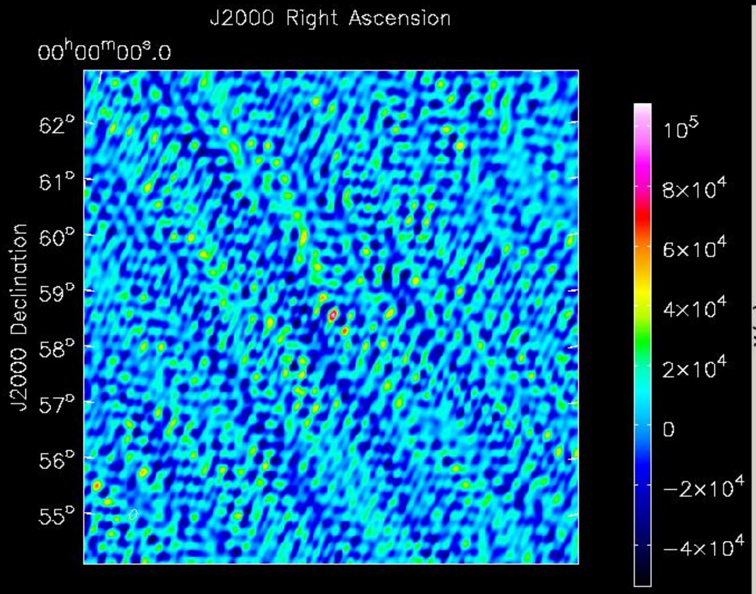


2 HOURS INTEGRATION

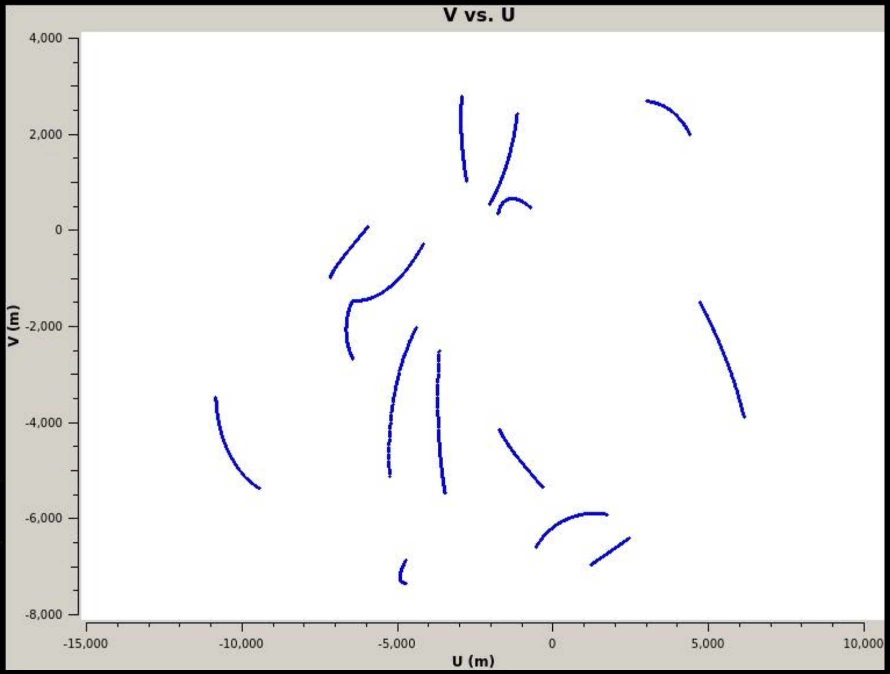
Dirty Beam



Noisy Cas A Image

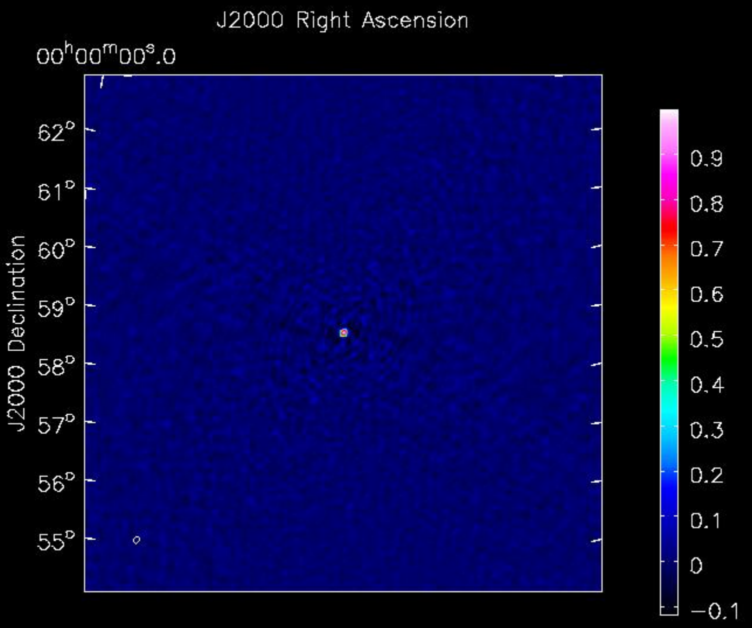


UV Coverage

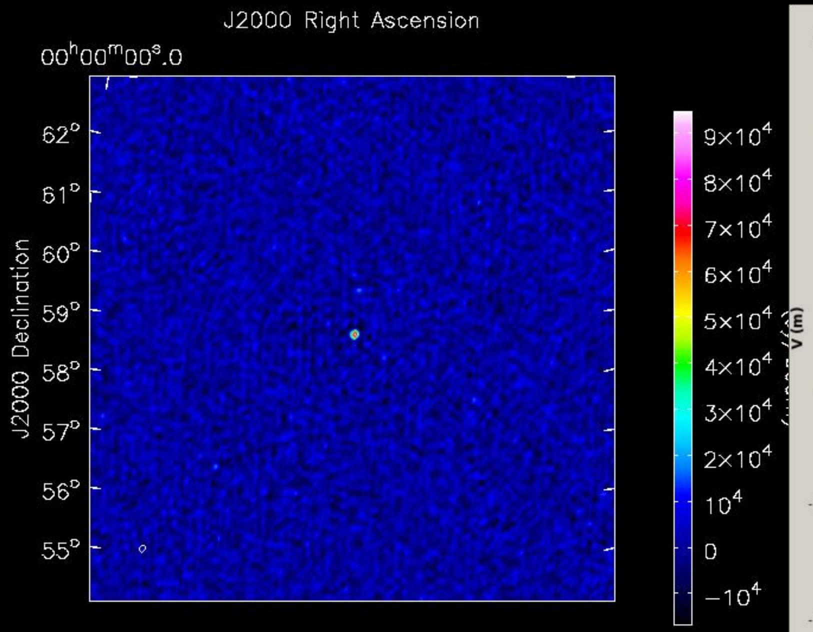


ORBIT INTEGRATION

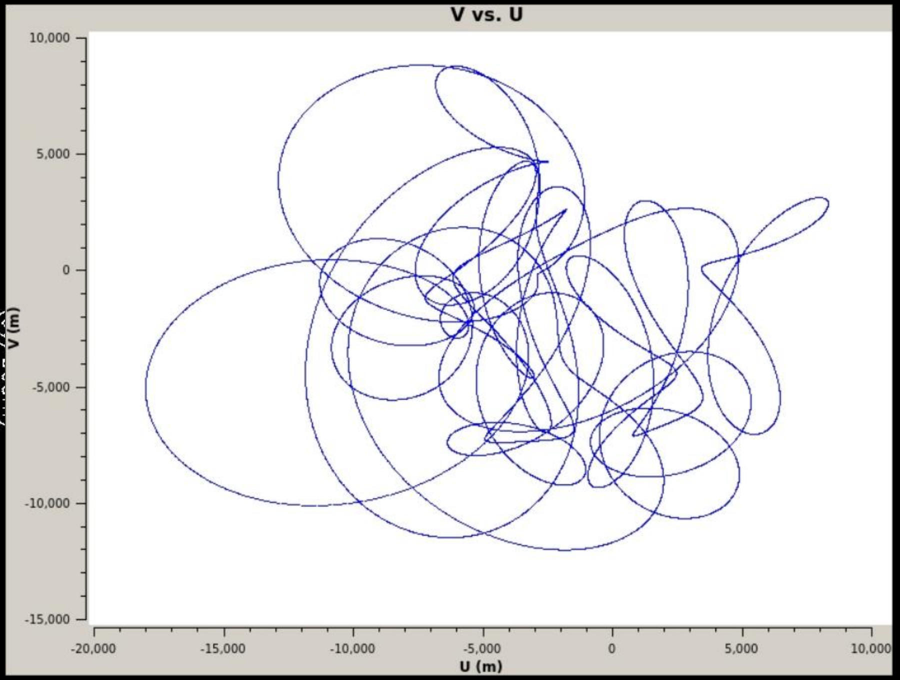
Dirty Beam



Noisy Cas A Image

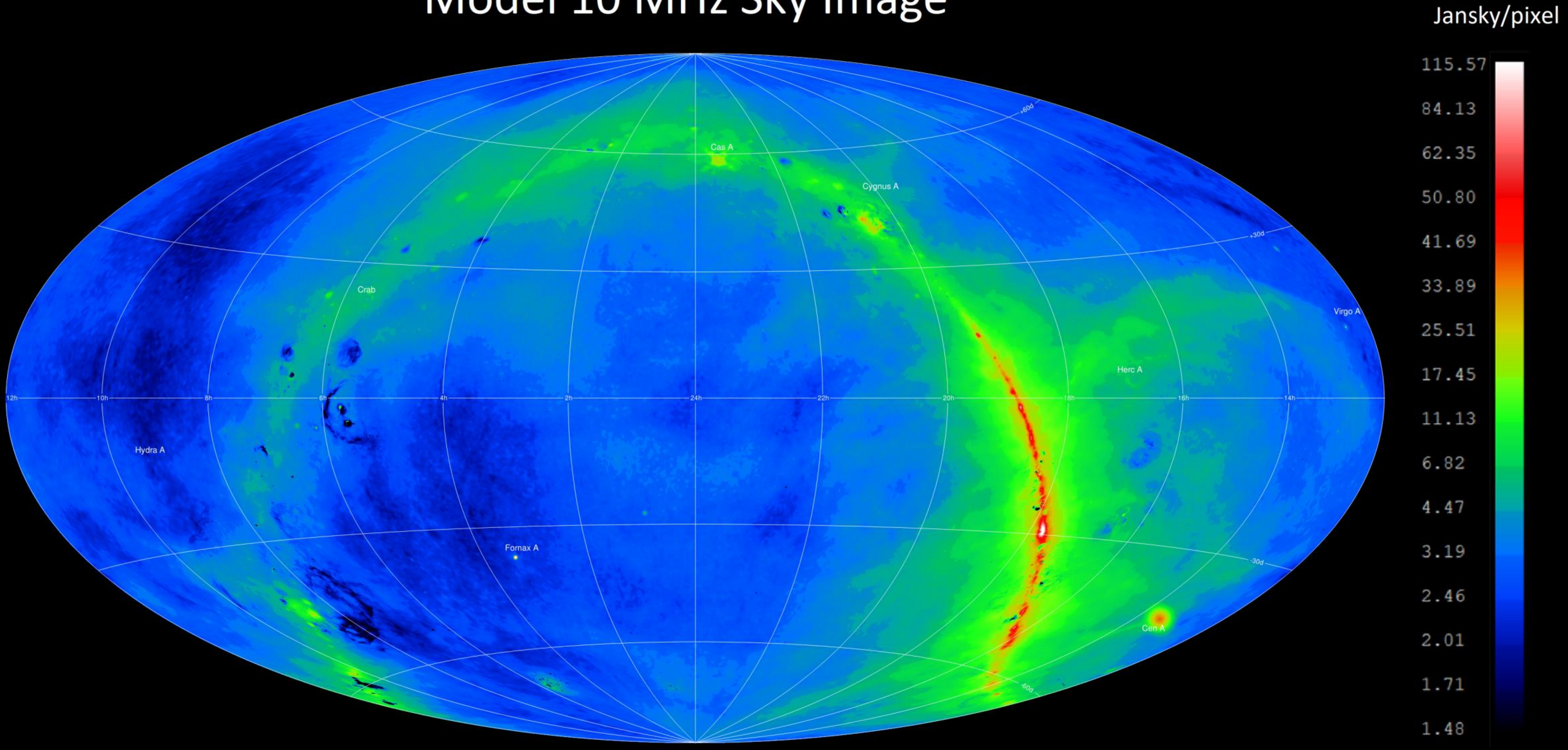


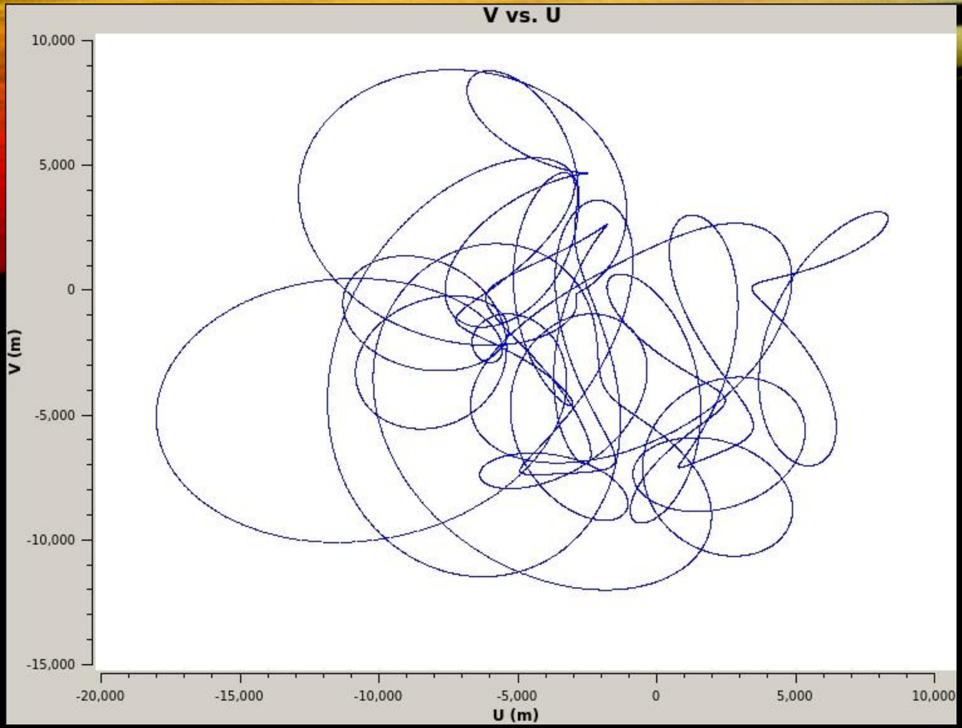
UV Coverage



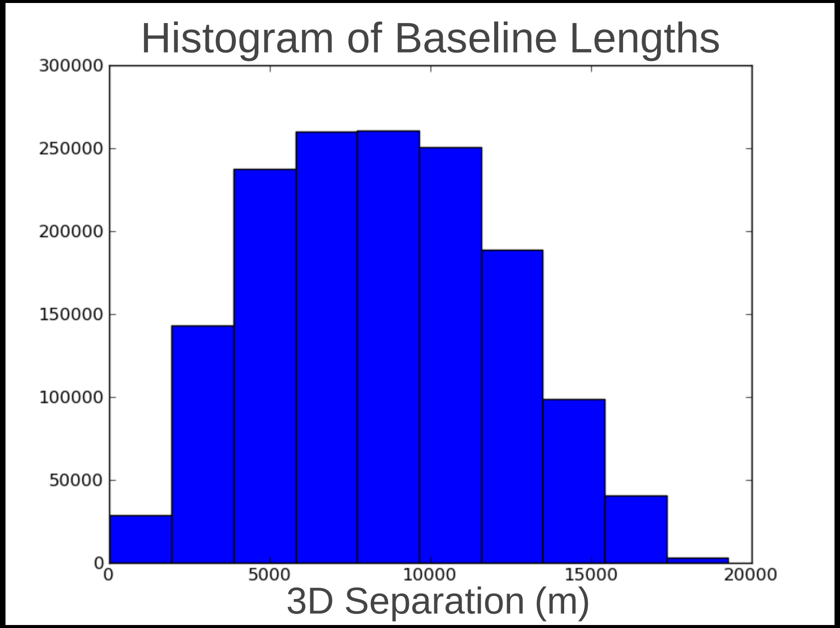
ALL SKY IMAGING

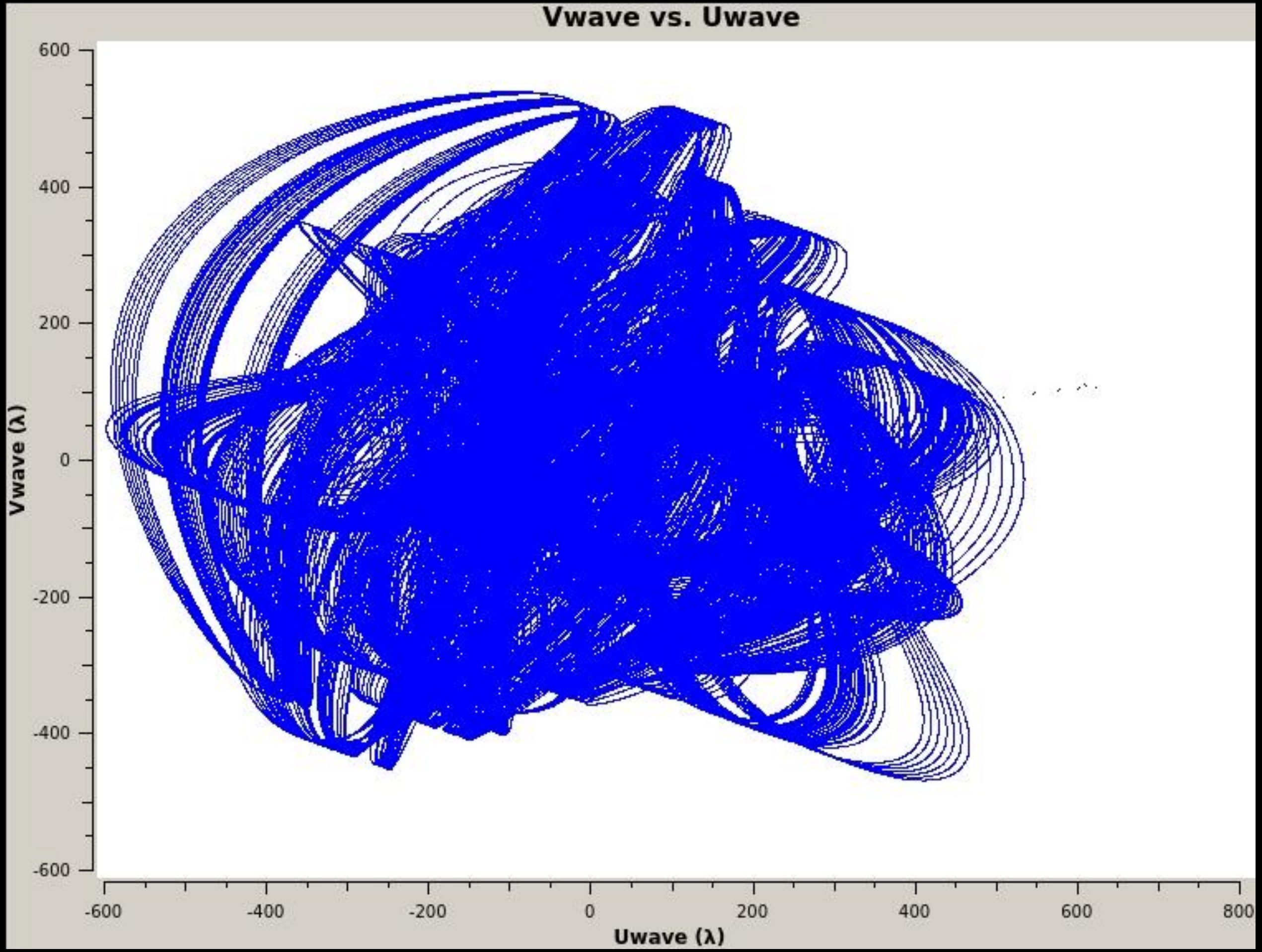
Model 10 MHz Sky Image



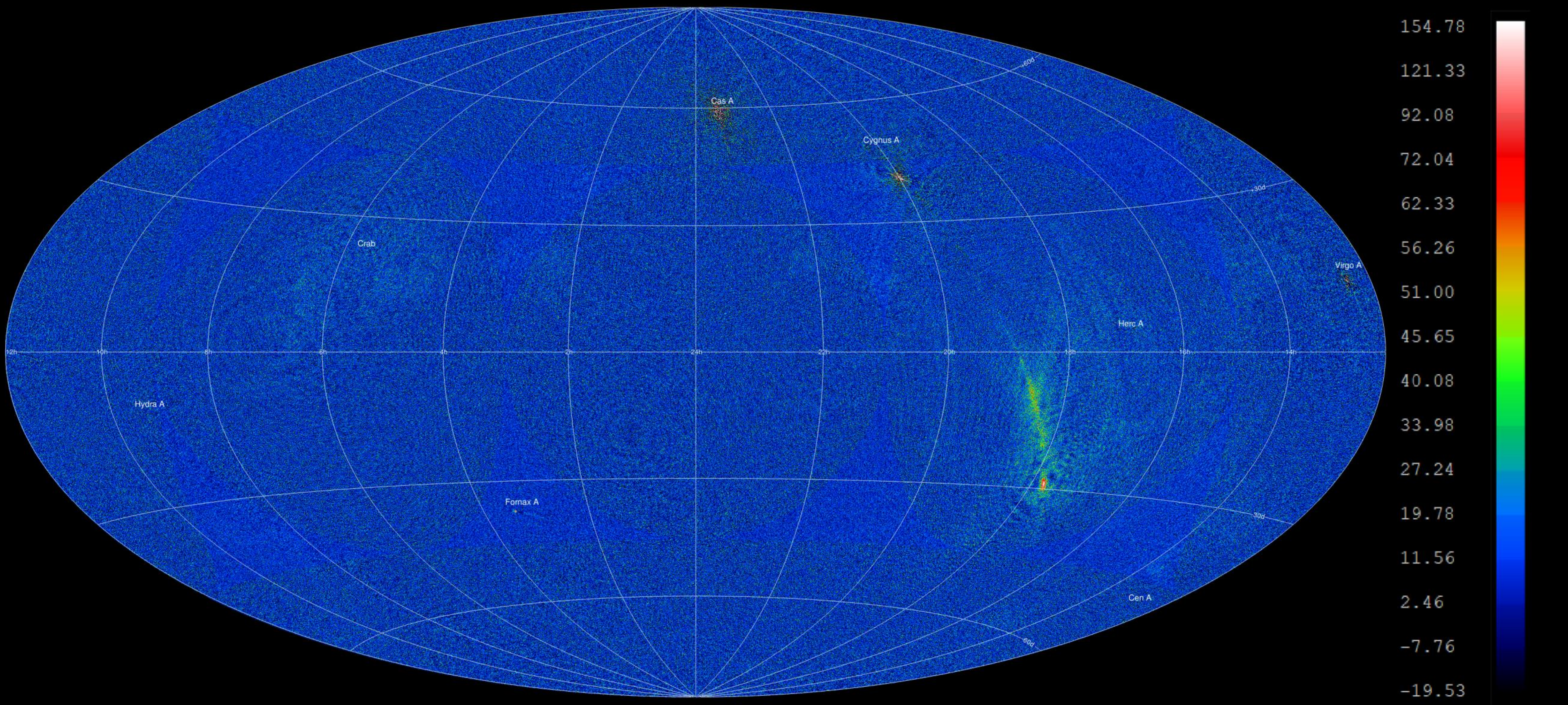


INTEGRATING 1 VS 10 WEEKS

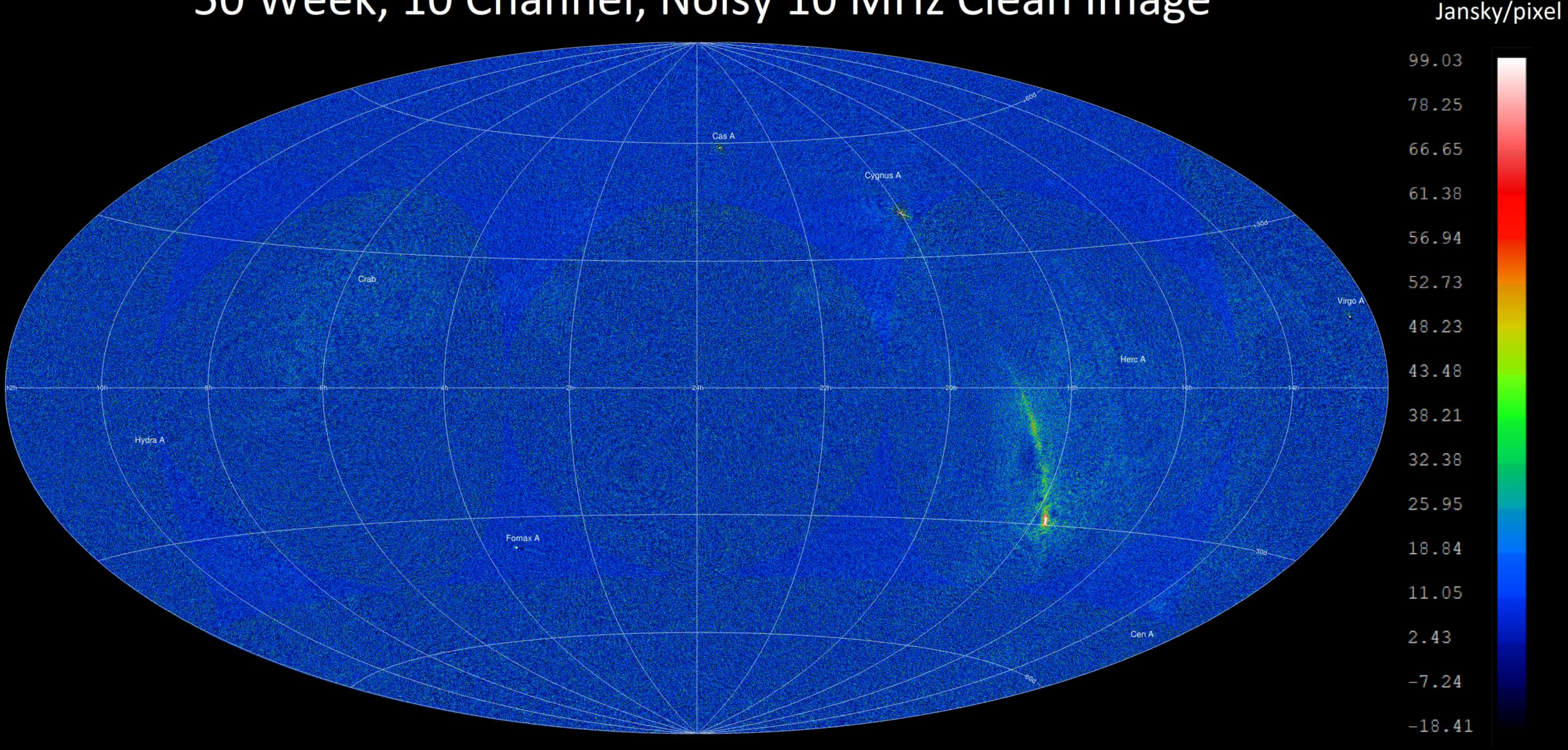




50 Week, 10 Channel, Noisy 10 MHz Dirty Image



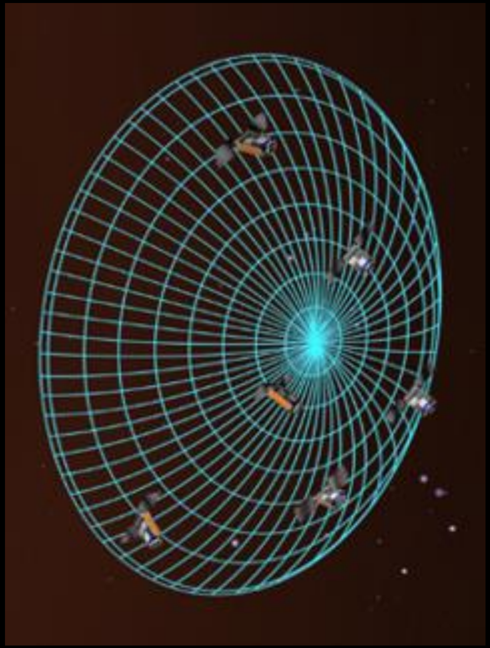
50 Week, 10 Channel, Noisy 10 MHz Clean Image

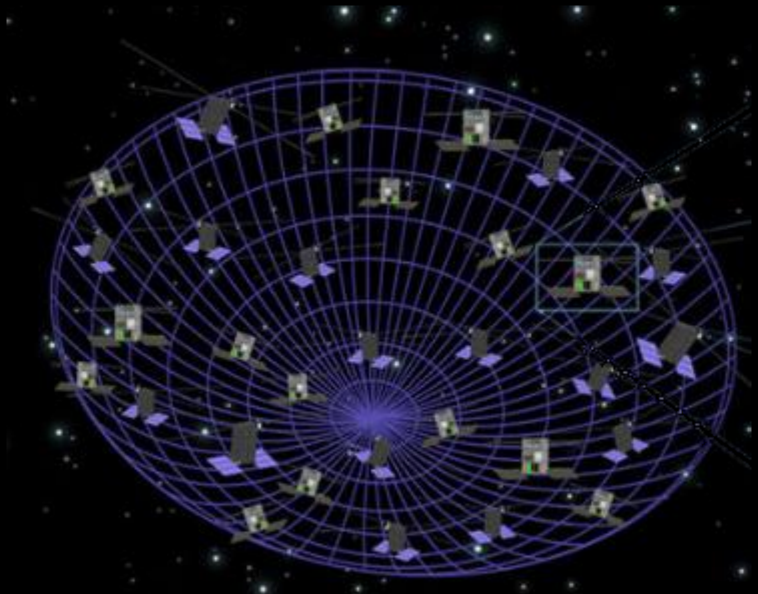


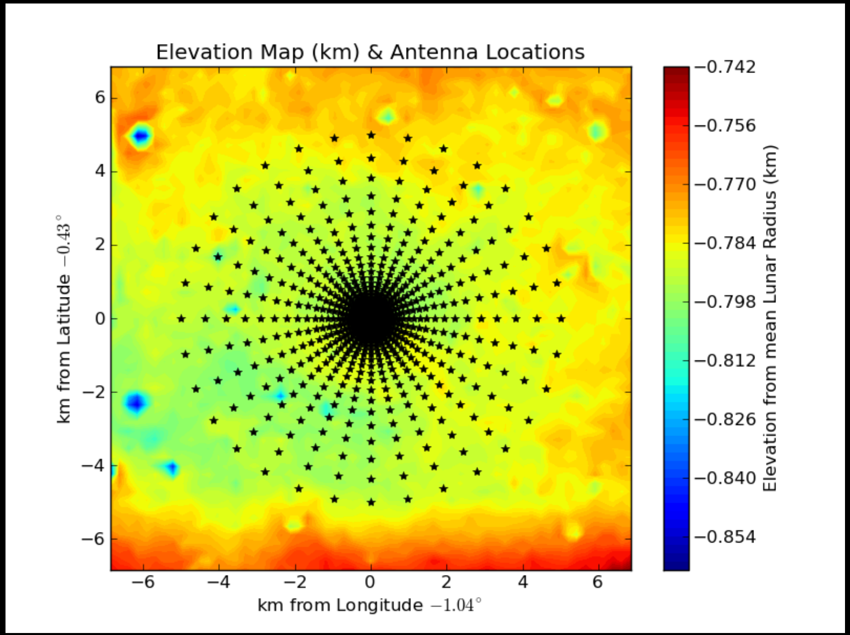
SUMMARY

- SunRISE, designed for observing Solar Radio Bursts, can see the entire Low Frequency Sky over 12 month mission
- SunRISE will make first maps of the Sky at these Frequencies
- Will allow preliminary Galactic foreground subtraction
- SunRISE can localize individual radio sources
- Data Processing mirrors that of a larger array that could detect Extrasolar Planetary Emission or 21 cm signal
- Space Based Interferometry will be huge, SunRISE is the pathfinder starting 2023

QUESTIONS?







SunRISE 6 Receivers

>10^6 Jy Instant
10^3 Jy Integration 1 year

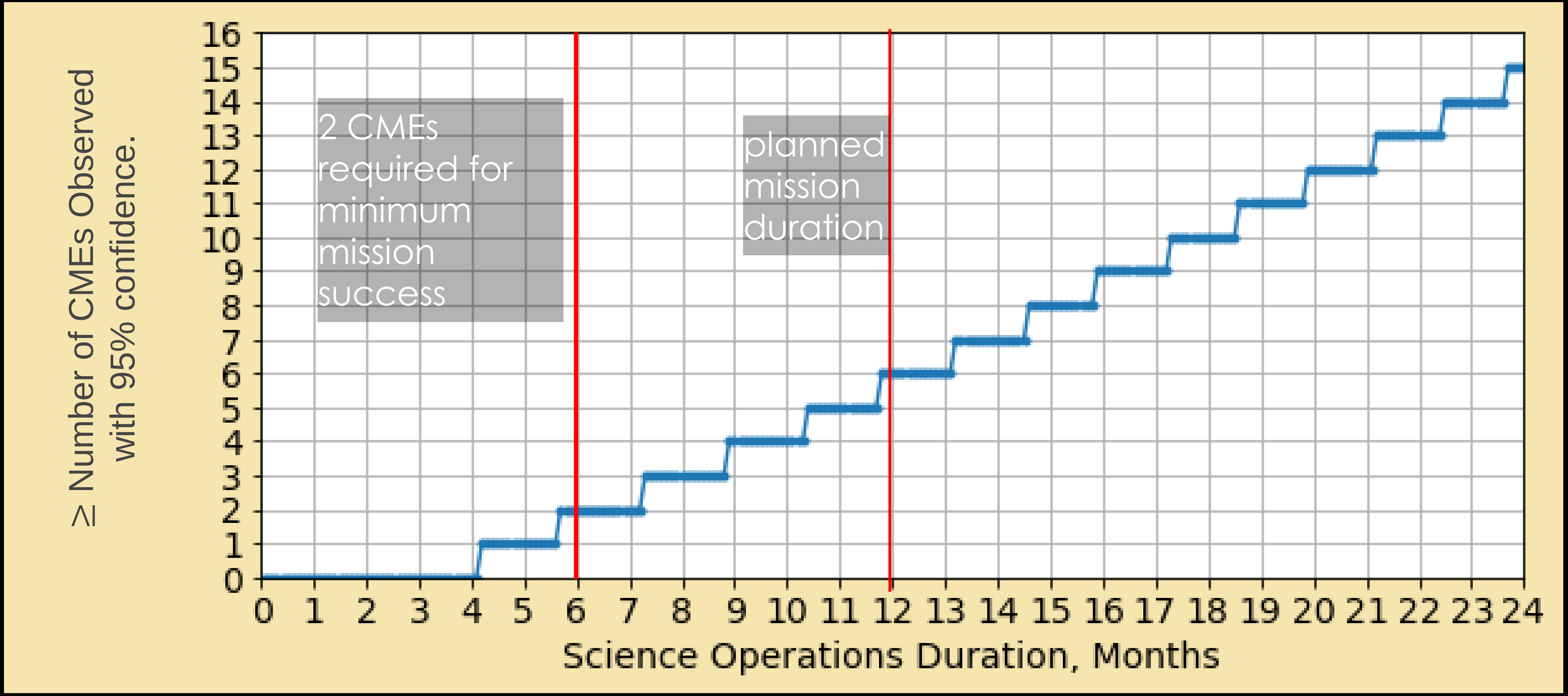
RELIC 32 Receivers

10-100 Jy Integration 1 day

Lunar Surface 1-16K Receivers

~0.25 Jy Integration 2-12 hours

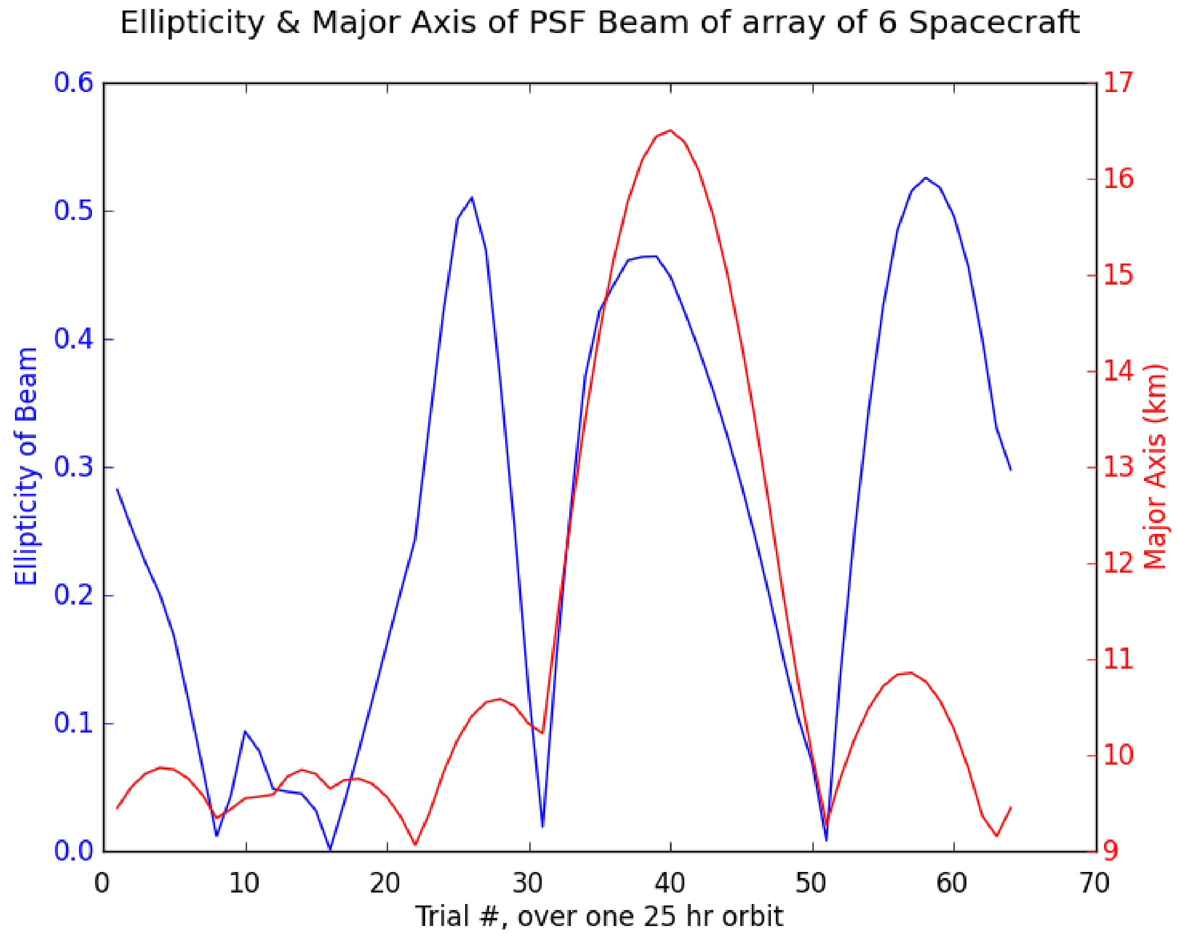
NUMBER OF CMES AND MISSION DURATION

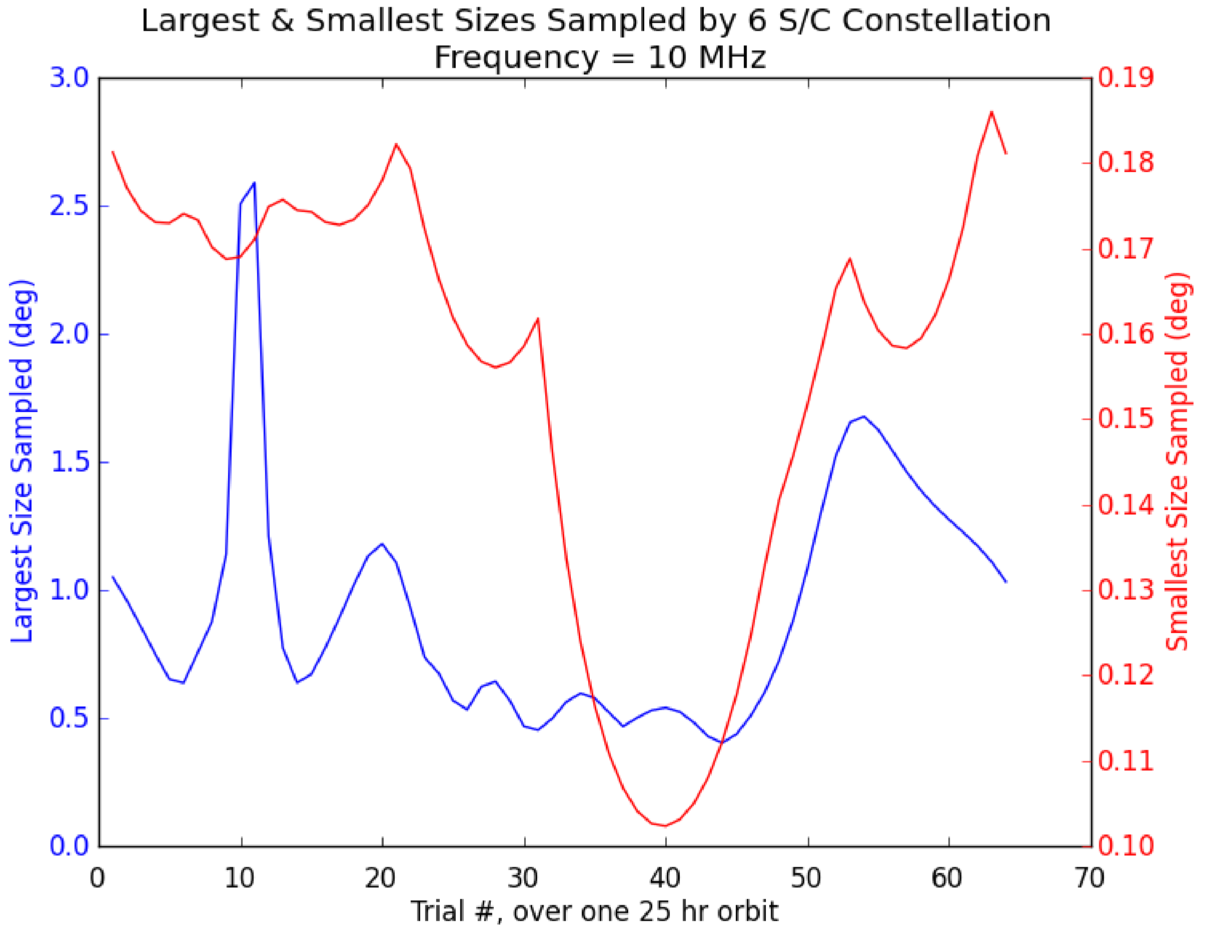


WEEKLY DOWNLINK BUDGET ALLOCATION

Data Type	Description	Cadence	Volume per downlink
Solar DH	Science Spectra (64 specified sub-bands × 2 pol. × complex amp. × 8 bits + 128 bit header)	10 Hz	13.2 Gb
	Diagnostic Spectra (4096 sub-bands × 2 pol. × 2 complex amp. × 24 bits + 128 bit headers)	0.3 mHz (1/hour)	66 Mb
	Diagnostic output (ADC samples; 32k × 24 bits + 128 bit headers)	12 mHz (1/day)	7 Mb
GNSS	Observables (phase, pseudo-range; 12 ch. × 2216 bits)	0.1 Hz	1.6 Gb
	On-board Navigation Solution (2088 bits)	0.1 Hz	0.13 Gb
Auxiliary	Log Messages (2776 bits)	0.1 Hz	0.17 Gb
	Housekeeping (1688 bits)	17 mHz (1/minute)	17 Mb
Total			15.2 Gb

ORBITING ARRAYS ARE IRREGULAR


Ellipticity & Major Axis of PSF Beam of array of 6 Spacecraft


Largest & Smallest Sizes Sampled by 6 S/C Constellation
Frequency = 10 MHz