Preparing for the Frequency-Agile Solar Radiotelescope (FASR)

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Outline

- FASR Retrospective and Status
- Review of FASR Instrument and Science
- Preparing for FASR—EOVSA
- Conclusions

FASR Retrospective

- In 1989, I recall a discussion at a CESRA meeting (Braunwald, Switzerland) about a U.S. solar-dedicated radio telescope that would extend the capabilities of the Owens Valley Frequency-Agile Interferometer to an array with far larger number of antennas.
- It was on the occasion of the dedication of the Nobeyama Radioheliograph in 1991 that the four of us (Tim Bastian, Gordon Hurford, Stephen White and me) first seriously discussed taking action to realize such an instrument.
- The first international FASR (then called SRT for Solar Radio Telescope) workshop was held in San Juan Capistrano in 1995.
- A series of papers and talks explored the idea, culminating in presentations in 1999/2000 to the solar and radio panels of the Astronomy & Astrophysics decadal survey.

FASR Retrospective, cont’d

- FASR started as a 40-antenna, single-reflector-type concept costing $20 M, and has grown over the years to its current size of >200 antennas of three different types covering 50 MHz-21 GHz, costing around $100 M.
- In the 2000 Astrophysics and 2003 Solar decadal surveys, FASR was a paper concept, with no detailed design or hardware prototypes.
- During 2004-2009, the team began a series of funded design studies and prototyping activities that greatly solidified the concept.
- During this time, we also responded to two funding opportunities for successively descoped versions (MSI proposal for $25 M, with 45 FASR-A and 15 FASR-B antennas; pathfinder opportunity for $7 M, with 15 FASR-A antennas + “bare” FASR-B feeds). We received all excellent reviews, but none were funded.

FASR Retrospective, cont’d

- In 2009, the American Recovery and Reinvestment Act (ARRA) provided a funding opportunity. NJIT submitted a $5 M proposal for an extension to OVSA (EOVSA), and this WAS successful and is currently under construction, which will be discussed later.
- Meanwhile, a new round of decadal surveys began (2010 and 2012), and FASR was again highly recommended, but this time with high-praise for its readiness to start.

> FASR is a mature effort that has been recommended in two previous NRC decadal surveys. Extensive development and design review have been funded and achieved, including the testing of prototype instrumentation and the detailed planning of FASR operations, maintenance, and management. Independent analysis of FASR characterized it as “doable today”. It could be completed by 2015-2018.
>
> —*New Worlds, New Horizons in Astronomy & Astrophysics* (Astro2010 decadal survey)

FASR Retrospective, cont’d

The major new initiatives are HERA, CCAT, and FASR. In terms of scientific importance, the panel ranks HERA first, with CCAT and FASR tied and close behind. However, there are issues of readiness that require a distinction between ranking and phasing of project starts. Of these, FASR is the most ready to proceed and, as the panel has noted, has excellent prospects for cross-directorate funding. The panel recommends that a funding strategy for FASR be developed with core contributions from both AST and AGS (the panel assumes here an even split).

—*New Worlds, New Horizons in Astronomy & Astrophysics* (Astro2010 decadal survey)

10.5.4.3 Frequency-Agile Solar Radiotelescope: Imperative: The SHP Panel assigns high priority to NSF’s funding of construction and operation of the FASR to produce three-dimensional images of the solar atmosphere with high temporal and spatial resolution

—*Solar & Space Physics: A Science for a Technological Society* (SSP2012 decadal survey)

FASR: What Is It?

- FASR's fundamental innovation is the ability to perform ***dynamic, broadband, imaging spectroscopy*** over an extremely large frequency bandwidth – from 50 MHz to 21 GHz (or λ=1.4 cm to 6 m).
- FASR therefore measures the polarized brightness temperature spectrum along every line of site as a function of time, enabling a wealth of diagnostics.
- By imaging the entire solar atmosphere at once, it will provide insights into these phenomena and processes as ***coupled phenomena.***

Frequency Agile Solar Radiotelescope

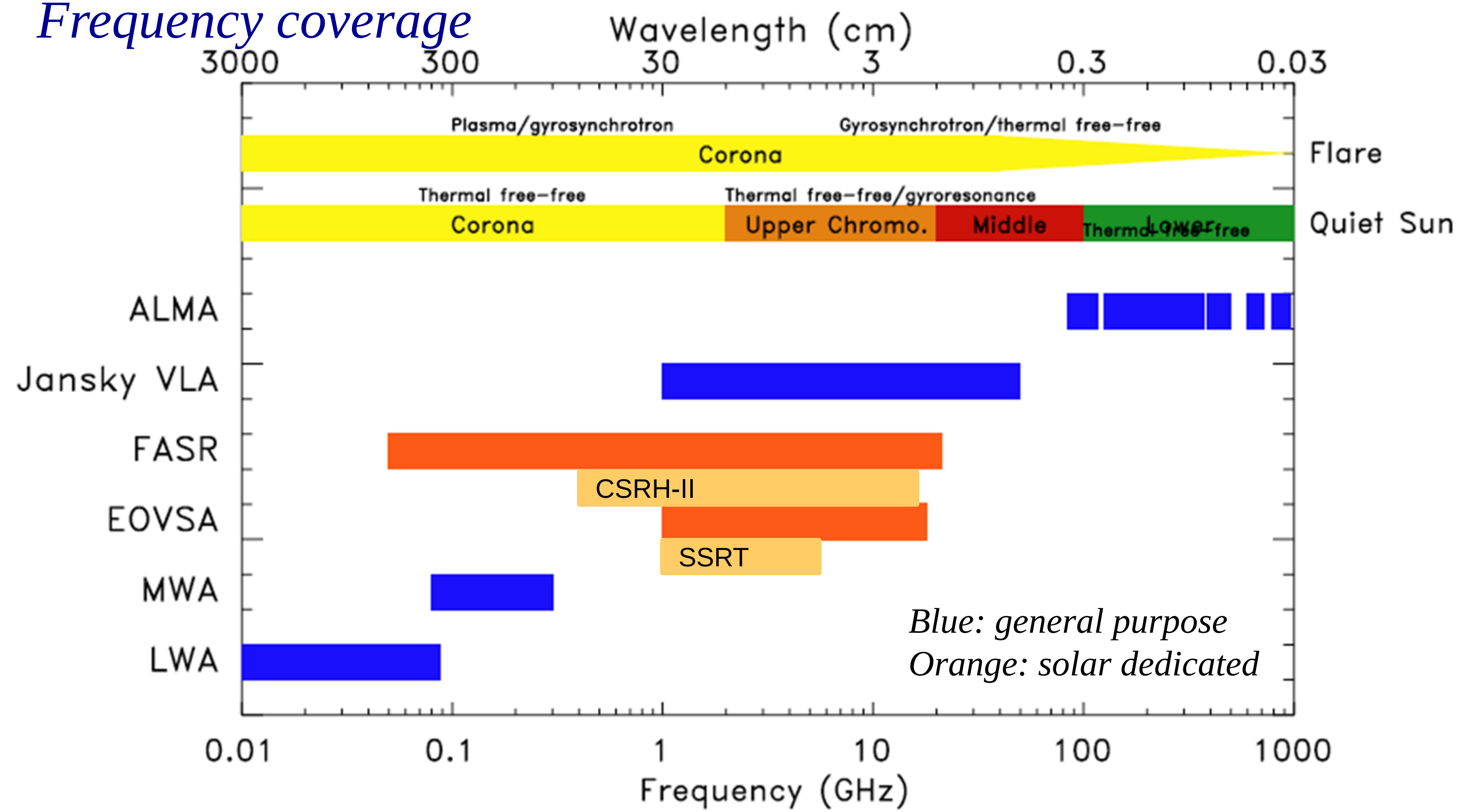
- **The Nature and Evolution of Coronal Magnetic Fields**
  - What is the quantitative distribution of coronal magnetic fields?
  - How do coronal magnetic fields evolve in time and space?
  - How is magnetic energy stored?
- **The Physics of Flares**
  - What is the physics of magnetic energy release?
  - How and where are electrons accelerated?
  - What are the relevant particle transport processes?
- **The Drivers of Space Weather**
  - How are CMEs initiated and accelerated?
  - What is the origin of coronal shocks?
  - How are solar energetic particles in the heliosphere accelerated?
- **The Physics of the Quiet Sun**
  - How are the solar chromosphere and corona heated?
  - What is the origin of the solar wind?
  - What is the structure of prominences and filaments?

Isaac Gary

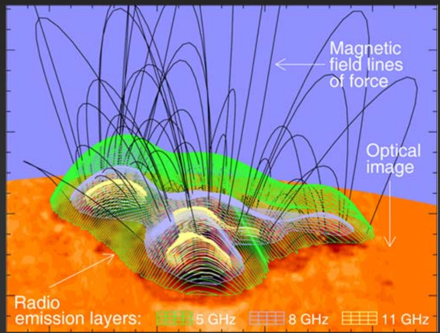
Specifications	
Angular resolution	20/ν_{GHz} arcsec
Frequency range	0.05-21 GHz
Frequency resolution	1%
Time resolution	1 s
Polarization	Stokes I & V (Q/U selectable)
Number of antennas	2-21 GHz: ~100 0.2-3 GHz: ~60-80 < 0.3 GHz: ~40-60
Size of antennas	2-21 GHz: 2 m parabolic 0.2-3 GHz: 6 m parabolic < 0.3 GHz: log-periodic dipoles
Maximum antenna spacing	4.25 km
Proposed Site	TBD

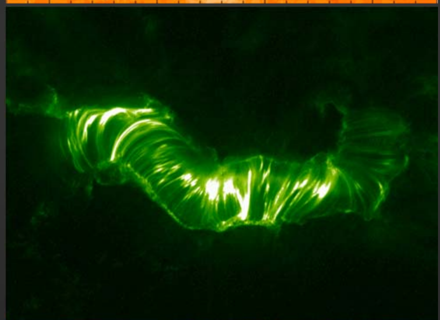
Current or Planned Solar Capabilities

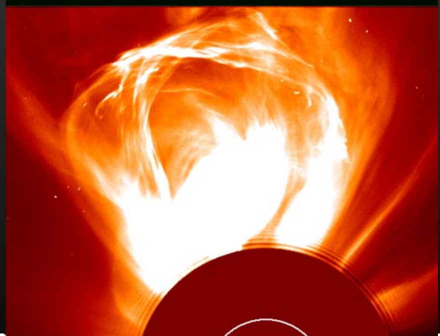
Frequency coverage



Key Science Objectives







- **Nature & Evolution of Magnetic Fields**
  - Coronal magnetography*
  - Temporal & spatial evolution of fields*
  - Coronal seismology

- **High energy solar physics**
  - Magnetic energy release*
  - Plasma heating and dynamics*
  - Electron acceleration and transport*

- **Drivers of Space Weather**
  - Birth & acceleration of CMEs
  - Prominence eruptions*
  - Origin of SEPs*
  - Radiative Inputs to upper atmosphere*

*EOVSA (FASR Pathfinder)

Coronal magnetography

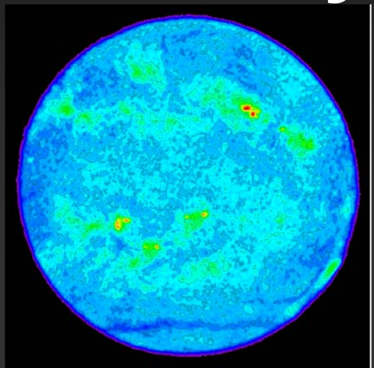
- Non-potential fields are the source of free energy for solar activity
- Radio observations provide a number of tools to measure or constrain coronal fields:
  - Thermal free-free polarization – AR,QS, CH, filament cavities
  - Thermal gyroresonance emission – active regions
  - Nonthermal gyrosynchrotron emission – flares, CMEs
  - Coronal "seismology" – sunspots, flaring magnetic loops
  - Radio bursts – outer corona
  - Propagation phenomena – topological constraints

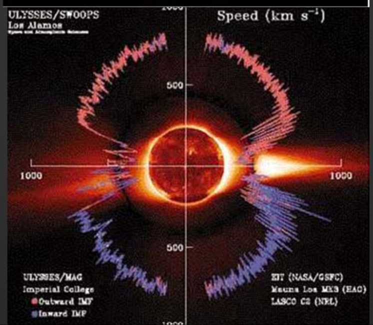
High Energy Solar Physics

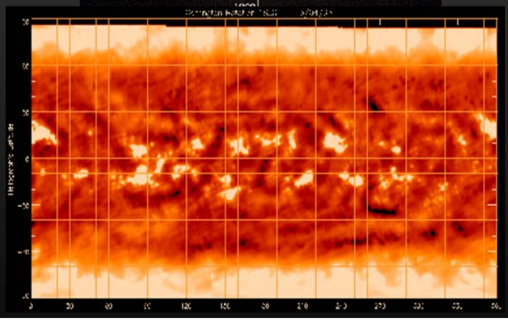
- The Sun is the most powerful particle accelerator in the solar system
  - Ions up to ~10s of GeV
  - Electrons up to ~100s of MeV
- Two types of energetic transients accelerate particles
  - Solar flares in the low corona
  - Fast coronal mass ejections
- Explosive magnetic reconnection *vs* destabilization and expulsion
- Both play a role in “space weather”

FASR

Key Science Objectives







- **The "thermal" solar atmosphere**
  - Coronal* & chromospheric heating
  - Thermal structure* & dynamics
  - Formation & structure of filaments*
- **The Solar Wind**
  - Solar wind sources
  - Coronal holes and fast solar wind
  - Turbulence* & waves
- **Synoptic Studies**
  - Radiative inputs to the upper atmosphere*
  - Global magnetic field & dynamo*
  - Flare statistics*

*EOVSA (FASR Pathfinder)

Preparing for FASR—EOVSA

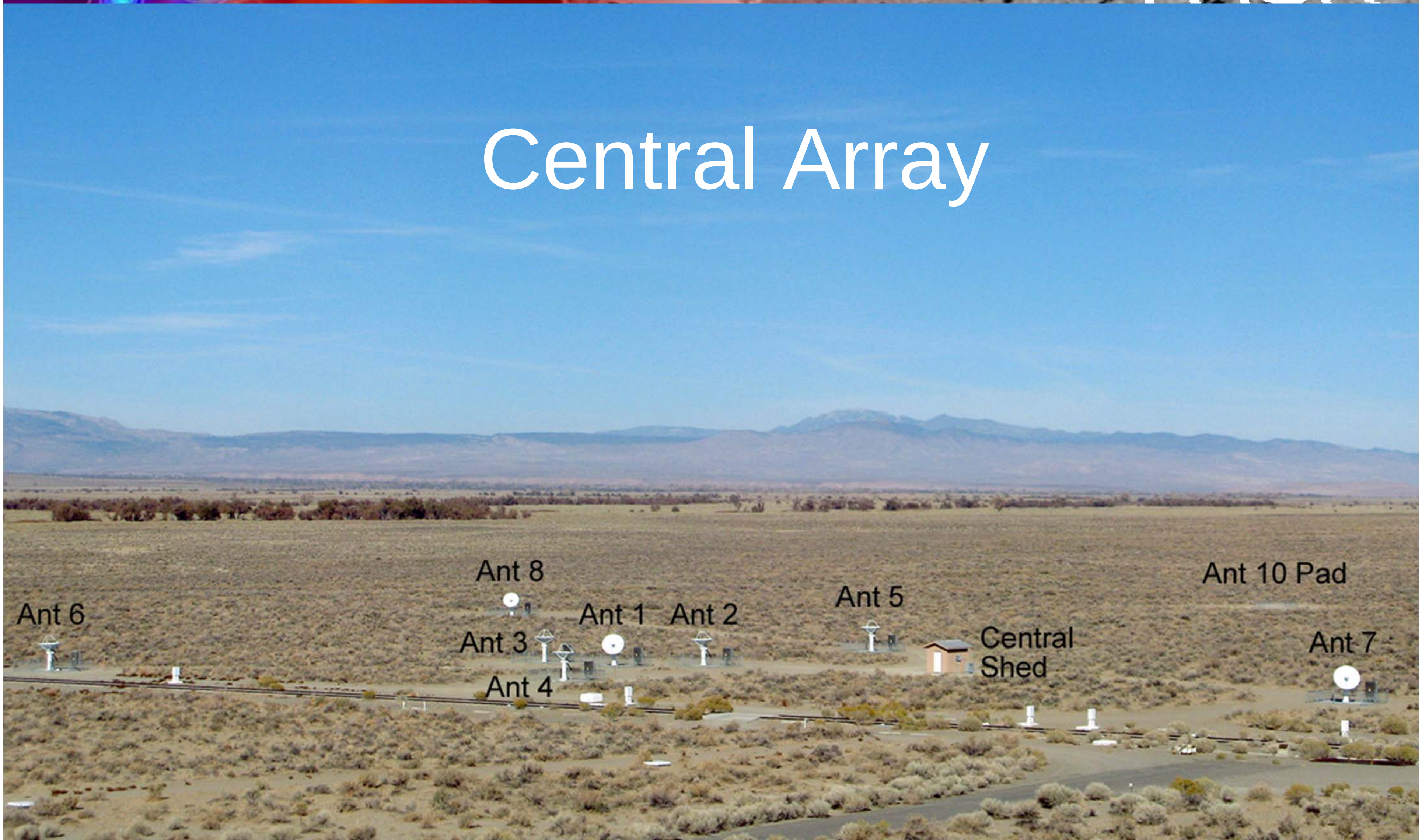
- The Expanded Owens Valley Solar Array
  - $1/10^{th}$ the size of FASR-A (13 antennas)
  - $1/10^{th}$ the cost of FASR-A (\$5 M)
- Excellent prototype for FASR-A
  - Similar frequency range (1-18 GHz vs. 2-21 GHz)
  - Same analog/RF electronics
  - Same correlator design
  - Same software/pipeline processing approach
  - Important subset of FASR science

FASR

Expanded Owens Valley Solar Array (EOVSA)

- Thirteen 2-m antennas (78 baselines)
- Two 27-m (90-ft) antennas (for calibration)
- 1-18 GHz frequency range
- Real-time, high-resolution images at 500 frequencies
- High-cadence (1 s) spectral imaging of flares and other radio bursts

Central Array

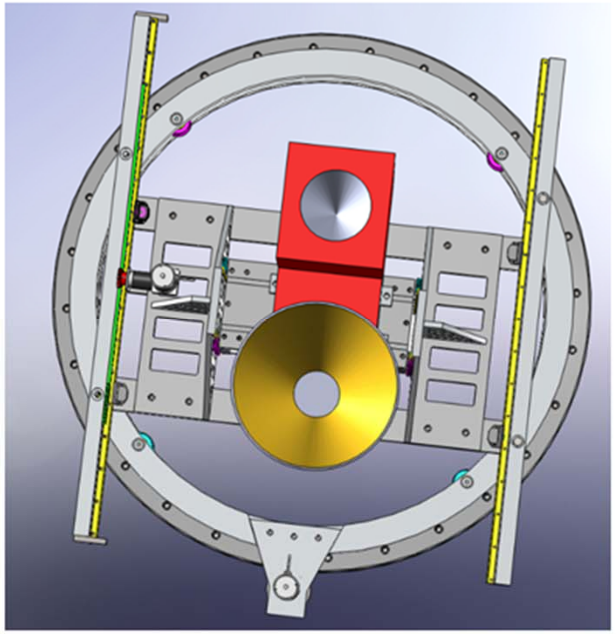


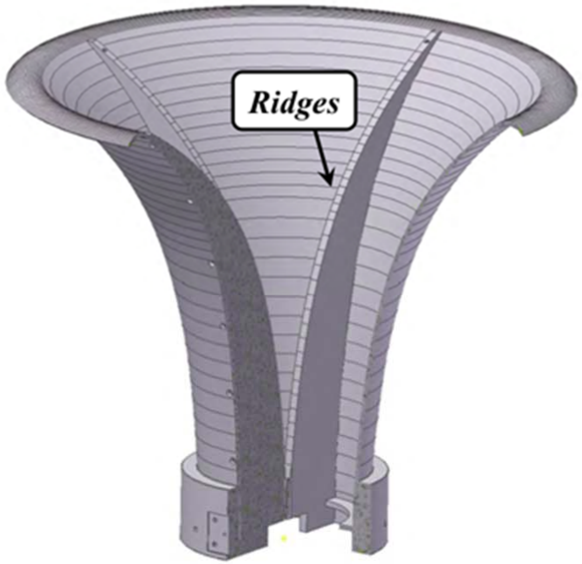
FASR

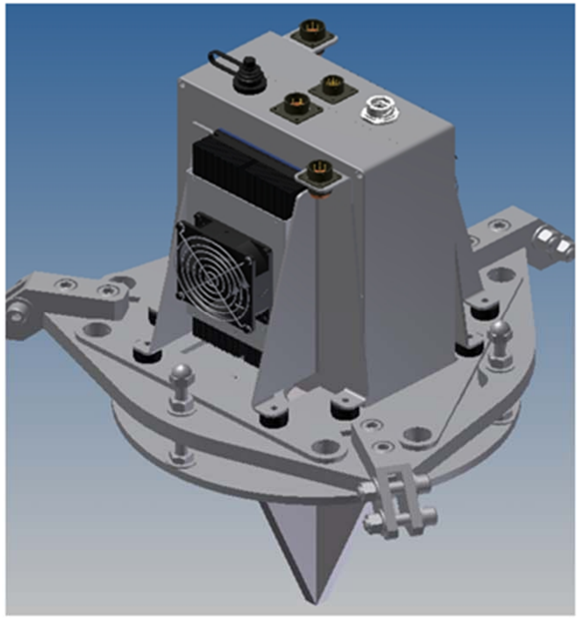
New Control Building

FASR

Feeds and Front Ends



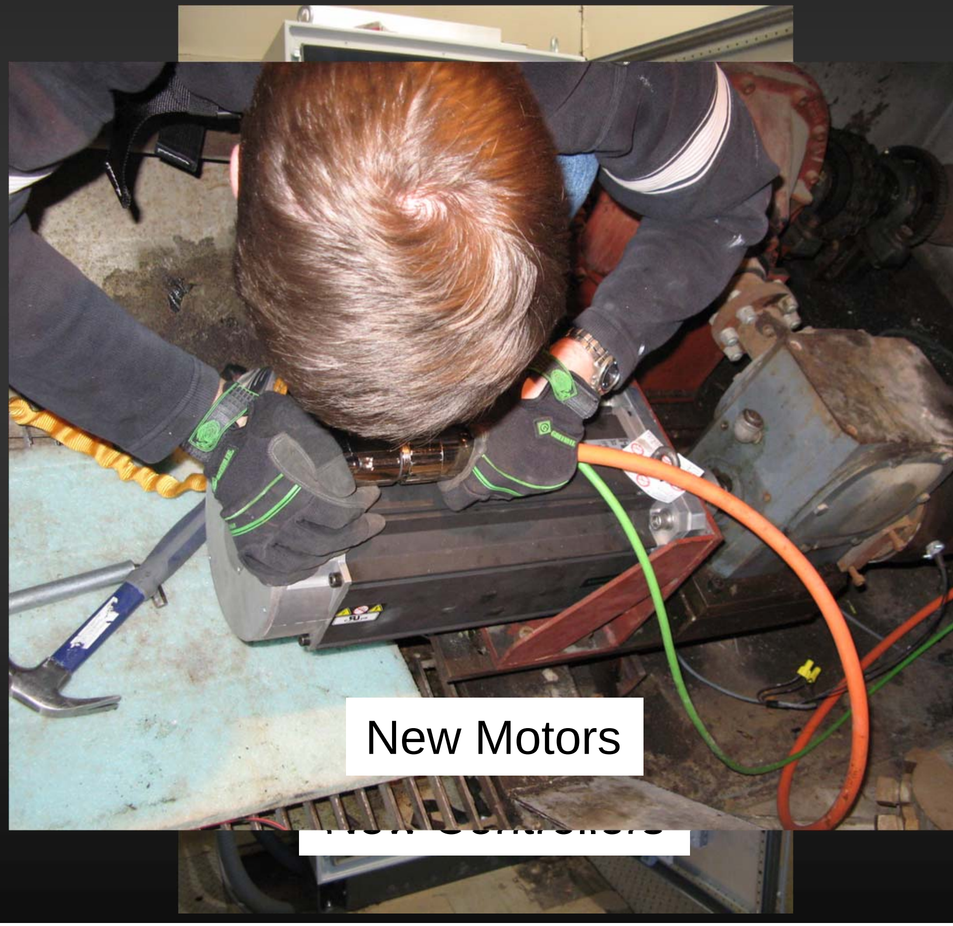




27-m Feed Apparatus | *27-m Feed Horns* | *2.1-m Front-End*

Refurbishment of 27-m Antennas

All New Wiring and Switches

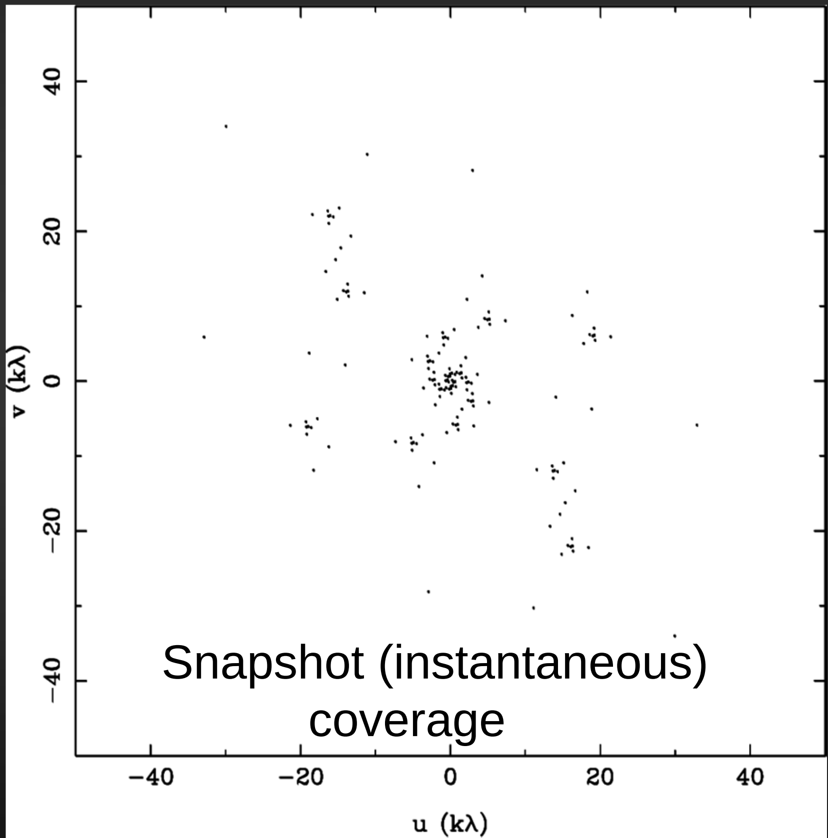


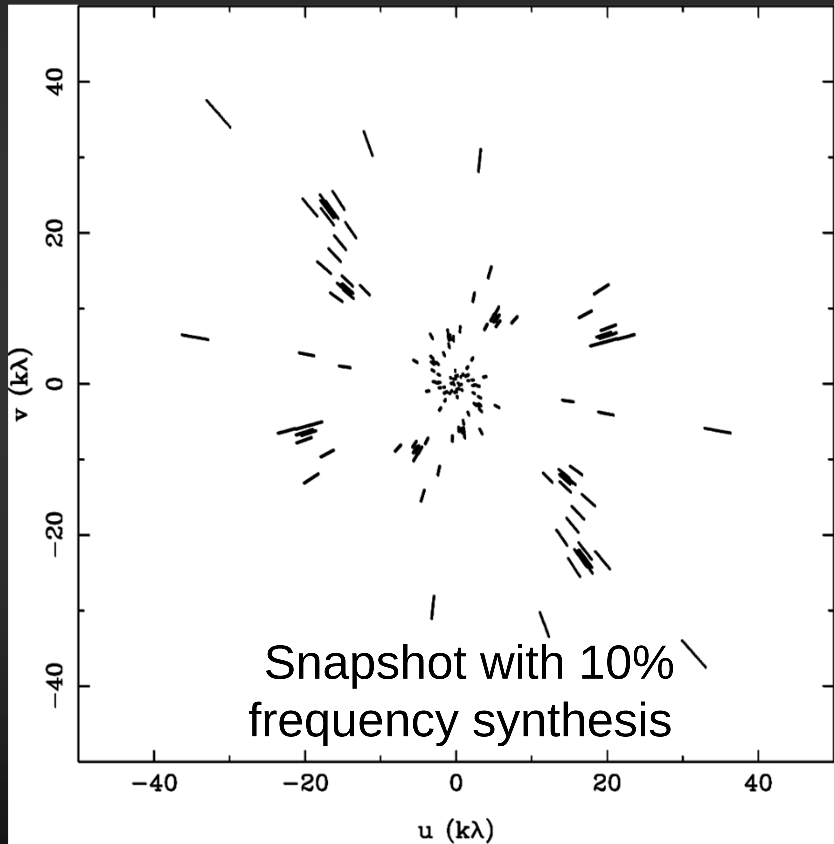
New Motors

Science with EOVSA

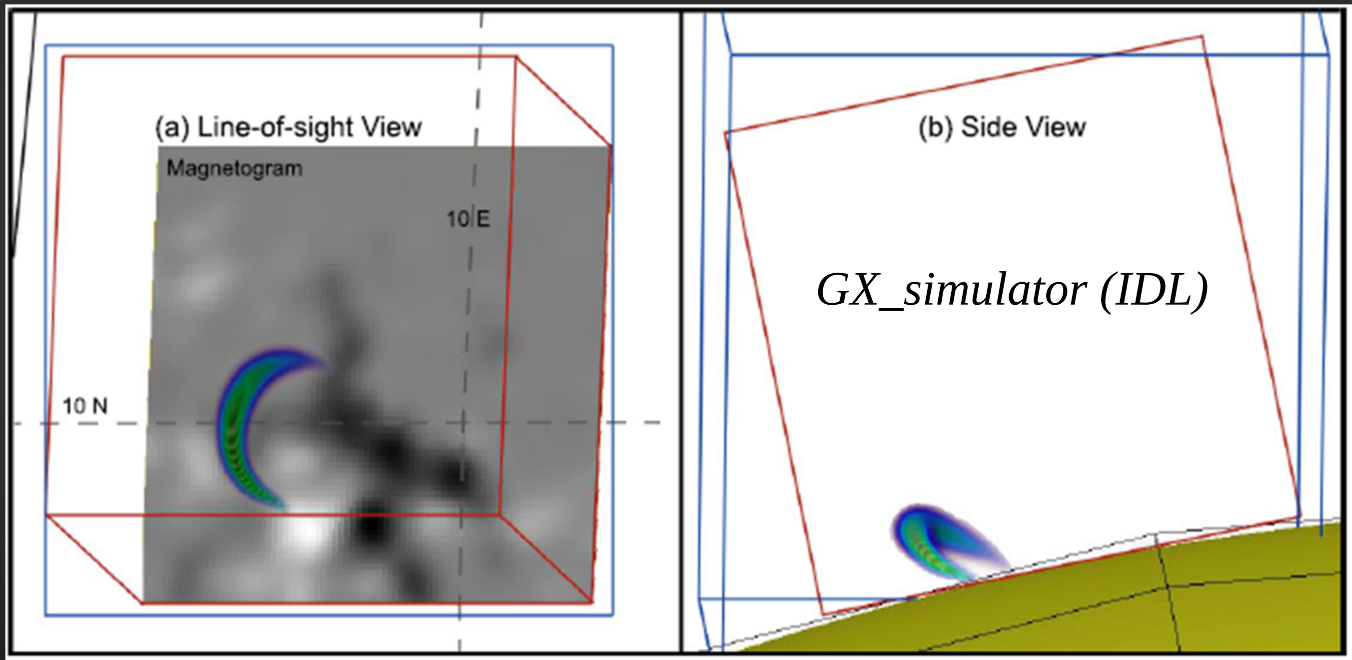
- Measure the 3D magnetic and plasma structure in the corona above solar active regions.
- Understand the process of particle acceleration and transport in solar flares.
- Detect, measure and better understand the drivers of space weather.
- Detect and study transient astrophysical sources.

UV Coverage for Flares

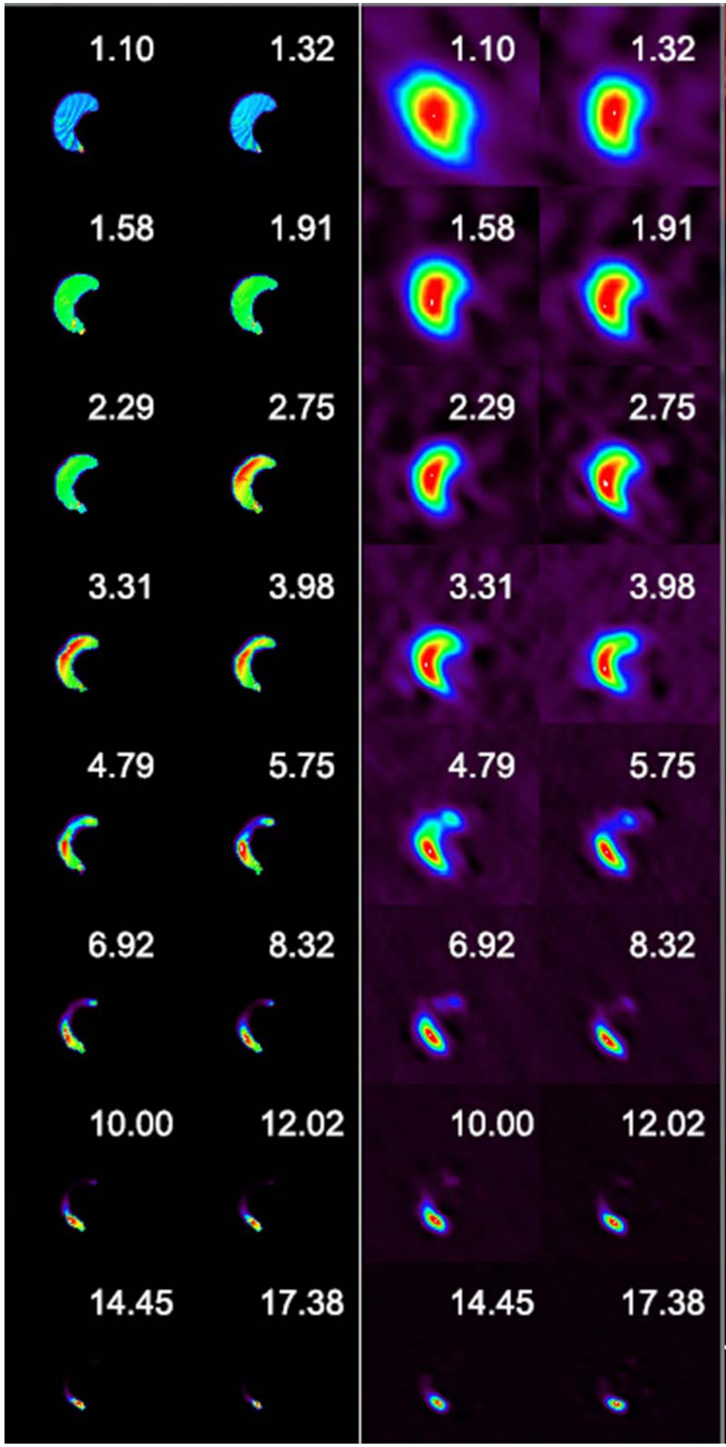




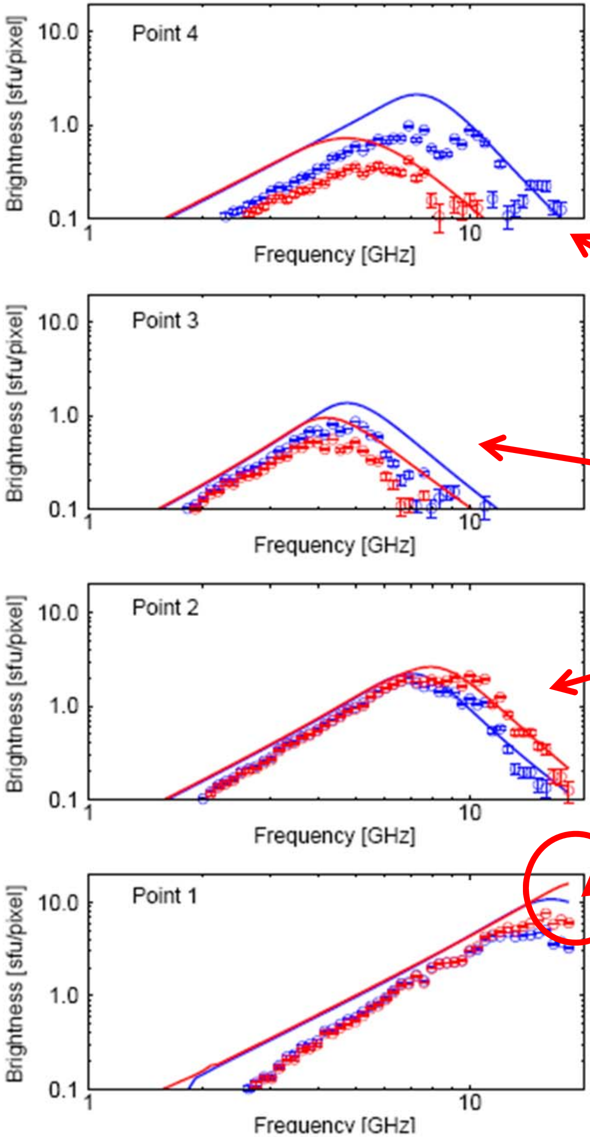
Dynamic Magnetography of Flaring Loops



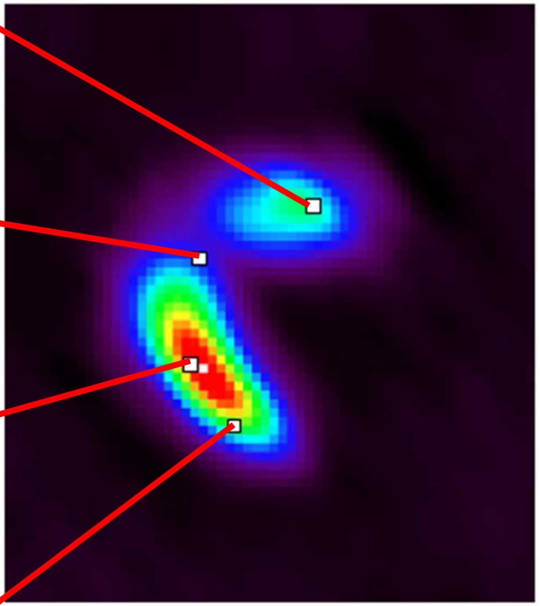
- Modeling of flaring loop—Fleishman et al. (2009, 2010); Nita et al. (2011); Kuznetsov et al. (2011)



FASR



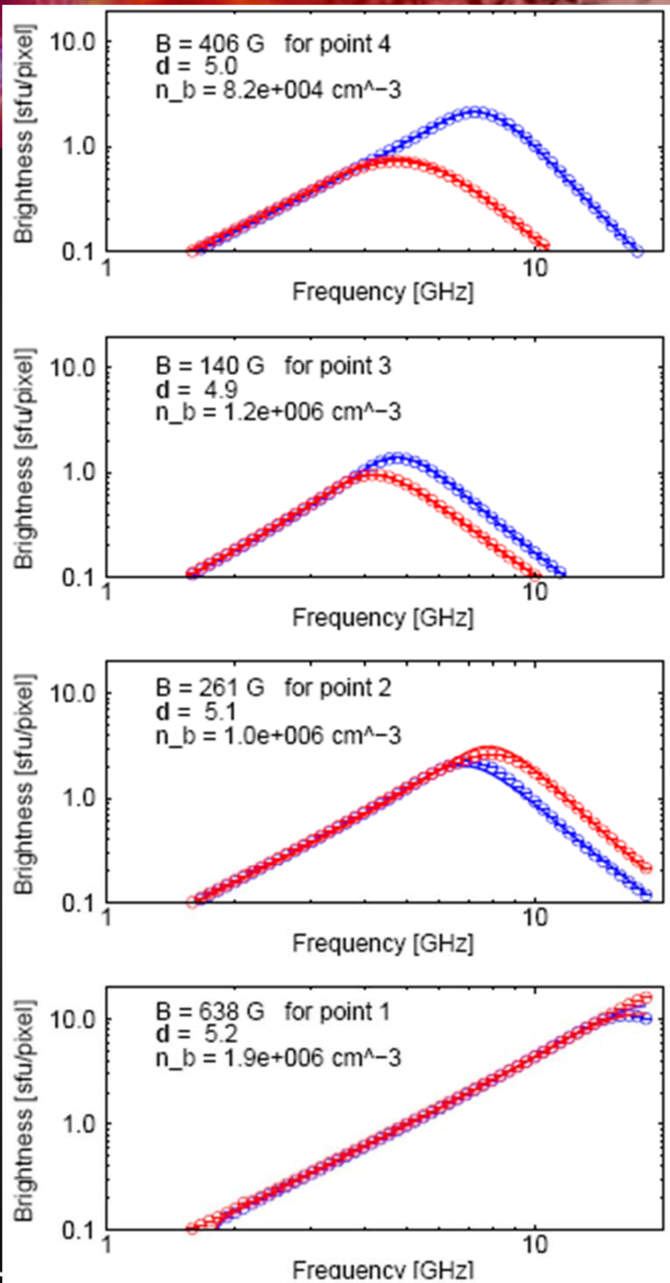
Radiative transfer through 3D model



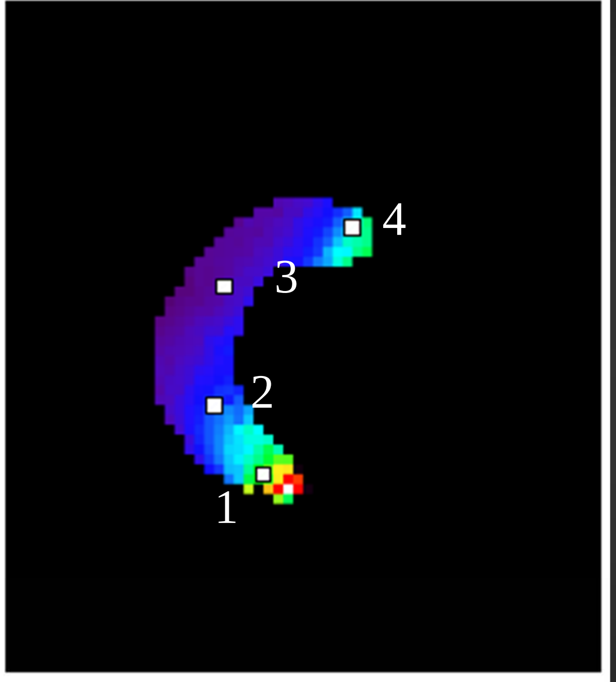
Note the effects of finite resolution

Nobeyama 34 GHz
Is needed!

FASR

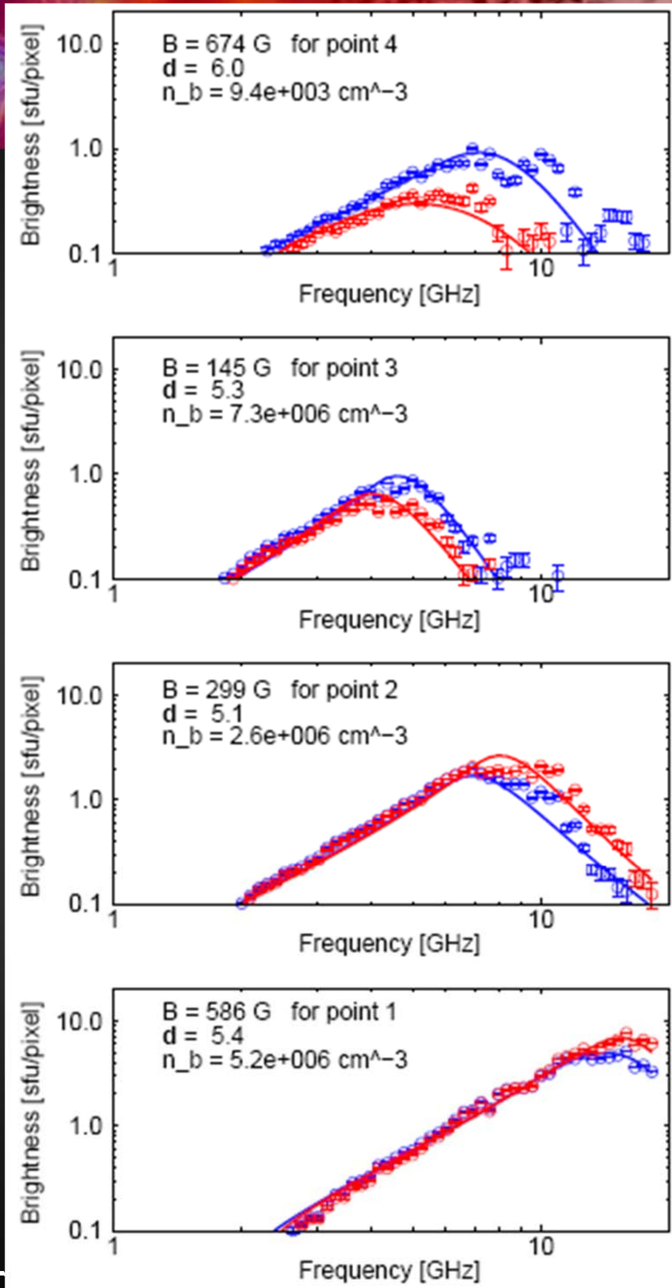


Parameters can be obtained from homogeneous fits directly from model "unfolded"

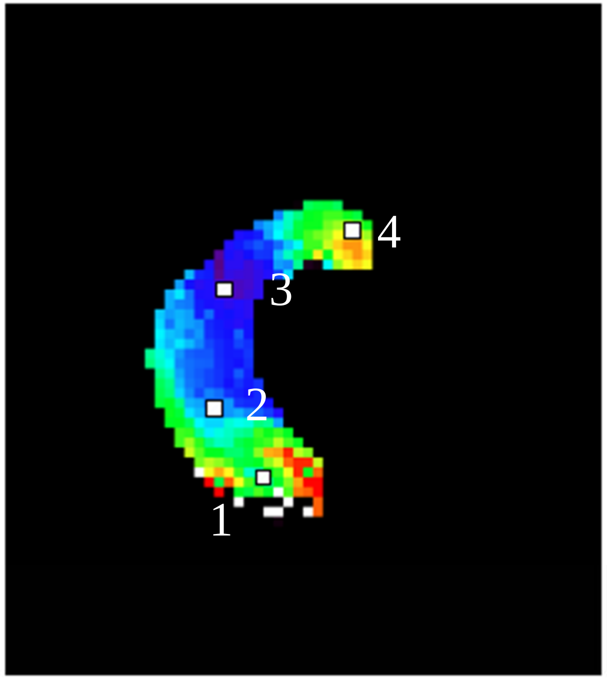


B Field Parameter Map

FASR data would approximate this result.



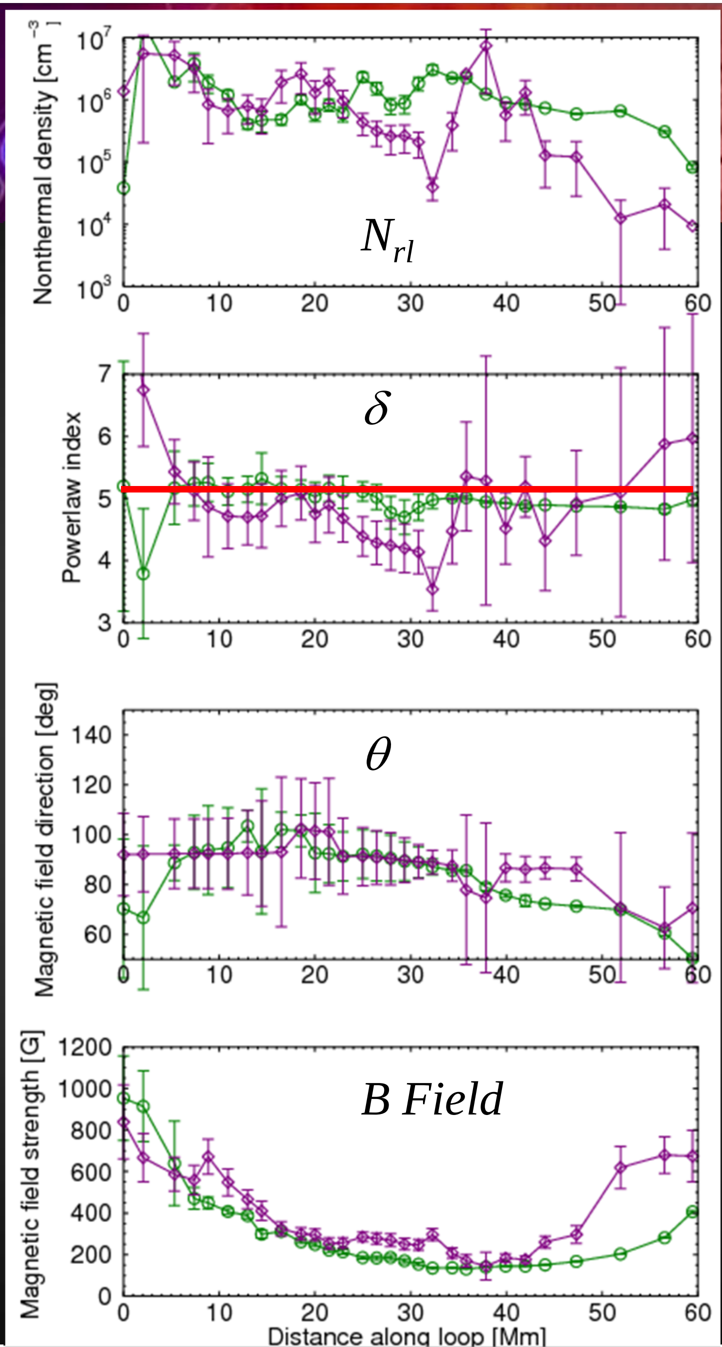
Parameters can be obtained from images as "observed" by EOVSA "folded"

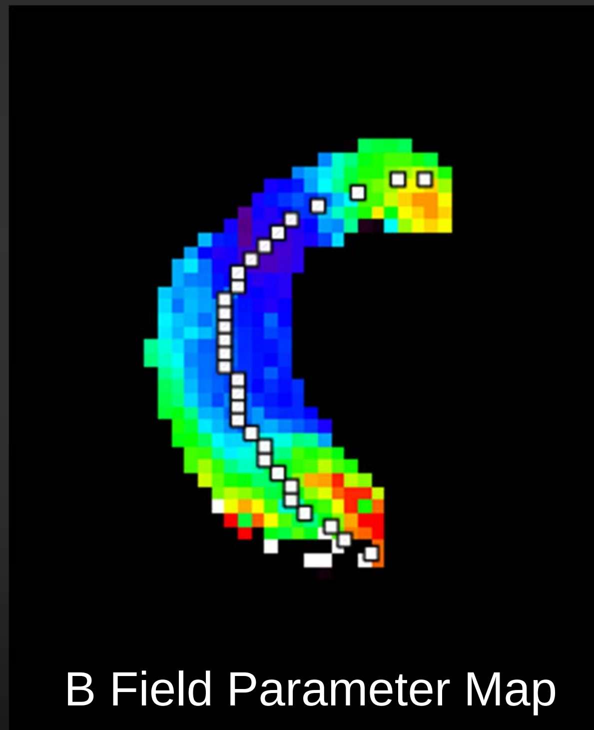


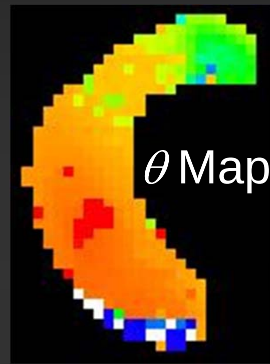
B Field Parameter Map

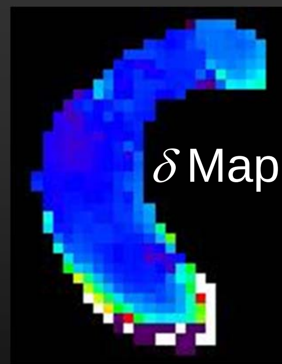
FASR

Parameter comparison along loop

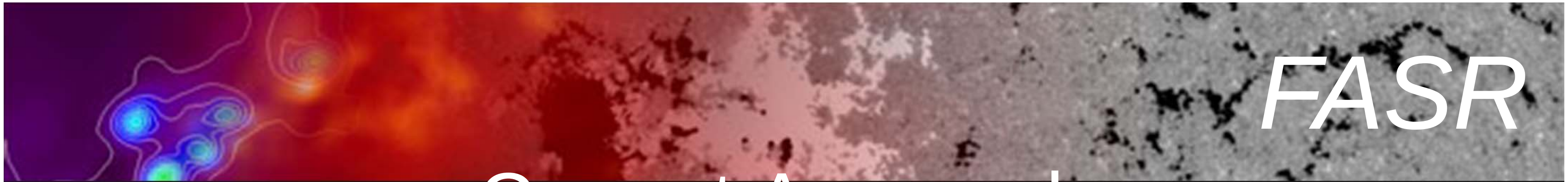




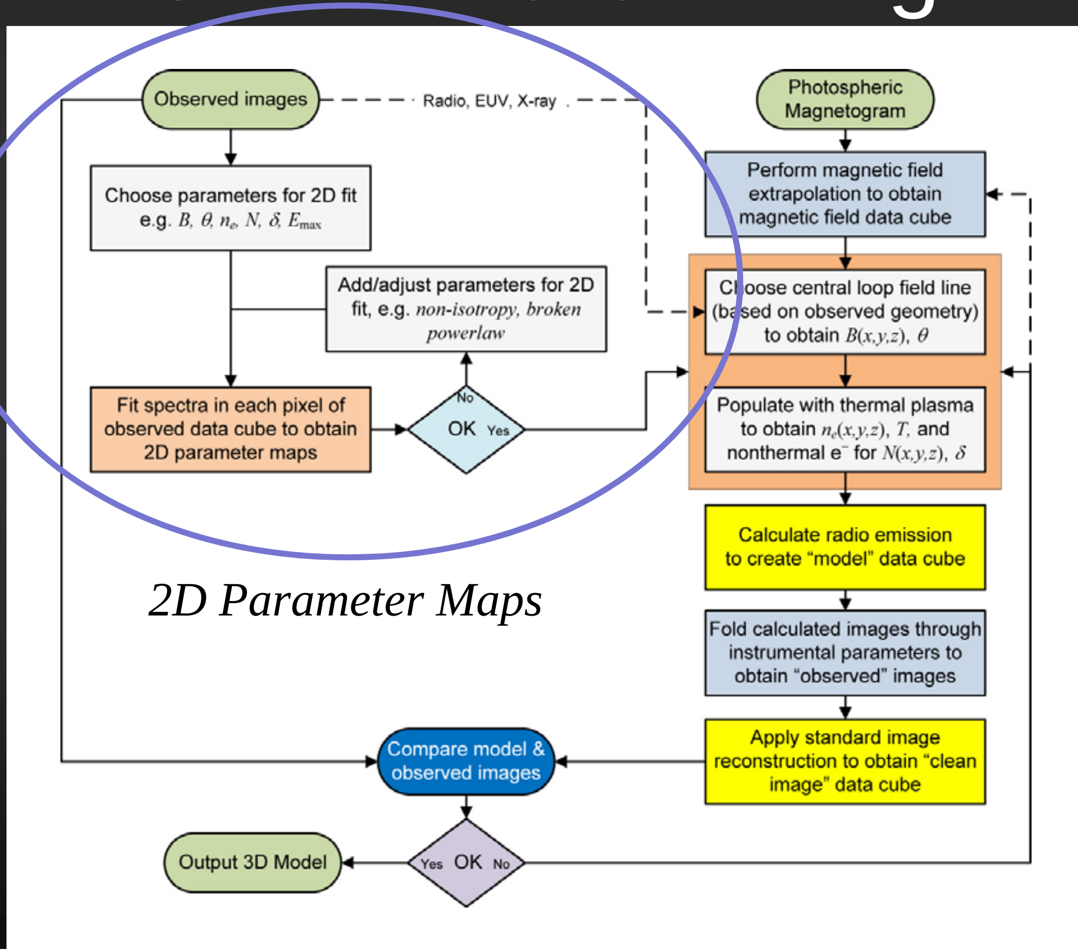




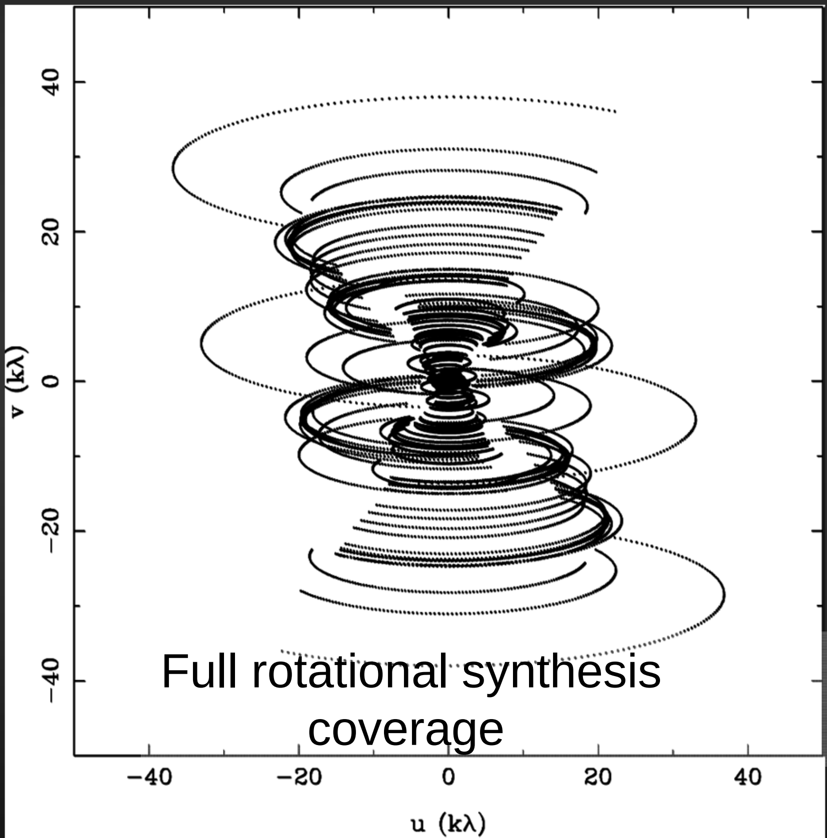
Such maps can be produced dynamically (once per s)

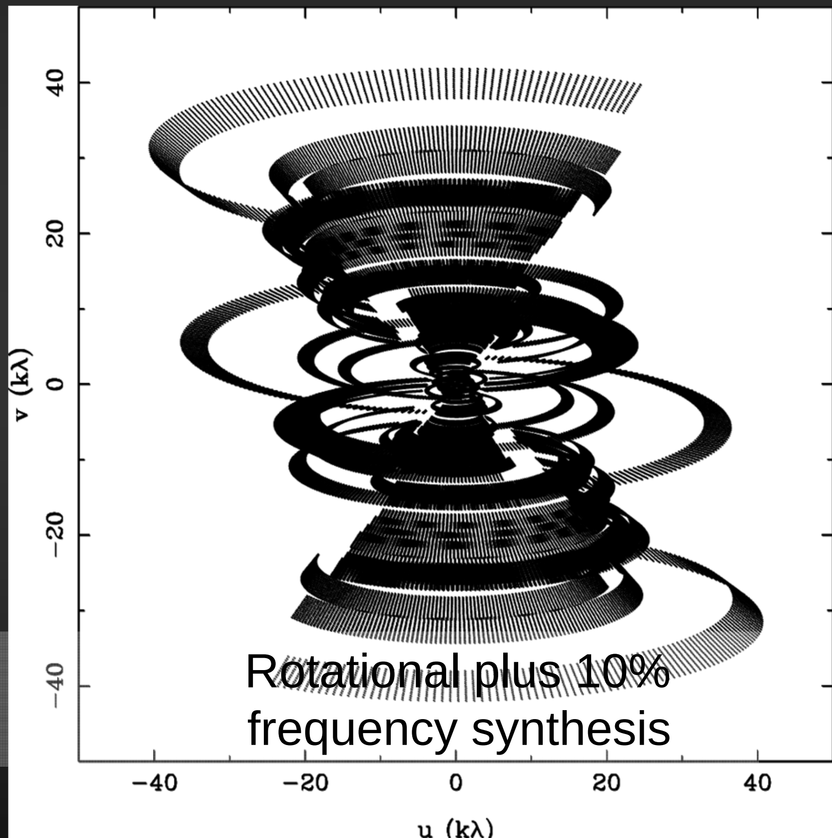


Correct Approach
3D Forward Fitting



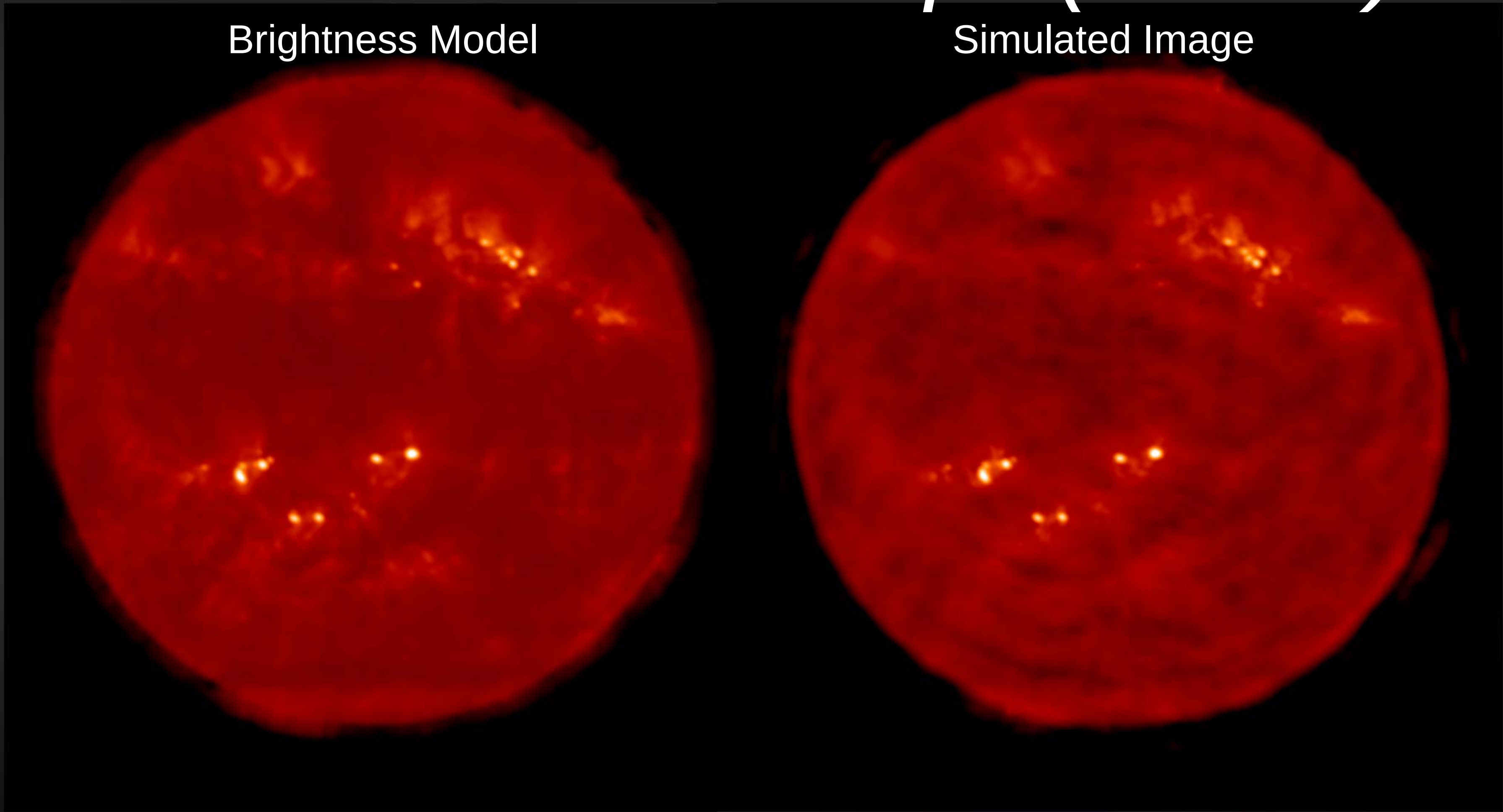
UV Coverage for Active Regions





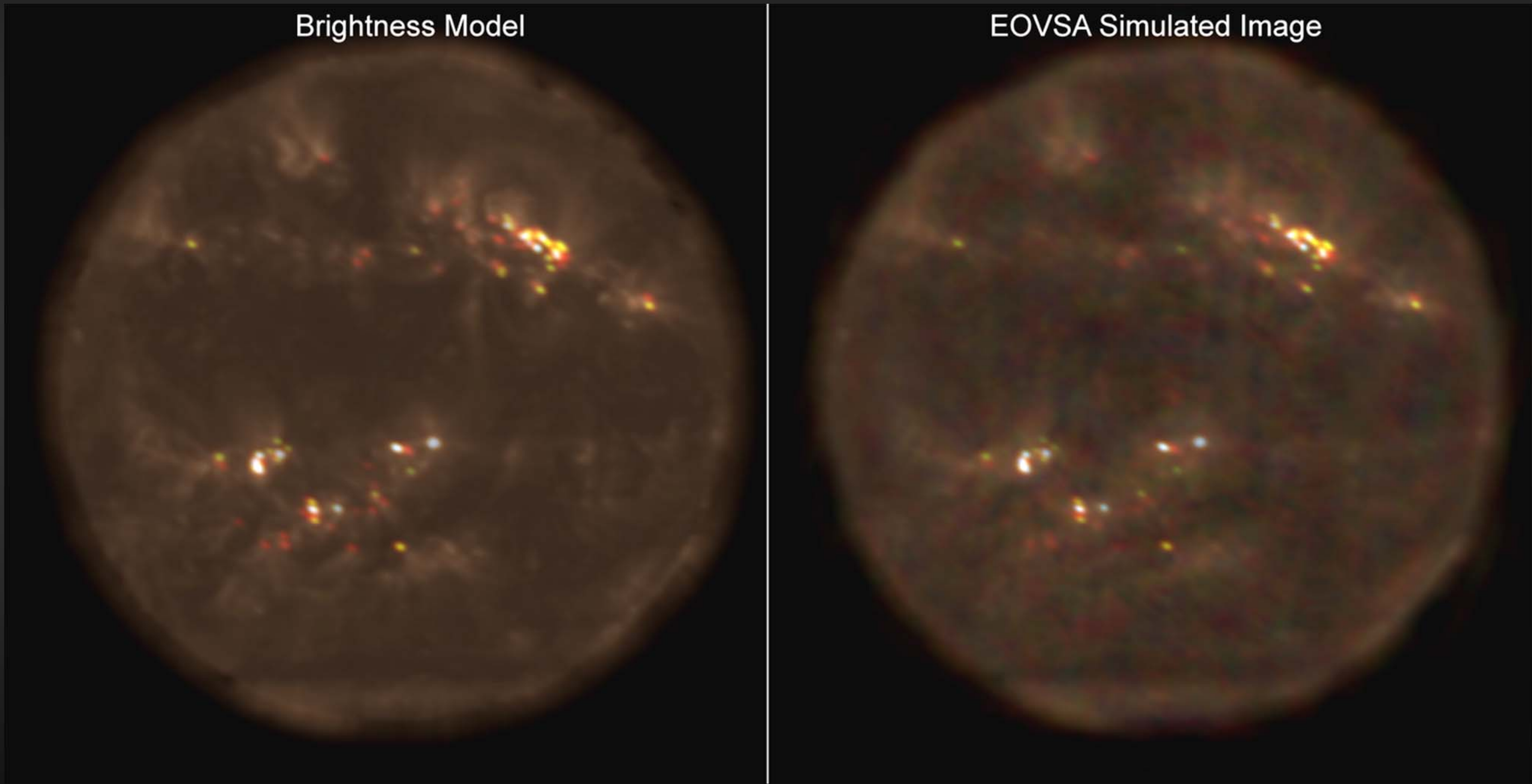
UT range 1400 -0203 UT in summer

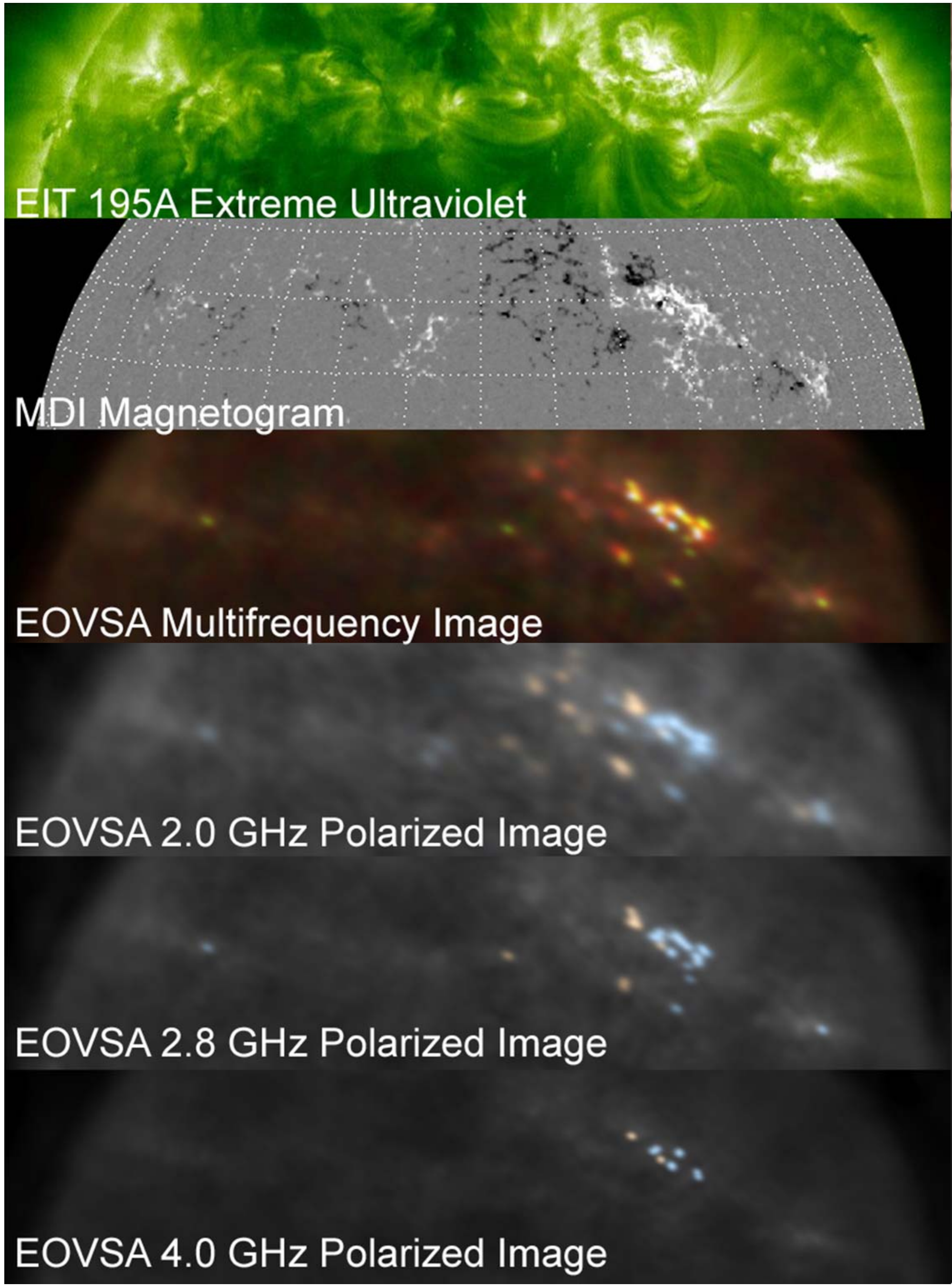
Full Disk and AR Maps (5 GHz)

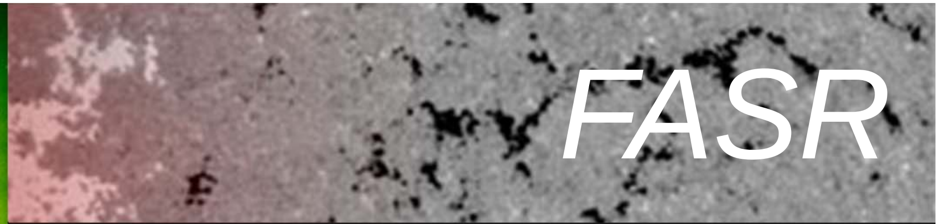


FASR

2.8 GHz (F10.7) Full Disk



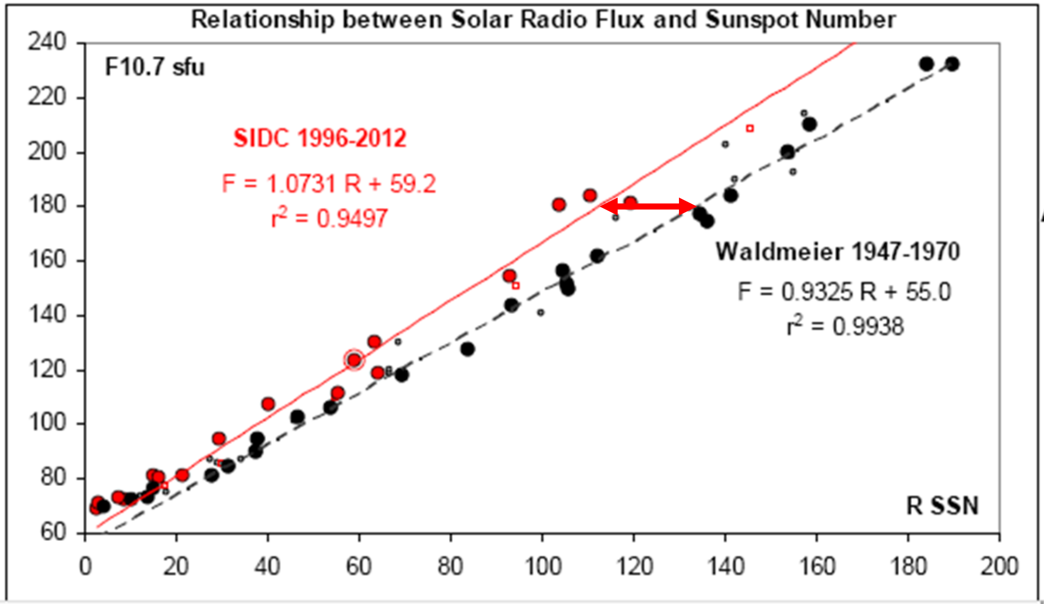


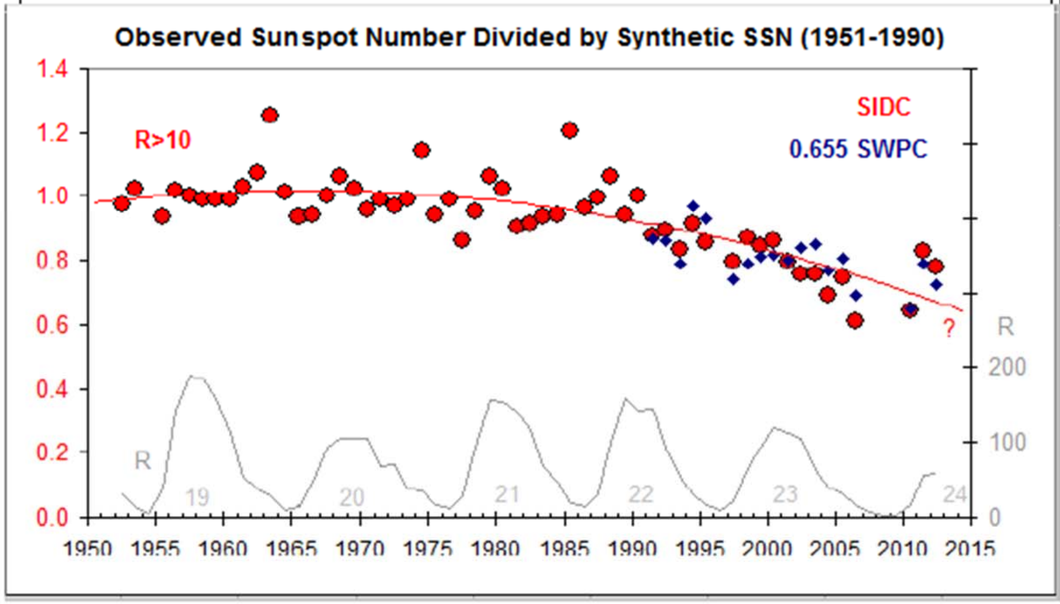


Spectropolarimetry

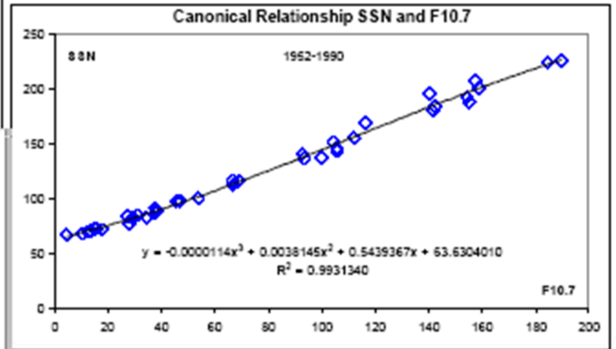
- 2.8 GHz flux, spectrum, and polarization show three components to F10.7
  - Disk (about 50% of flux density)
  - Hot coronal plasma (about 30% of flux density)
  - Spot-associated GR (about 20% of flux density)
- Can understand solar-cycle variation of these distinct components.
- Spectropolarimetry of active regions over 1-18 GHz will provide coronal magnetic field maps through analysis of gyroresonance emission (several times per day).

FASR





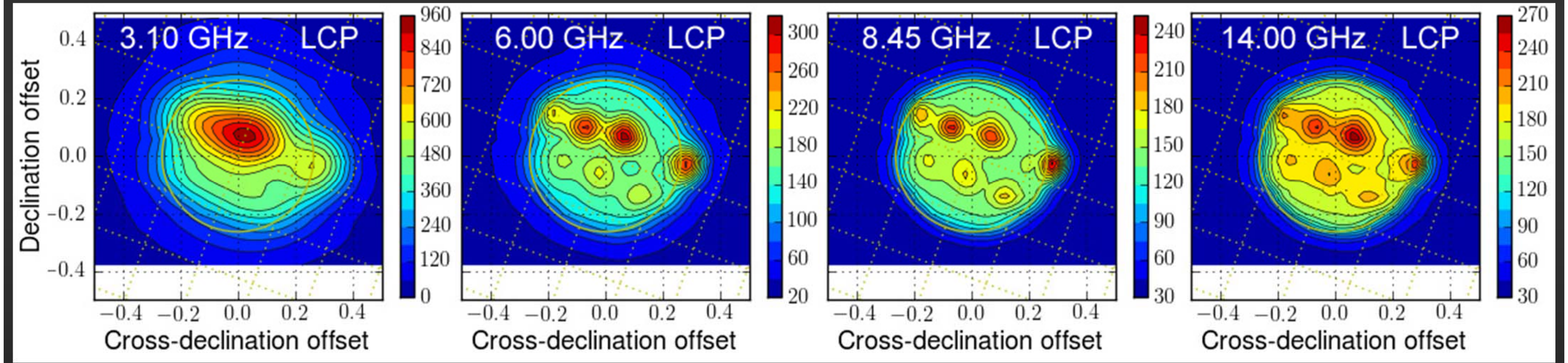
Is the SSN Always a Good Measure of Solar Activity?



Since ~1990 we record progressively fewer sunspots than expected from observations of F10.7 microwave flux

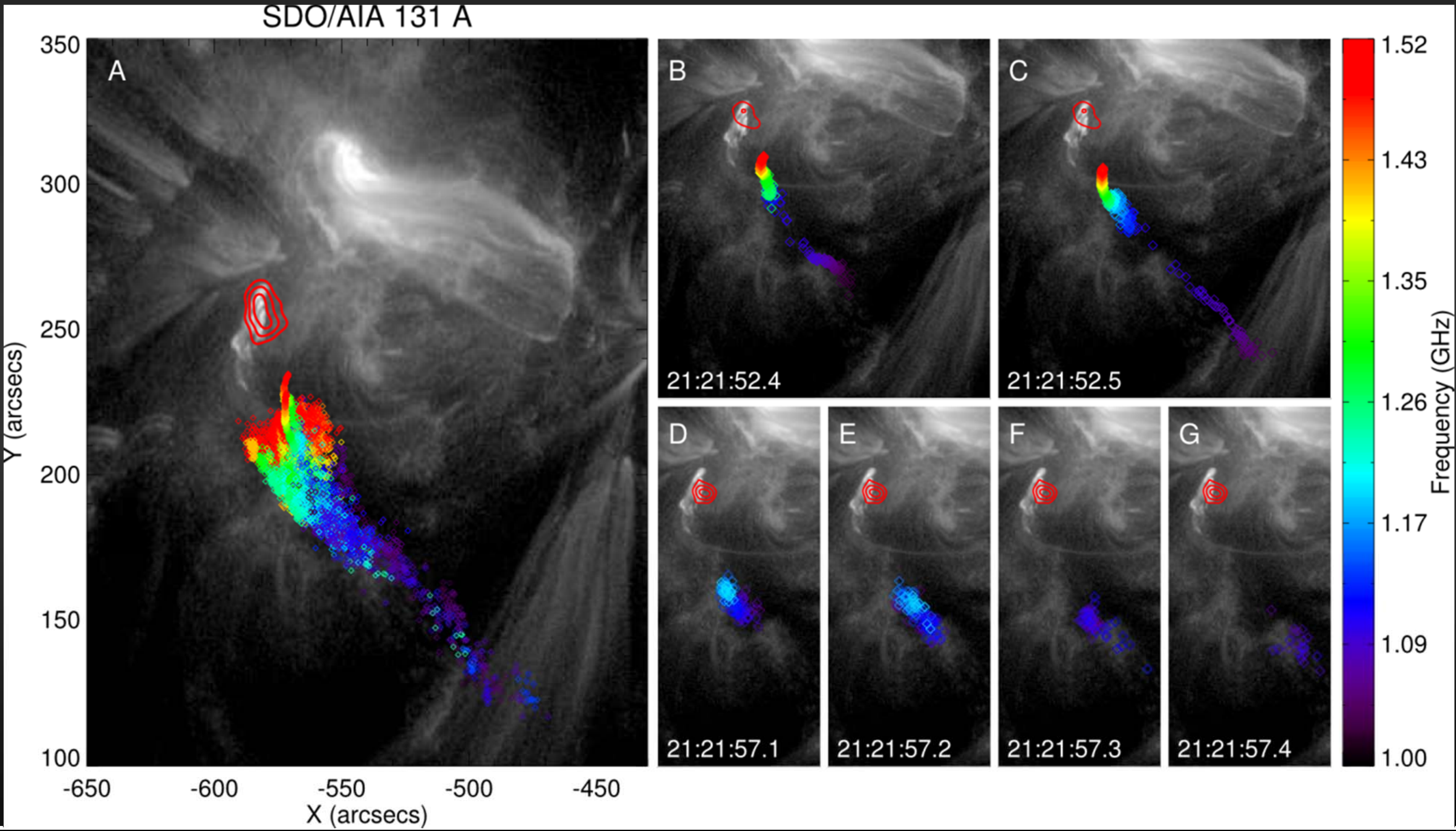
Leif Svalgaard, Stanford U.

Will Incorporate Disk Model from 34-m DS-28 Raster Scans

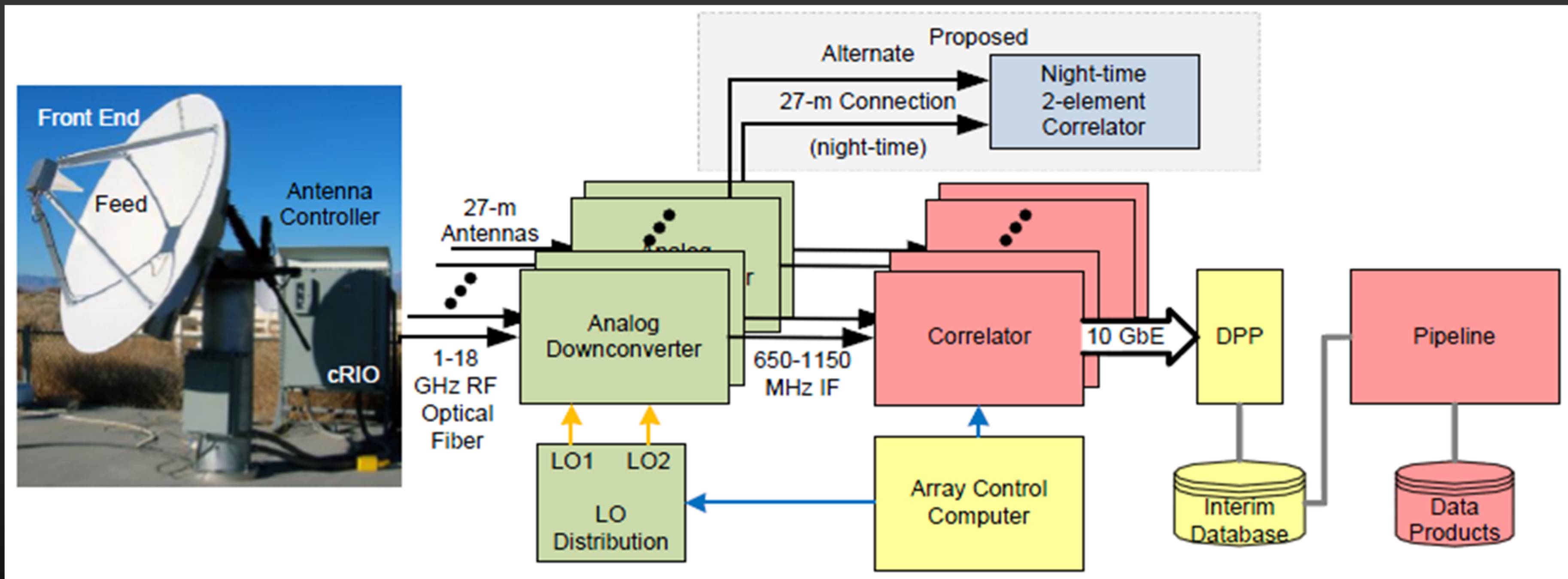


Tom Kuiper, JPL

Type III Trajectories



EOVSA Block Diagram



Key Parameters for EOVSA Performance

- Simultaneous dual-polarization, digital hybrid

g = complex gains
D = cross terms

$$
\begin{bmatrix} X^R \\ X^I \\ Y^R \\ Y^I \end{bmatrix} =
\begin{bmatrix}
g_x^{R'} & g_x^{I'} & -g_y^{R'}D_x^R - g_y^{I'}D_x^I & -g_y^{I'}D_x^R + g_y^{R'}D_x^I \\
-g_x^{I'} & g_x^{R'} & g_y^{I'}D_x^R - g_y^{R'}D_x^I & -g_y^{R'}D_x^R - g_y^{I'}D_x^I \\
-g_x^{R'}D_y^R - g_x^{I'}D_y^I & -g_x^{I'}D_y^R + g_x^{R'}D_y^I & g_y^{R'} & g_y^{I'} \\
g_x^{I'}D_y^R - g_x^{R'}D_y^I & -g_x^{R'}D_y^R - g_x^{I'}D_y^I & -g_y^{I'} & g_y^{R'}
\end{bmatrix}
\begin{bmatrix} X^{R'} \\ X^{I'} \\ Y^{R'} \\ Y^{I'} \end{bmatrix}
$$

$$
\begin{bmatrix} R^R \\ R^I \\ L^R \\ L^I \end{bmatrix} = \frac{1}{\sqrt{2}}
\begin{bmatrix}
1 & 0 & 0 & -1 \\
0 & 1 & 1 & 0 \\
1 & 0 & 0 & 1 \\
0 & 1 & -1 & 0
\end{bmatrix}
\begin{bmatrix} X^R \\ X^I \\ Y^R \\ Y^I \end{bmatrix}
$$

Key Parameters for EOVSA Performance

- Simultaneous dual-polarization, digital hybrid
- Stable system
  - Temperature-stabilized front end, optical transmission
  - Tightly controlled ripple, linearity, slope across RF/IF bands
  - Downconversions done in environmentally controlled electronics room
- RFI excision using Spectral Kurtosis
- Excellent calibration on cosmic sources (100s available)
- Better than 100:1 dynamic range (w/o frequency synth)
- Use of multi-frequency synthesis
- Uniform, mono-mode observing

EOVSA Data Management

- Data Volume
  - 50 GB/day interim database
  - 2.8 GB/day archival databases
    - Active region database (500 frequencies, 10 s avg)
    - Flare database (100 frequencies 1-18 GHz, 1 s full resolution)
    - Decimeter database (100 frequencies 1-3 GHz, 200 ms resolution)
- Data Products
  - UV data in Miriad format (convertible to UVFITS)
  - Metadata (light curves, spectra, quick-look images)
  - Pipeline-processed coronal B field maps, temperature maps
- Analysis via RHESSI-like user interface

Conclusions (FASR)

- FASR remains highly ranked in national US science surveys.
- FASR is considered in a high state of readiness.
- US National Science Foundation has been directed to create a “mid-size” funding line, which would be appropriate for FASR.
- The FASR will propose as soon as such a funding line is announced, and we will anticipate the announcement as it gets closer, in order to update the FASR design and reorganize the consortium.
- You can help by speaking positively of FASR at every opportunity, and considering getting directly involved through the consortium.
- Meanwhile, EOVSA will act as a FASR Pathfinder, producing valuable engineering and science to support our efforts.

Conclusions (EOVSA)

- EOVSA will be completed soon (2013 October, with “first-fringes” for our 3-antenna prototype in 2013 January).
- EOVSA data and data products will be completely open—please use them!
- EOVSA science is itself revolutionary, taking microwave spectropolarimetry to a new level. It will realize the long-recognized potential of radio emission to produce accurate diagnostics on magnetic fields, thermal plasma, and high-energy electrons.
- EOVSA success relies on collaborations with other observatories, especially Nobeyama, CSRH and SSRT, to extend our frequency range and provide additional capabilities and time coverage.
- Nobeyama imaging at 34 GHz will be especially important for flares.