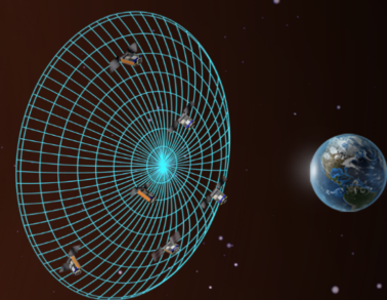
Using SunRISE as a Pathfinder for Detecting Low Frequency Radio Emission from Extrasolar Planets with Space Based Radio Arrays



Alexander M. Hegedus*[1], Justin C. Kasper[1], Joseph Lazio[2], Andrew Romero-Wolf[2], Timothy S. Bastian[3]

[1]Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI

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SunRISE

Sun Radio Interferometer Space Experiment

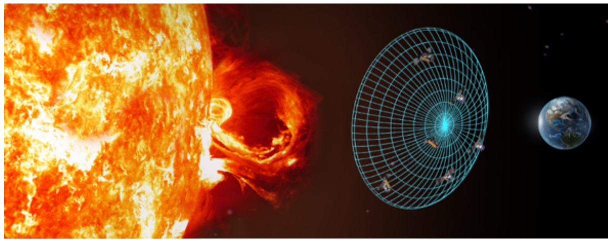
PRINCIPAL INVESTIGATOR: Justin C. Kasper (University of Michigan)

URSI 2019 Session J3: Radio Emission from Extrasolar Planets

Talk Outline

SunRISE
Sun Radio Interferometer Space Experiment

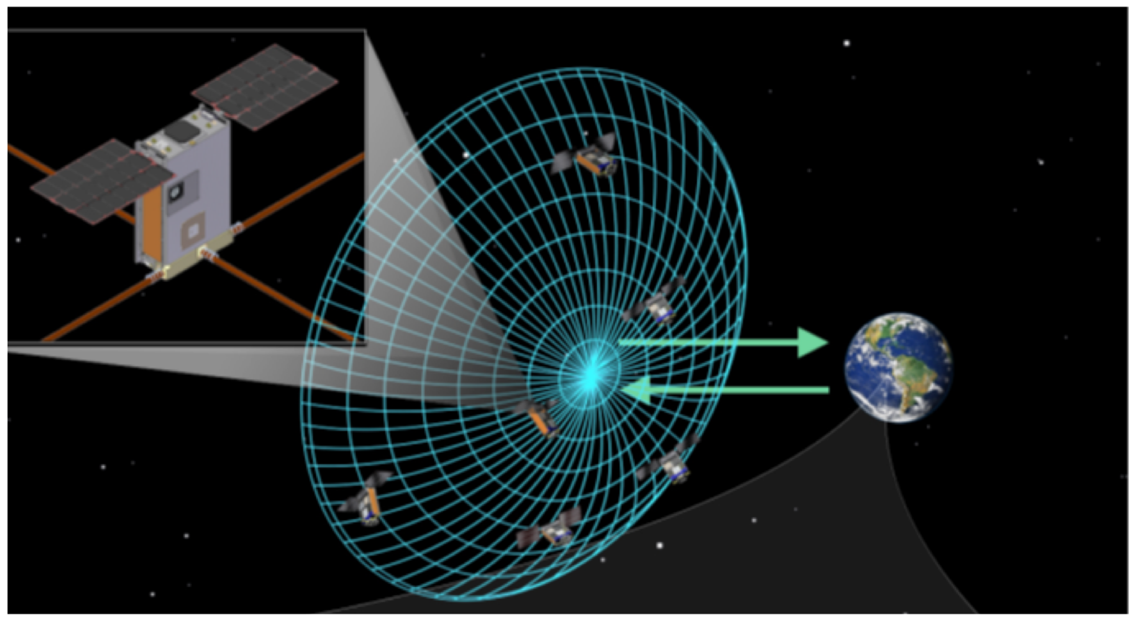
- Introduction to SunRISE
- Primary Science Objectives
- Science Operation Pipeline
- Additional Science Targets
- Preliminary Sky Maps
- Planetary Emission & Other Weak Sources



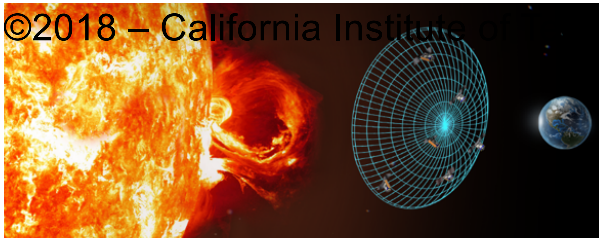
SunRISE Introduction

SunRISE
Sun Radio Interferometer Space Experiment

- SunRISE – Sun Radio Interferometer Space Experiment
- Heliophysics Explorers Mission of Opportunity ($55 M)
- Done with Phase A
- Will launch 2022 if funded
- 6 CubeSats in GEO Graveyard Orbit
- Can see below Ionospheric Cutoff

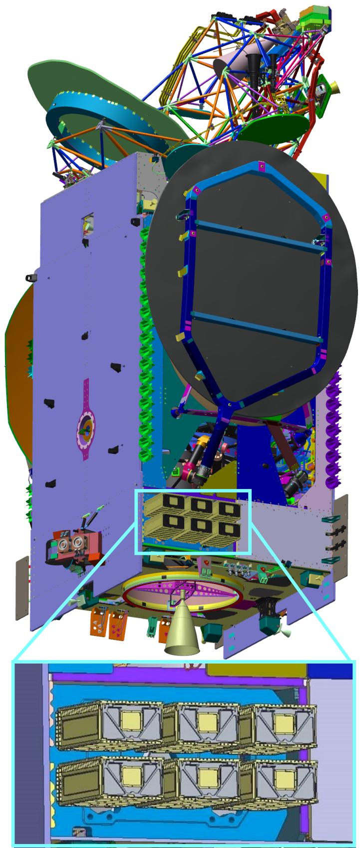


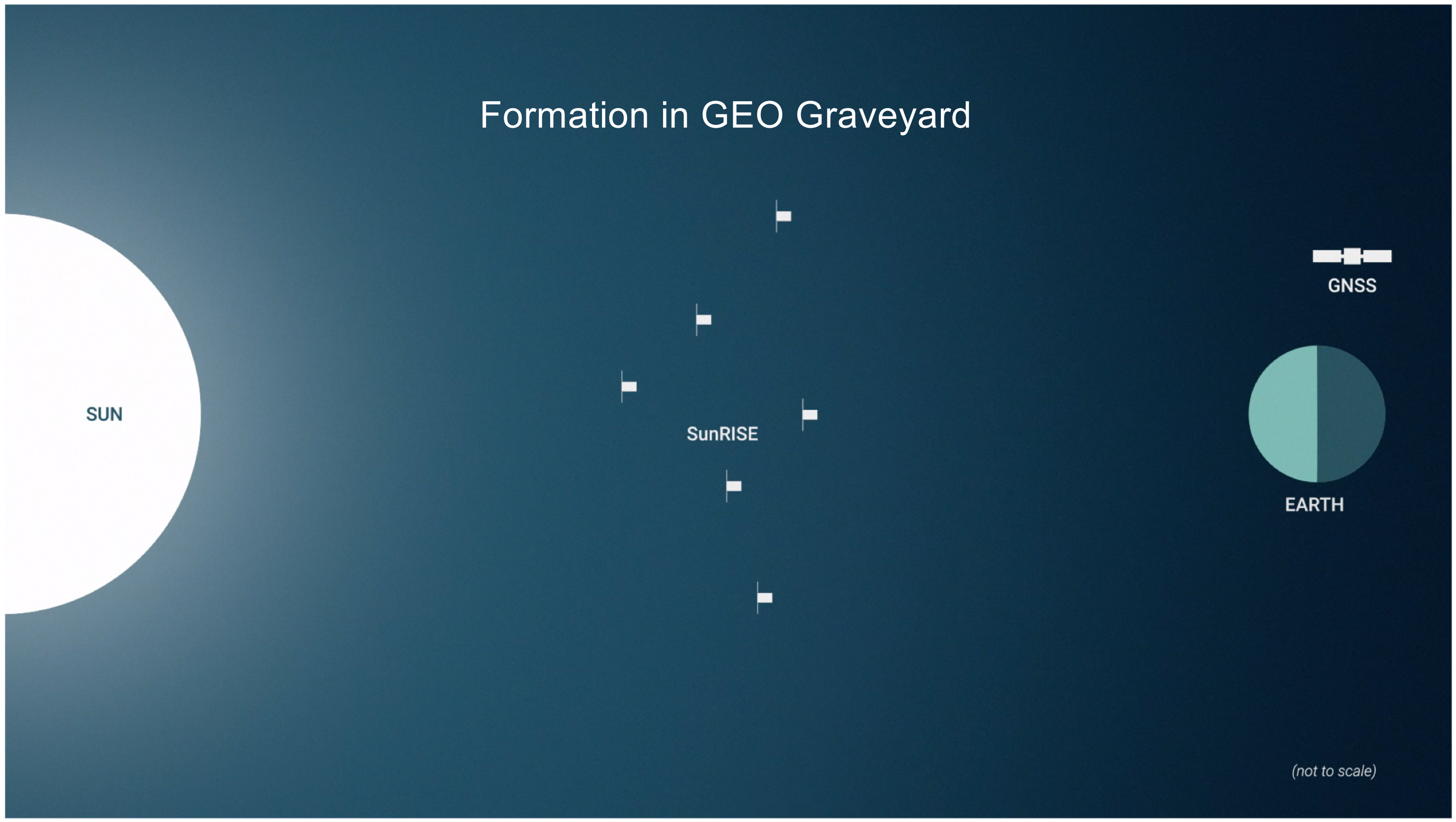

M
UNIVERSITY OF MICHIGAN
JPL
Jet Propulsion Laboratory
California Institute of Technology
SunRISE
Sun Radio Interferometer Space Experiment
SSL
A MAXAR COMPANY
Space Dynamics
LABORATORY
Utah State University Research Foundation

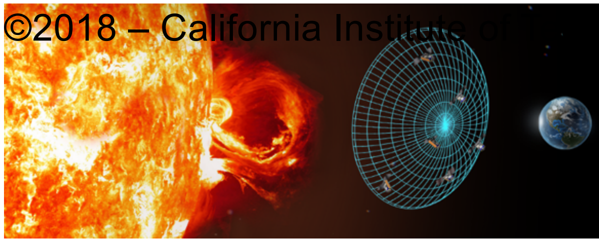


SunRISE Orbital Access & Operations

SunRISE
Sun Radio Interferometer Space Experiment

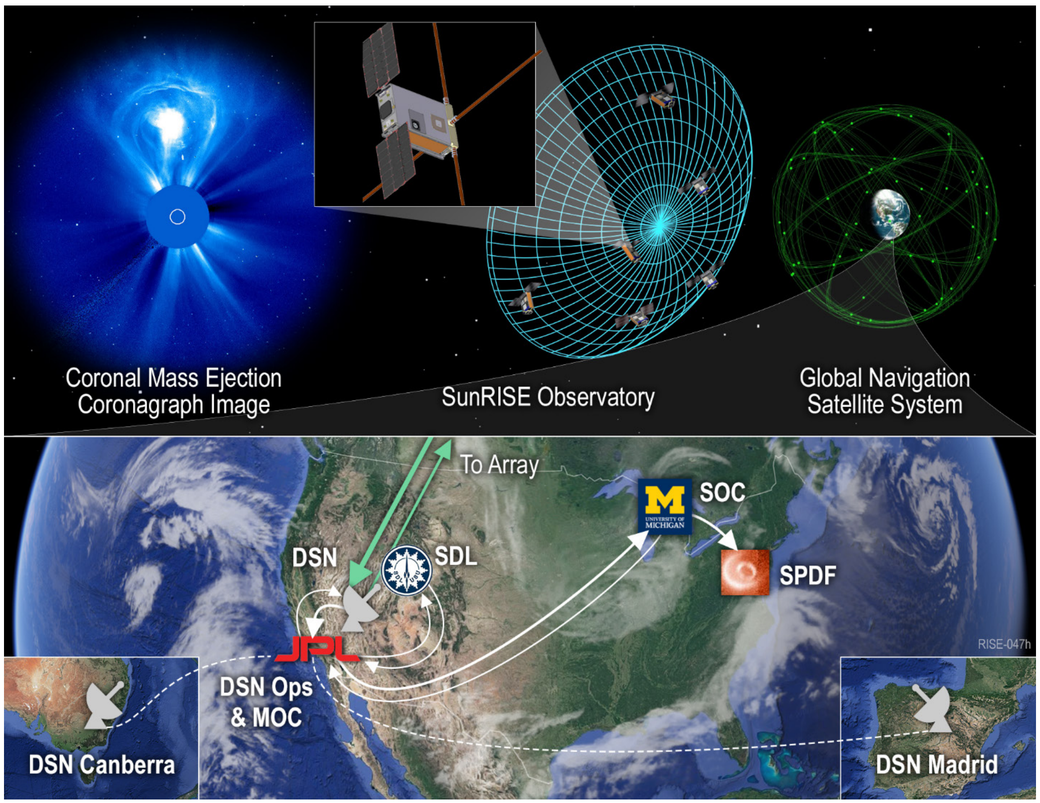


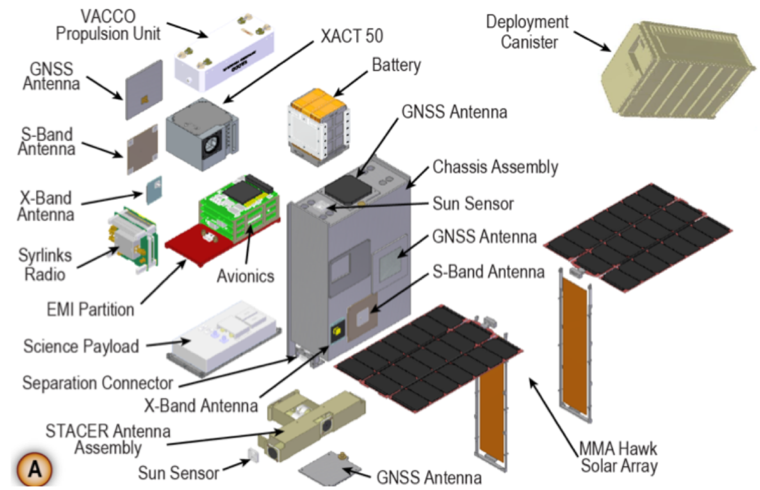


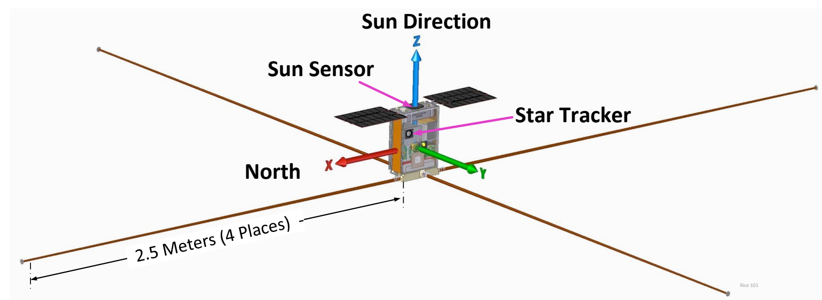


SunRISE Mission & Spacecraft

SunRISE
Sun Radio Interferometer Space Experiment



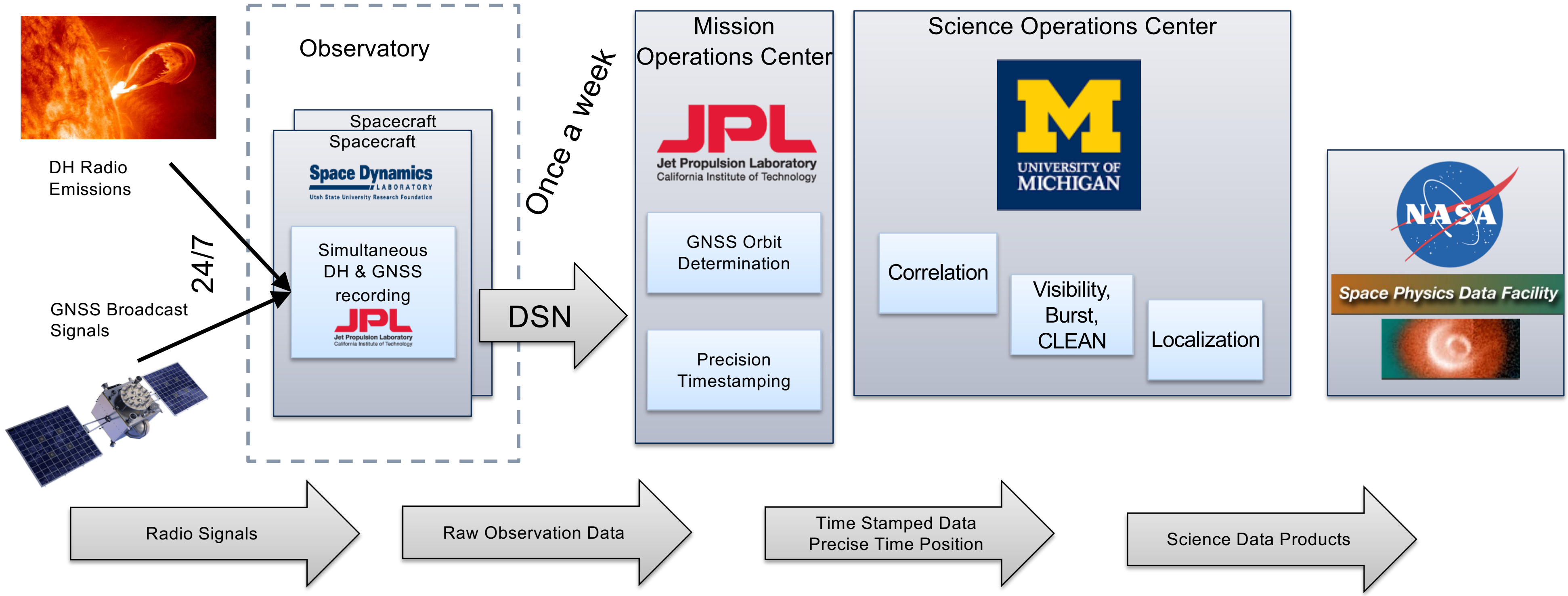


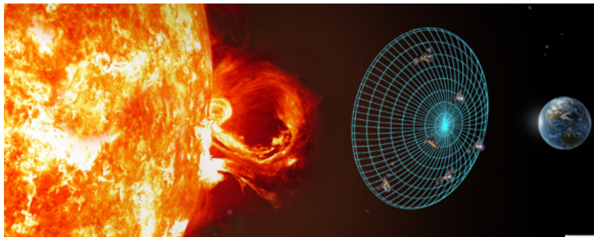


CSR Fig. D-1

Regular and Routine SunRISE Operations

SunRISE
Sun Radio Interferometer
Space Experiment

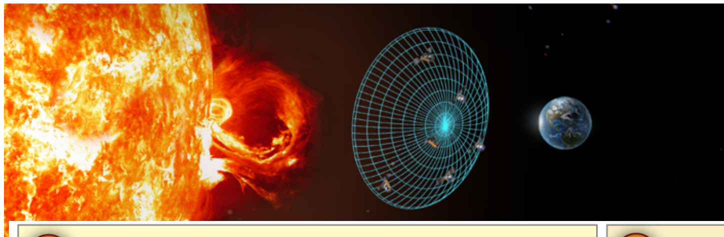




Weekly Downlink Budget Allocation

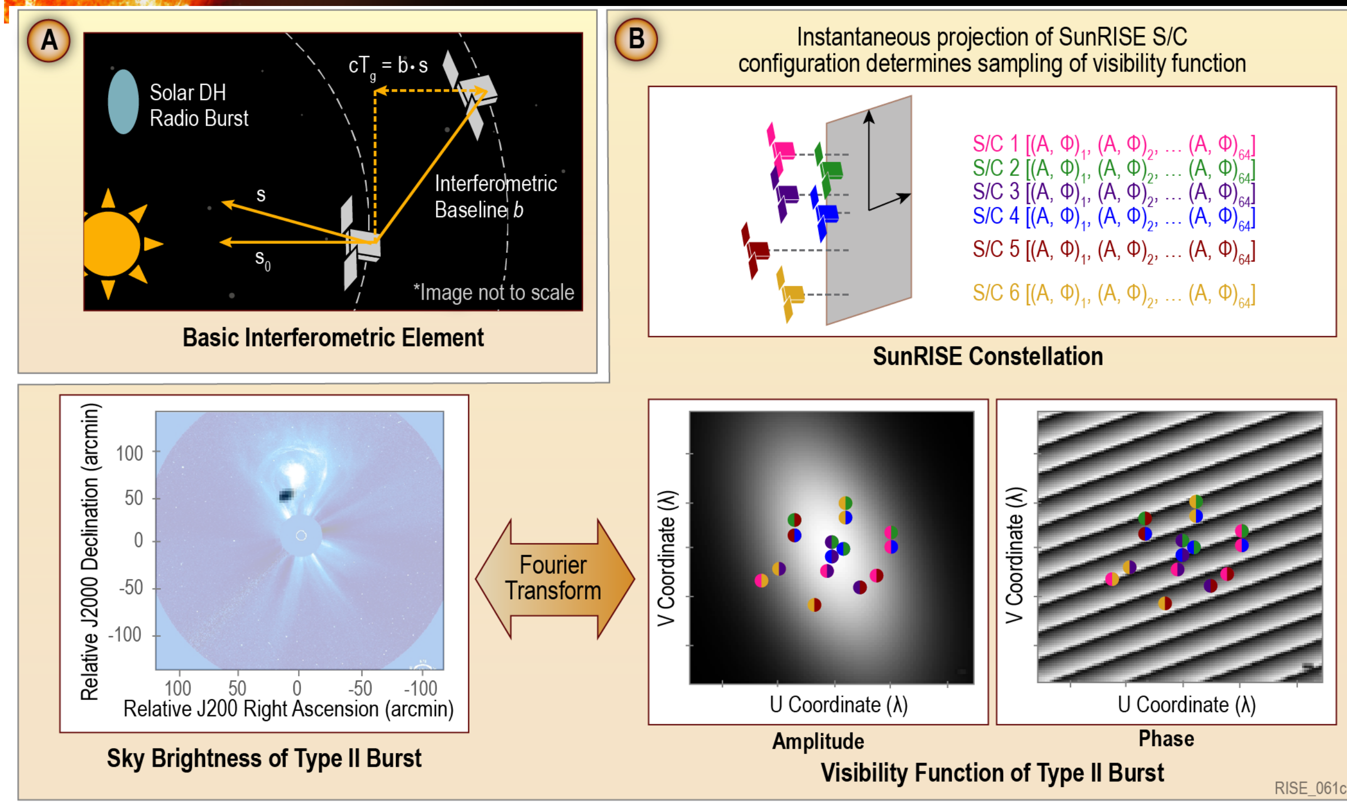
SunRISE
Sun Radio Interferometer Space Experiment

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



Radio Interferometry Basics

SunRISE
Sun Radio Interferometer Space Experiment

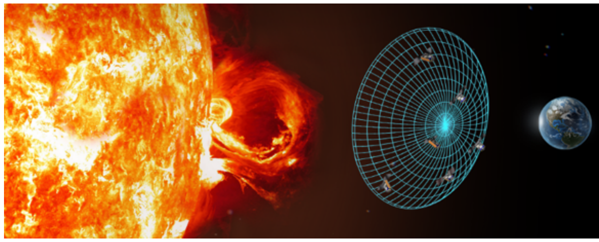


$$\mathcal{V}(u,v,w) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} A_N(l,m)\, I(l,m) \times \exp\left\{-j2\pi\left[ul + vm + w\left(\sqrt{1-l^2-m^2}-1\right)\right]\right\} \frac{dl\, dm}{\sqrt{1-l^2-m^2}}.$$

- Compute UVW from GPS Files
- Compute Visibilities from Integral definition
- Insert into CASA MS file
- Add Thermal & Phase Noises
- Image & Analysis

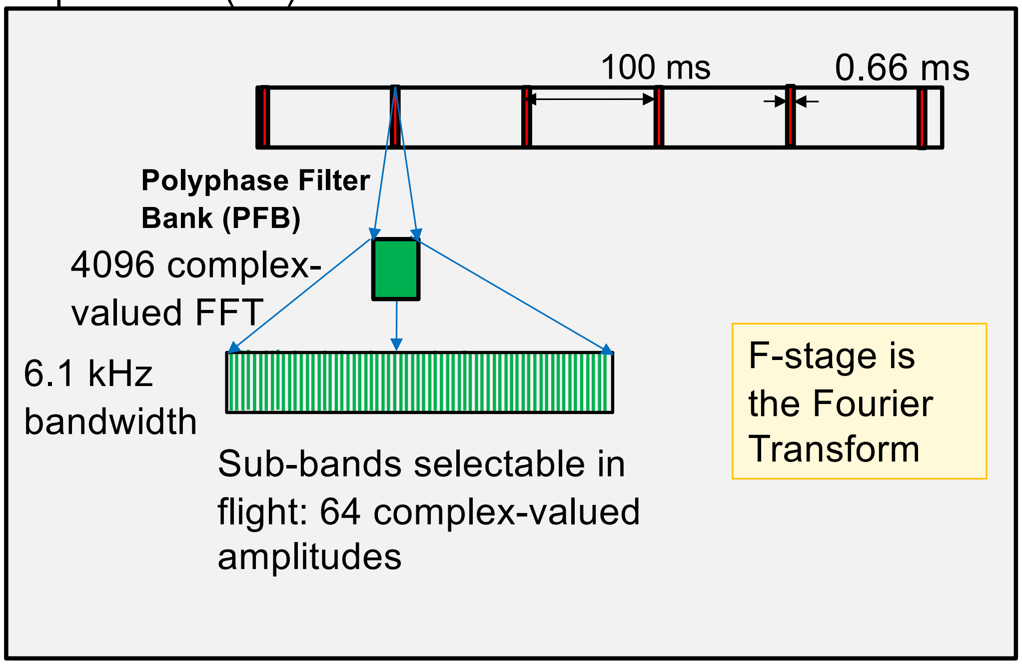
Taken from SunRISE CSR

CASA by McMullin, J. P., et al. 2007, Astronomical Data Analysis Software and Systems XVI, 127.



FX Correlation

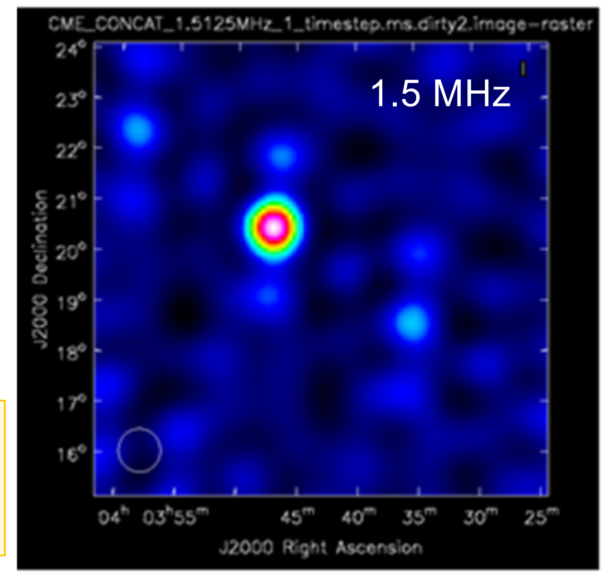
Spacecraft (×**6**)



All spacecraft synchronized by GNSS.

Data telemetered to ground

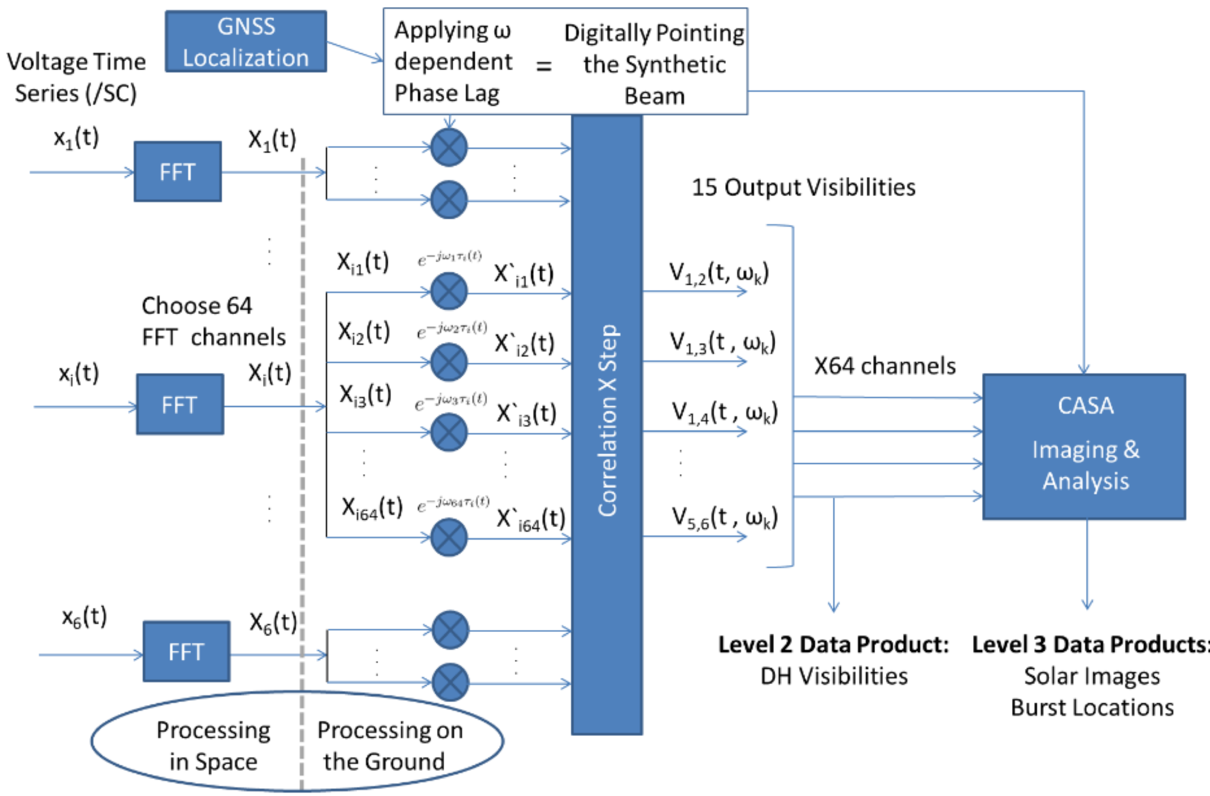
Fourier amplitudes are combined to form visibilities to form the CLEANed image.

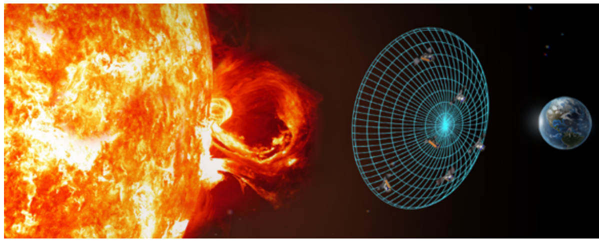


X-stage is the Correlation

FX Correlation cont.

SunRISE
Sun Radio Interferometer Space Experiment

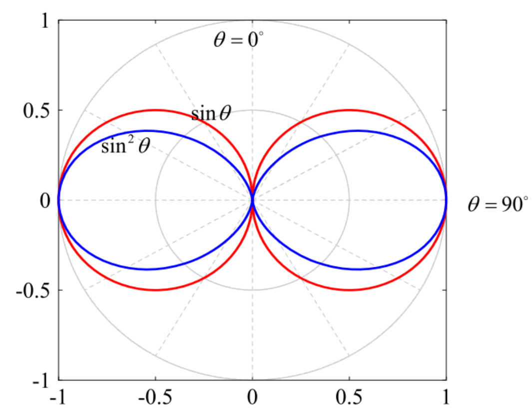


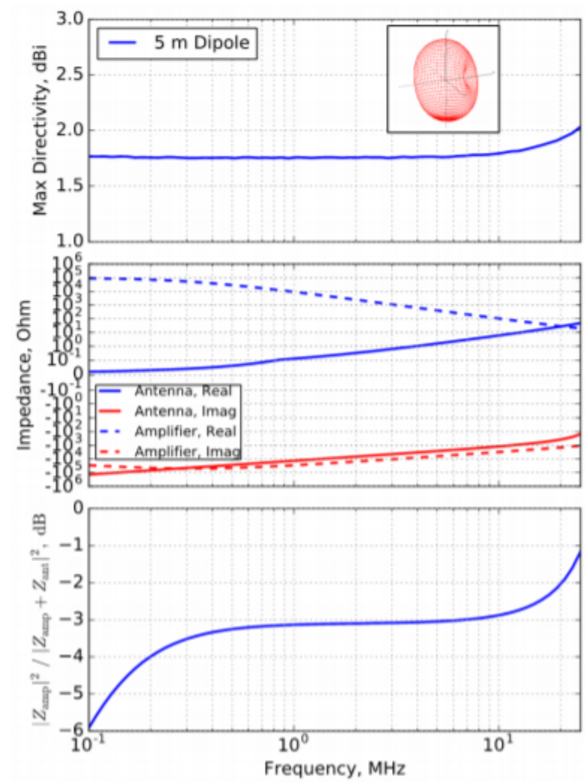


Antenna Patterns

SunRISE
Sun Radio Interferometer Space Experiment

- 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, $\sin^2(\theta)$)

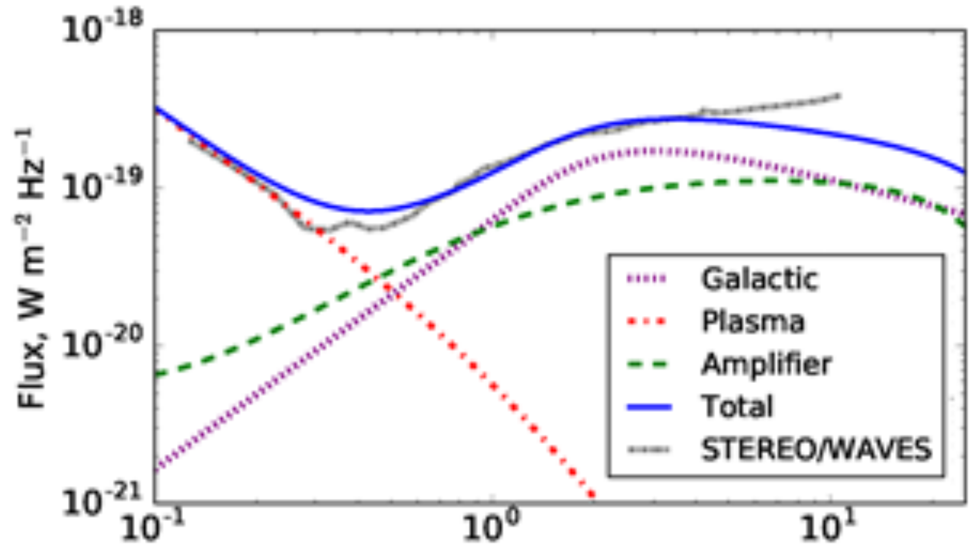




Signal to Noise Calculation

SunRISE
Sun Radio Interferometer Space Experiment

- Assume 5 m dual polarization isotropic dipoles (electrically short)
- 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

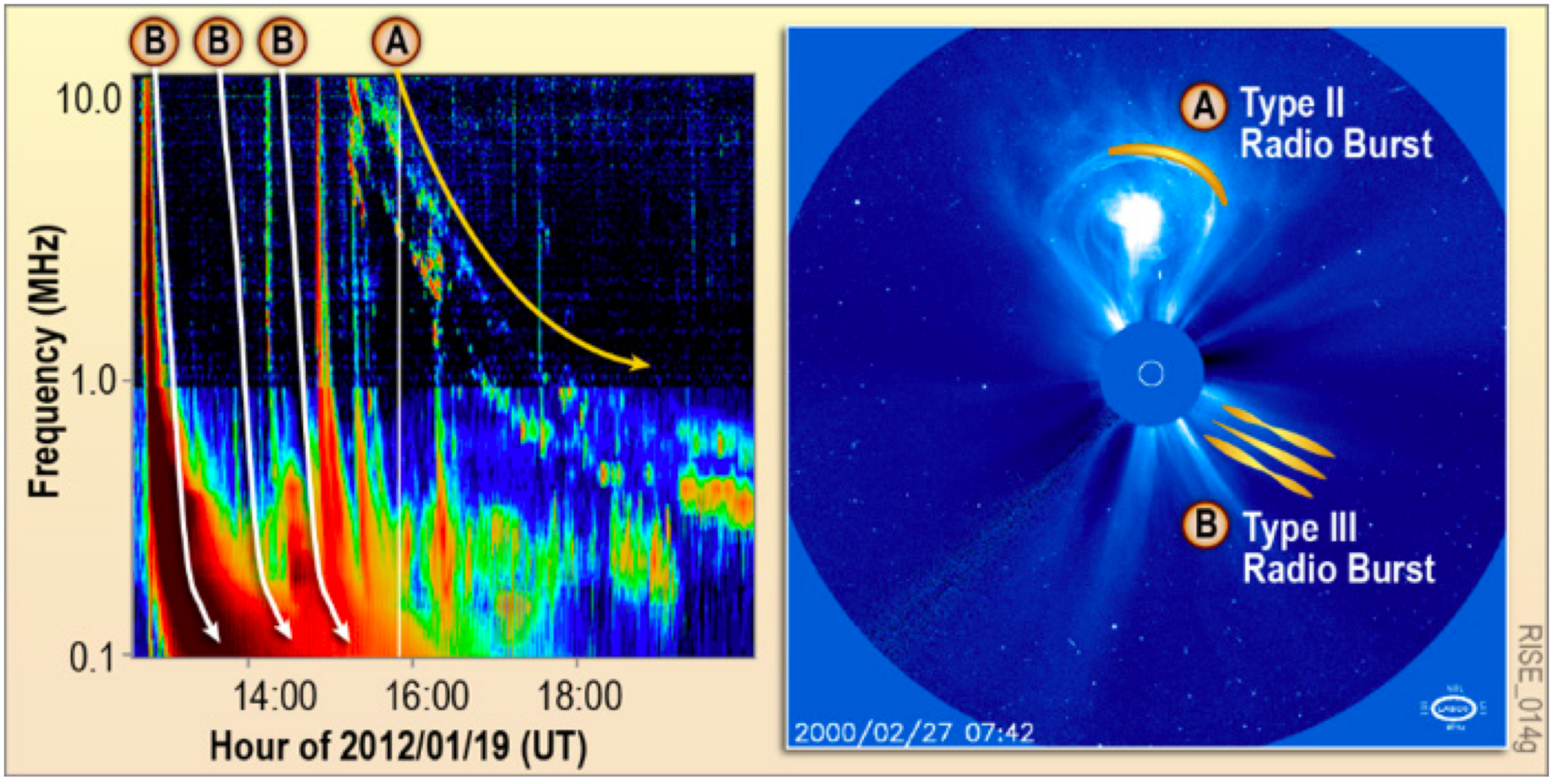


Taken from SunRISE CSR

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

Primary Science: Solar Type II & III Bursts

SunRISE
Sun Radio Interferometer Space Experiment

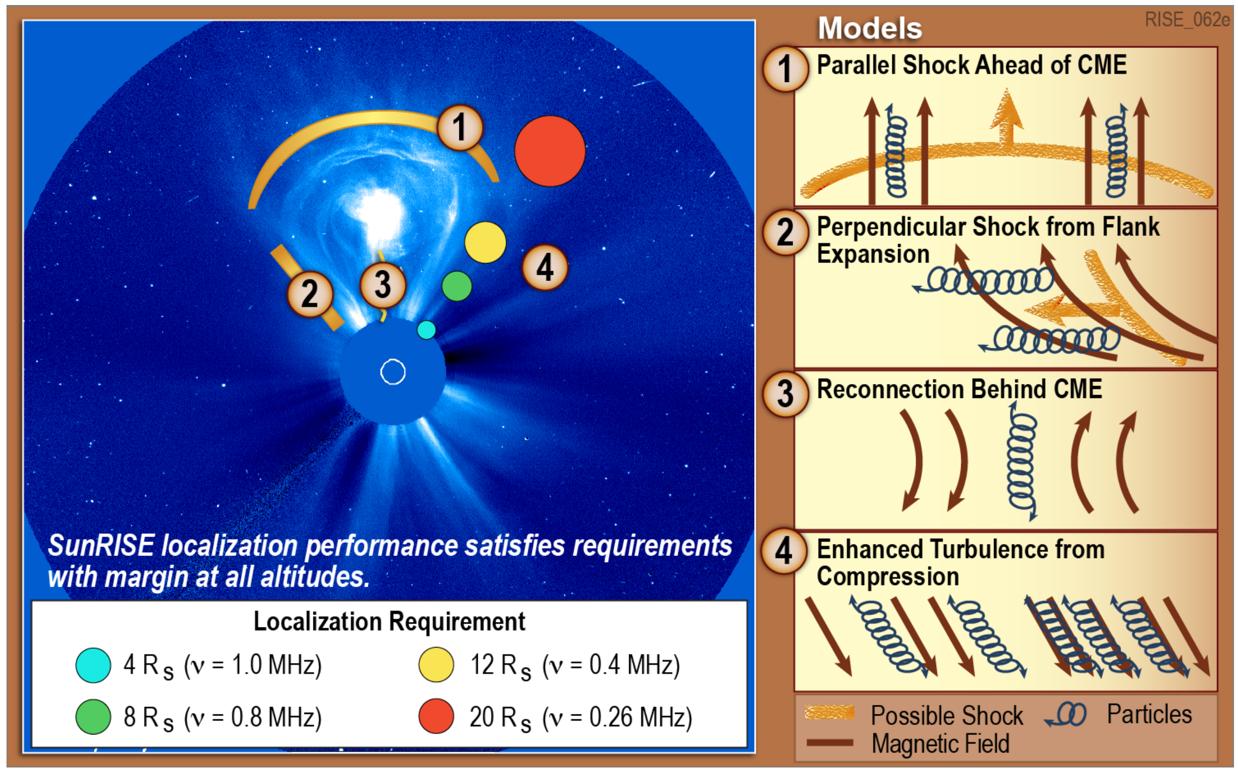


Connect Evolution of Radio Burst to One of Four Models

SunRISE
Sun Radio Interferometer Space Experiment

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.



Jet Propulsion Laboratory
California Institute of Technology

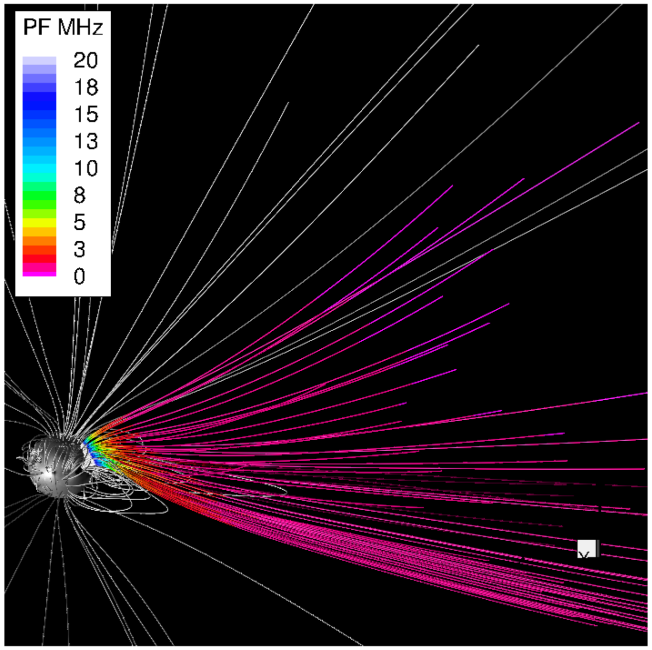
Mapping Magnetic Field Lines

SunRISE
Sun Radio Interferometer Space Experiment

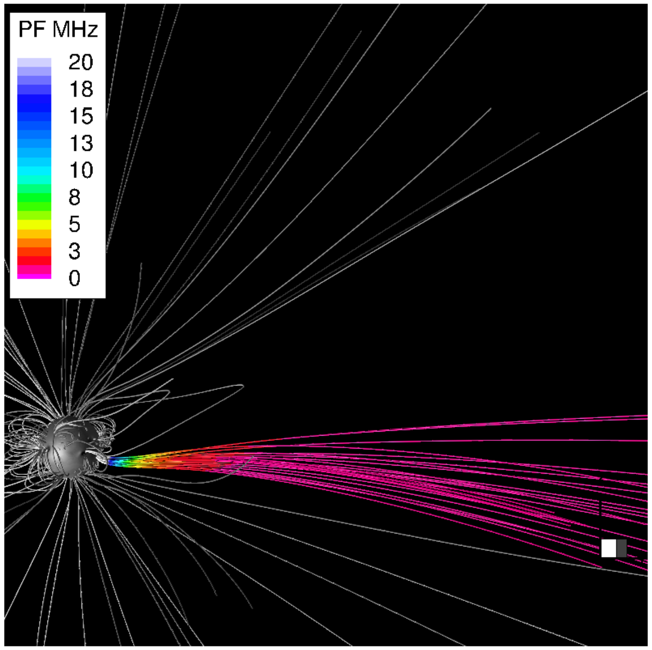
SunRISE Objective 2

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)

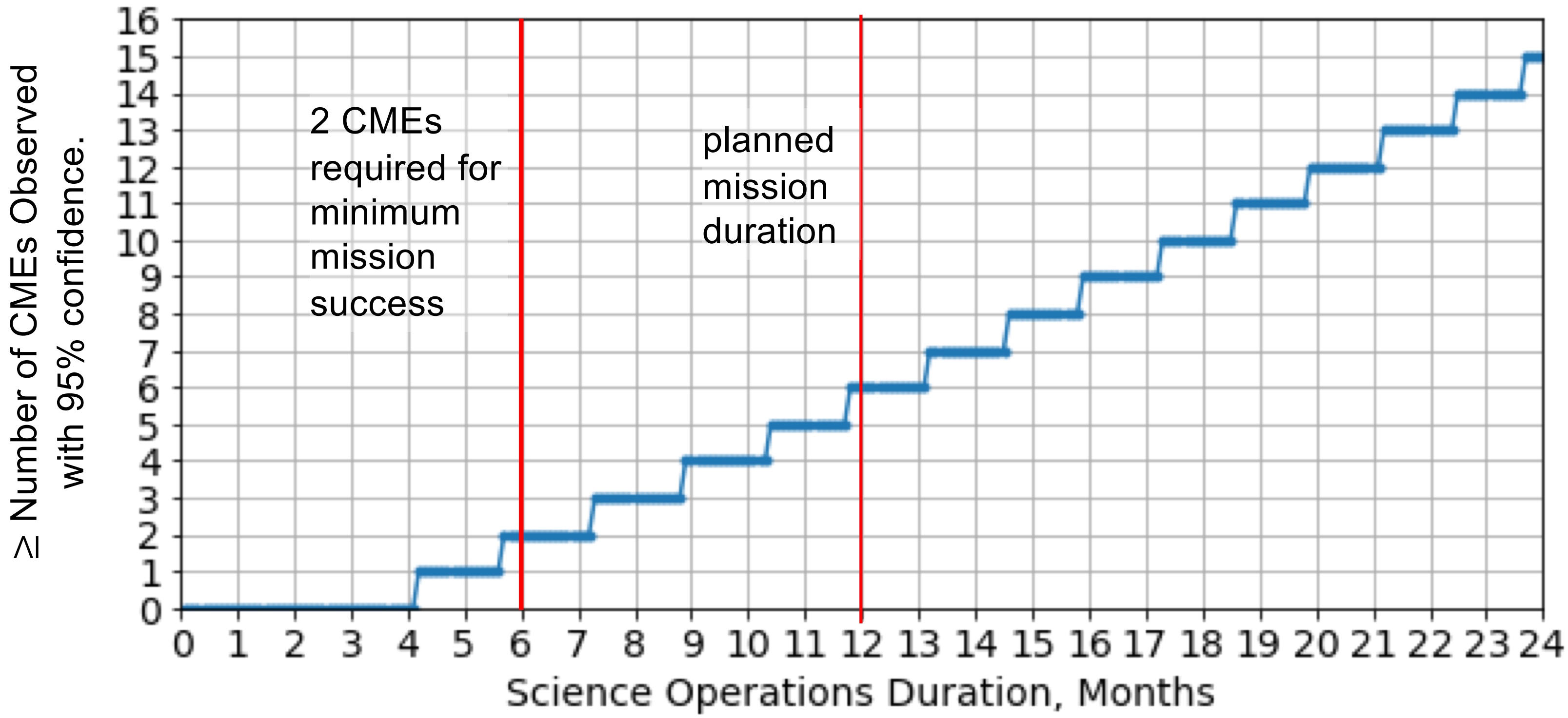


Random Walk Scenario (ii)



Number of CMEs and Mission Duration

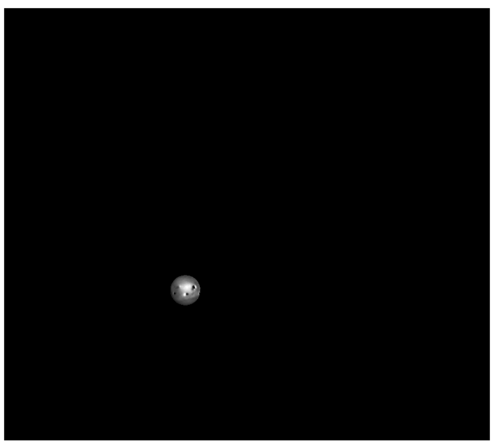
SunRISE
Sun Radio Interferometer Space Experiment

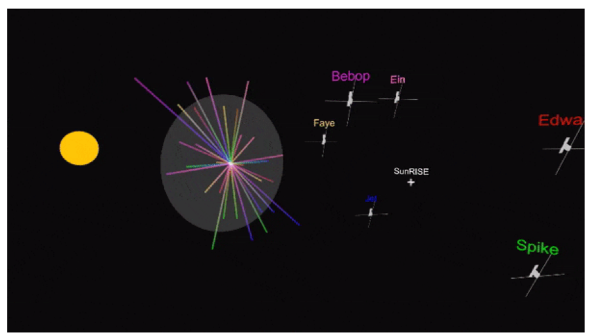


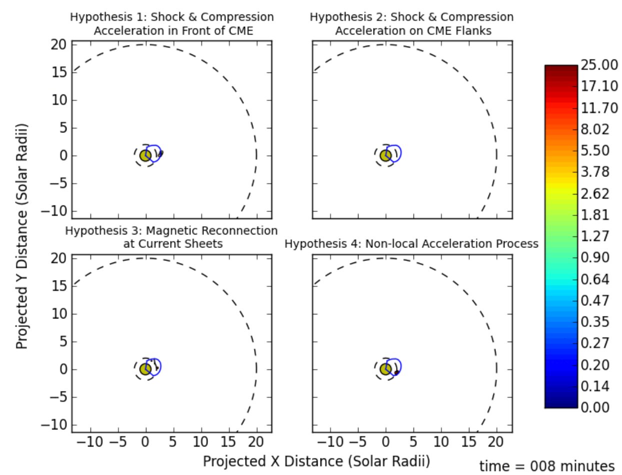
High Level Pipeline Testing Overview

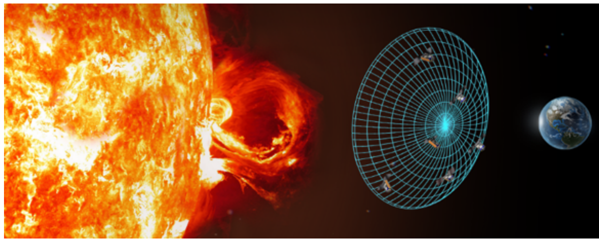
SunRISE
Sun Radio Interferometer Space Experiment

MHD CME Simulation → **SunRISE Simulation** → **Science Operation Center Analysis Pipeline**



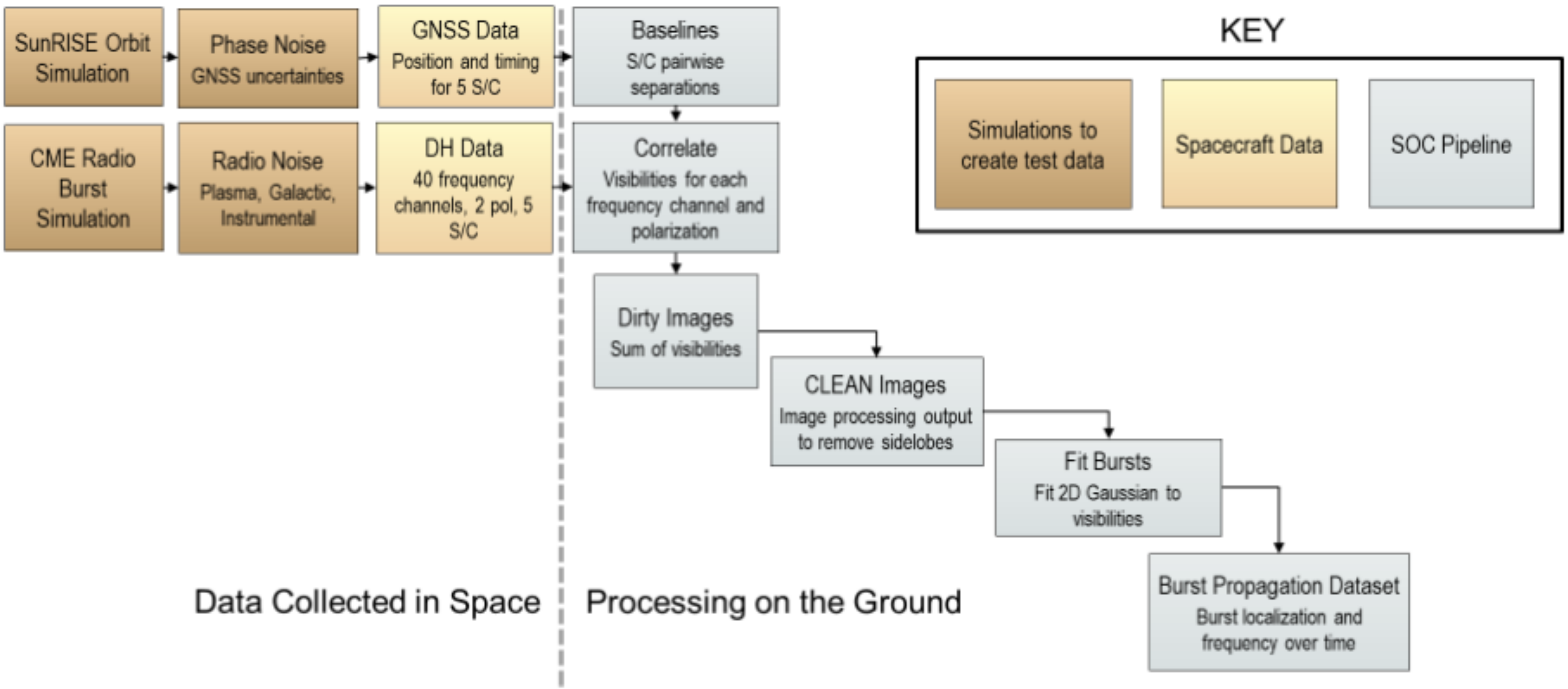






Pipeline Overview

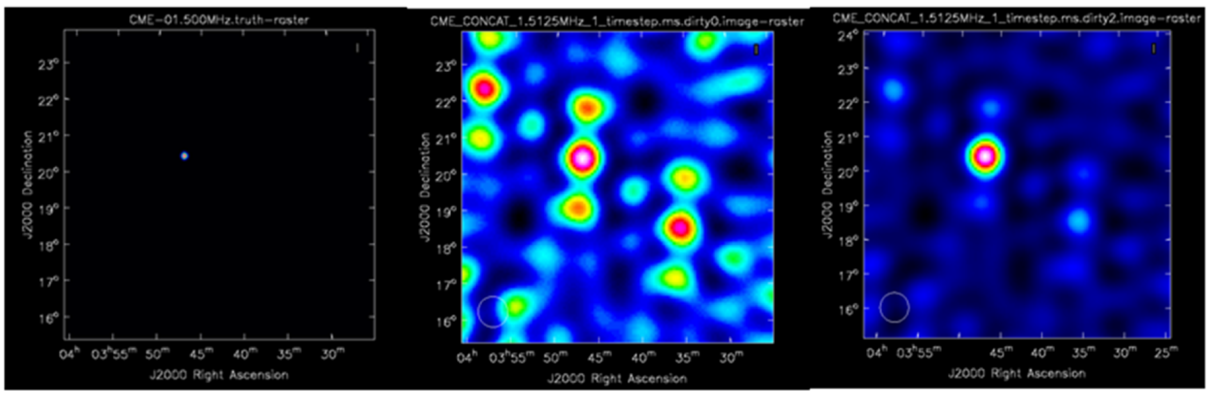
SunRISE
Sun Radio Interferometer Space Experiment



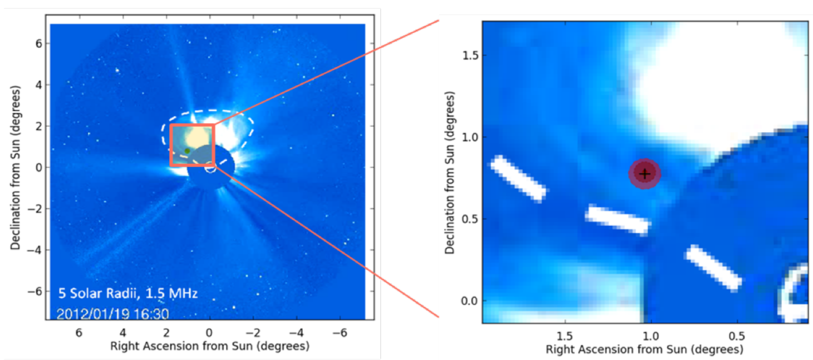
Imaging Pipeline at 1.5 MHz

SunRISE
Sun Radio Interferometer Space Experiment

1 2 3



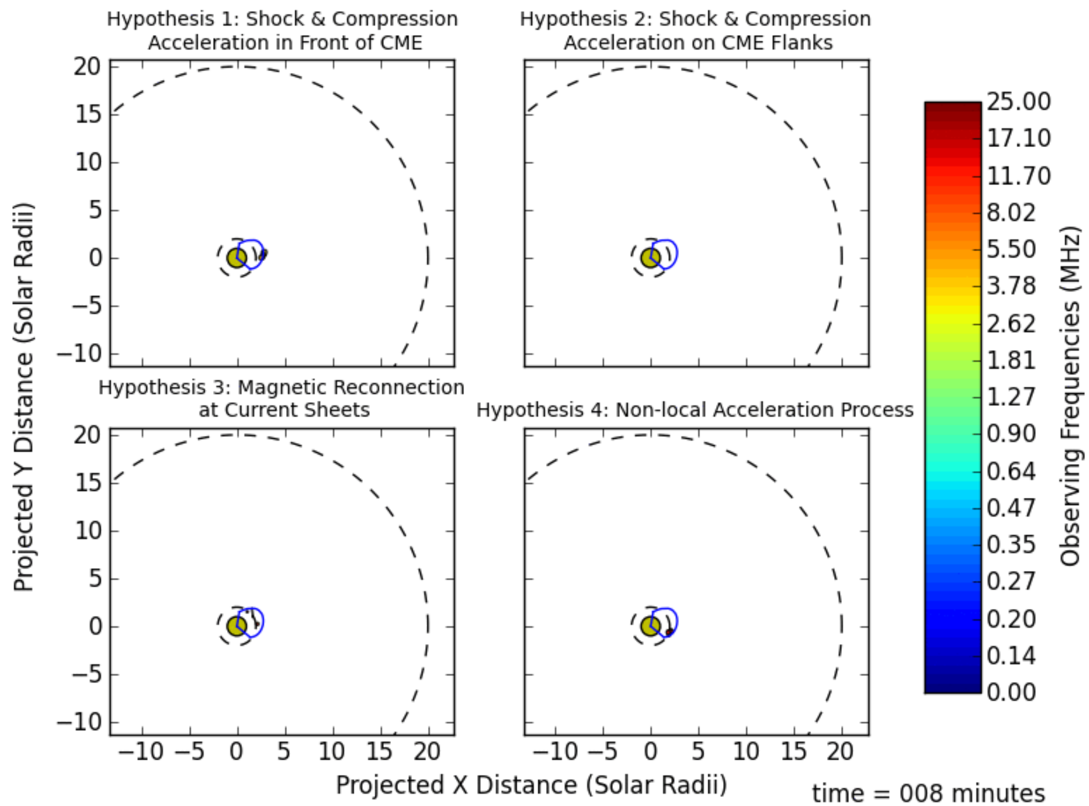
4

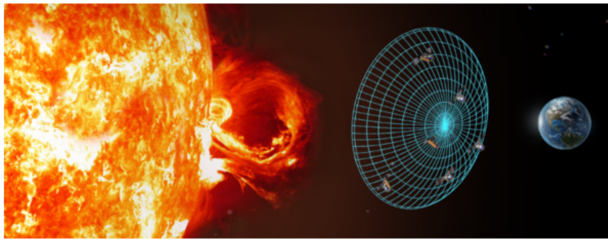


1. Simulation informed input emission distribution
2. Dirty Image with sidelobes
3. CLEANed Image with sidelobes removed
4. 2D Gaussian fit to data & put into context of CME Coronagraph Movie

SunRISE Recovered Radio Emission

SunRISE
Sun Radio Interferometer Space Experiment

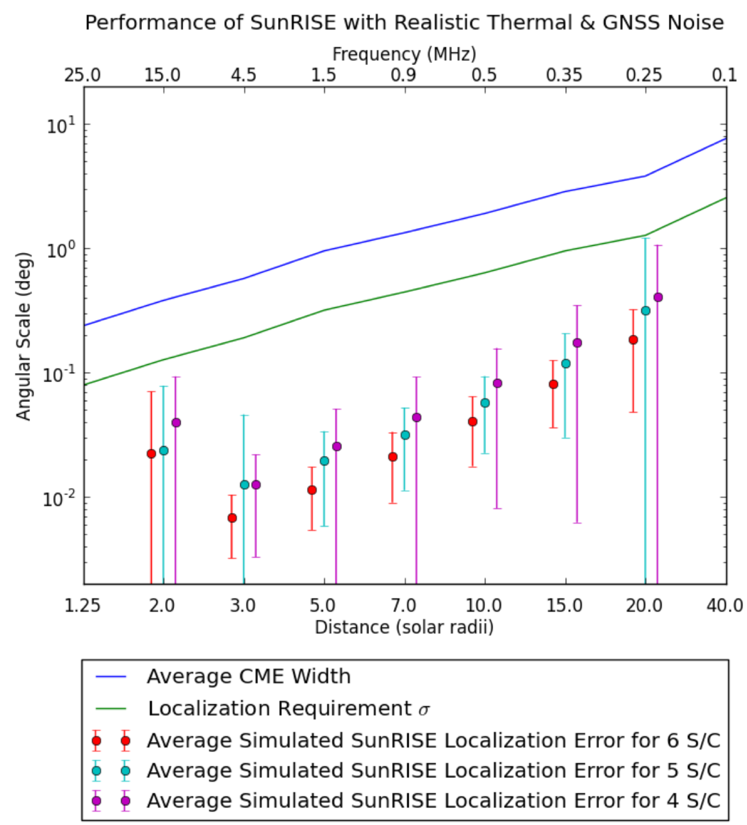


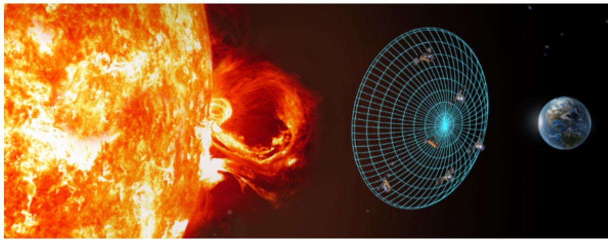


Localization Resolution

SunRISE
Sun Radio Interferometer Space Experiment

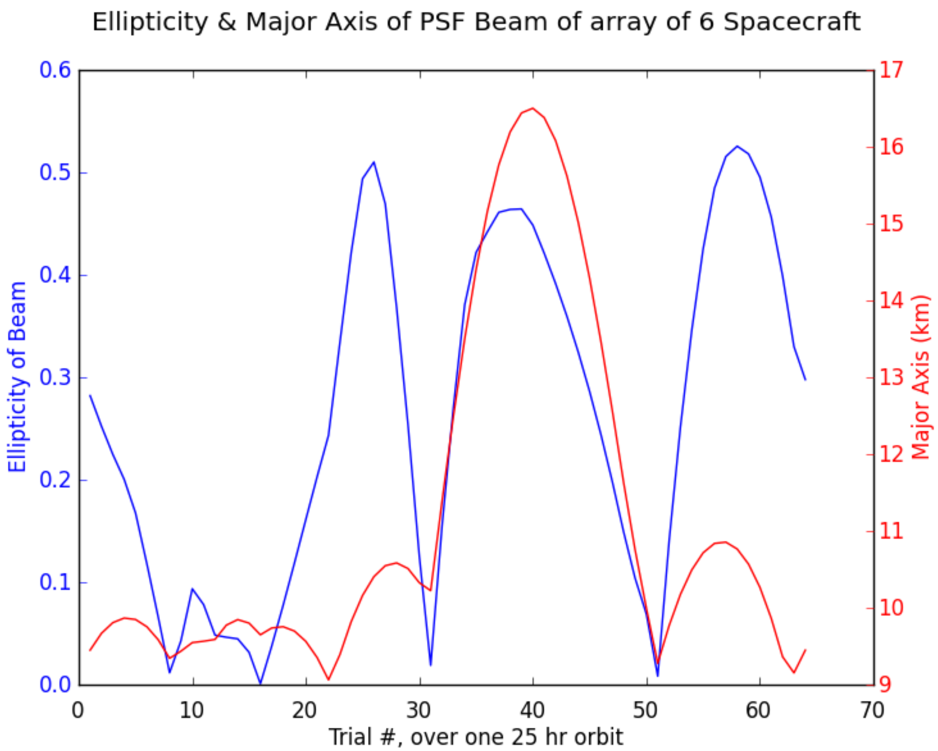
- Localization resolution determined by array configuration and frequency.
- SunRISE localization resolution ranges from 0.01 – 0.1 degrees (or 0.6 – 6 arcseconds)

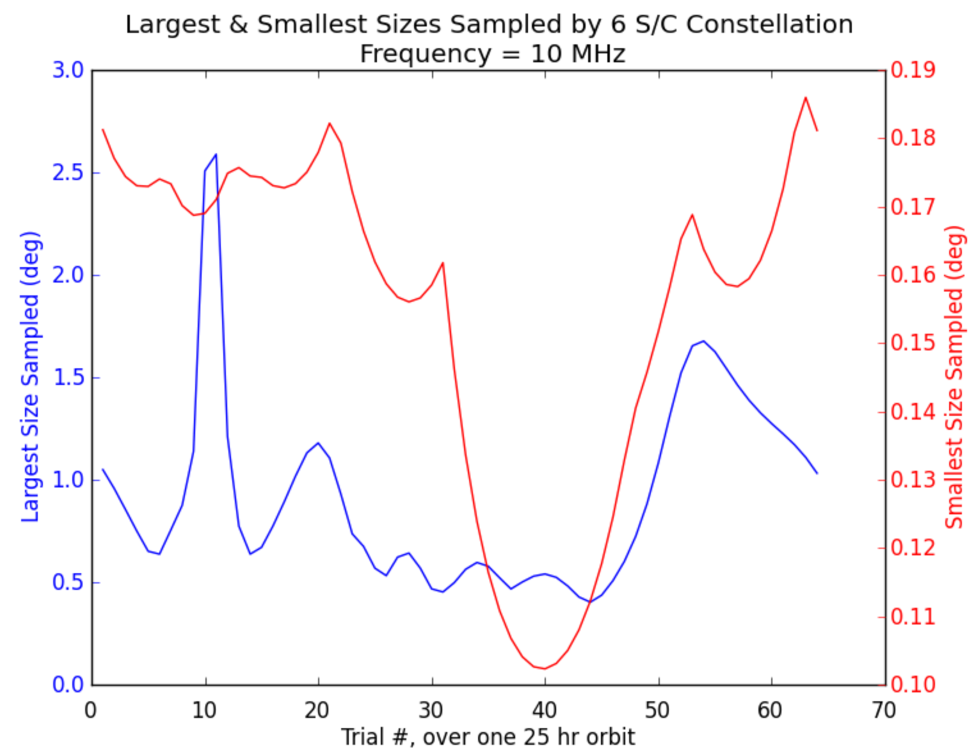


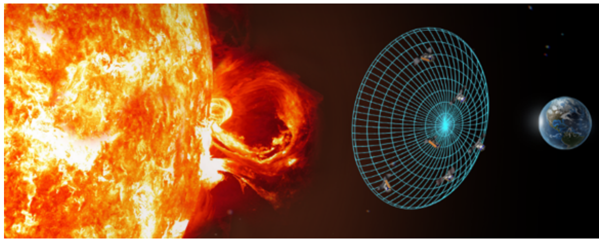


Orbiting Arrays are Irregular

SunRISE
Sun Radio Interferometer Space Experiment







Additional Science

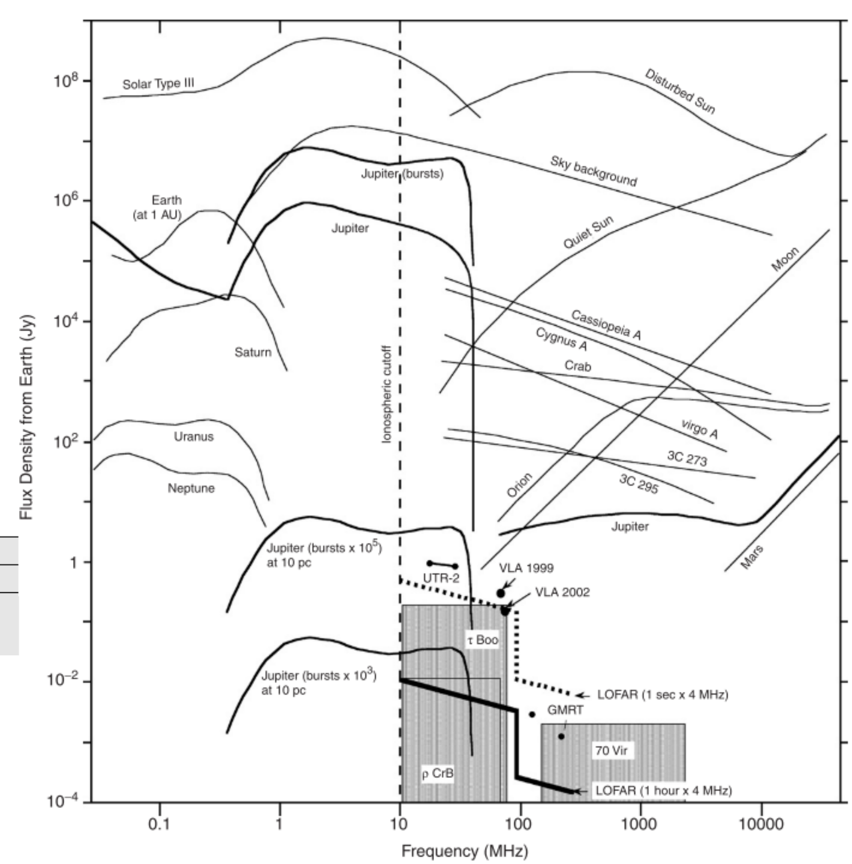
SunRISE
Sun Radio Interferometer Space Experiment

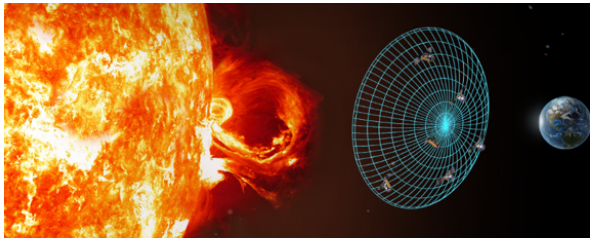
- SunRISE might be first array that can make basic images at low Frequencies below Ionospheric cutoff
- New Window into the universe, plenty to look at
- Astronomy review papers have detailed requirements for every possible source

Topic	Our Sections	*Requirements*					
		Frequency/MHz	Resolution ϑ	Baselines/km	Expected signal[a]	N(Antennas)	t_{exp} (5-σ)
Transients	3.4						
Solar and planetary bursts	3.4.1	0.1–30	degrees	0.5–200	MJy	1–100	min–h
Extrasolar planets	3.4.2	0.5–30	$\lesssim 1'$	$\gtrsim$ 35–1000	1–10 mJy	$10^4 - 10^{5f}$	15 min

S. Jester, H. Falcke / New Astronomy Reviews 53 (2009) 1–26

P. Zarka / Planetary and Space Science 55 (2007) 598–617





Calibrating with Galactic Brightness

SunRISE
Sun Radio Interferometer Space Experiment

- Mirror galactic calibration of STEREO antenna from Zaslavsky et al 2011

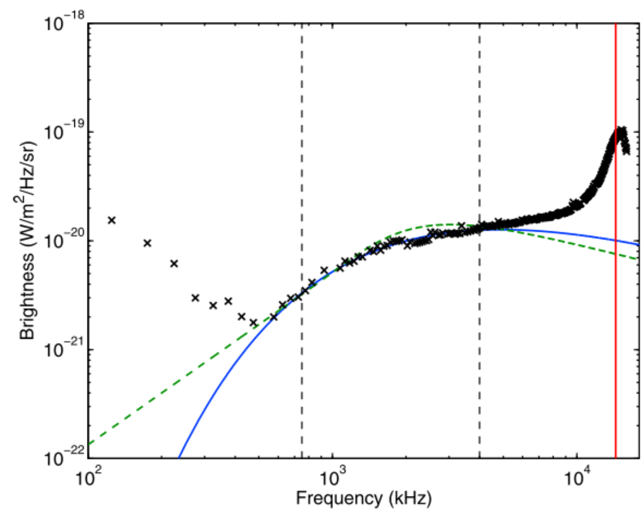
- Must understand Antenna and Stray impedance, goes into Γ^2

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

- 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

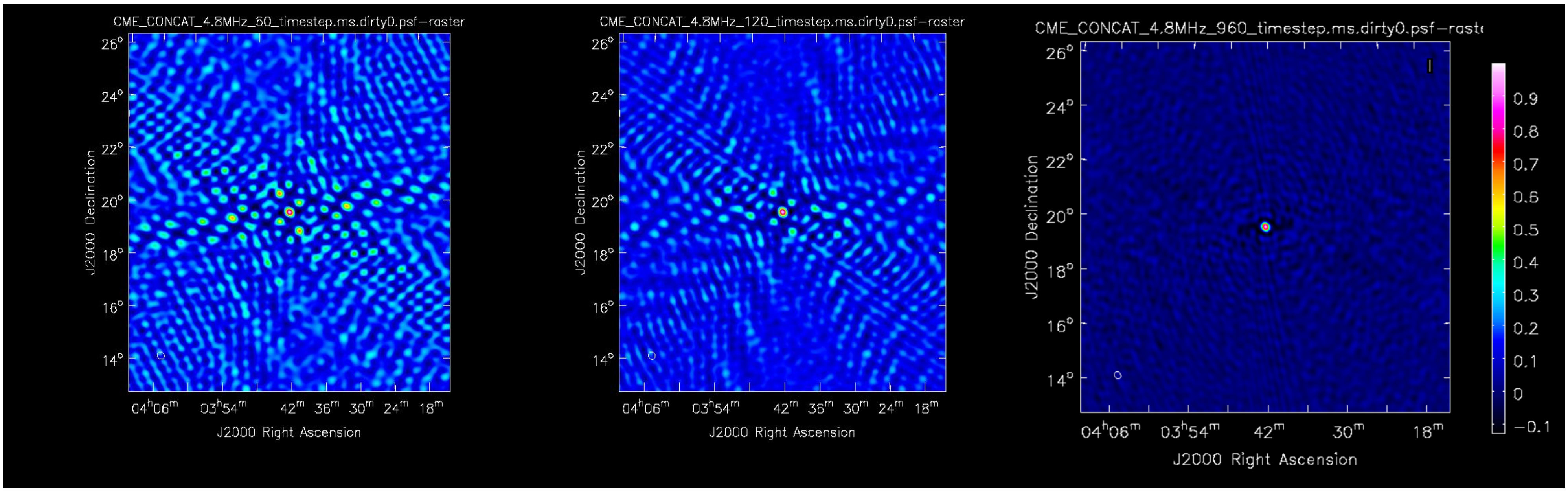
- Compare calibrated data (crosses) with Galactic brightness models
Novacco and Brown [1978] (blue solid line) and Cane [1979] (green dashed line)



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

SunRISE Integration over time

SunRISE
Sun Radio Interferometer Space Experiment

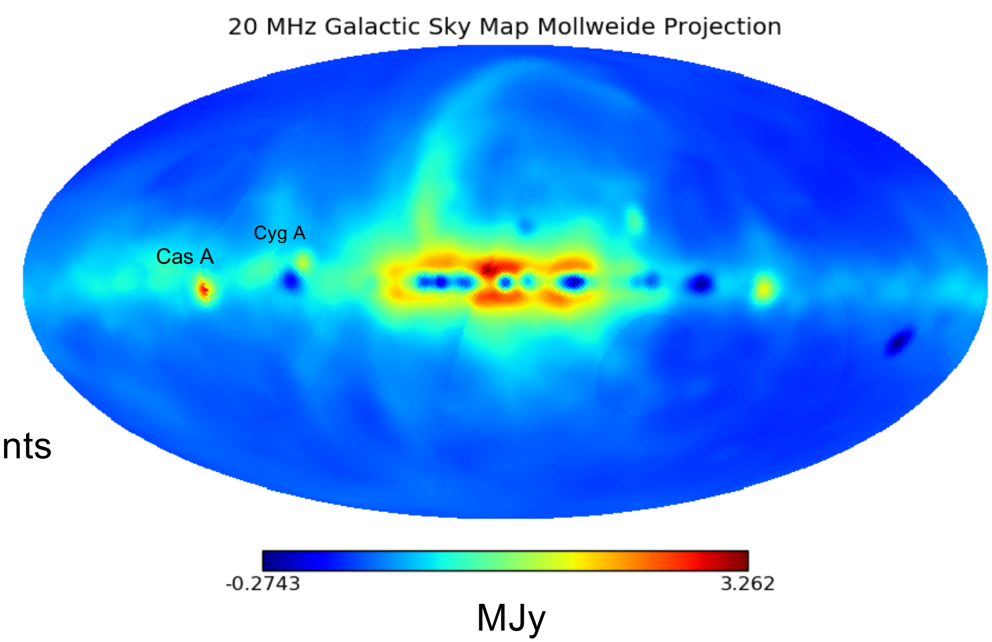


PSFs at 5 MHz after 1, 2 and 24 hours of integration. All images share the same color scale, normalized to 1.0.

Preliminary All Sky Mapping

SunRISE
Sun Radio Interferometer Space Experiment

- Will have 1 year's worth of data to sift through
- Choose least bright periods to create constant Sky Maps
- For given area of sky, use SPICE to compute times when it is unobscured by Earth, Sun, Jupiter, etc.
- Can subtract constant sky model to look for weak transients
- Working on simulated SunRISE Global Sky Map



Created with gsm2016 Principal Component Analysis
Zheng et al. MNRAS 464, 3486–3497 (2017)

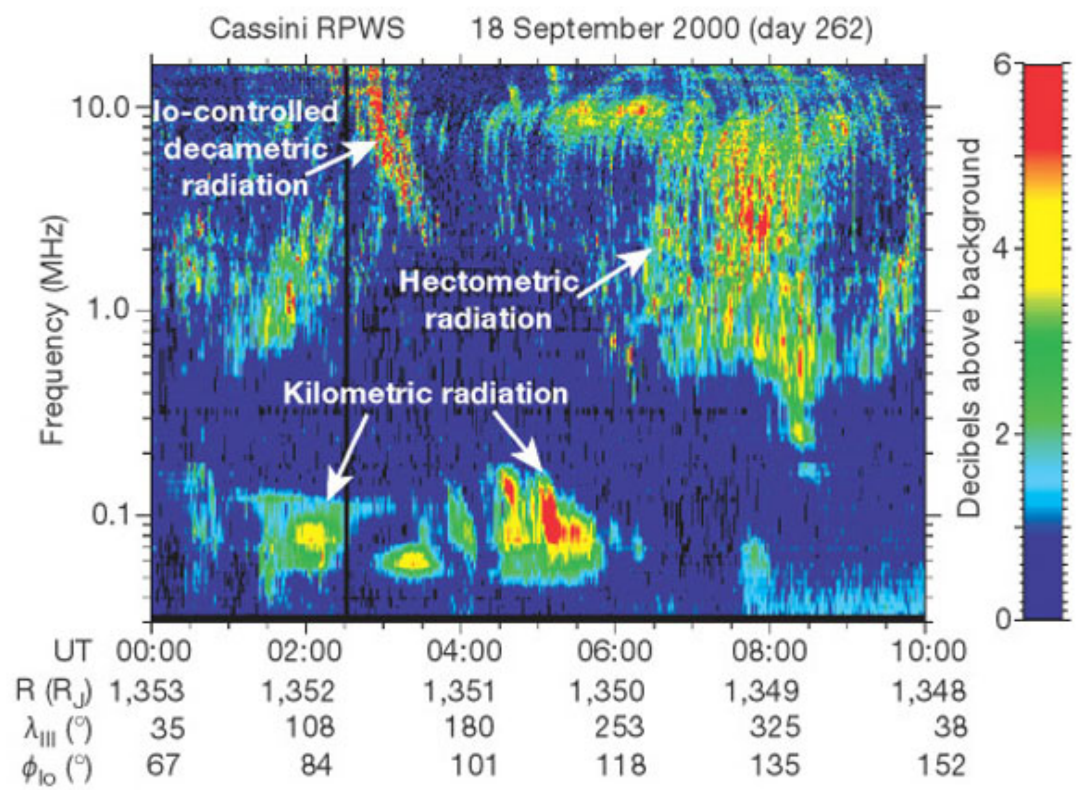
Looking for Planetary Emission

SunRISE
Sun Radio Interferometer Space Experiment

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



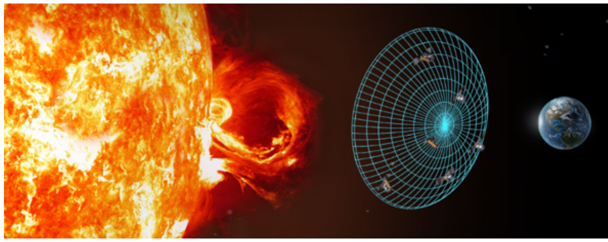
Calibration / Validation with Jovian Bursts

SunRISE
Sun Radio Interferometer Space Experiment

Jupiter's Io Decametric Radiation as a Calibration Source

Property	Range	Notes
Frequency	0.3 MHz – 35 MHz	Significant overlap with SunRISE band.
Occurrence	~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} 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.



SunRISE
Sun Radio Interferometer
Space Experiment

Summary

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