Reduction and Analysis of Solar Radio Observations

T. S. Bastian

NRAO

Notes available on Summer School website:

1. Continuum Radiative Transfer and Emission Mechanisms
2. Electromagnetic Waves in a Plasma
3. Radio Interferometry and Fourier Synthesis Imaging

Also see the 9th NRAO Synthesis Imaging Summer School

http://www.aoc.nrao.edu/events/synthesis/2004/presentations.html

Observation: use of an instrument to acquire signals

Data reduction: conversion of signals to conventional (e.g., international system) units

- Always involves calibrations
- Often involves conversion/inversion
- Sometimes involves additional data processing/distillation

Data analysis: the process of describing, comparing, and/or interpreting data in a logical narrative

- statistical study
- analytical and/or numerical modeling
- theoretical motivation, framework, or content

Plan

1. Types of radio data
2. General data reduction issues
3. Synthesis imaging and deconvolution
4. Data analysis: examples & a case study
5. Future directions

Types of Radio Observations

1. Total polarized flux density vs time at a fixed frequency

   radiometry, polarimetry: RSTN, NoRP

2. Total polarized flux density vs time and frequency

   dynamic spectroscopy: Culgoora, Hiraiso, Green Bank, SRBL, Ondrejov, Tremsdorf, PHOENIX, WIND/WAVES

---

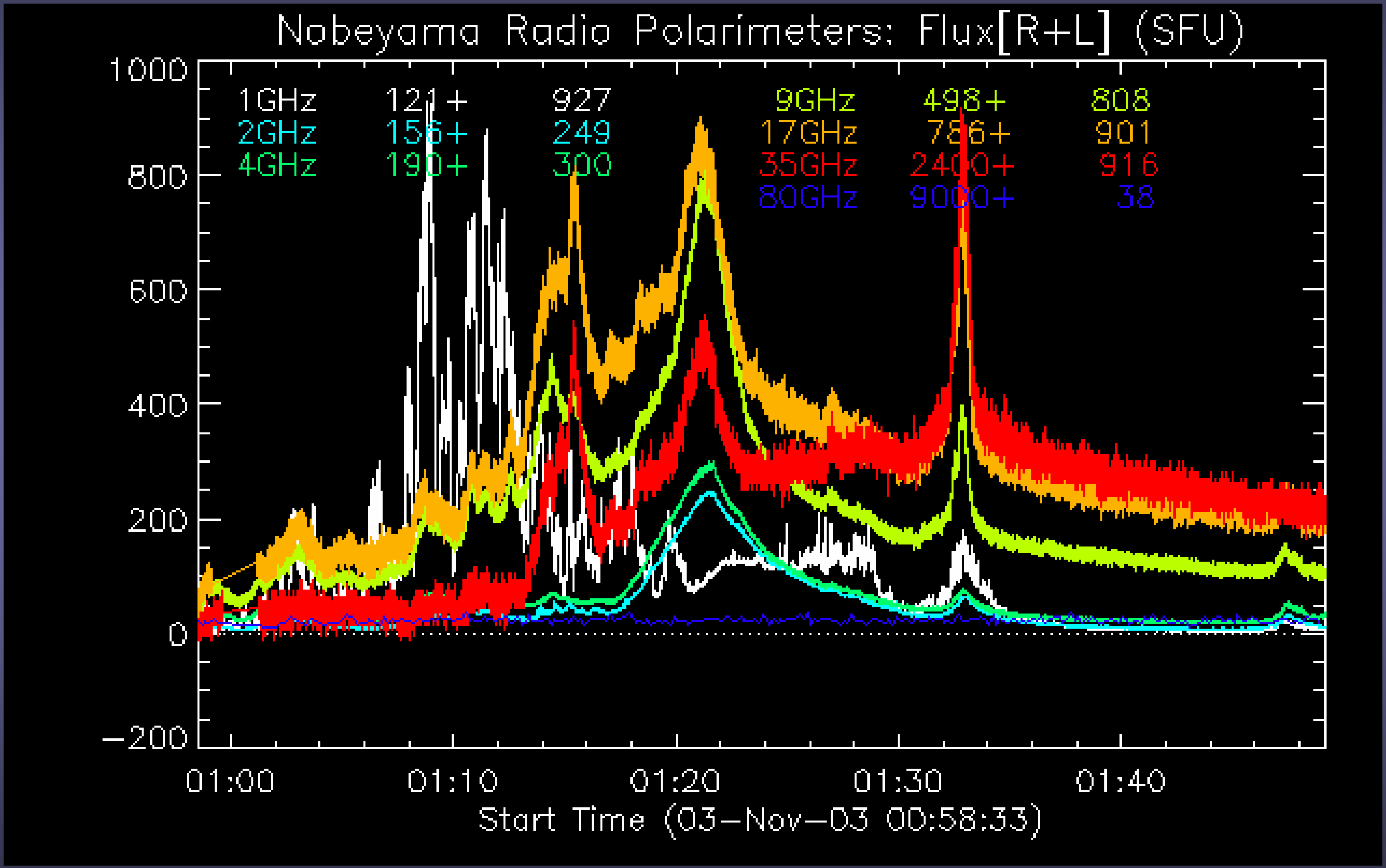
3. Imaging the polarized flux density distribution vs time at a fixed frequency

   synthesis mapping: VLA, NoRH, NRH, SSRT

4. Imaging the polarized flux density vs time and frequency

   dynamic imaging spectroscopy: NRH, OVSA, FASR

Radiometers/Polarimeters



Types of Radio Observations

1. Total polarized flux density vs time at a fixed frequency

   radiometry, polarimetry: RSTN, NoRP

2. Total polarized flux density vs time and frequency

   dynamic spectroscopy: Culgoora, Hiraiso, Green Bank, SRBL, Ondrejov, Tremsdorf, PHOENIX, WIND/WAVES

---

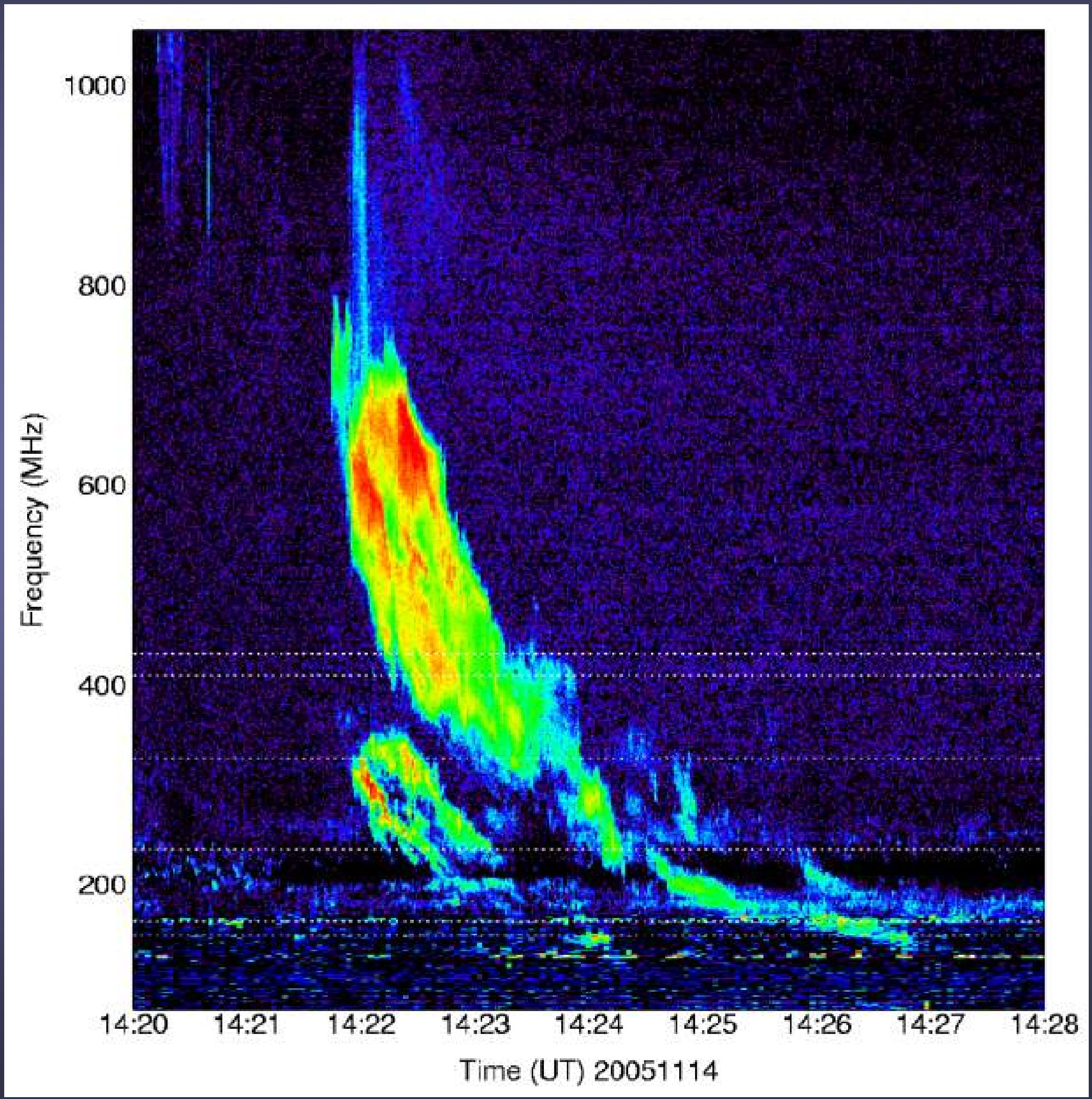
3. Imaging the polarized flux density distribution vs time at a fixed frequency

   synthesis mapping: VLA, NoRH, NRH, SSRT

4. Imaging the polarized flux density vs time and frequency

   dynamic imaging spectroscopy: NRH, OVSA, FASR

Broadband Spectrometers



Ultra-high frequency type II
Composite spectrum
GB/SRBS + RSTN

- Calibration
- Background subtraction
- RFI excision/mitigation

White et al 2006

Types of Radio Observations

1. Total polarized flux density vs time at a fixed frequency

   radiometry, polarimetry: RSTN, NoRP

2. Total polarized flux density vs time and frequency

   dynamic spectroscopy: Culgoora, Hiraiso, Green Bank, SRBL, Ondrejov, Tremsdorf, PHOENIX, WIND/WAVES

---

3. Imaging the polarized flux density distribution vs time at a fixed frequency

   synthesis mapping: VLA, NoRH, NRH, SSRT

4. Imaging the polarized flux density vs time and frequency

   dynamic imaging spectroscopy: NRH, OVSA, FASR

Radio Synthesis Observations

Observation: complex visibility data

Data reduction:

- calibration
- Fourier inversion of the data → mapping
- removal of the inst response function → deconvolution

Data analysis:

- statistical studies
- analytical and/or numerical modeling
- theoretical motivation/framework/content

Usually involves data from other sources … optical, EUV, SXR, HXR, etc.

Reduction of Synthesis Telescope Data

Calibration

A modern synthesis imaging telescope requires many calibrations:

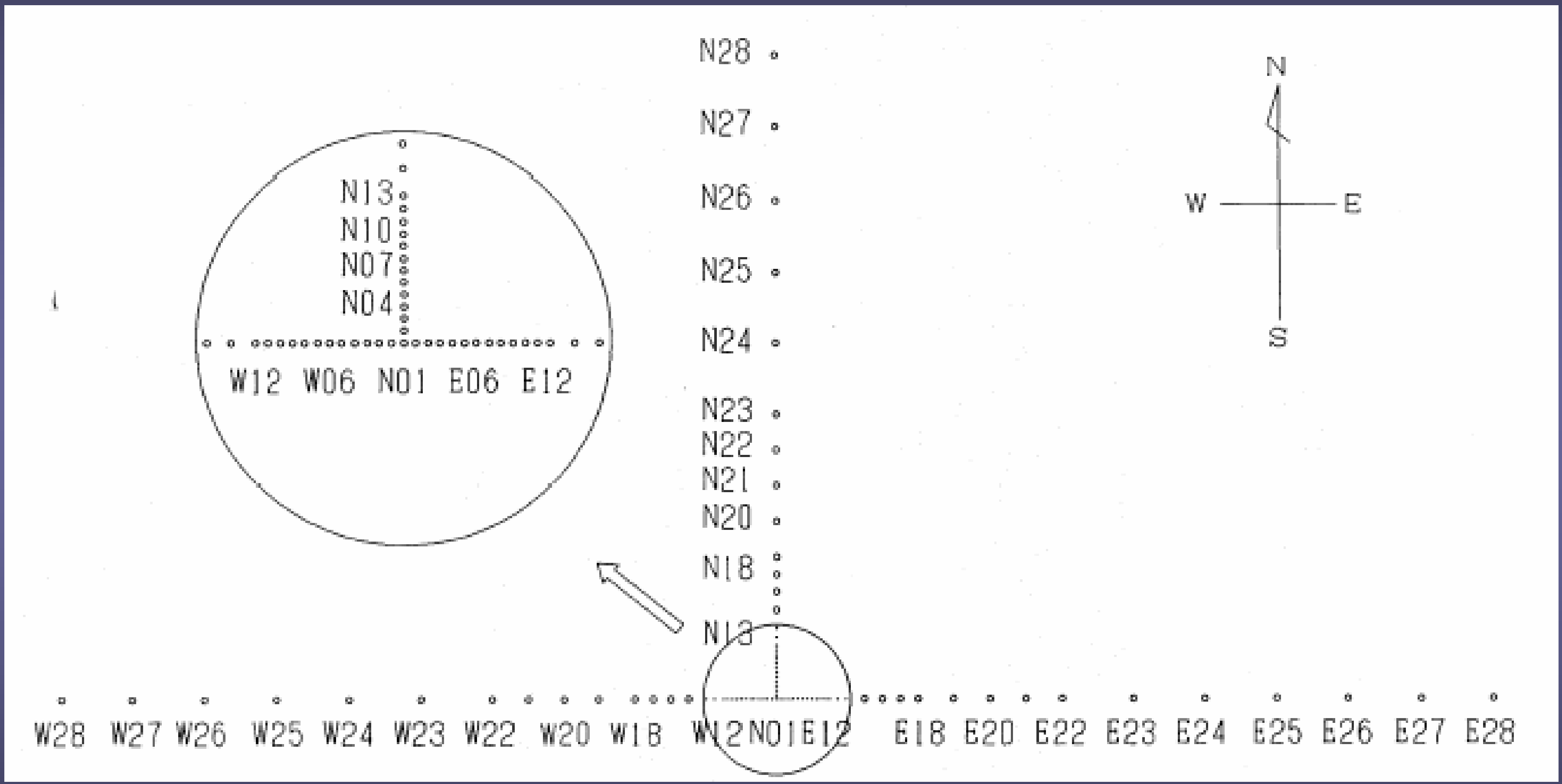
Antenna optics, antenna pointing, antenna positions, antenna (complex) gain, spectral bandpass, atmosphere, correlator offsets

Some calibrations are required once, some infrequently, some regularly and often. I will mention only one type of calibration that is common to all synthesis telescopes:

calibration of the complex gain

The VLA uses non-redundant baselines. Therefore it must calibrate the complex gain of each antenna by observing cosmic sources with known properties. This usually entails observing a point source of known position in the same isoplanatic patch as the source (usually within a few degrees).

In contrast, the NoRH uses geometric baseline spacings and therefore is able to employ a redundant calibration scheme. The advantage is that it never has to leave the Sun. The disadvantage is that absolute position and flux information are lost.



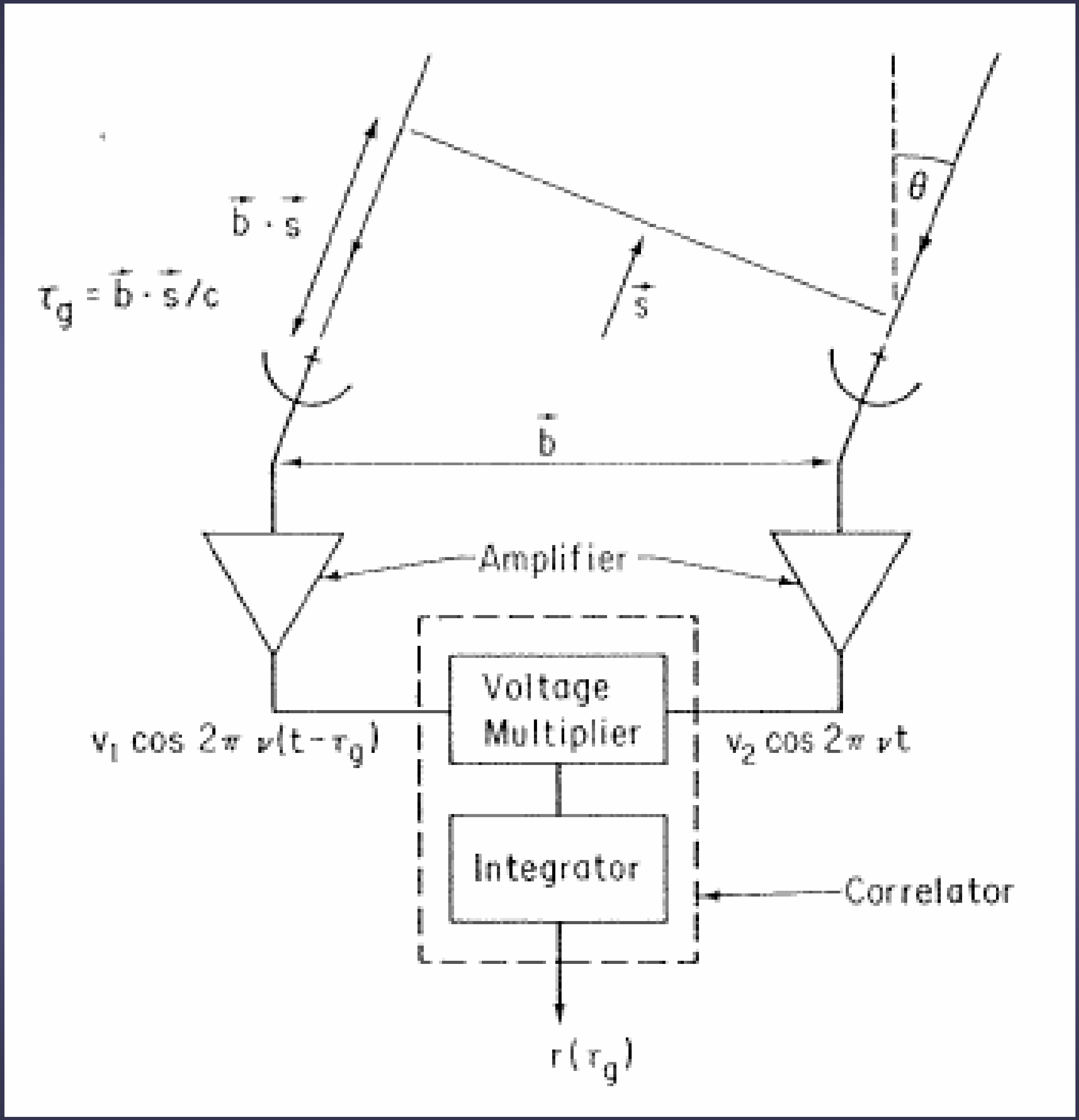
N28
N27
N26
N25
N24
N23
N22
N21
N20
N18
N13
N13
N10
N07
N04
W12 W06 N01 E06 E12
N
W
E
S
W28 W27 W26 W25 W24 W23 W22 W20 W18 W12 N01 E12 E18 E20 E22 E23 E24 E25 E26 E27 E28

From the practicum:

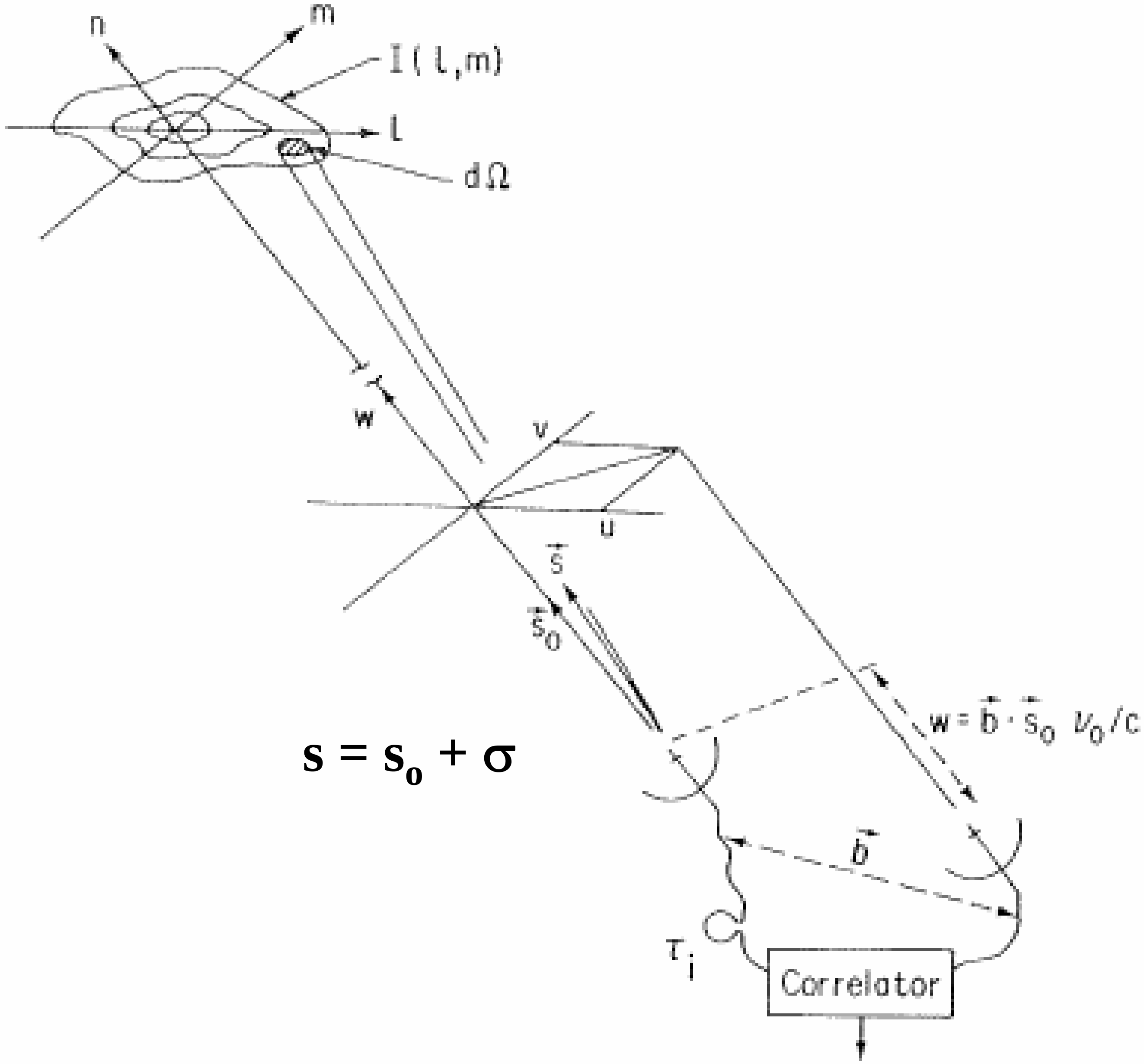
$$V(\mathbf{b}) = R_C + iR_S = A_V e^{-i\phi_V} = \iint I_\nu(s) e^{-2\pi i\nu \mathbf{b}\cdot\mathbf{s}/c} d\Omega$$

$$A_V = \sqrt{R_C^2 + R_S^2}$$

$$\phi_V = \tan^{-1}\left(\frac{R_S}{R_C}\right)$$



$\vec{b} \cdot \vec{s}$
$\tau_g = \vec{b} \cdot \vec{s} / c$
$\vec{s}$
θ
$\vec{b}$
Amplifier
Voltage Multiplier
Integrator
Correlator
$v_1 \cos 2\pi \nu(t - \tau_g)$
$v_2 \cos 2\pi \nu t$
$r(\tau_g)$



$$s = s_o + \sigma$$

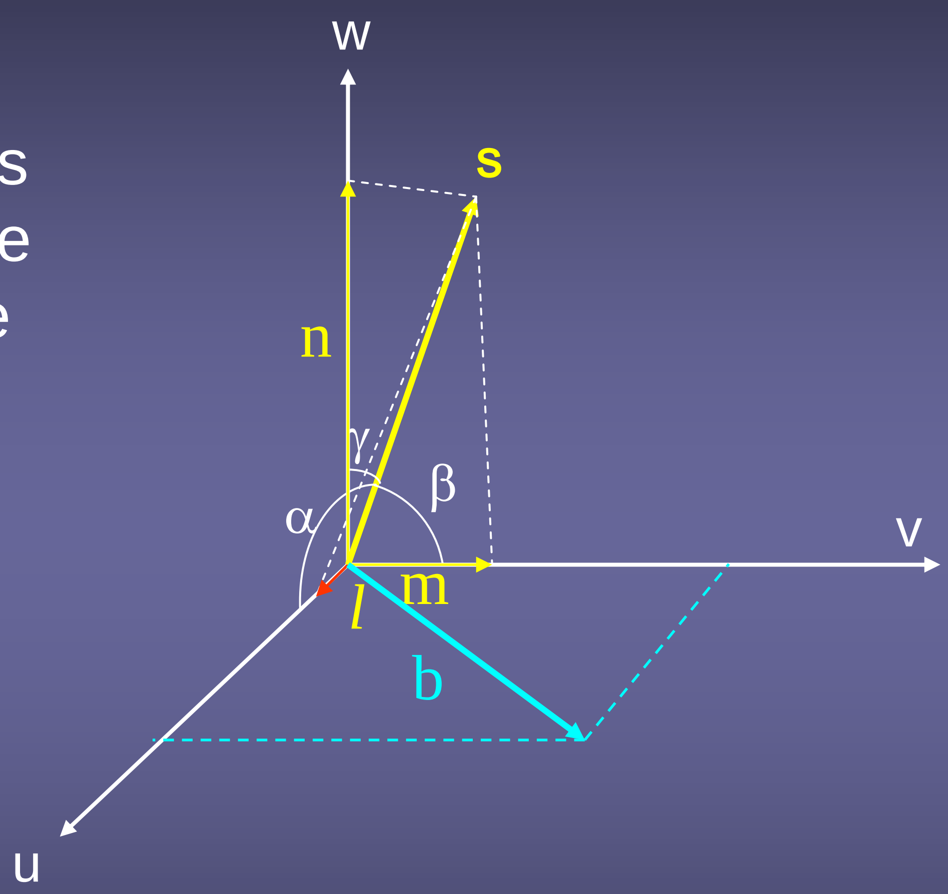
Direction Cosines

The unit direction vector **s** is defined by its projections on the (u,v,w) axes. These components are called the direction cosines.

$$l = \cos(\alpha)$$

$$m = \cos(\beta)$$

$$n = \cos(\gamma) = \sqrt{1 - l^2 - m^2}$$



The baseline vector b is specified by its coordinates (u,v,w) (measured in wavelengths).

$$\mathbf{b} = (\lambda u, \lambda v, \lambda w)$$

Coordinate transformation

Let's choose w to be along the unit vector s toward the source:

$$\frac{\nu\,\mathbf{b}\cdot\mathbf{s}}{c} = ul + vm + wn \qquad \frac{\nu\,\mathbf{b}\cdot\mathbf{s}_o}{c} = w$$

$$d\Omega = \frac{dl\,dm}{n} = \frac{dl\,dm}{\sqrt{1-l^2-m^2}}$$

$$V(u,v,w) = \iint I_\nu(l,m)\,e^{-2\pi i\left[(ul+vm+w(\sqrt{1-l^2-m^2}-1)\right]}\frac{dl\,dm}{\sqrt{1-l^2-m^2}}$$

2D Fourier Transform!

If $|l|$ and $|m|$ are small, we have

$$w(\sqrt{1-l^2-m^2}-1) \approx -\frac{1}{2}\left(l^2+m^2\right)w \approx 0$$

$$V(u,v) = \iint I_\nu(l,m)\, e^{-2\pi\,\mathrm{i}\,(\mathrm{ul}+\mathrm{vm})}\, dl\, \mathrm{dm}$$

$$V(u,v) = \iint A(l,m) I_\nu(l,m)\, e^{-2\pi\,\mathrm{i}\,(ul+vm)}\, dl\, \mathrm{d}m$$

$$A(l,m) I(l,m) = \iint V(u,v)\, e^{2\pi\,\mathrm{i}\,(ul+vm)}\, du\, \mathrm{d}v$$

Synthesis imaging in practice

In reality, our visibility measurements are noisy. Let's designate the noisy measurement $V'(u,v)$. Moreover, because we only have a finite number of antennas and a finite amount of time, our sampling of the visibility function is incomplete. Let the actual sampling function be designated $S(u,v)$.

$$I^D(l,m) = \iint S(u,v)V'(u,v)e^{2\pi i(ul+vm)}du\,dv$$

If we write
$$S(u,v) = \sum_{k=1}^{M} \delta(u-u_k, v-v_k)$$

The sampled visibility function above becomes

$$V^S(u,v) = \sum_{k=1}^{M} \delta(u-u_k, v-v_k)V'(u,v)$$

Synthesis imaging in practice

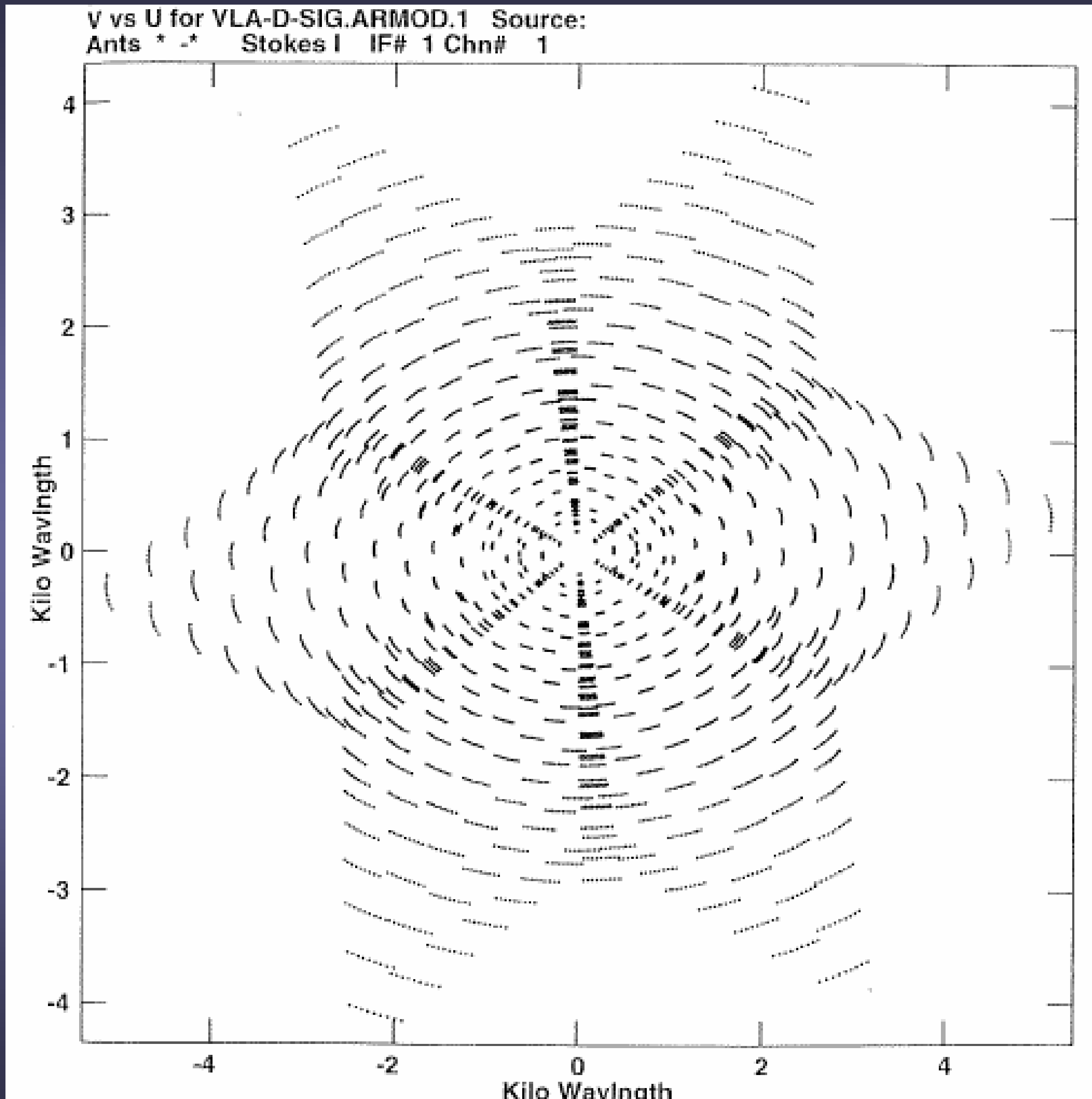
If we now denote the (inverse) Fourier transform operation as **F** we can write the following shorthand sequence

$$I^D = \mathbf{F}(V^S) = \mathbf{F}(SV') = \mathbf{F}(S) * \mathbf{F}(V') = B * I'$$

Where the inverse Fourier transform of the sampling function is the dirty beam, B, the inverse Fourier transform of V' is I', the desired measurement, and * denotes a convolution.

The point is: the dirty map I^D, obtained by Fourier inverse of the measured (noisy) visibilities is a convolution between the "true" brightness distribution I' and the dirty beam $\boldsymbol{B}$!

Therefore, to recover I' from the measurements, we must deconvolve B from I^D! So how do we do this?


V vs U for VLA-D-SIG.ARMOD.1 Source:
Ants * -* Stokes I IF# 1 Chn# 1
Kilo Wavlngth
Kilo Wavlngth
4
3
2
1
0
-1
-2
-3
-4
-4
-2
0
2
4

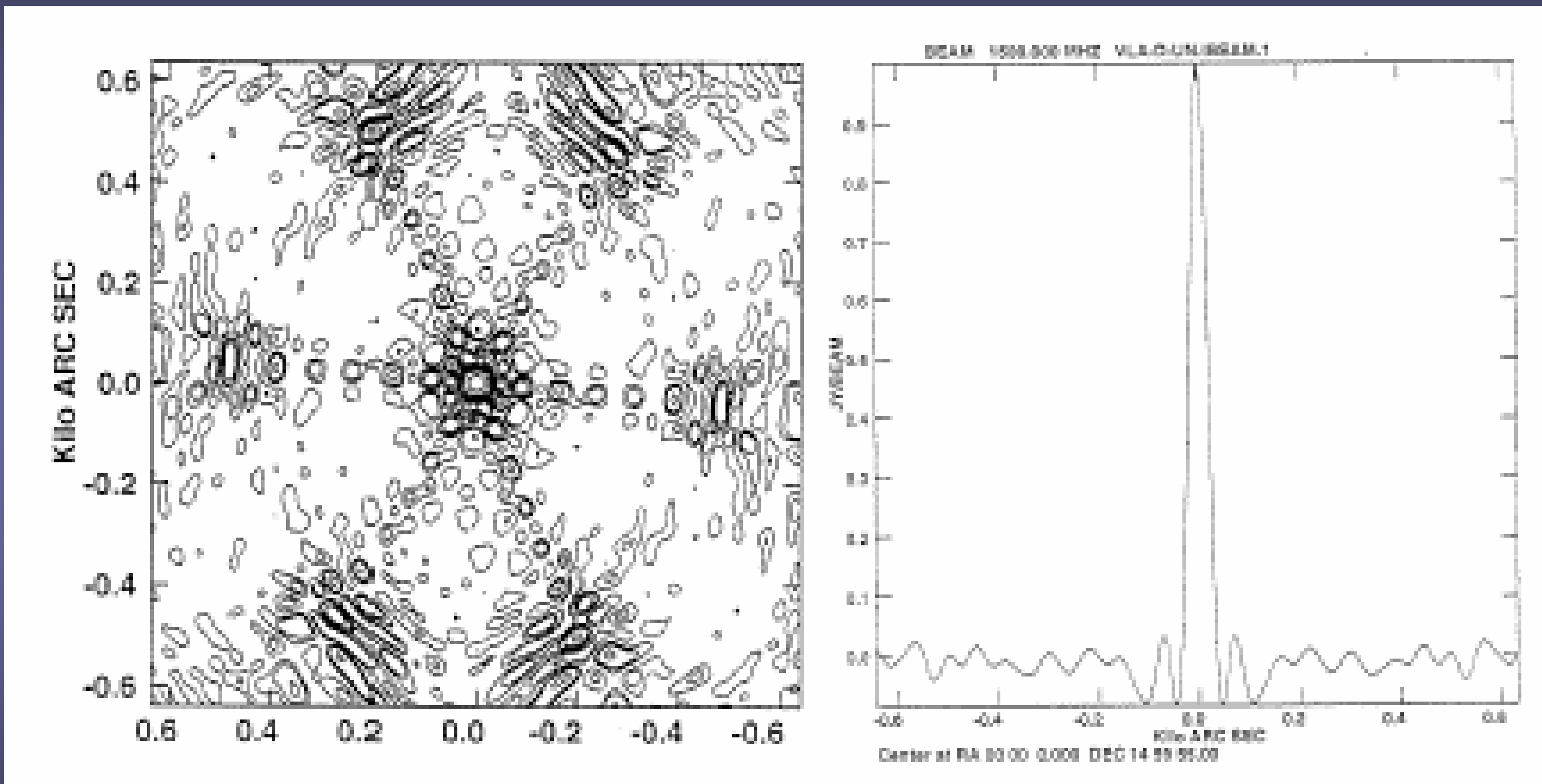

Kilo ARC SEC
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6

Image formation & deconvolution

To make an image, we must represent the represent the dirty map and beam in discrete (pixel) form; i.e., we must evaluate $I^D(l.m)$ on a uniform grid. One way is to compute the Discrete Fourier Transform" on an N x N grid:

$$I^D(l,m) = \frac{1}{M}\sum_{k=1}^{M} V'(u_k, v_k)\, e^{2\pi i (ul+vm)}$$

Far more commonly, because M is large and because the number of desired pixels is large, the Fast Fourier Transform is used. However, the data must be sampled on a uniform grid to use the FFT.

This is done by convolving the data with a smoothing function and resampling onto a uniform grid.

Image formation & deconvolution

One final point: it is usually very useful to be able to weight the visibility function, which is somewhat analogous to tapering the illumination of an antenna. We can write a weighting function

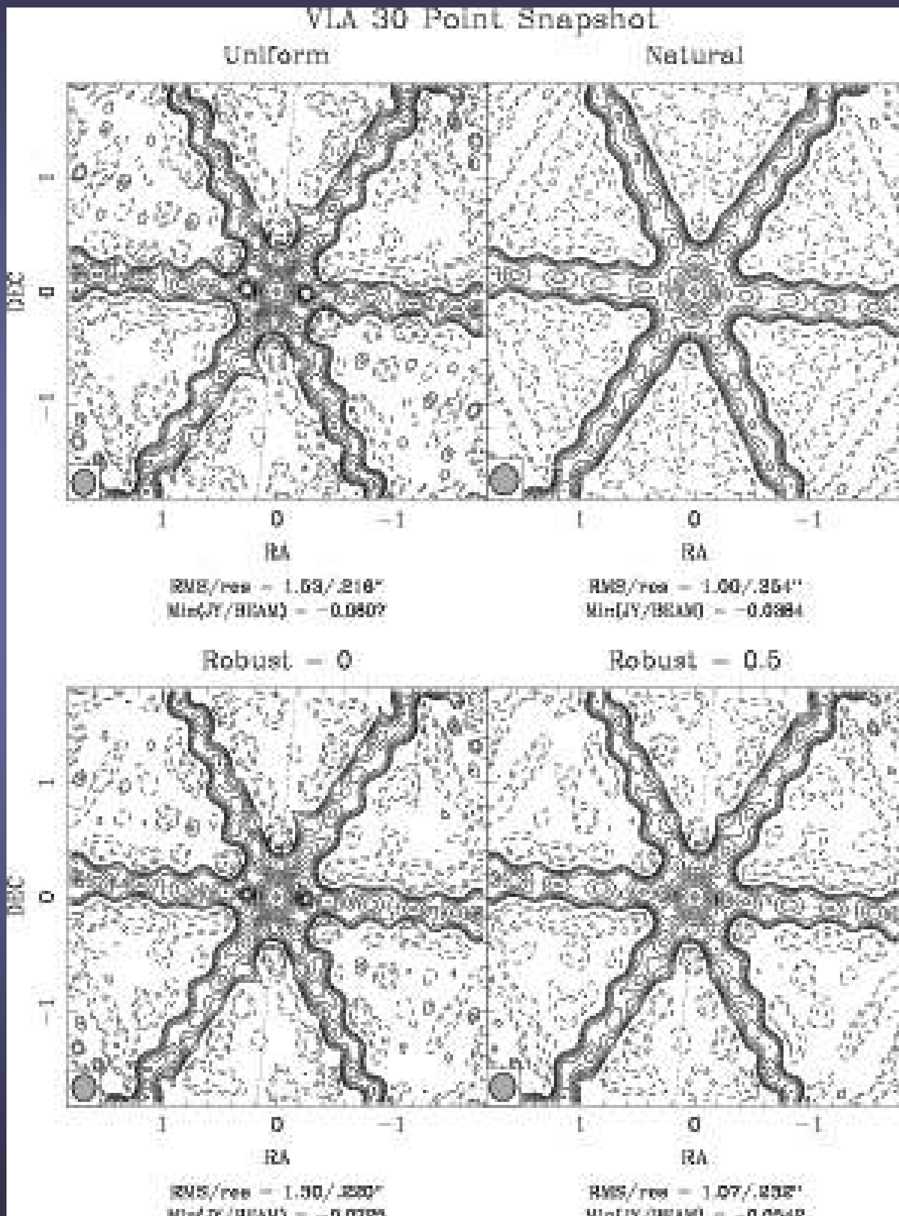
$$W(u,v) = \sum_{k=1}^{M} T_k D_k \delta(u-u_k, v-v_k)$$

where T_k is a taper and D_k is a density weighting. The weighted, sampled visibility function is then

$$V^W(u,v) = \sum_{k=1}^{M} T_k D_k \delta(u-u_k, v-v_k) V'(u,v)$$

which allows control over sidelobe weighting and noise. Natural and uniform weighting are commonly used, as is a more optimum weighting scheme called "robust" weighting.

Examples of weighting



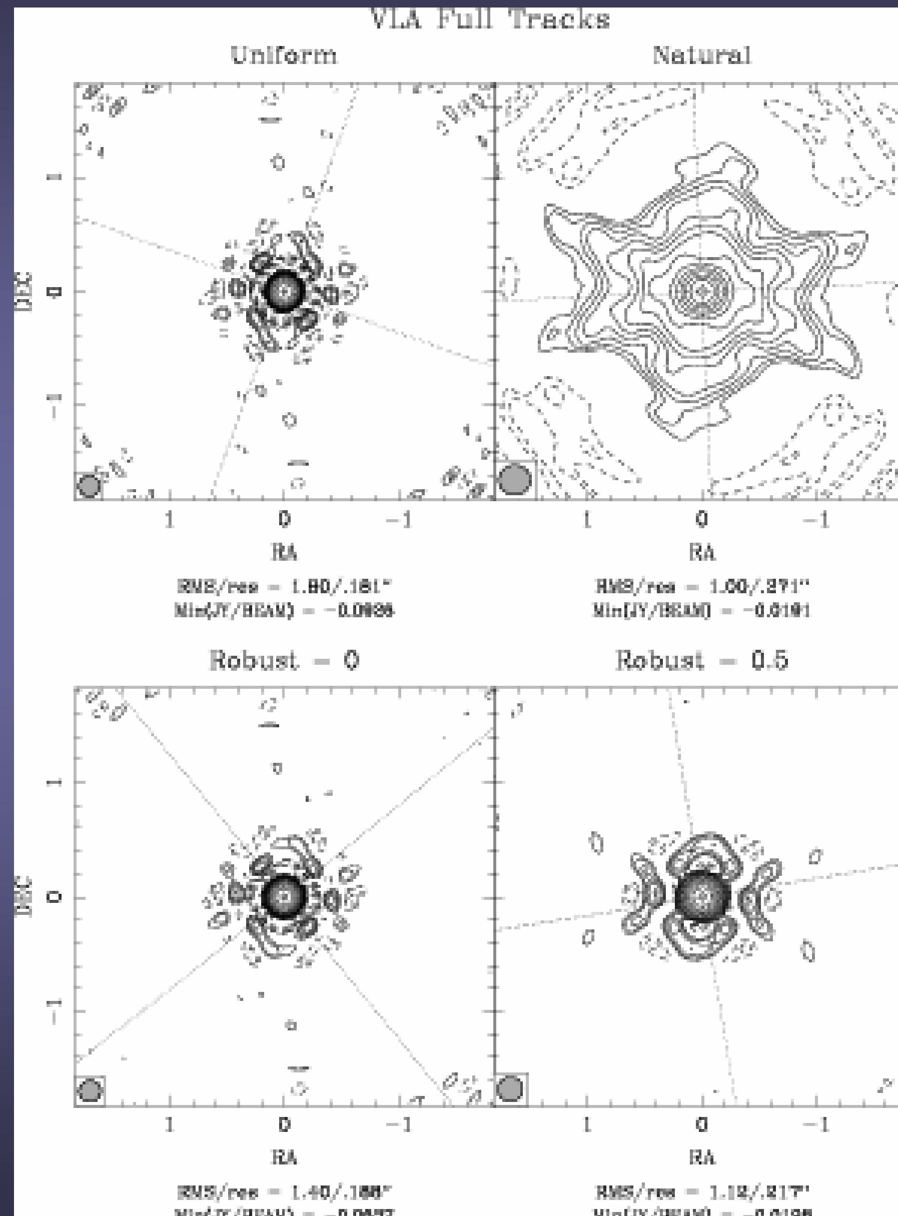


Image formation & deconvolution

The deconvolution problem can be expressed simply as

$$I^D = B * I + n$$

where n has been separated out as additive noise. The measurement equation is ill-posed. Implicit in the principle solution I^D is the assumption that all visibilities that were not measured are zero.

Let z be a brightness distribution that contains only those spatial frequencies that were unmeasured. Then is I is a solution to the measurement equation, so is $I+\alpha z$ (since $B*z=0$)!

Deconvolution is that process by which the unmeasured visibilities are estimated.

Image formation & deconvolution

Two classes of algorithm are commonly employed in radio astronomy:

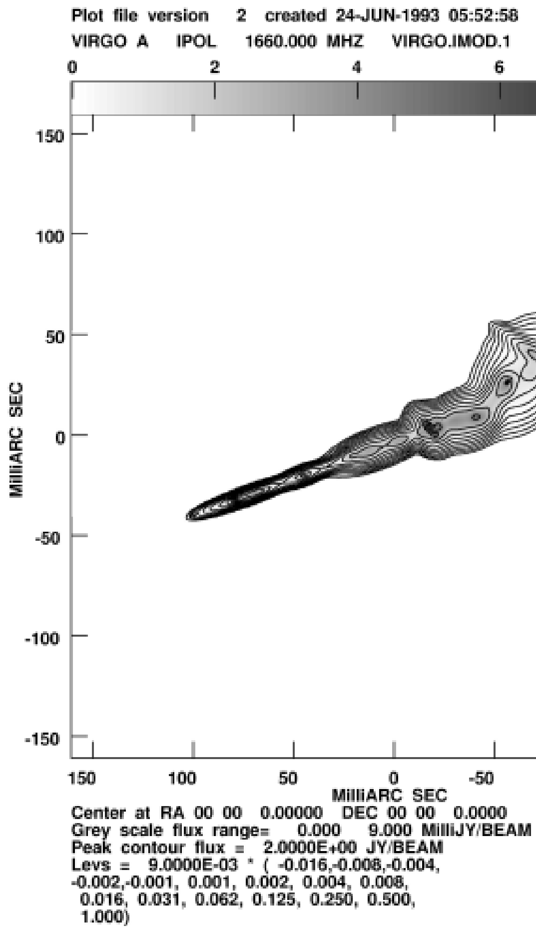
CLEAN and MEM

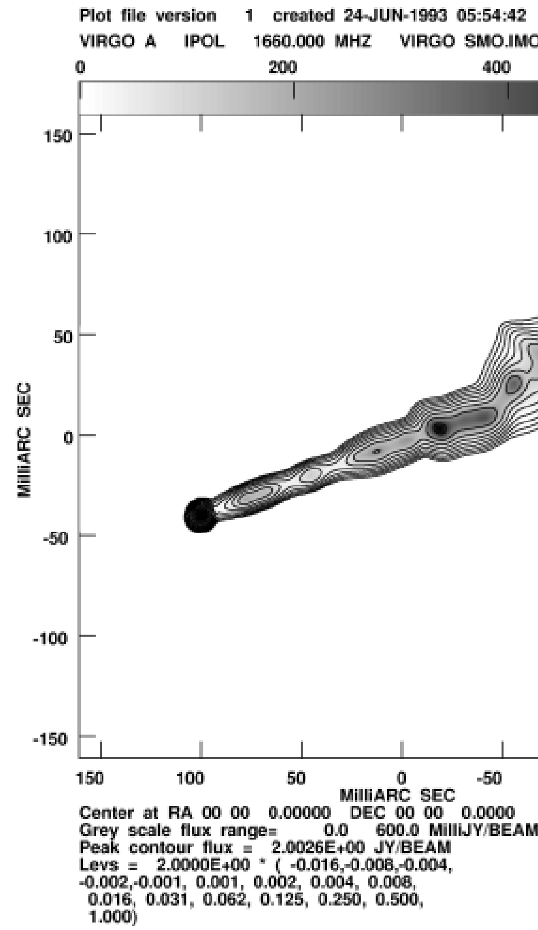
CLEAN is a simple shift-and-subtract algorithm with many variants designed to speed up and/or stabilize its performance. Good for compact emission.

MEM and related algorithms maximize the configurational entropy of the model image, usually subject to known constraints such as the noise and total flux. Good for smooth, diffuse emission.

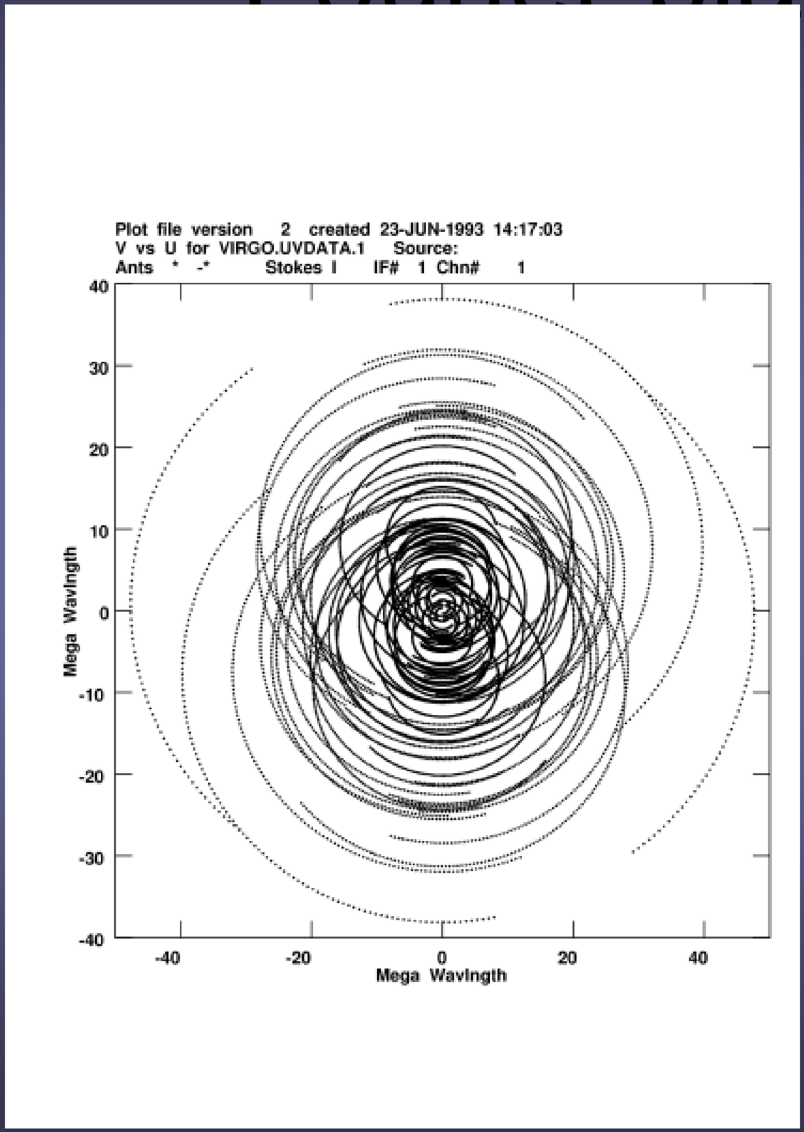
Other deconvolution schemes: SVD, algebraic, SDI, MRC, …

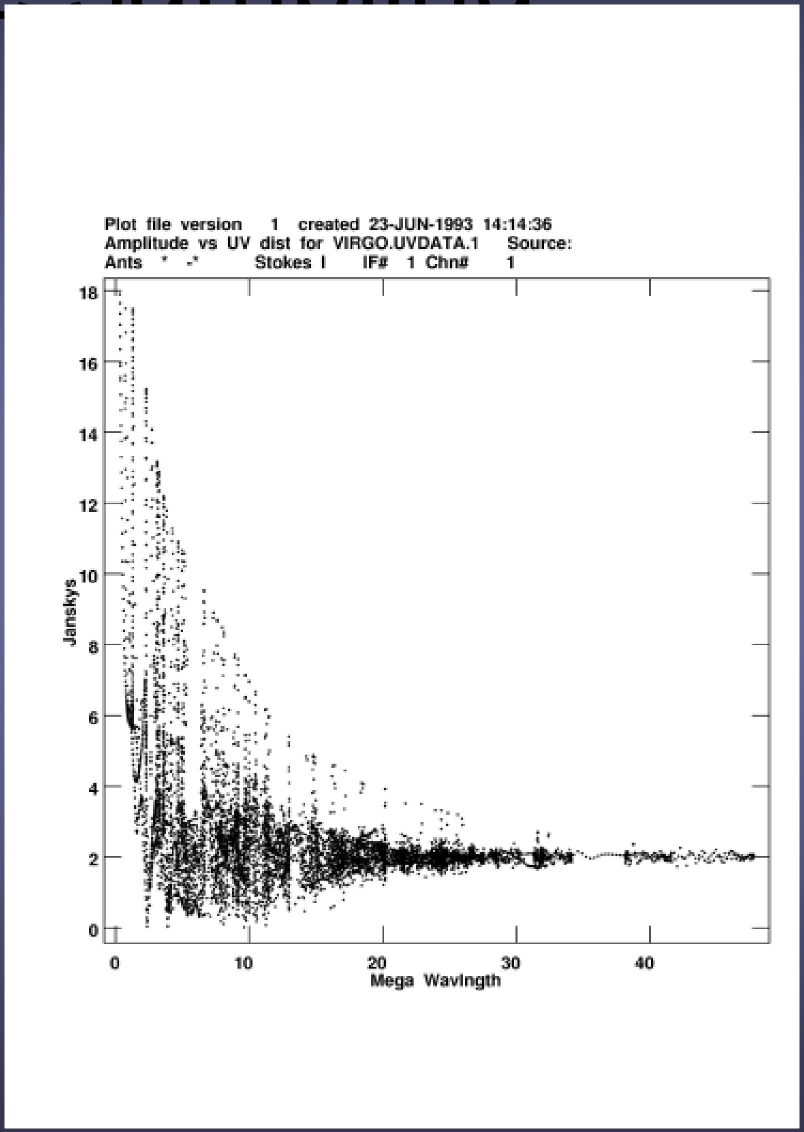
Original and smoothed model



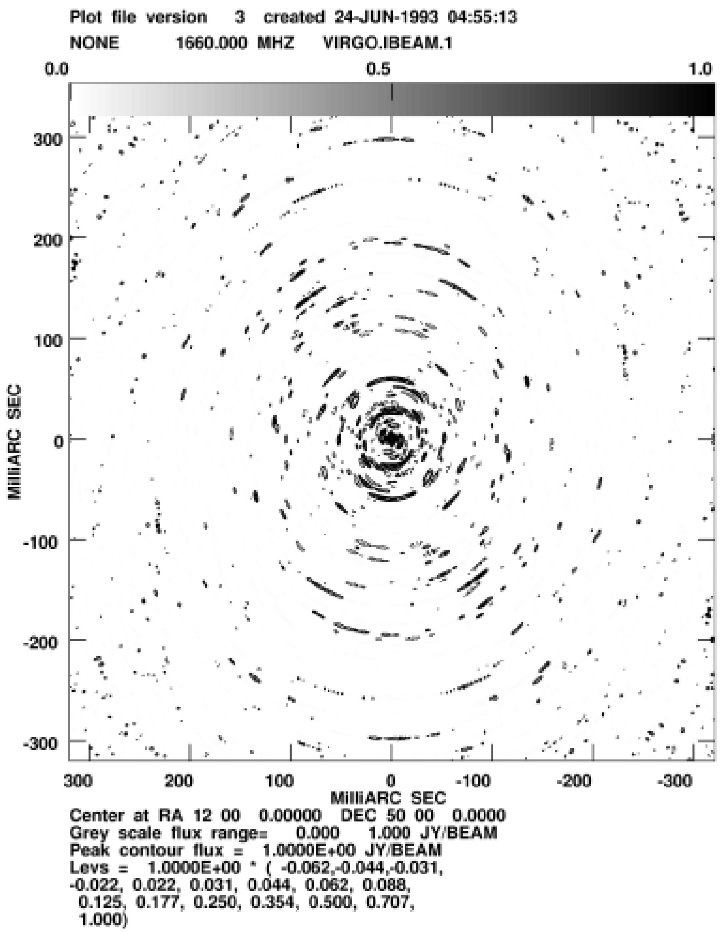


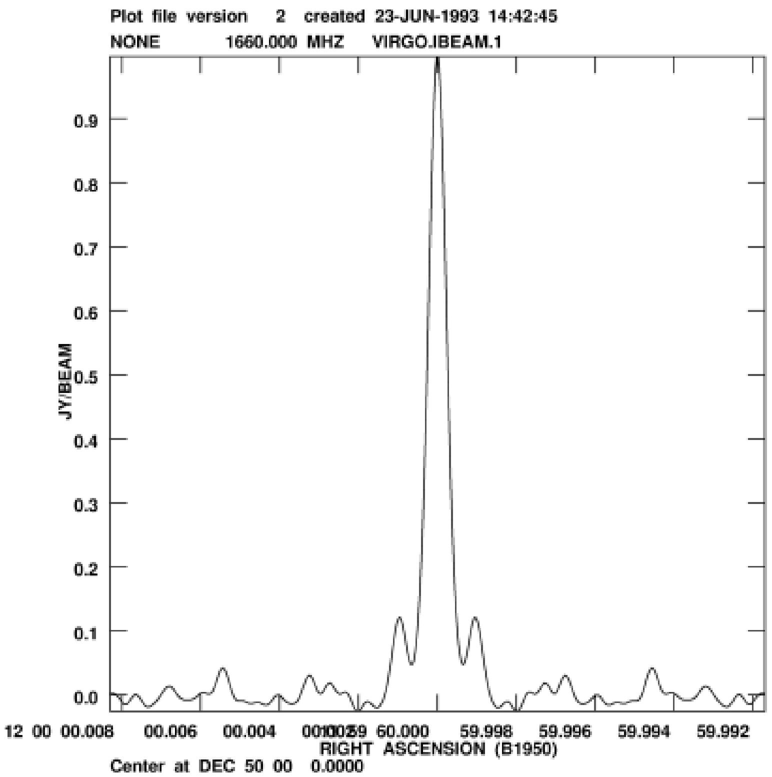
Fourier plane sampling



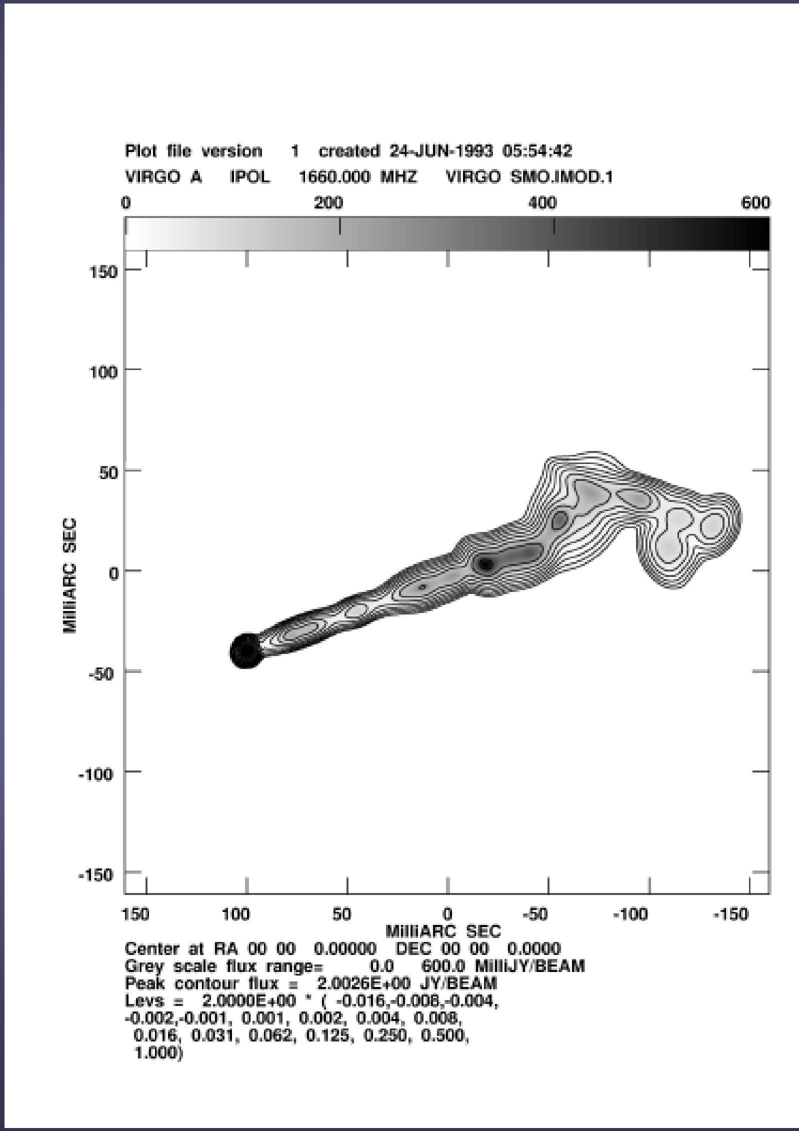


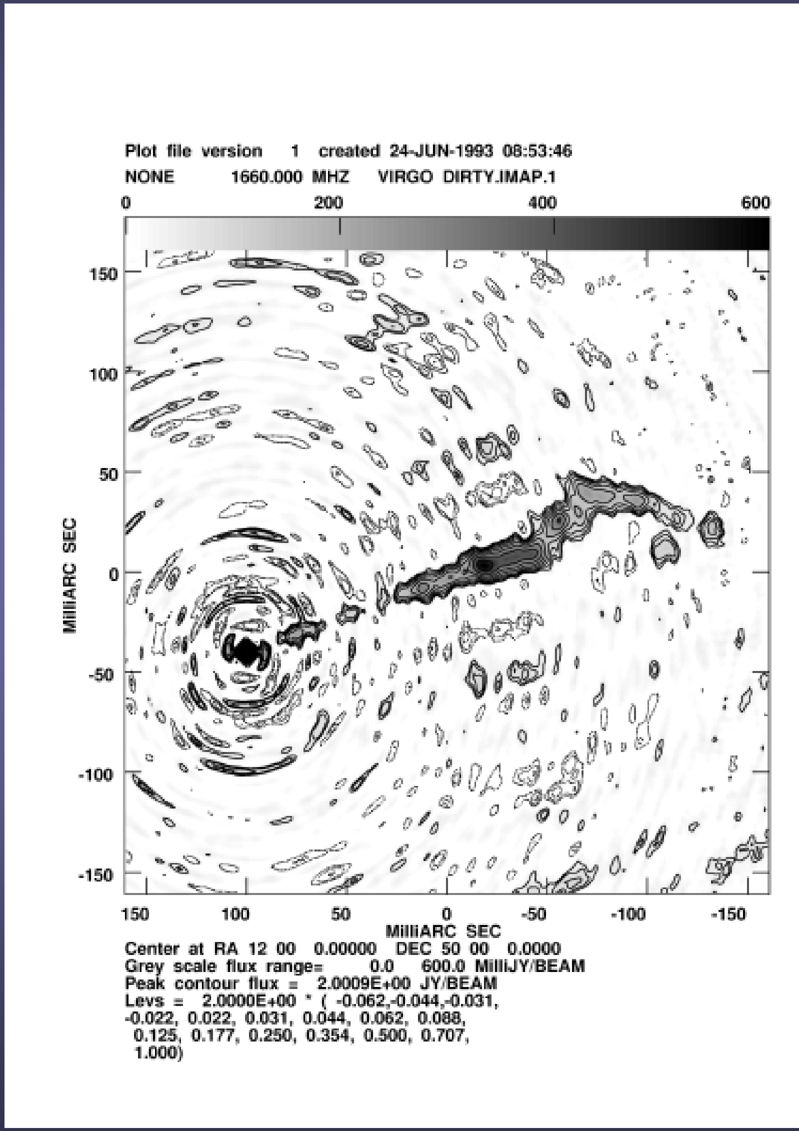
Point Spread Function



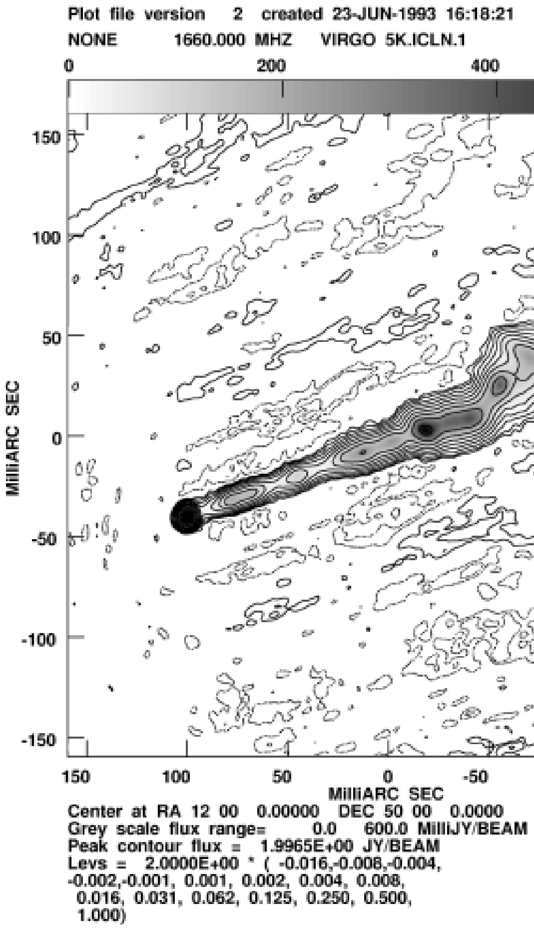


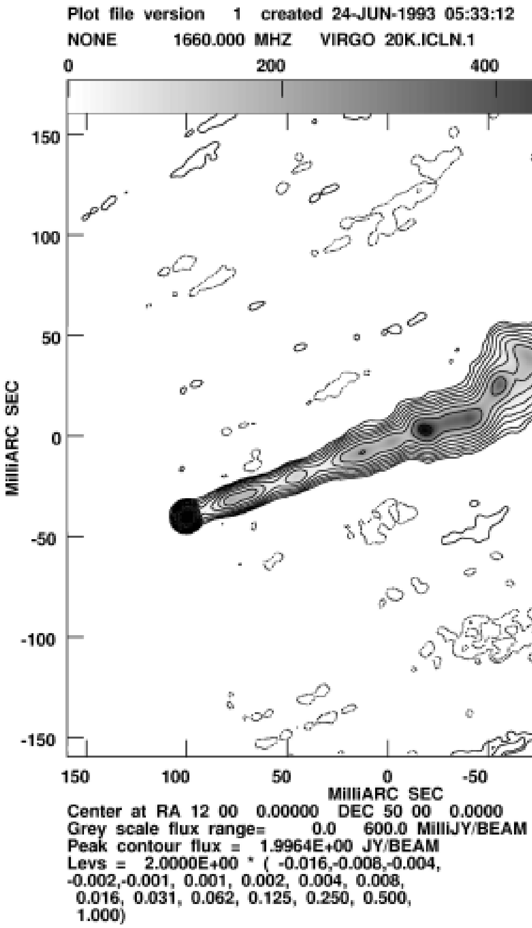
Original model and Dirty image



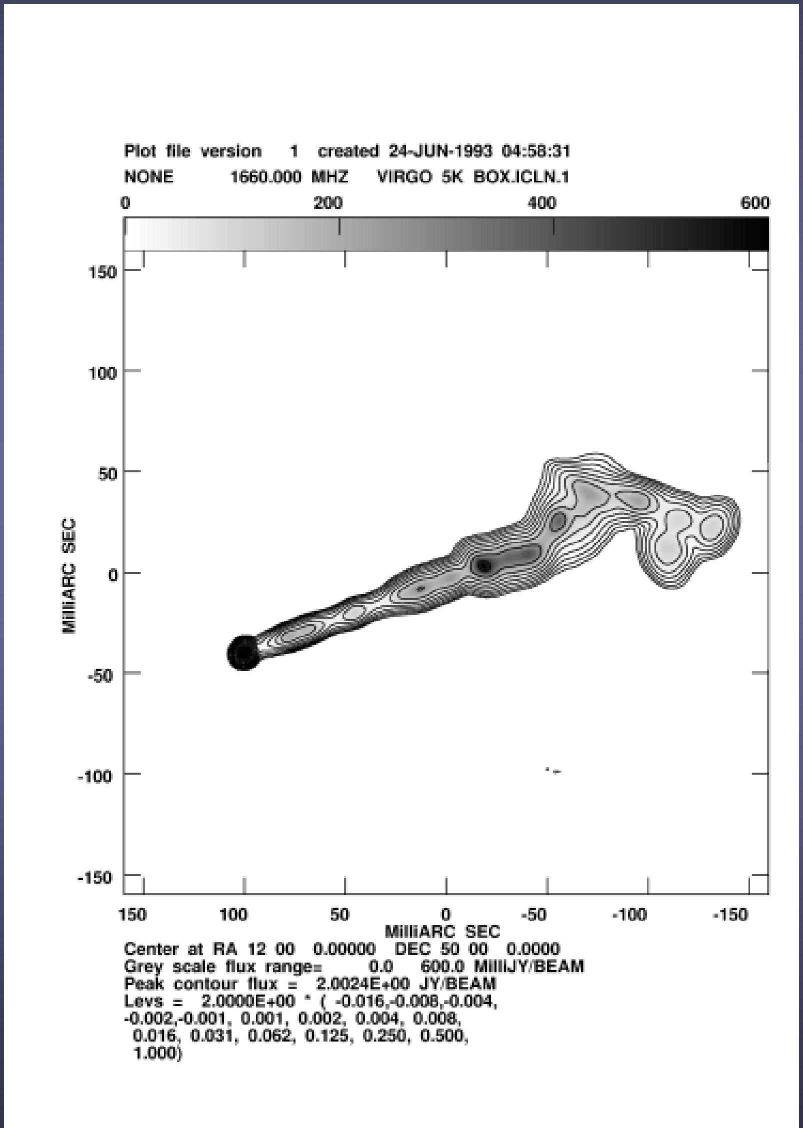


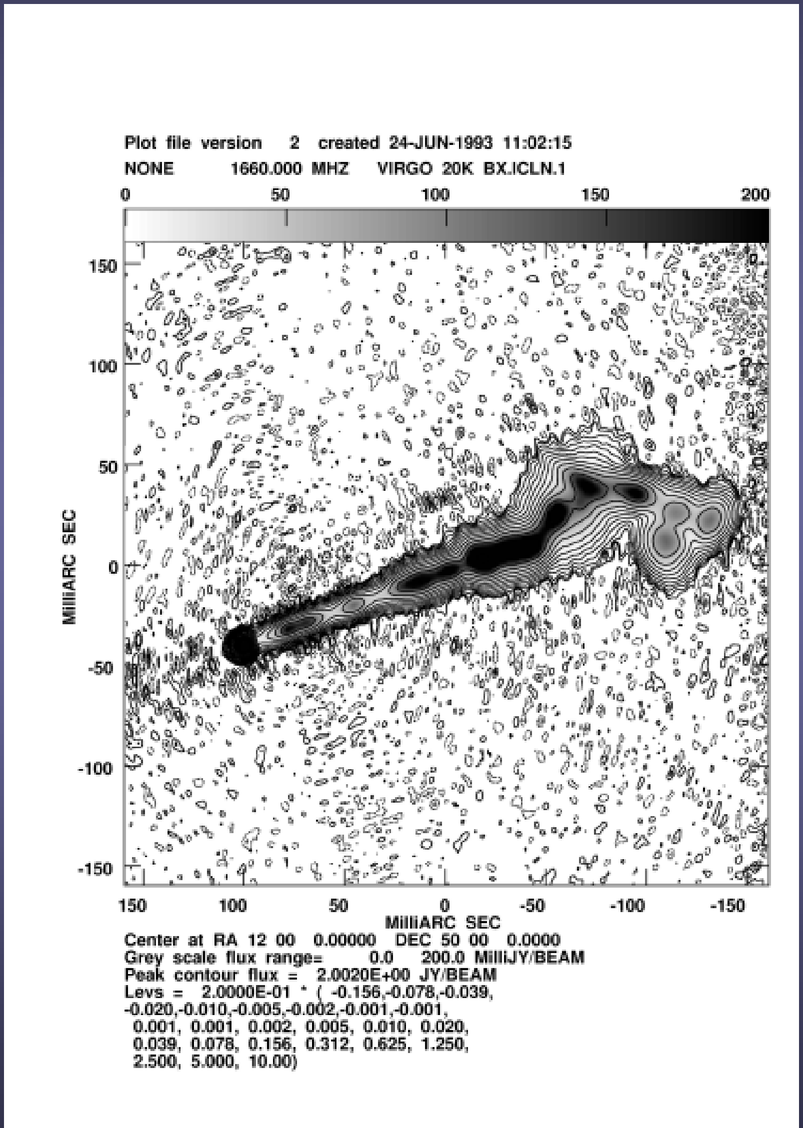
CLEAN: 5000 and 20000 comps



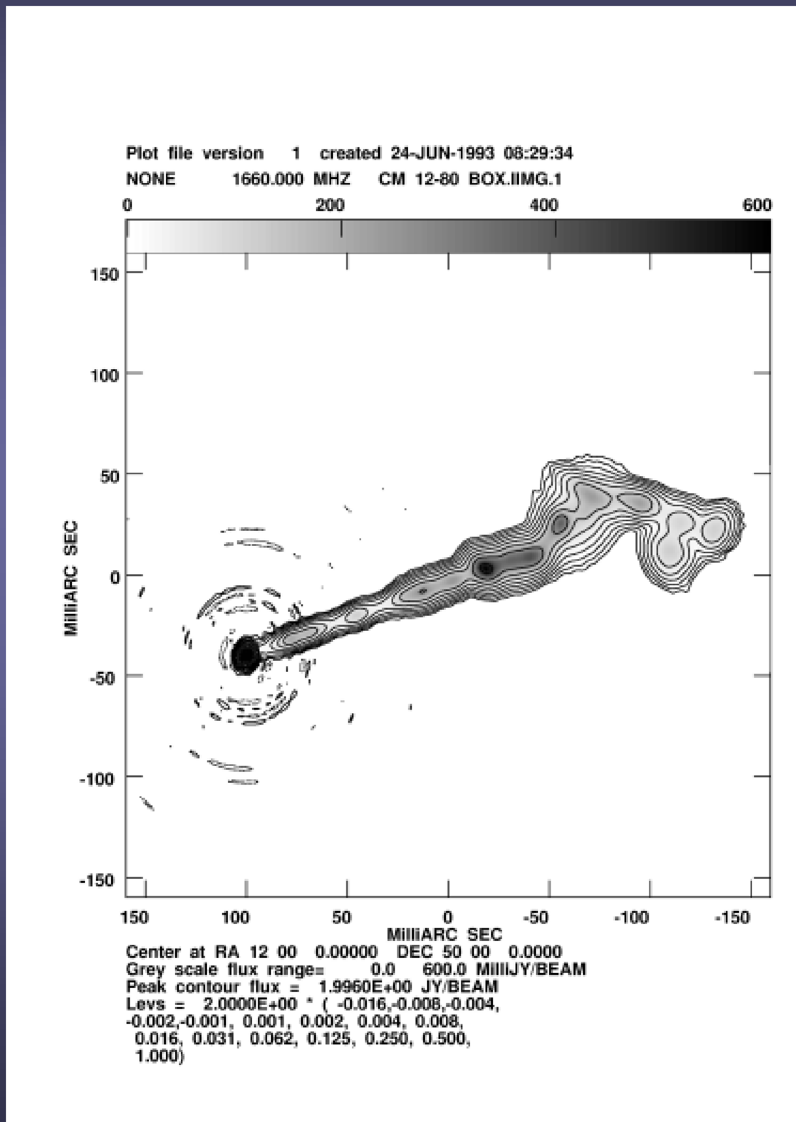


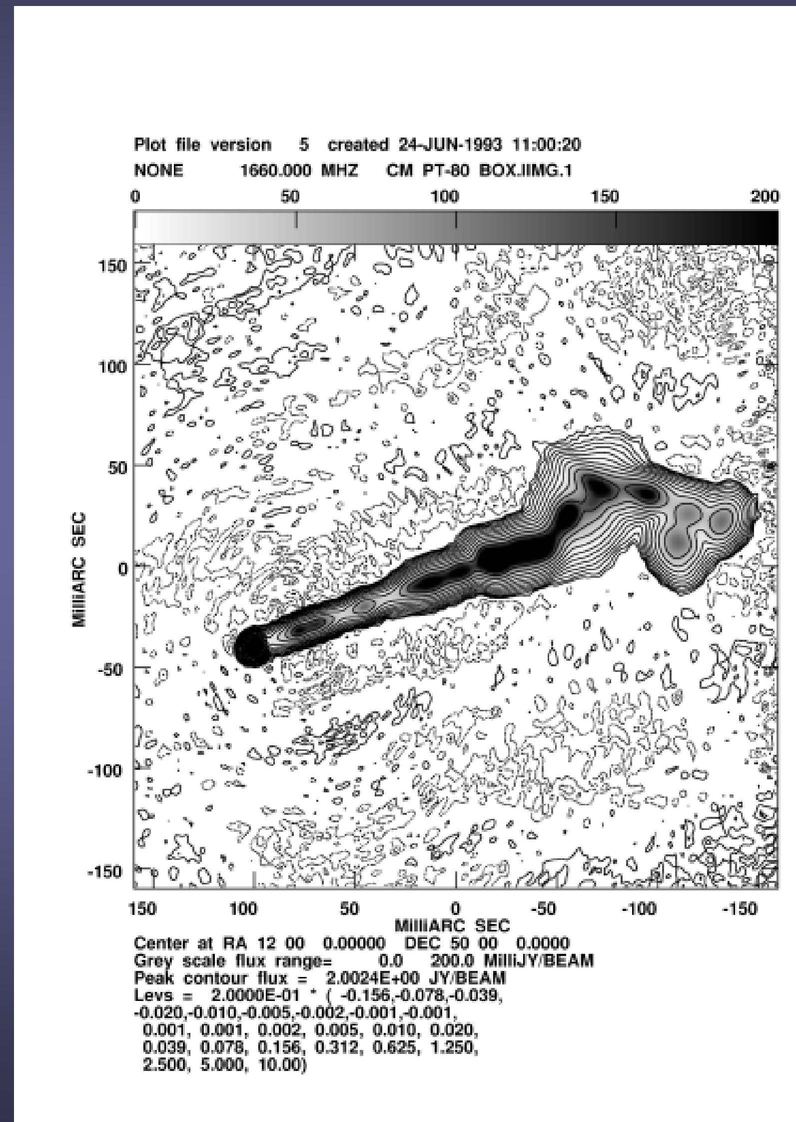
Window CLEAN: 5000 and 20000 comps



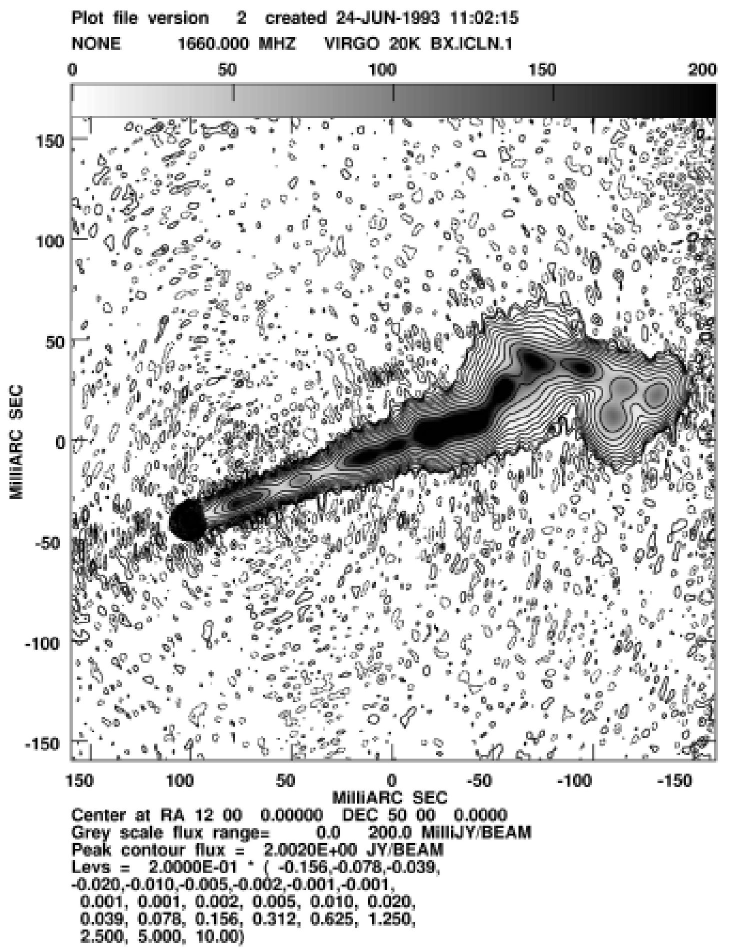


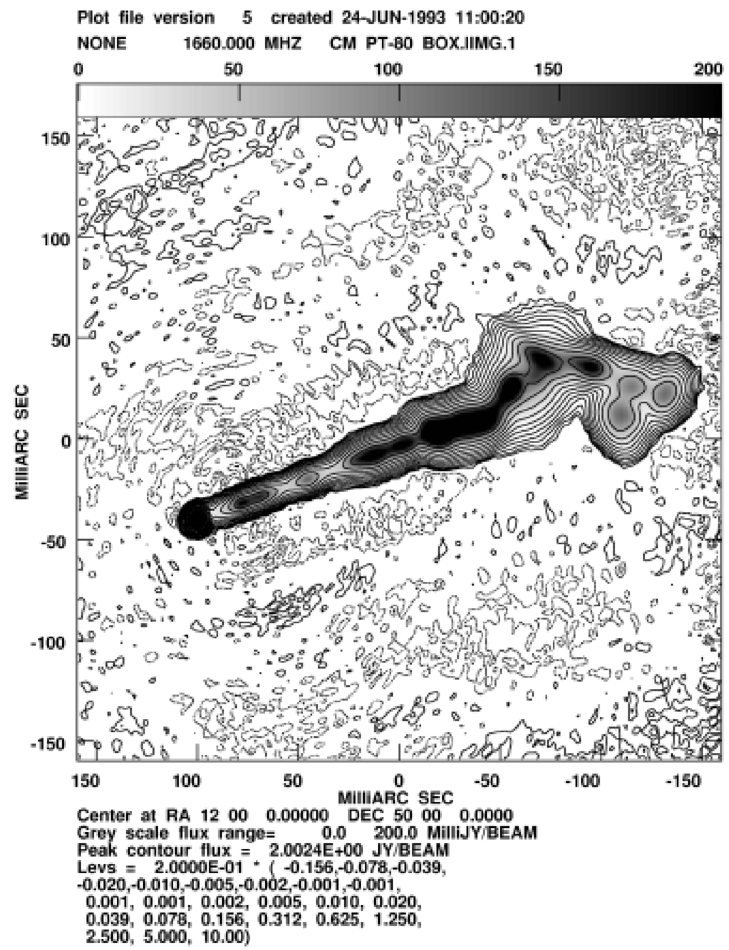
MEM: boxed, with point source removed



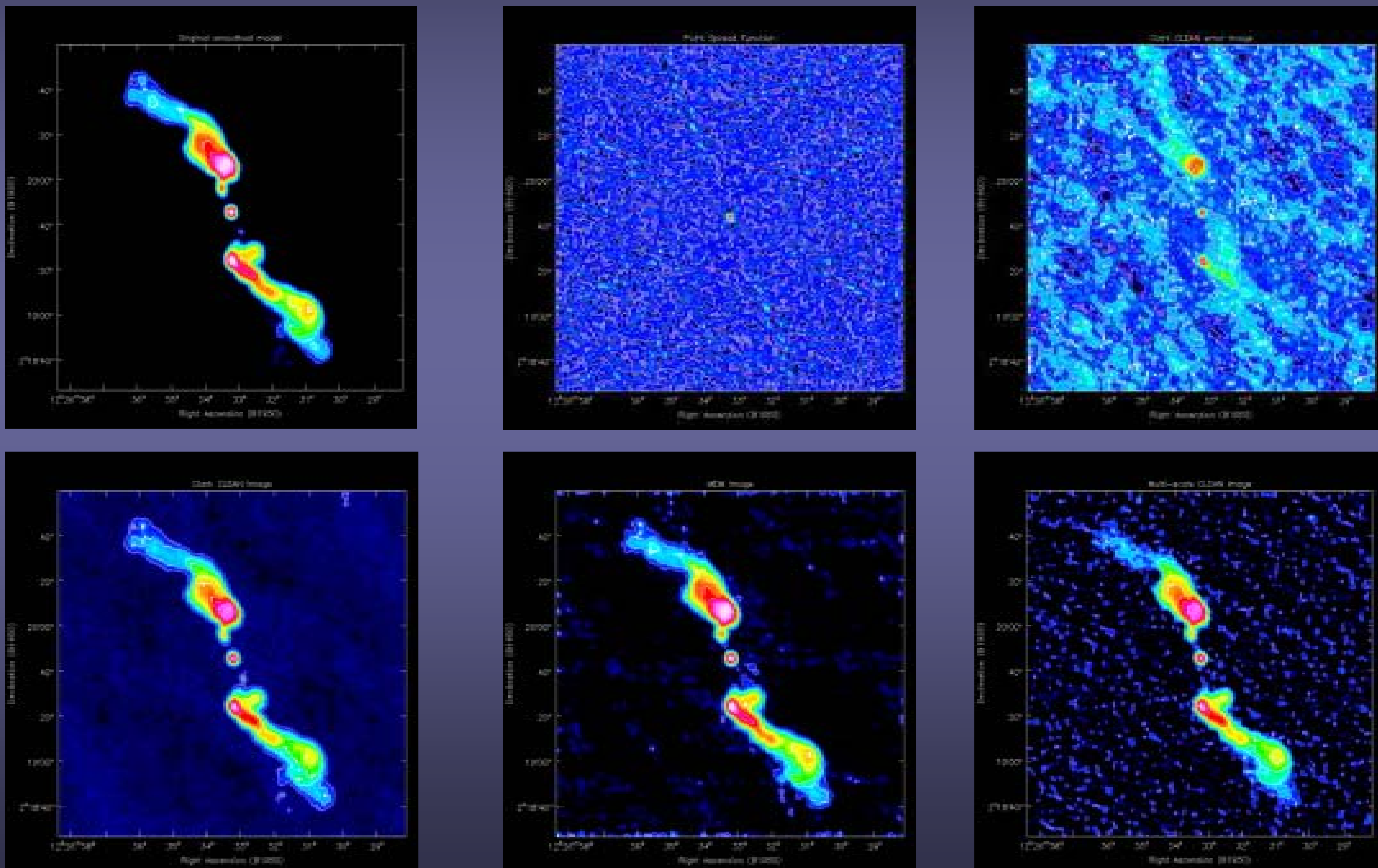


Best Clean and Best MEM





Model, PSF, Dirty image, CLEAN, MEM, Multi-scale CLEAN



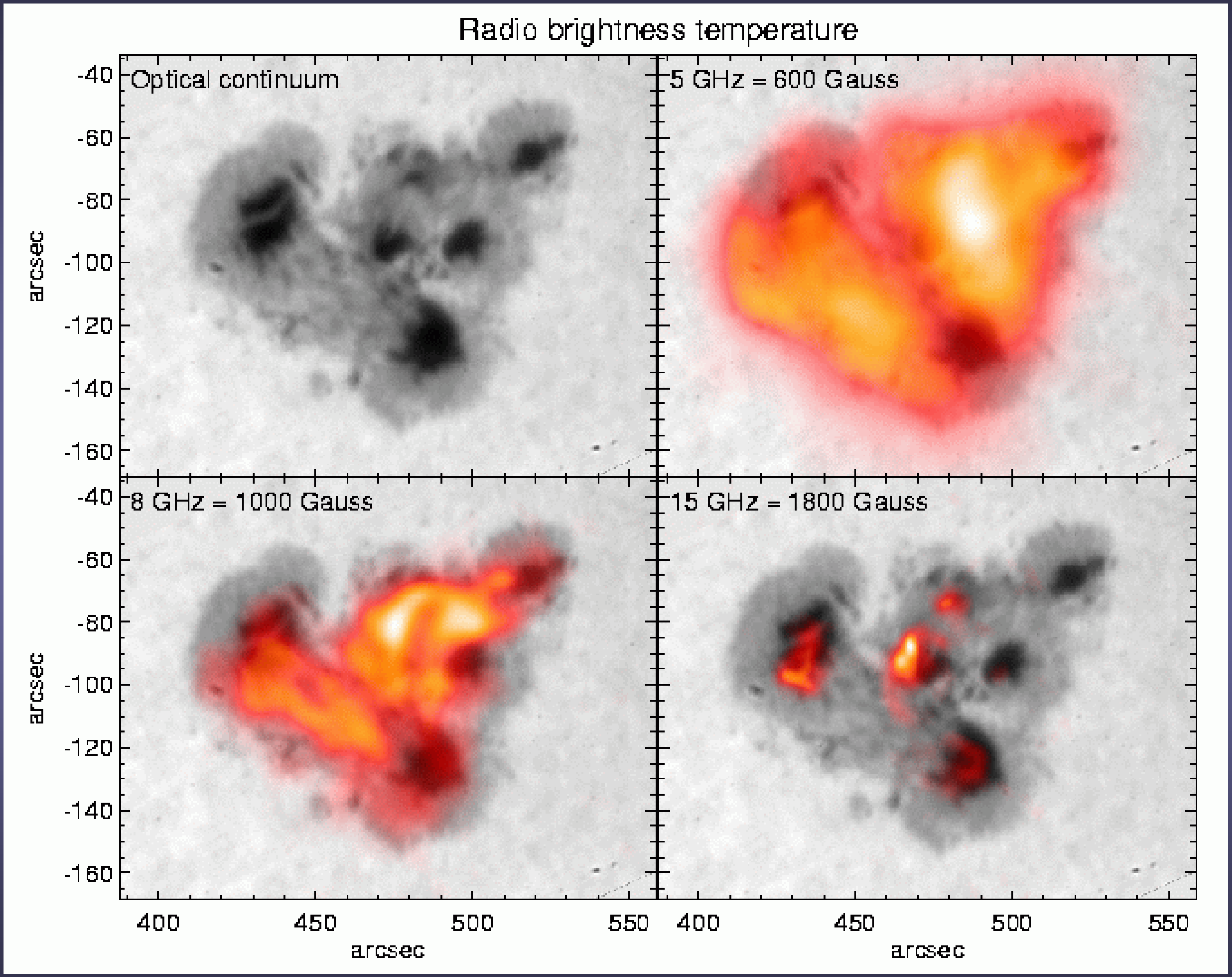
Data types

- Light curves of integrated flux density
- Spectra and dynamic spectra
- Map of specific intensity (Stokes I/V)
- Time sequence of such maps (Stokes I/V)
- Time sequences of such maps at many frequencies
- Time sequences of maps of physical parameters derived from principle data (T, B, n_e, etc) Goal.

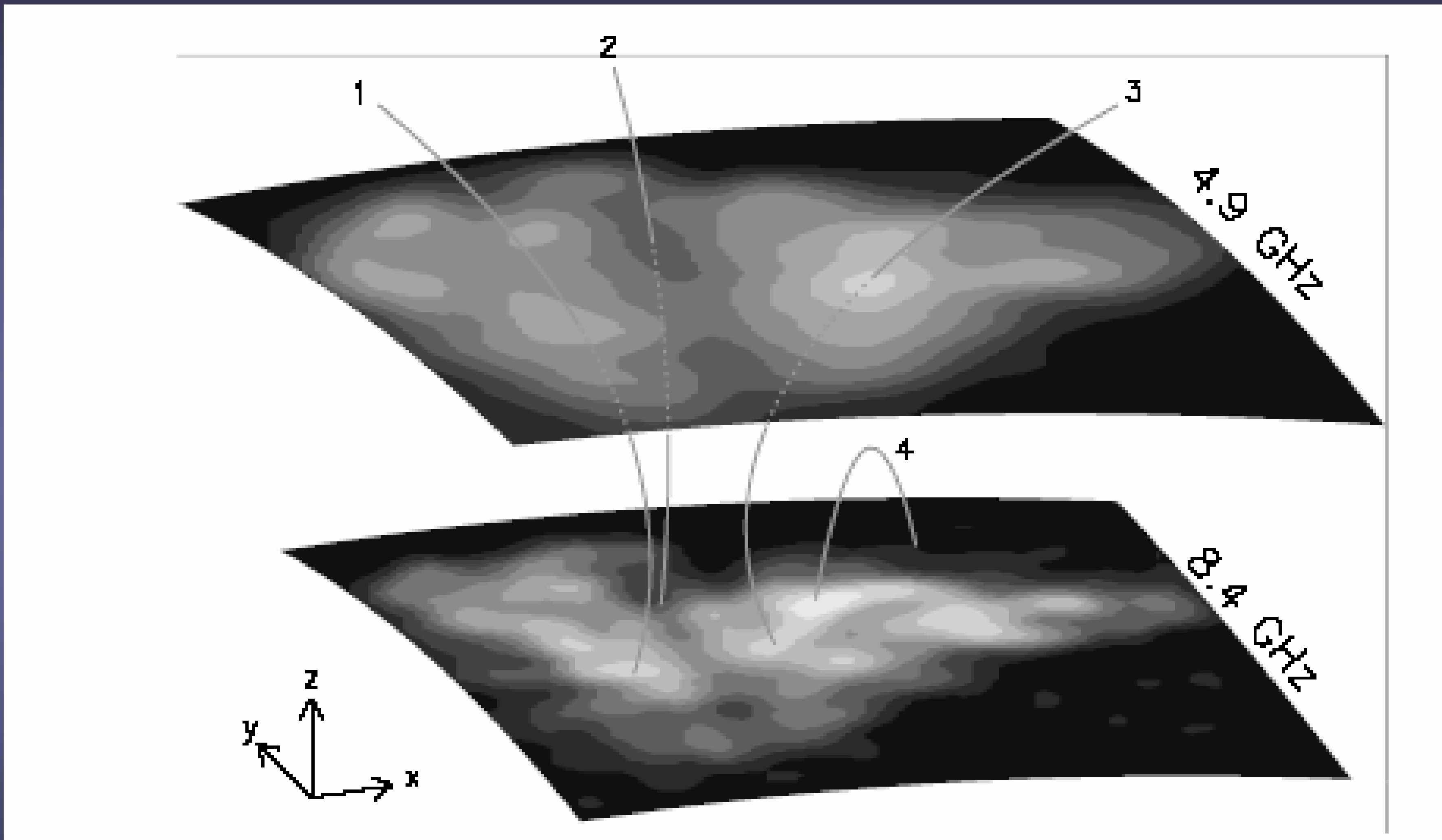
New data visualization techniques needed!

Data analysis

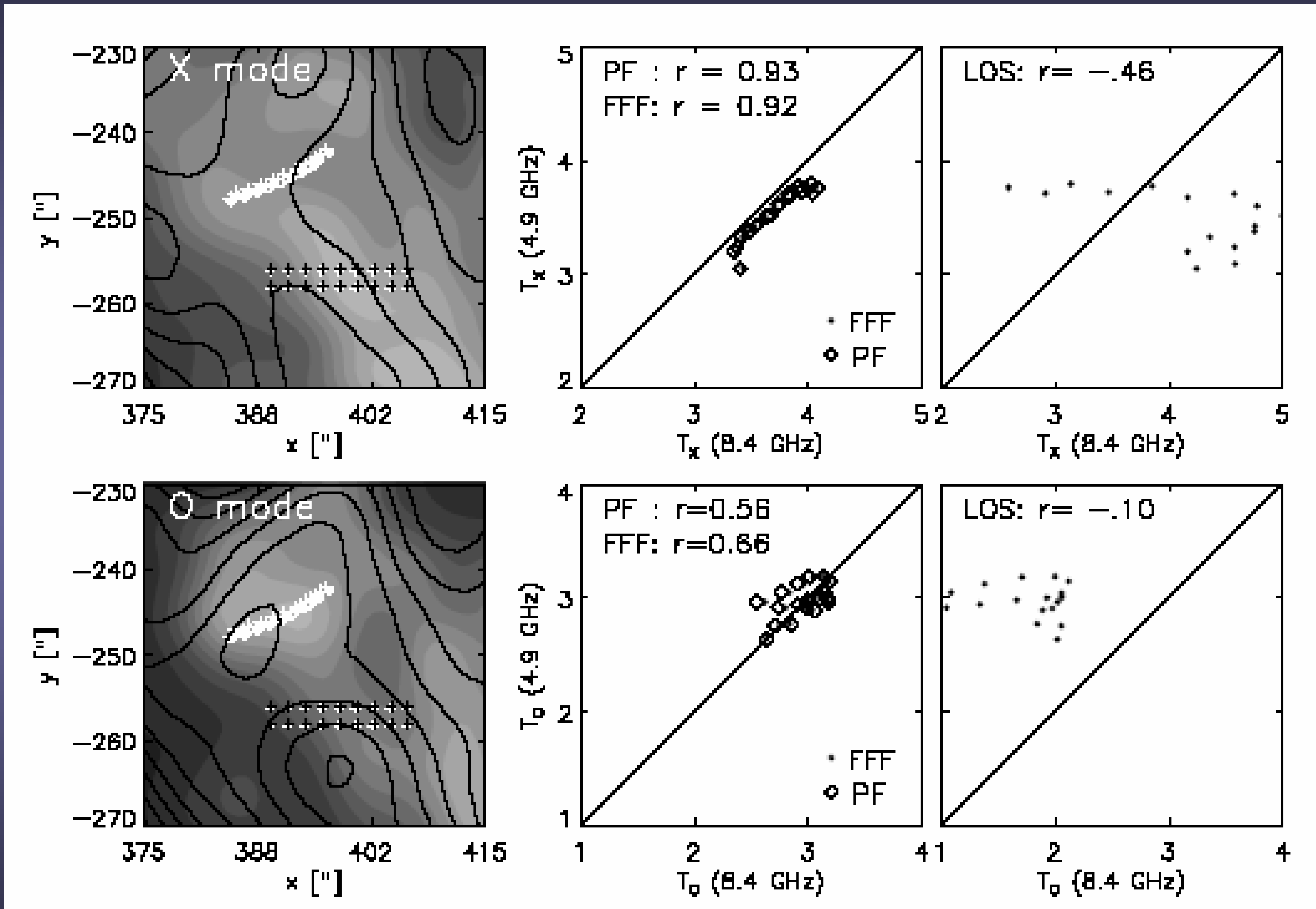
Once radio data are reduced, data analysis proceeds much as it would in any other wavelength regime, the differences being in the details of the RT and the microphysics implicit therein.



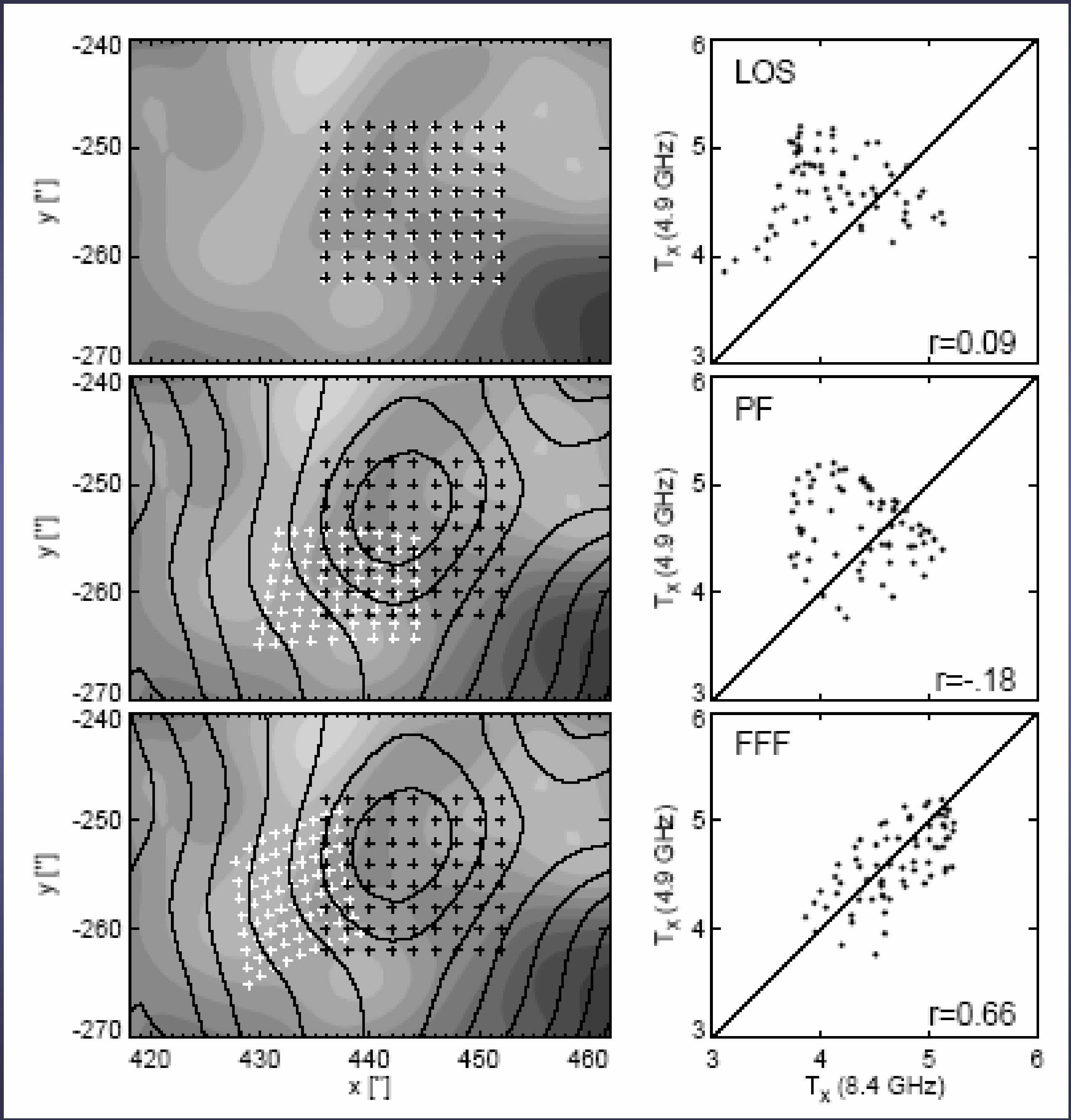
Lee et al (1998)



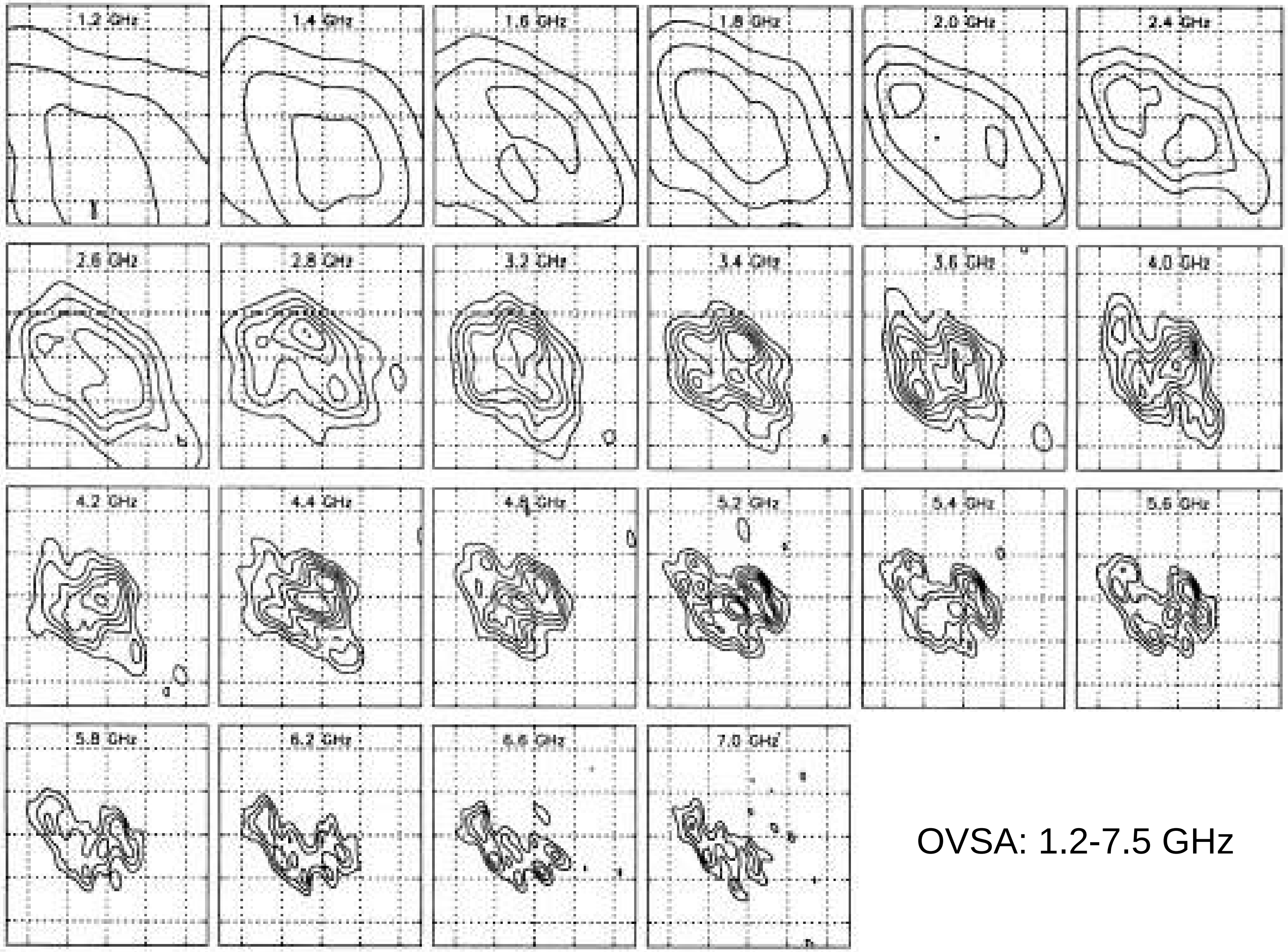
Lee et al. 1999



Lee et al. 1999

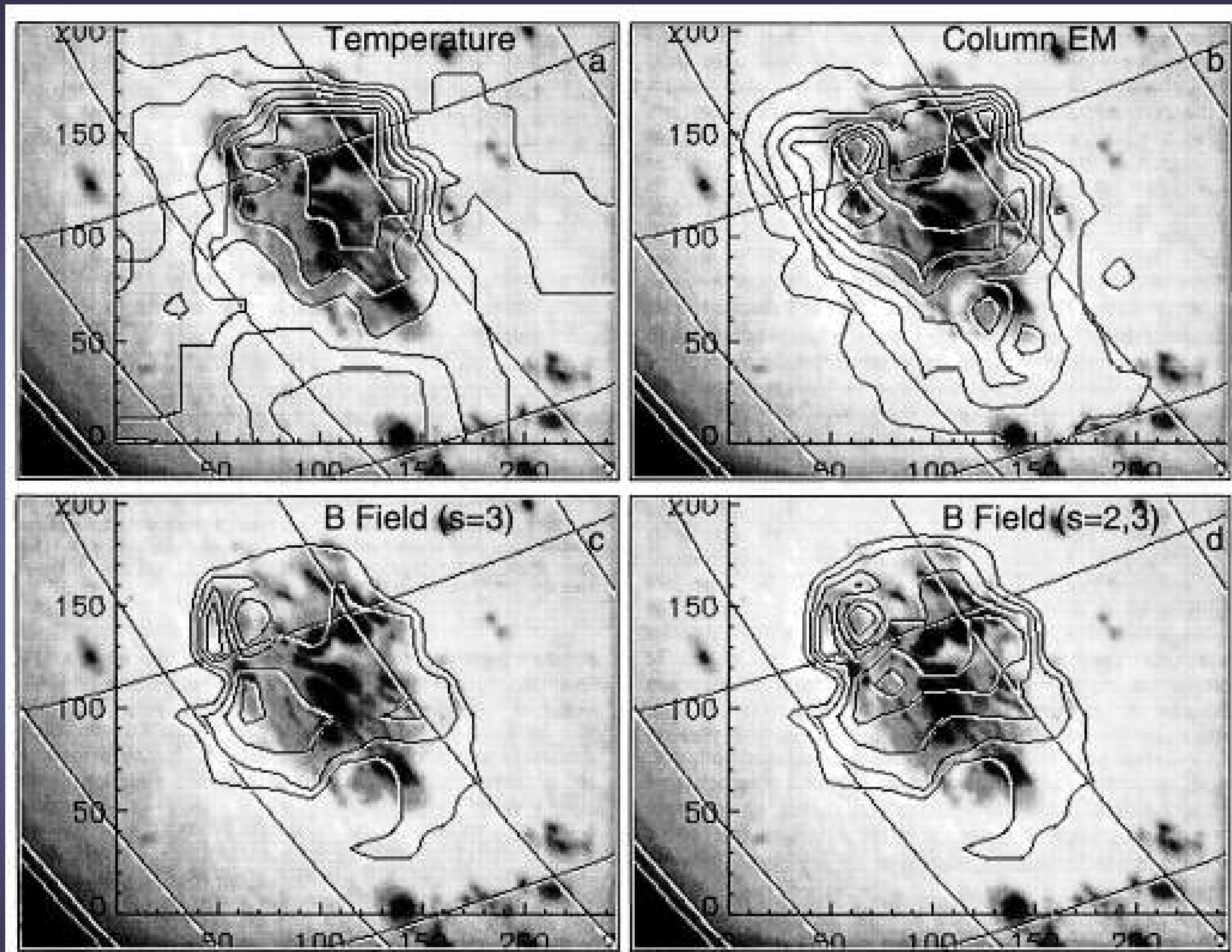


Lee et al. 1999



OVSA: 1.2-7.5 GHz

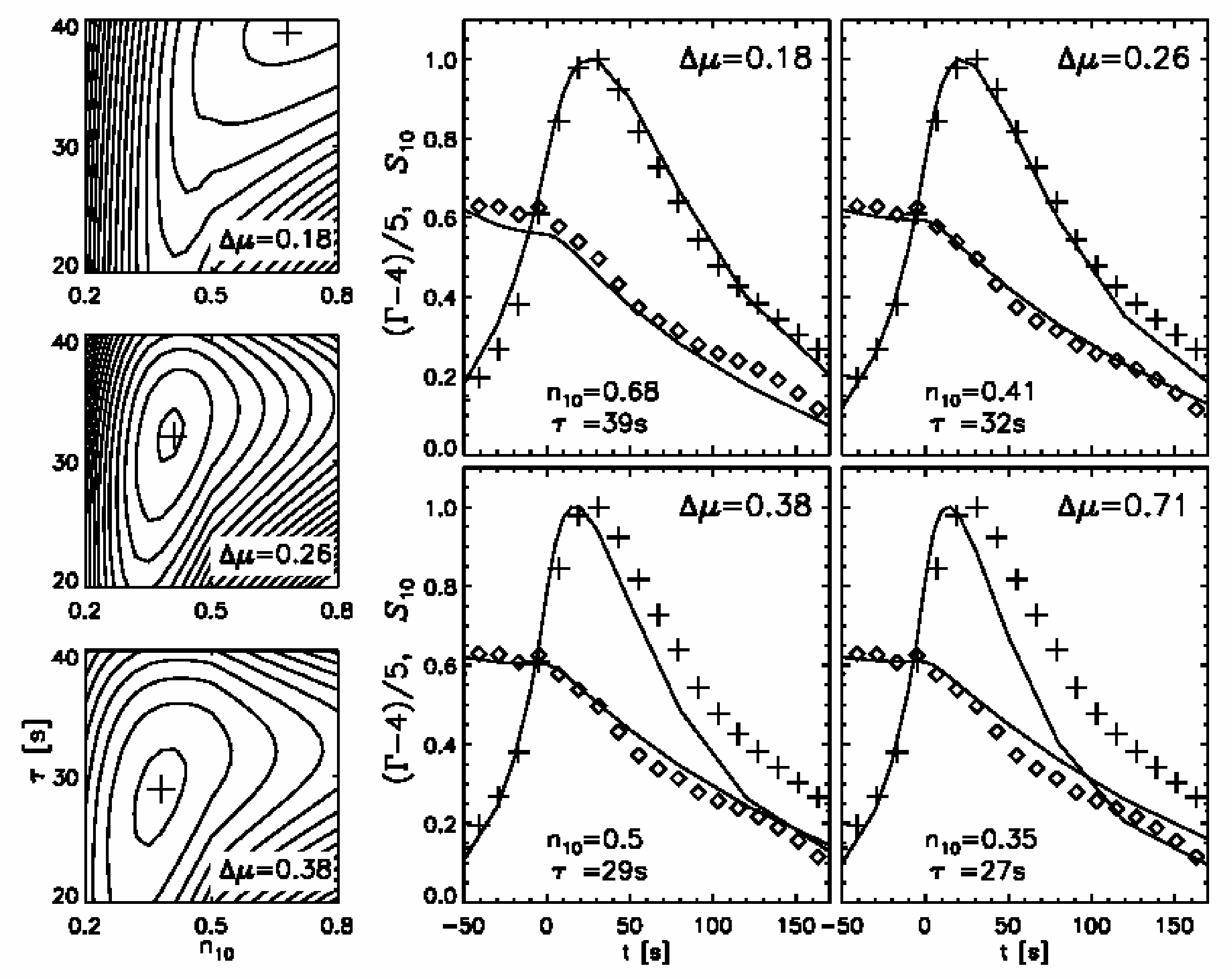
Gary & Hurford 1994



Gary & Hurford 1994

1993 June 3

OVSA



μ_o=0

$$P_\gamma(\mu)\,|_{s=0} = \frac{1}{\sqrt{\pi}\Delta\mu}\exp\left[-4\,\frac{(\mu-\mu_0)^2}{\Delta\mu^2}\right].$$

Lee & Gary 2000

24 Oct 2001
A Cool, Dense Flare?

T. S. Bastian[1], G. Fleishman[1,2], D. E. Gary[3]

[1]National Radio Astronomy Observatory

[2]Ioffe Institute for Physics and Technology

[3]New Jersey Institute of Technology,
Owens Valley Solar Array

Radio Observations

OVSA: 1-14.8 GHz, 2 s cadence, total flux, Stokes I

NoRP: 1, 2, 3.75, 9.4, 17, 35, and 80 GHz, 0.1 s cadence, total flux, Stokes I/V

NoRH: 17 GHz, 1 s cadence, imaging (10”), Stokes I/V

34 GHz, 1 s cadence, imaging (5”), Stokes I

EUV/X-ray Observations

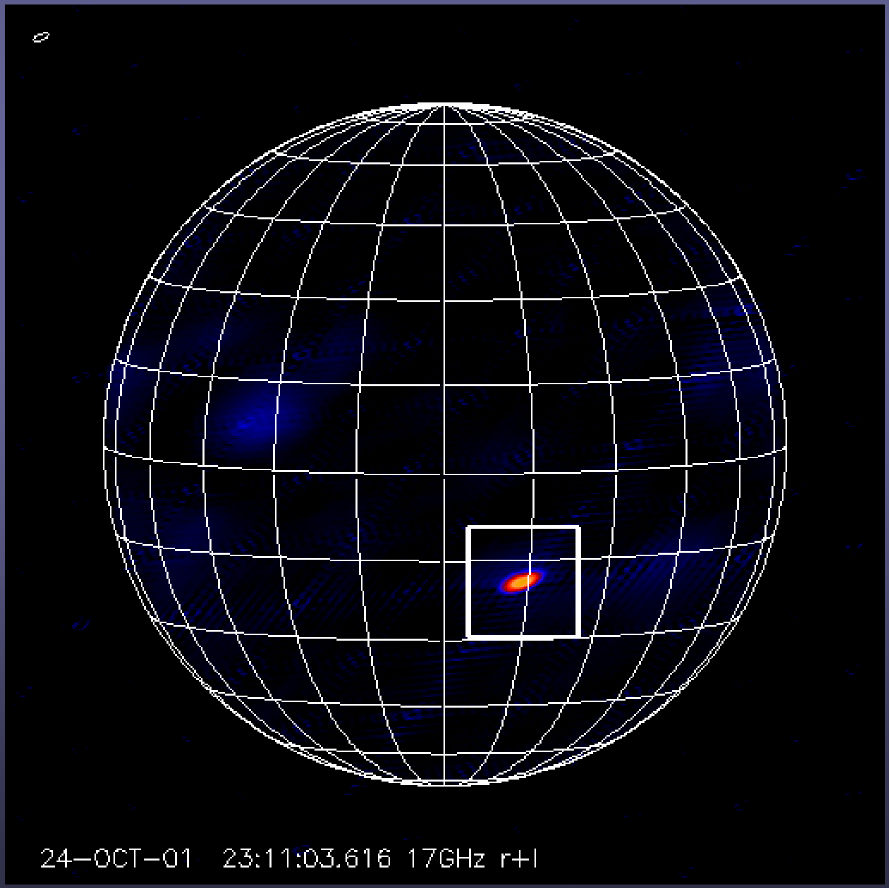
TRACE: 171 A imaging, 40 s cadence (0.5”)

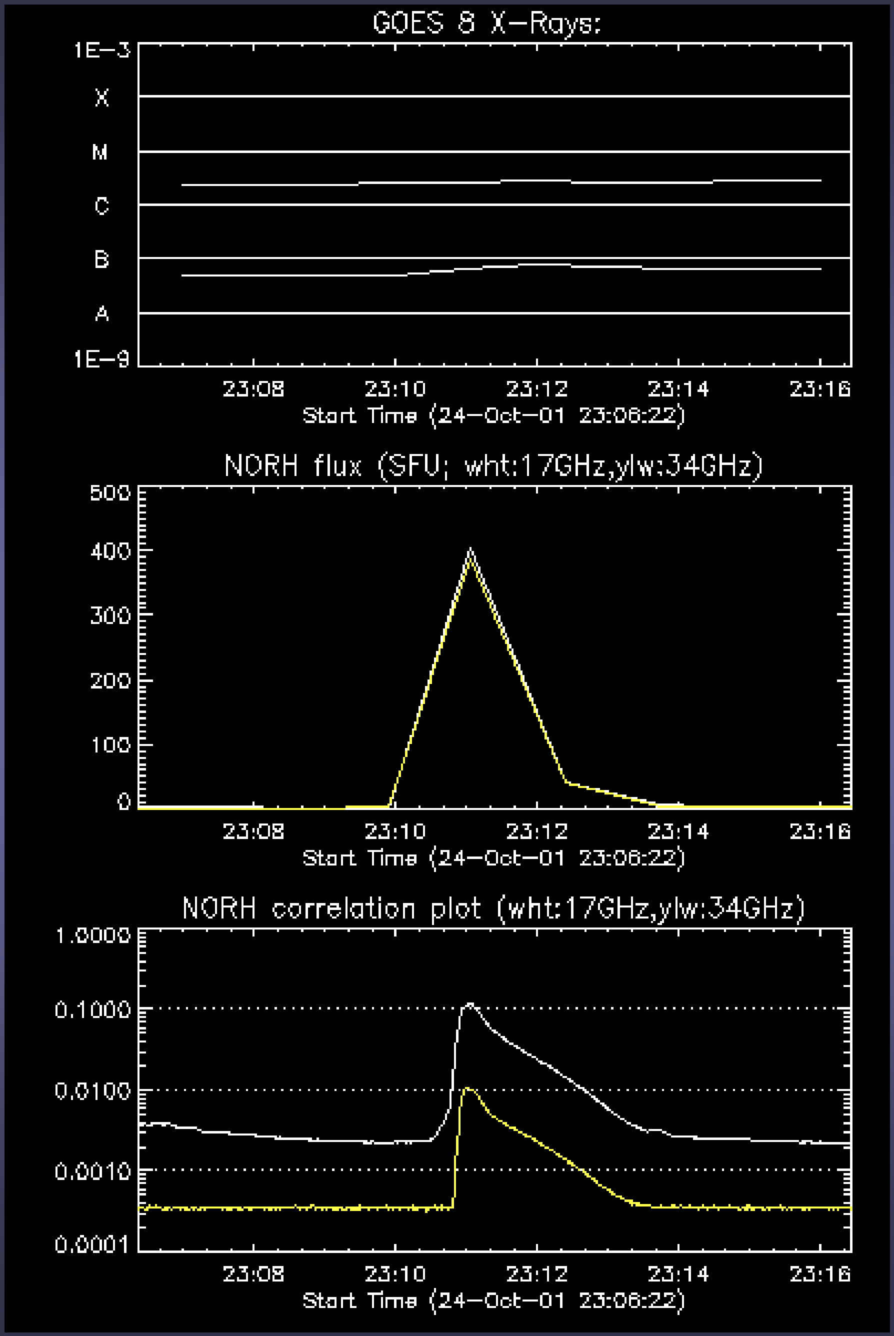
Yohkoh SXT: Single Al/Mg full disk image (4.92”)

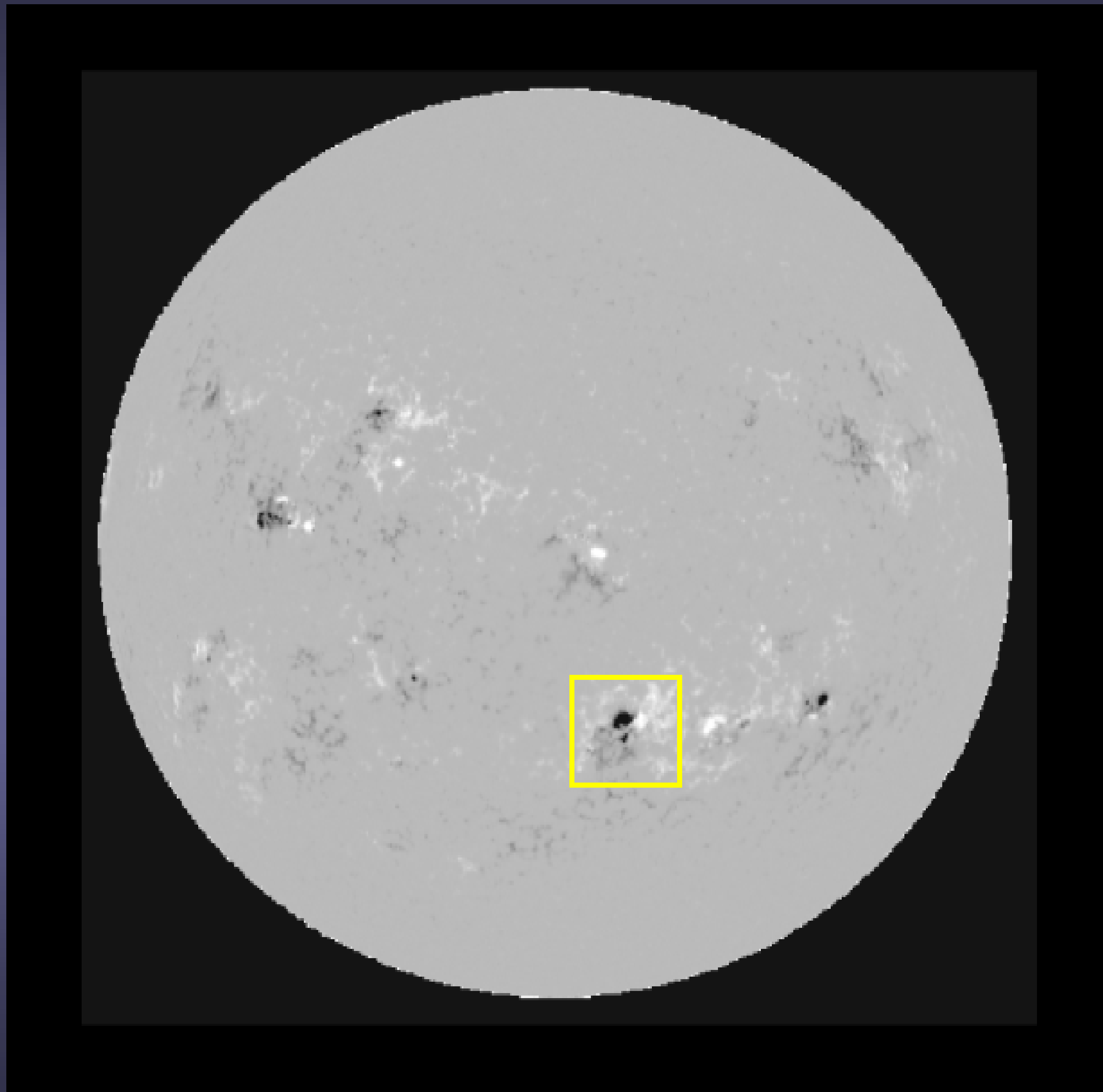
Yohkoh HXT: Counts detected in L band only

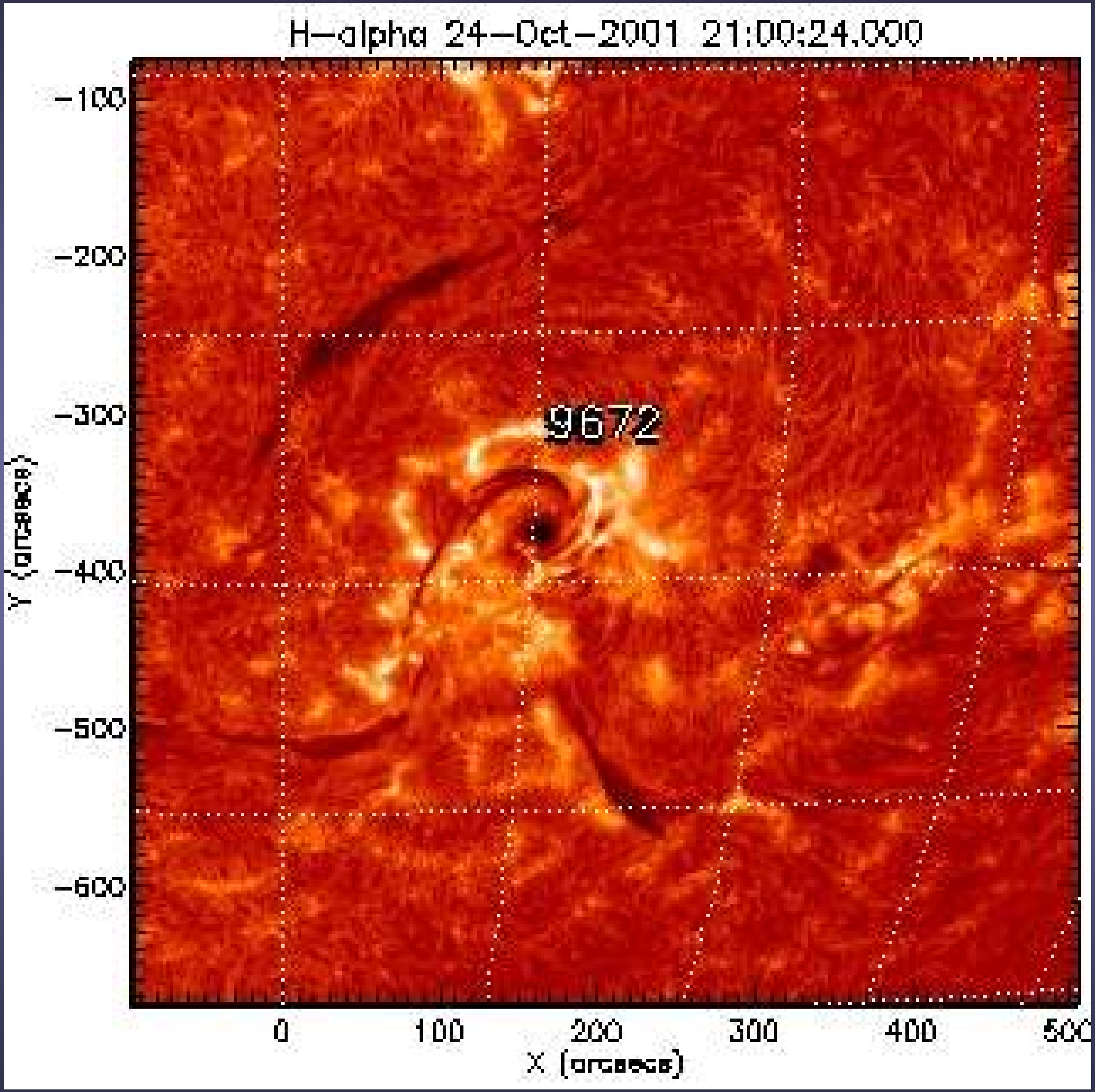
24 October 2001

AR 9672

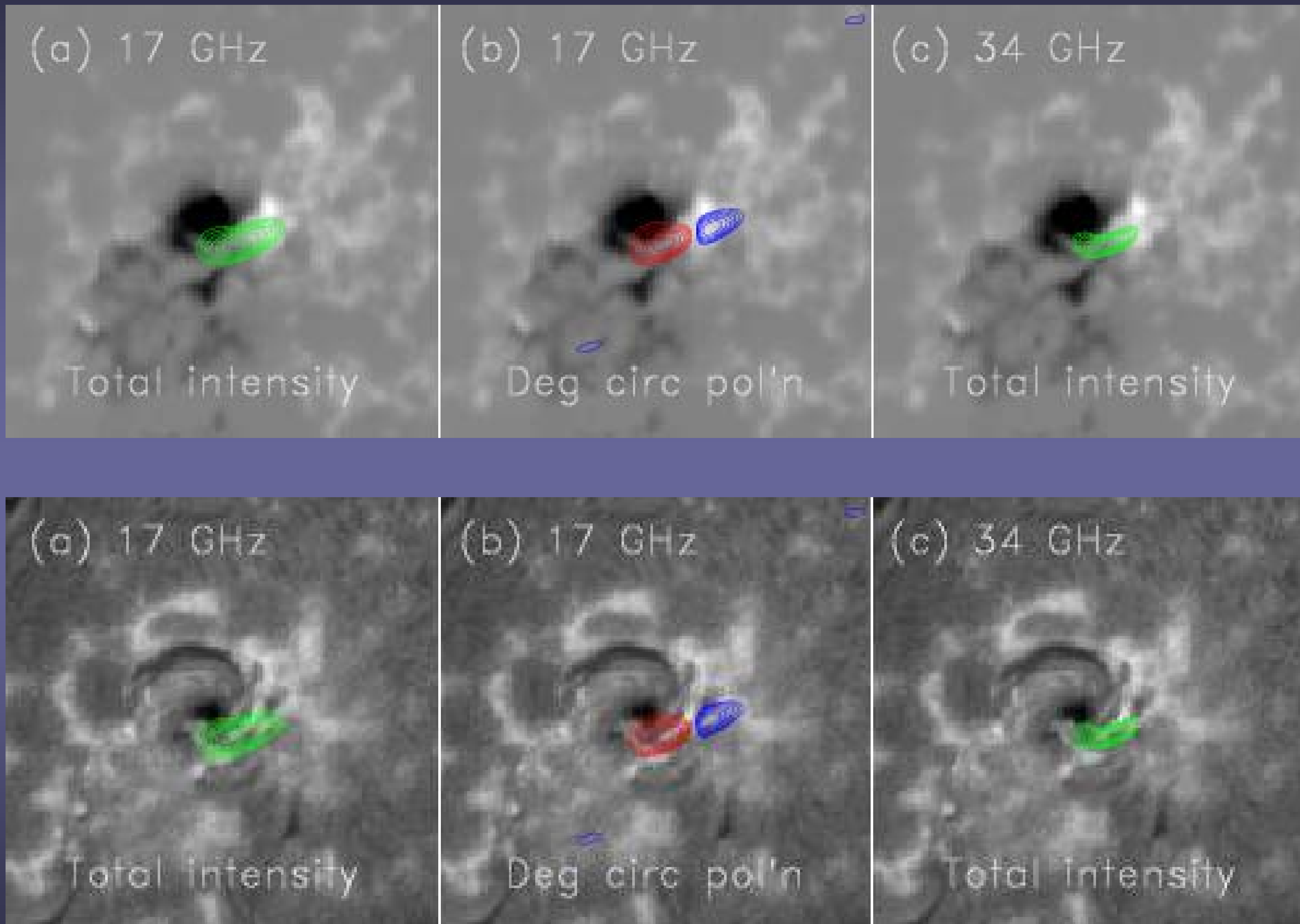


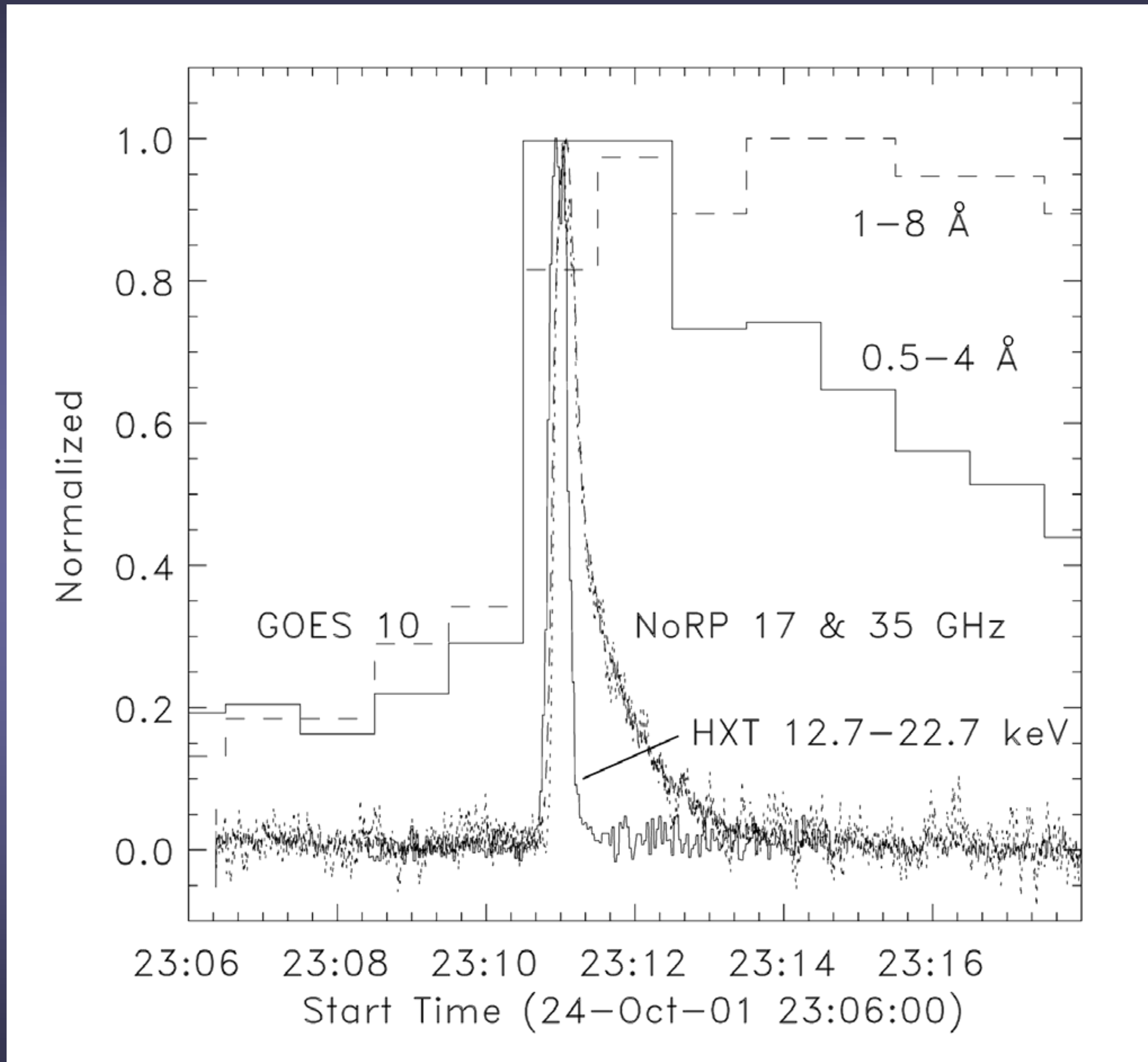


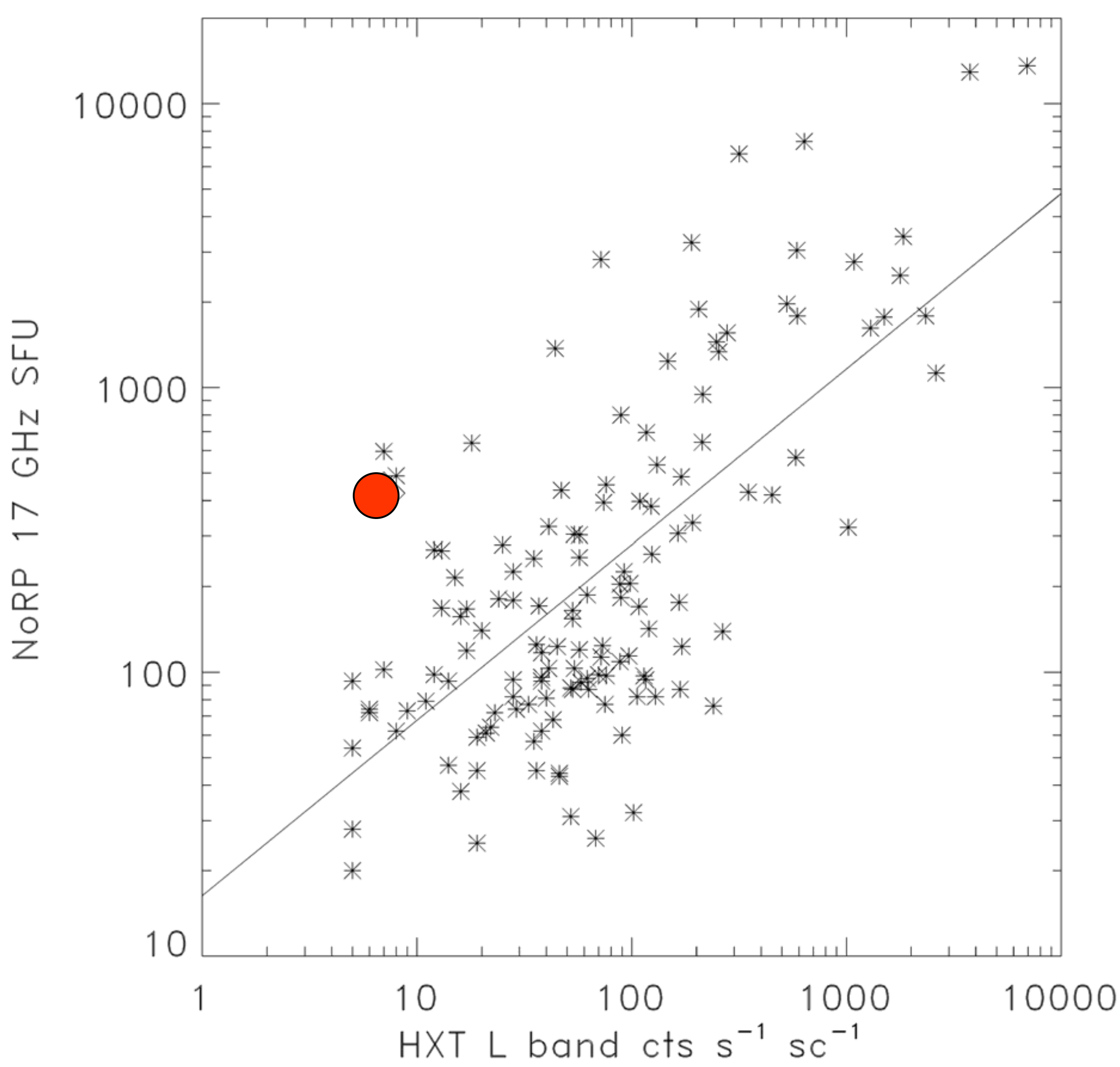




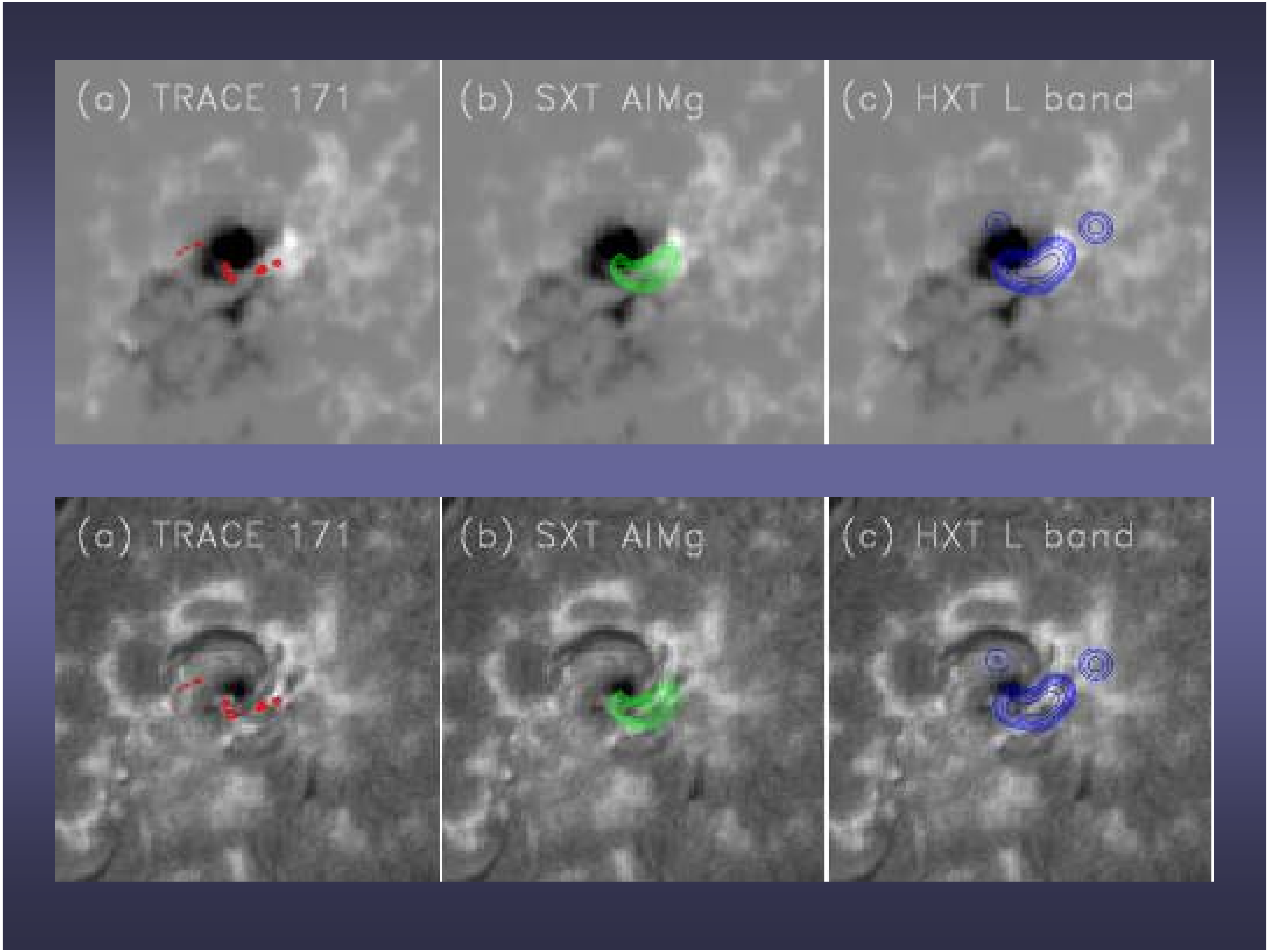
H-alpha 24-Oct-2001 21:00:24.000
9672
-100
-200
-300
-400
-500
-600
Y (arcsecs)
0
100
200
300
400
500
X (arcsecs)

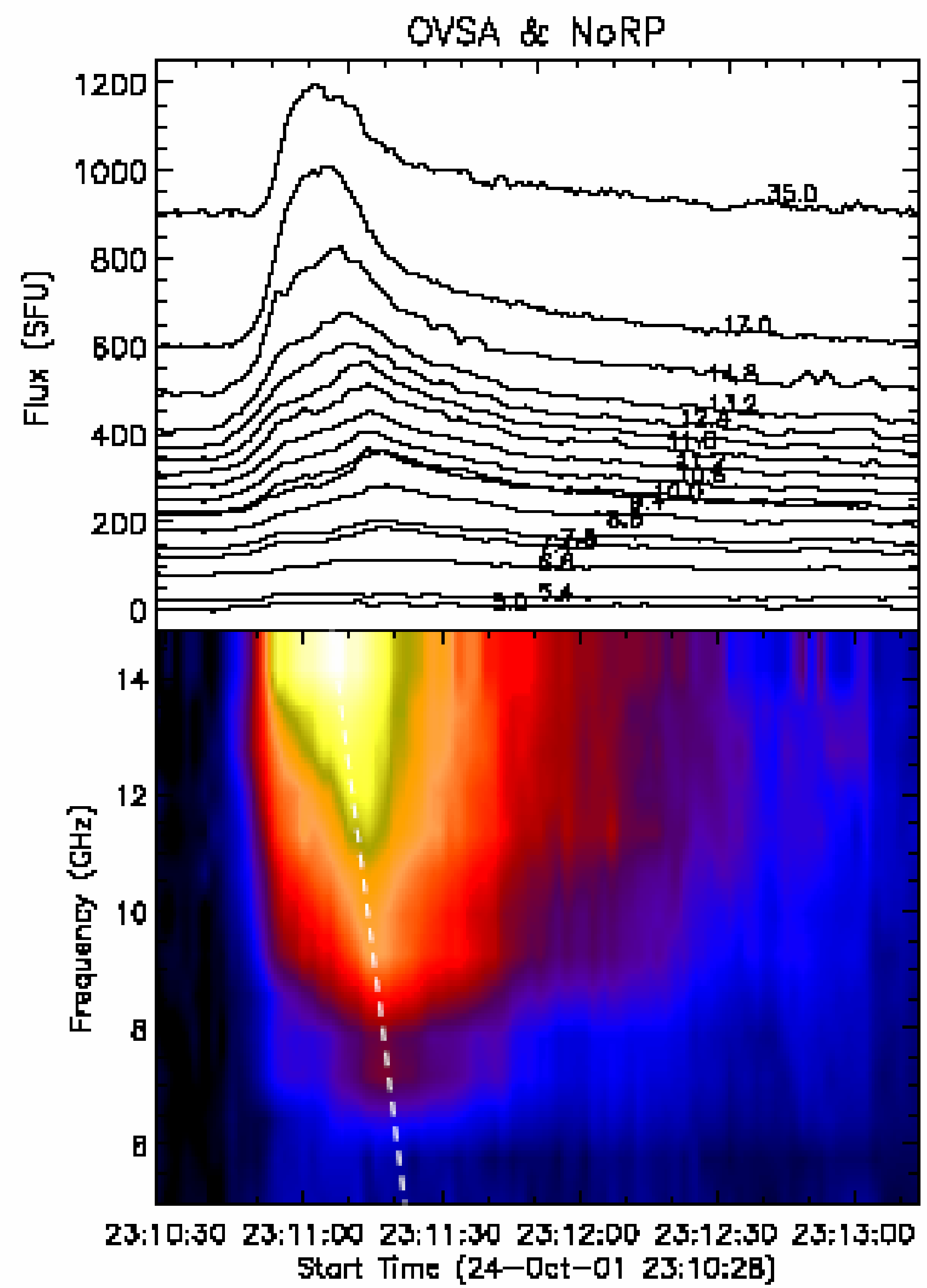

(a) 17 GHz
Total intensity
(b) 17 GHz
Deg circ pol'n
(c) 34 GHz
Total intensity
(a) 17 GHz
Total intensity
(b) 17 GHz
Deg circ pol'n
(c) 34 GHz
Total intensity


1.0
0.8
0.6
0.4
0.2
0.0
Normalized
1–8 Å
0.5–4 Å
GOES 10
NoRP 17 & 35 GHz
HXT 12.7–22.7 keV
23:06
23:08
23:10
23:12
23:14
23:16
Start Time (24-Oct-01 23:06:00)

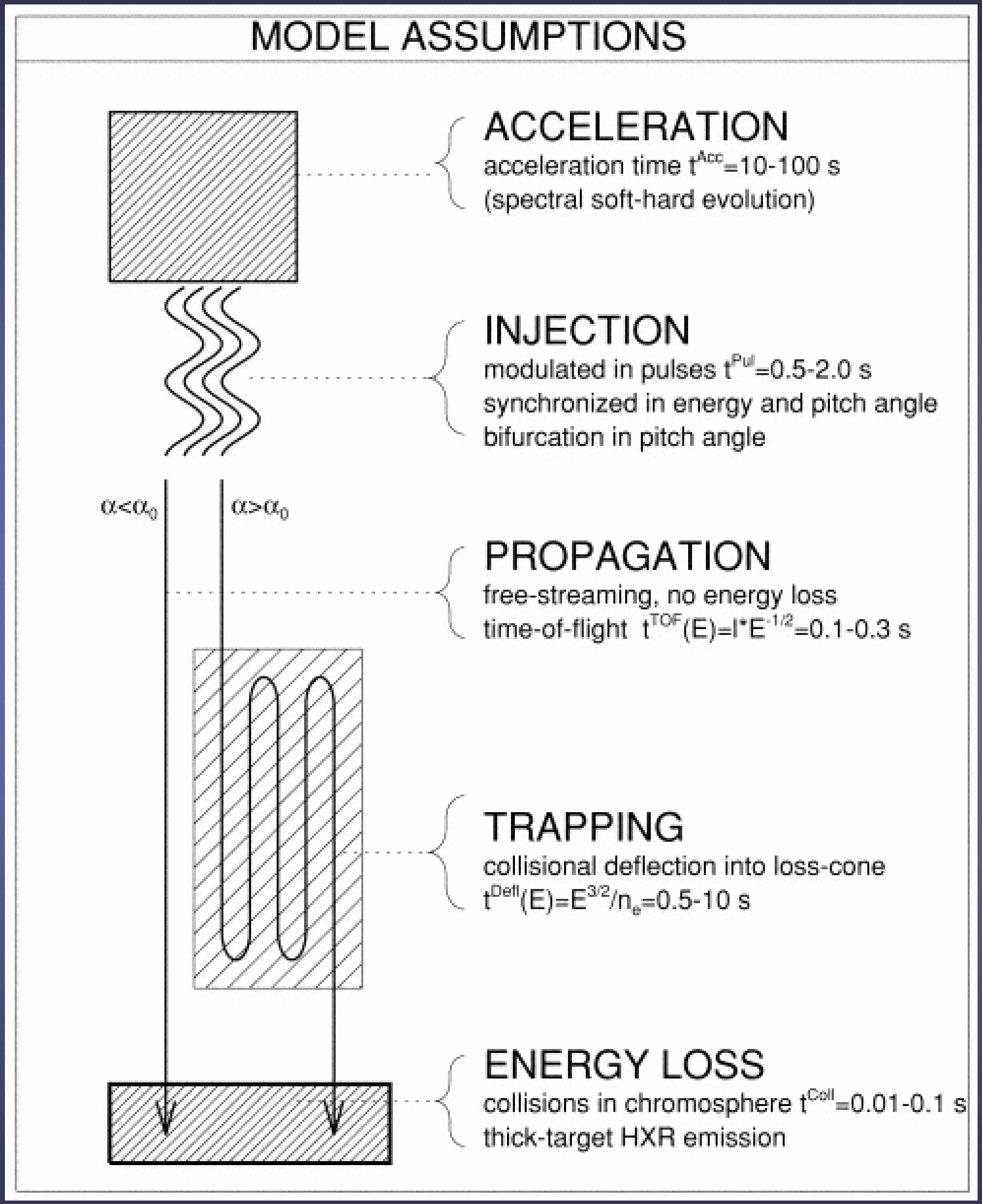


10000
1000
100
10
NoRP 17 GHz SFU
1
10
100
1000
10000
HXT L band cts s^{-1} sc^{-1}


(a) TRACE 171
(b) SXT AlMg
(c) HXT L band
(a) TRACE 171
(b) SXT AlMg
(c) HXT L band



OVSA & NoRP
Flux (SFU)
1200
1000
800
600
400
200
0
35.0
17.0
14.8
13.2
12.4
11.6
11.4
10.6
10.0
9.4
8.6
7.8
6.6
5.4
5.0
Frequency (GHz)
14
12
10
8
6
23:10:30
23:11:00
23:11:30
23:12:00
23:12:30
23:13:00
Start Time (24-Oct-01 23:10:28)



TPP/DP Model

$$\nu_D \propto \nu_E \propto E^{-3/2}$$

from Aschwanden 1998

Interpretation

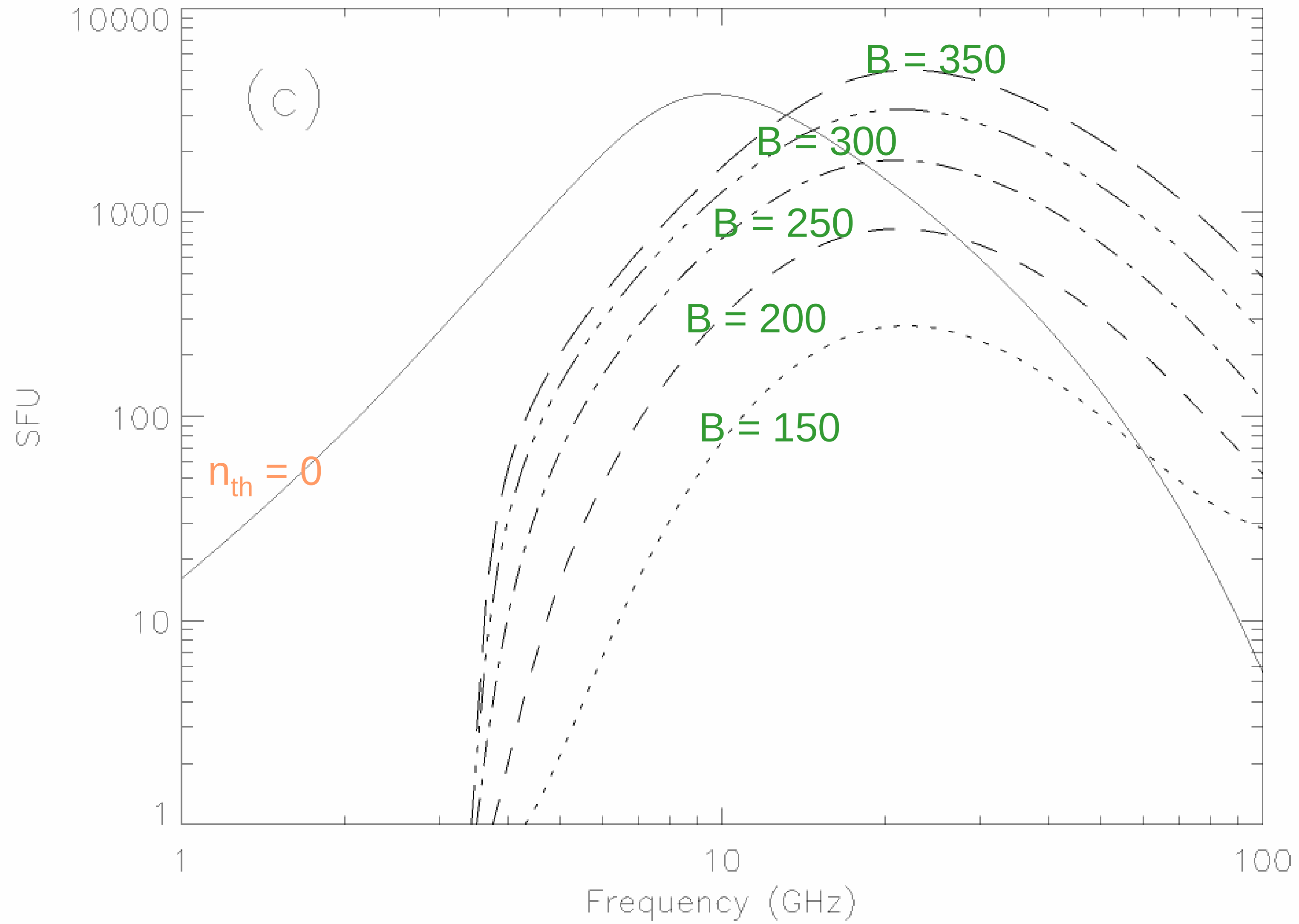
- Radio emission is due to GS emission from non-thermal distribution of electrons in relatively cool, dense plasma
- Ambient plasma density is high – therefore, Razin suppression is relevant
- Thermal free-free absorption is also important ($\sim n^2 T^{-3/2} \nu^{-2}$)

Include these ingredients in the source function (cf. Ramaty & Petrosian 1972)

The idea is that energy loss by fast electrons heats the ambient plasma, reducing the free-free opacity with time, thereby accounting for the reverse delay structure.

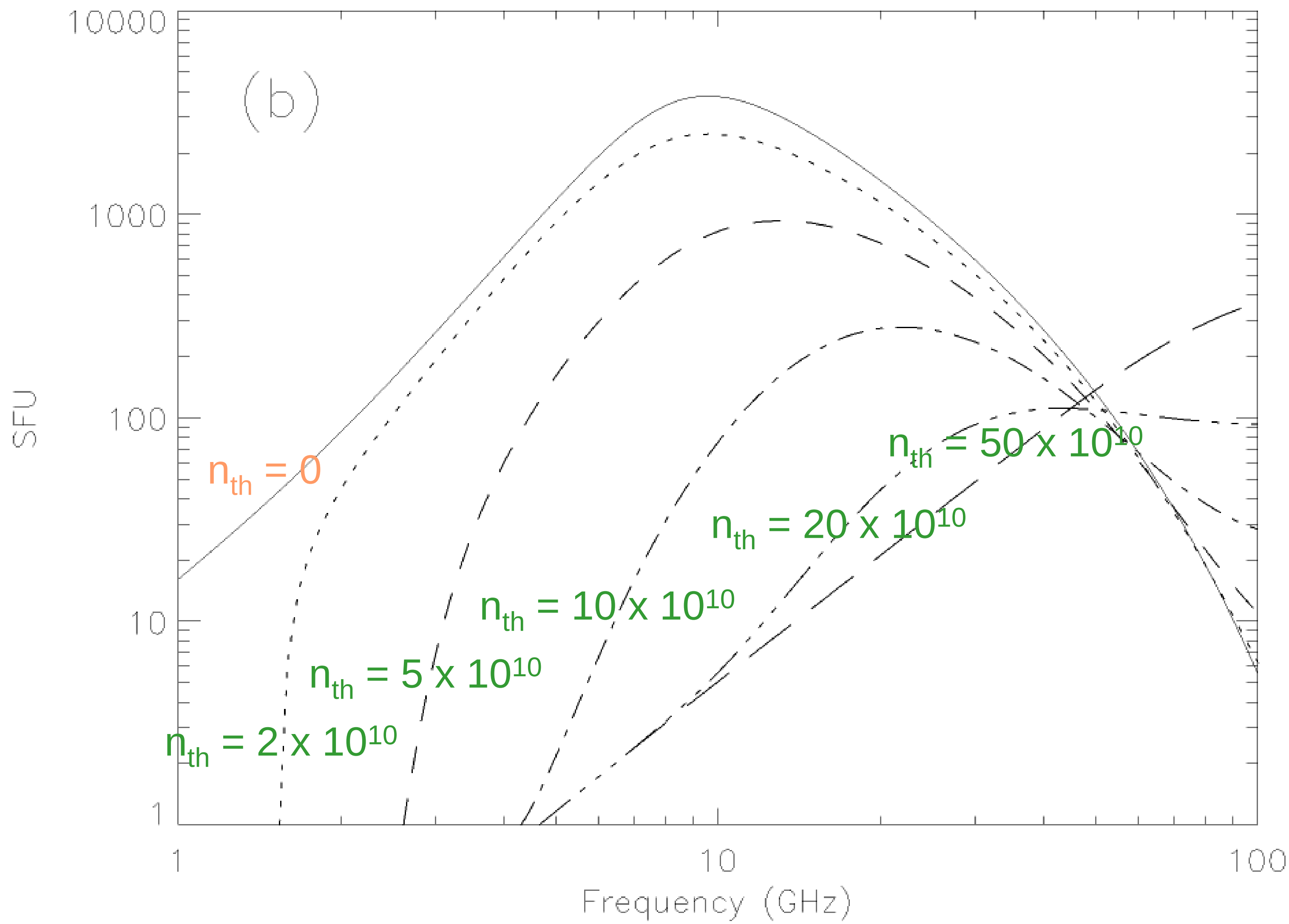
$\delta = 3.5$, $E_1 = 100$ keV, $E_2 = 2.5$ MeV, $n_{rl} = 5 \times 10^6$ cm^{-3}

$n_{th} = 10^{11}$ cm^{-3}, $T = 2 \times 10^6$ K, $A = 2 \times 10^{18}$ cm^2, $L = 9 \times 10^8$ cm



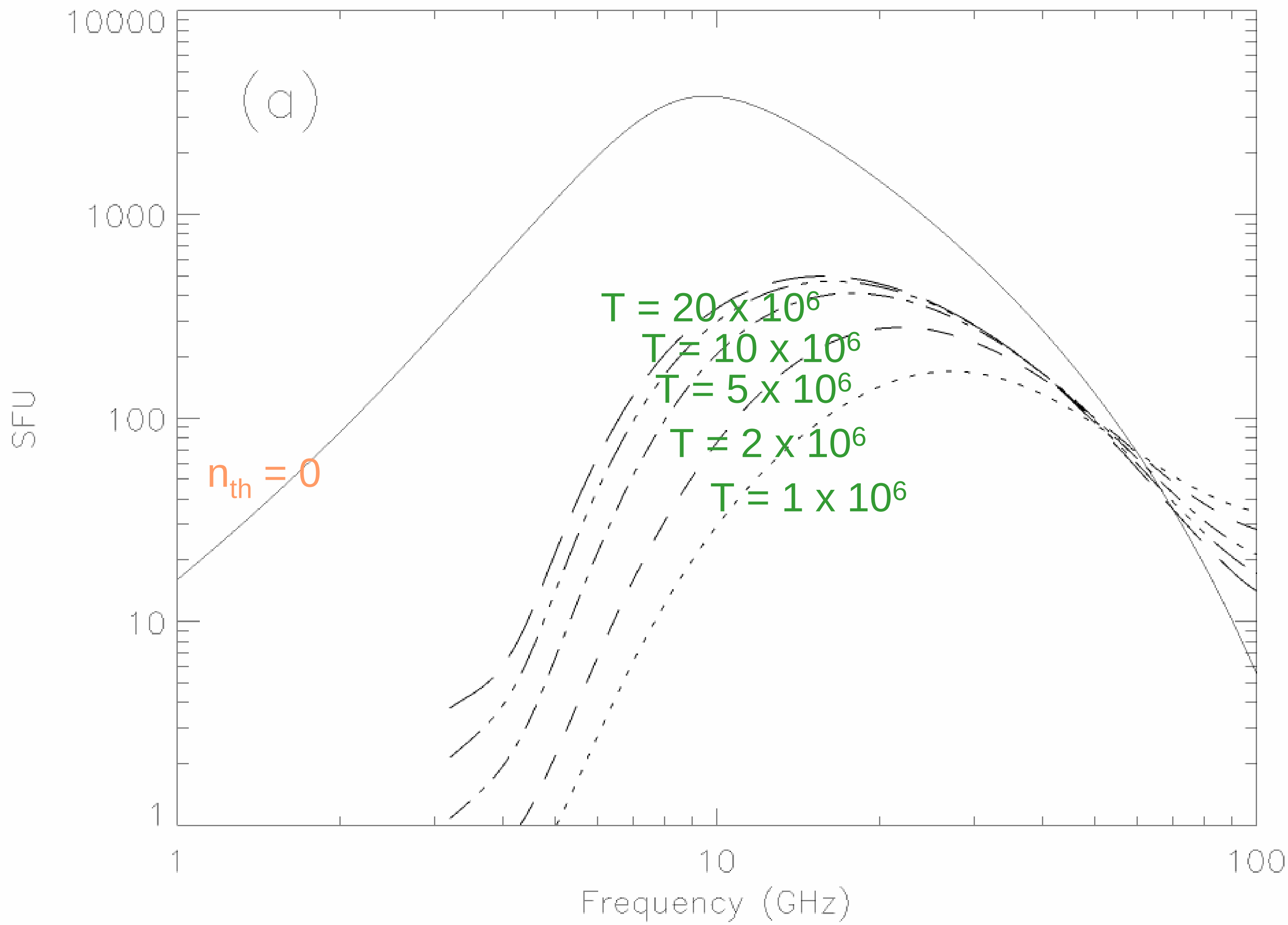
$\delta = 3.5$, $E_1 = 100$ keV, $E_2 = 2.5$ MeV, $n_{rl} = 5 \times 10^6$ cm^{-3}

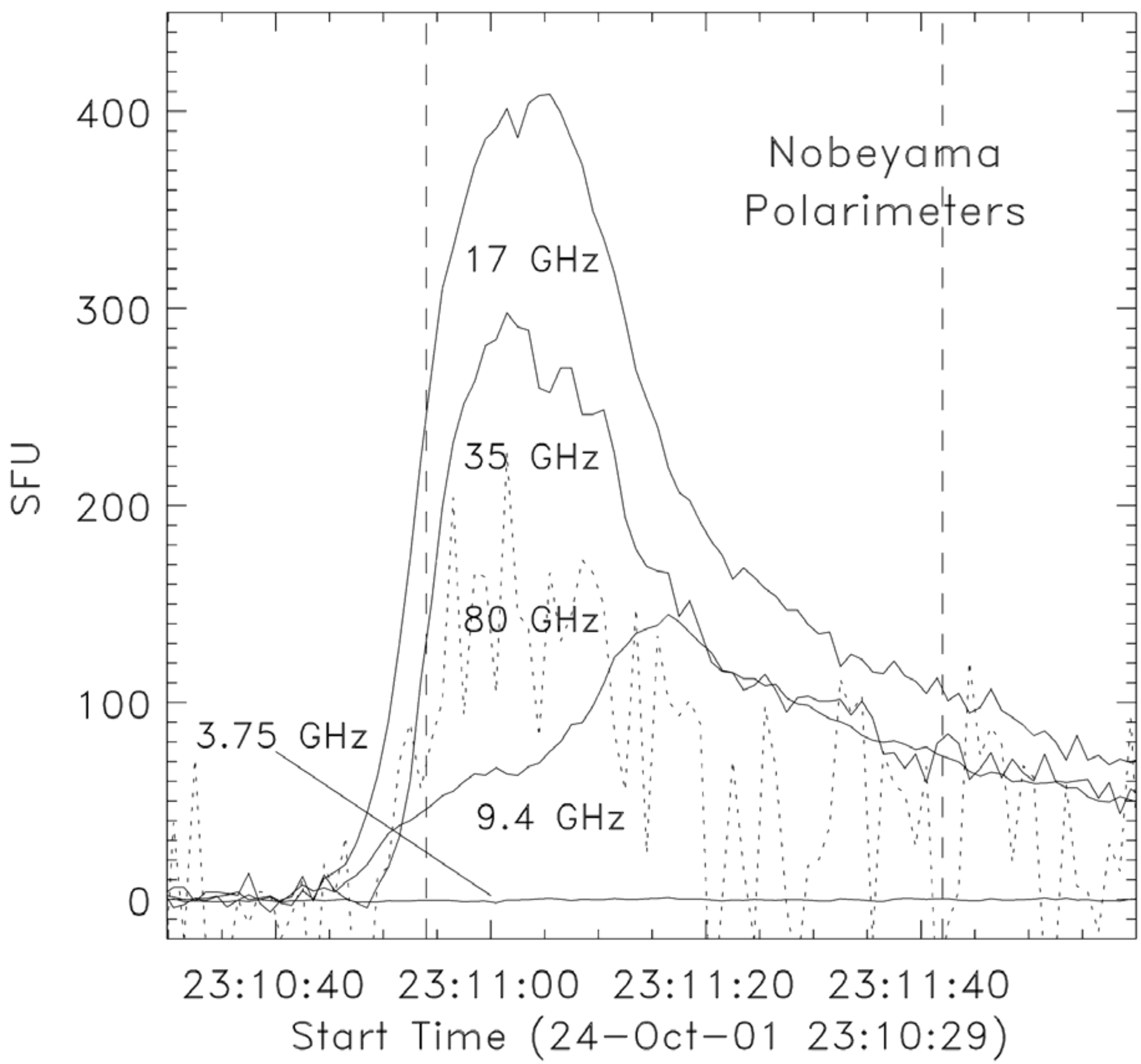
B = 150 G, T = 2×10^6 K, A = 2×10^{18} cm^2, L = 9×10^8 cm



δ = 3.5, E_1 = 100 keV, E_2 = 2.5 MeV, n_{rl} = 5 x 10^6 cm^{-3}

B=150 G, n_{th} = 10^{11} cm^{-3}, A = 2 x 10^{18} cm^2, L = 9 x 10^8 cm





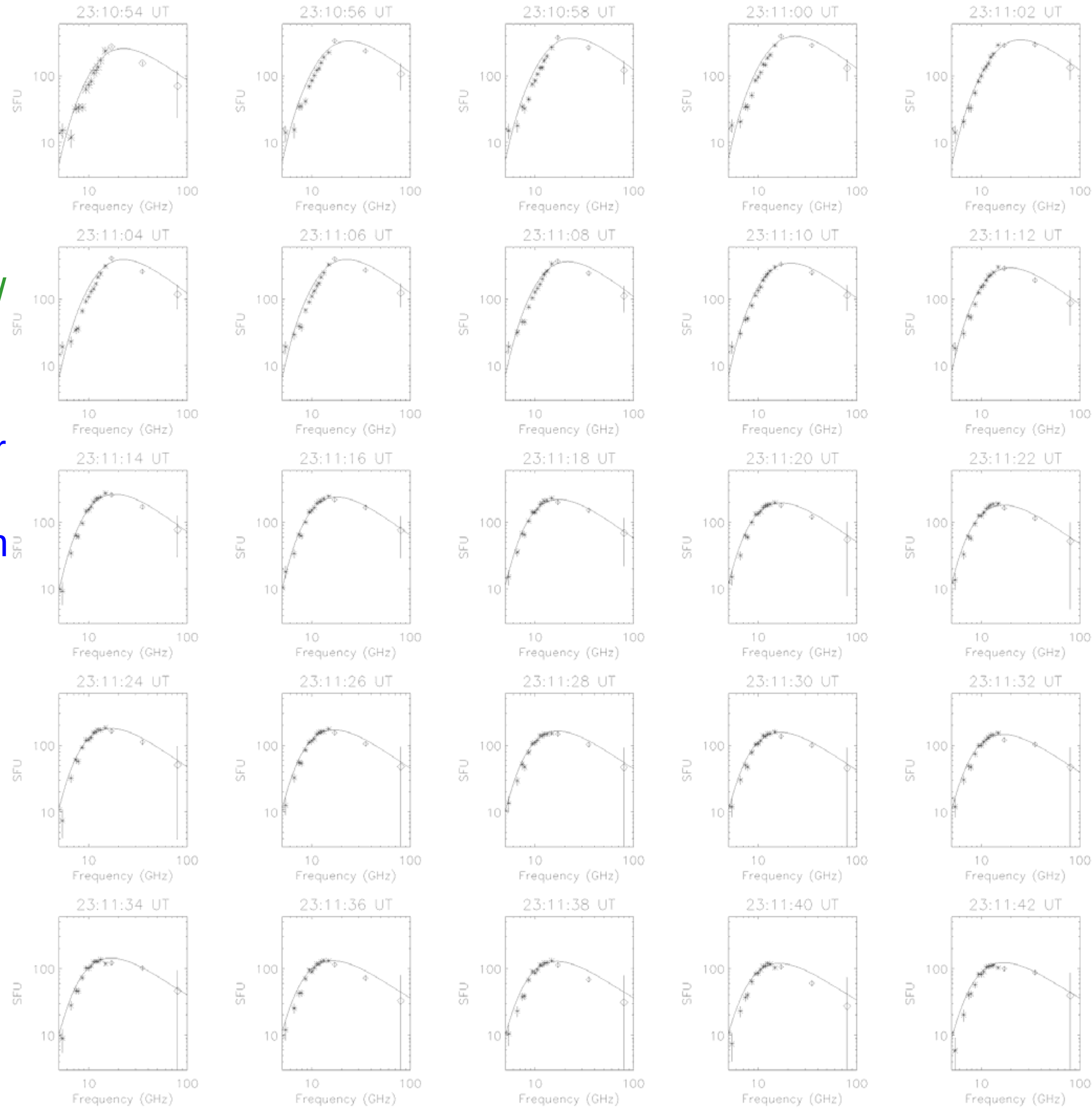
Nobeyama
Polarimeters
17 GHz
35 GHz
80 GHz
3.75 GHz
9.4 GHz
SFU
0
100
200
300
400
23:10:40
23:11:00
23:11:20
23:11:40
Start Time (24-Oct-01 23:10:29)

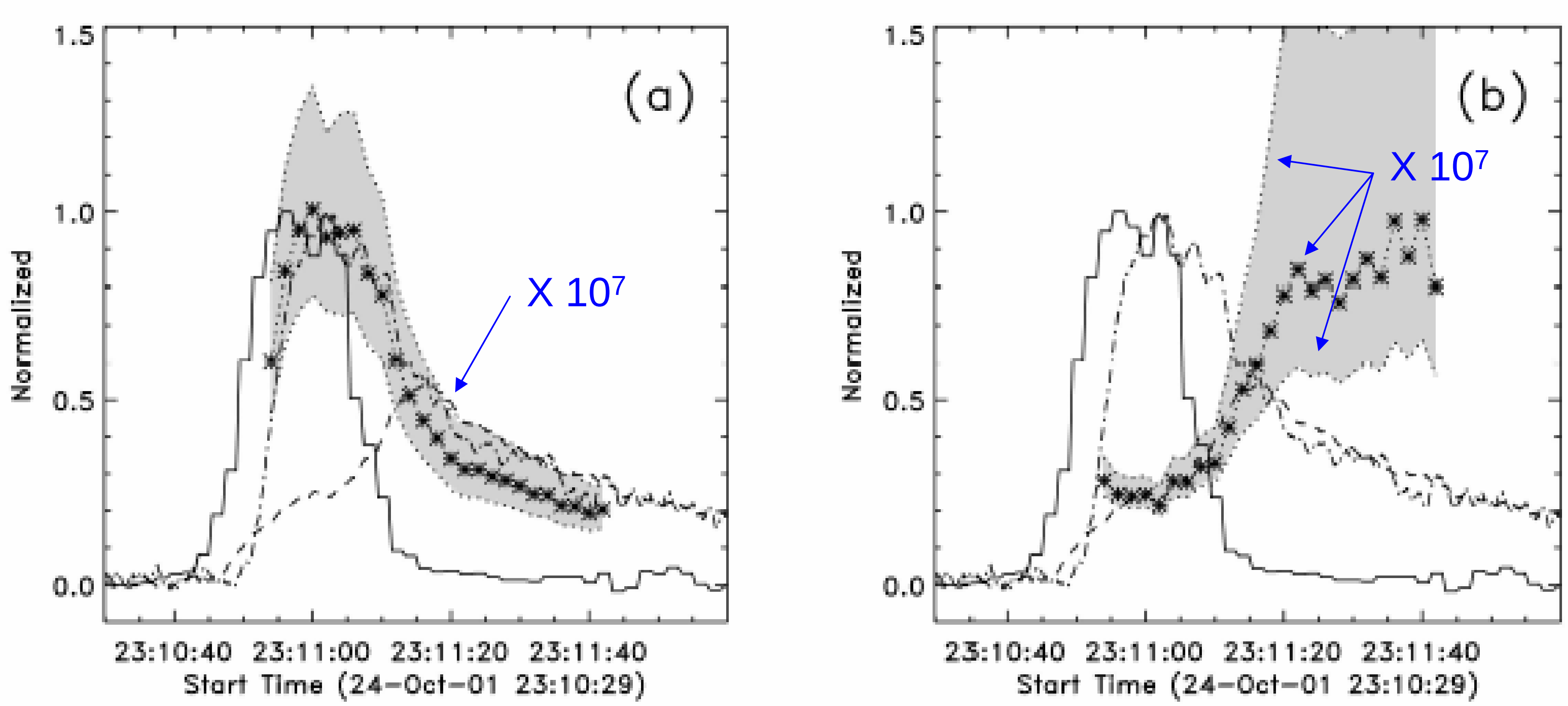
1 spectrum/ 2 sec

2-parameter fits via χ^2-minimization

n_{rl}, T

B, θ, n_{th}, A, L, E_1, E_2, δ fixed





(a)
X 10^7
1.5
1.0
0.5
0.0
Normalized
23:10:40 23:11:00 23:11:20 23:11:40
Start Time (24-Oct-01 23:10:29)
(b)
X 10^7
1.5
1.0
0.5
0.0
Normalized
23:10:40 23:11:00 23:11:20 23:11:40
Start Time (24-Oct-01 23:10:29)

Future directions

FASR FREQUENCY-AGILE SOLAR RADIOTELESCOPE

FASR will be a ground based solar-dedicated radio telescope designed and optimized to produce images over a broad frequency range with

- high angular, temporal, and spectral resolution
- high fidelity and high dynamic range

As such, FASR will address an extremely broad science program.

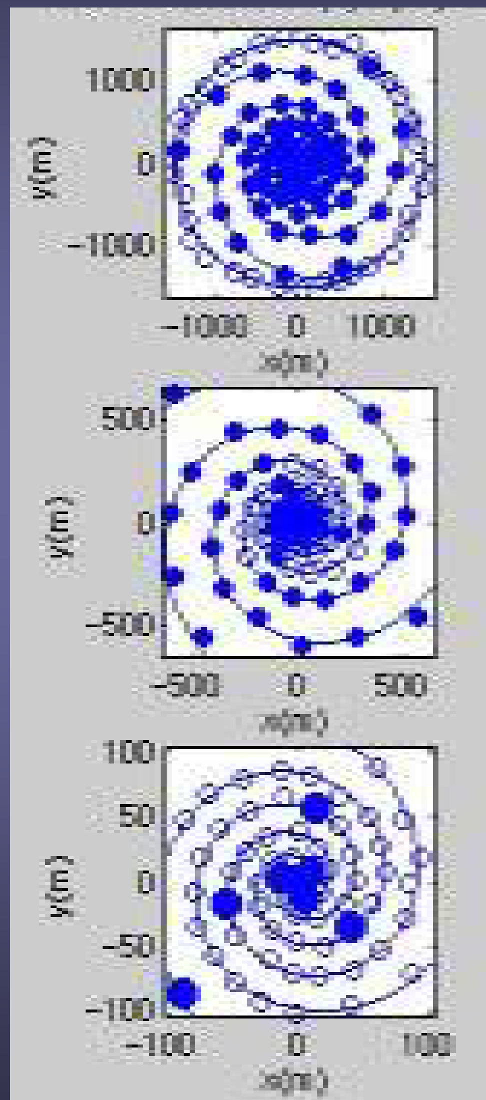
An important goal of the project is to mainstream solar radio observations by providing a number of standard data products for use by the wider solar physics community.

FASR Specifications

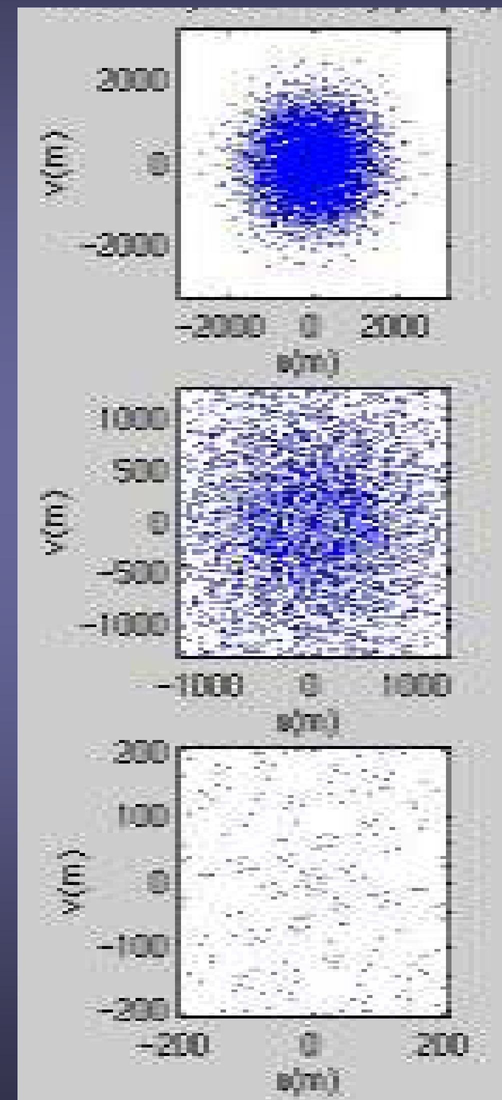
Frequency range	0.05-30 GHz
Frequency resolution	1%
Time resolution	100 ms
Number antennas	~100 (5000 baselines)
Size antennas	LPA, 6 m, 2 m
Polarization	Stokes IV(QU)
Angular resolution	$20/\nu_9$ arcsec
Footprint	~4 km
Field of View	>0.5 deg

Array configuration

"self-similar"
log spiral



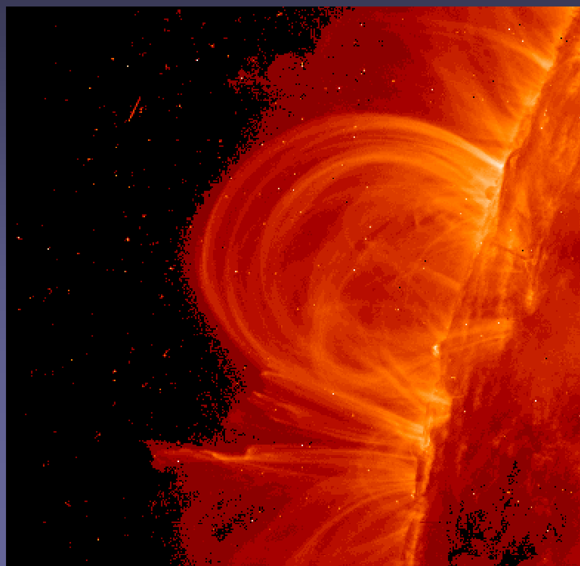
AC



Conway 2000

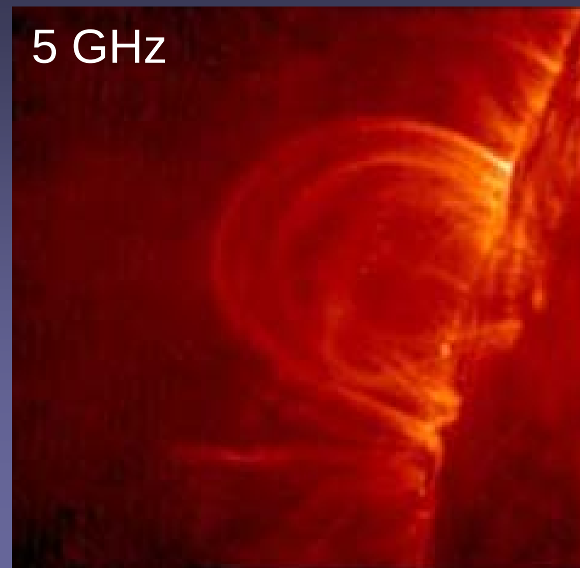
Imaging

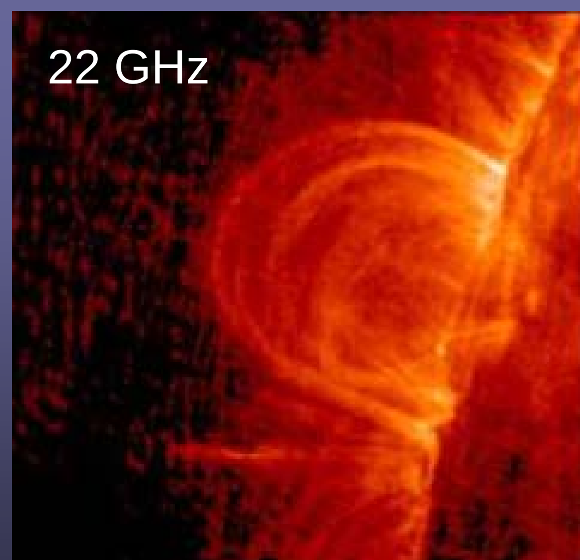
model



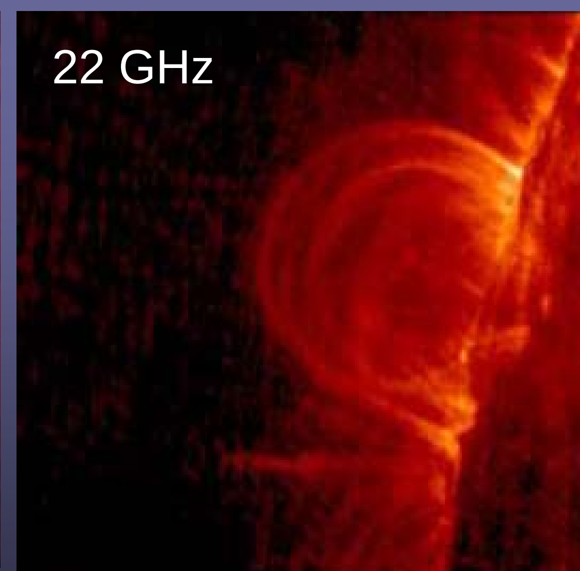
TRACE: 6 Nov 1999

snapshots





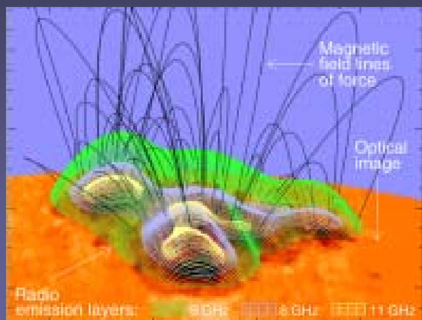
10 min synth.



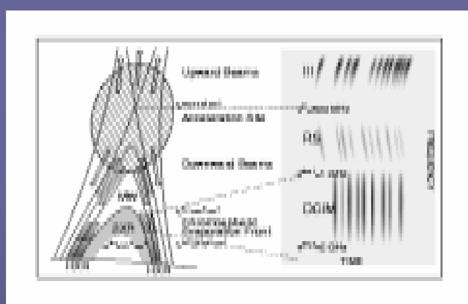
102 antenna log-spiral
in three arms

(noiseless data)

FASR Key Science



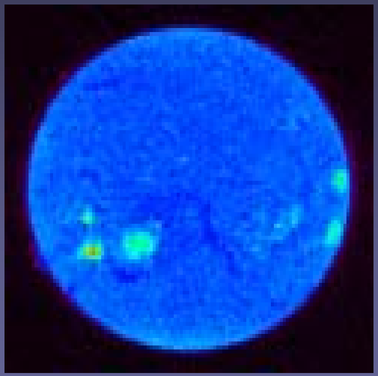
- **Nature & Evolution of Coronal Magnetic Fields**
  - Measurement of coronal magnetic fields
  - Temporal & spatial evolution of fields
  - Role of electric currents in corona
  - Coronal seismology



- **Flares**
  - Energy release
  - Plasma heating
  - Electron acceleration and transport
  - Origin of SEPs

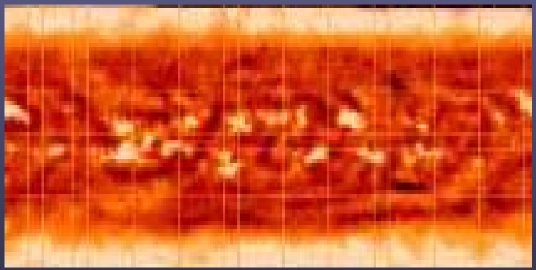
- **Drivers of Space Weather**
  - Birth & acceleration of CMEs
  - Prominence eruptions
  - Origin of SEPs
  - Fast solar wind streams

FASR Science (cont)



- **The "thermal" solar atmosphere**
  - Coronal heating - nanoflares
  - Thermodynamic structure & dynamics
  - Formation & structure of filaments

- **Solar Wind**
  - Birth in network
  - Coronal holes
  - Fast/slow wind streams
  - Turbulence and waves



- **Synoptic studies**
  - Radiative inputs to upper atmosphere
  - Global magnetic field/dynamo
  - Flare statistics