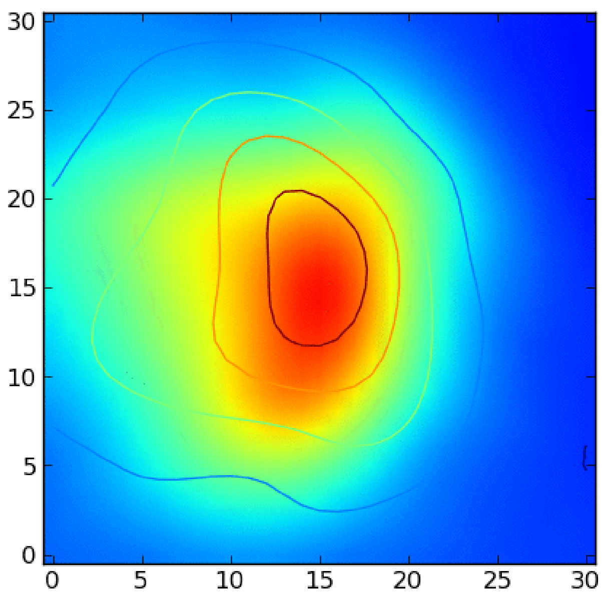
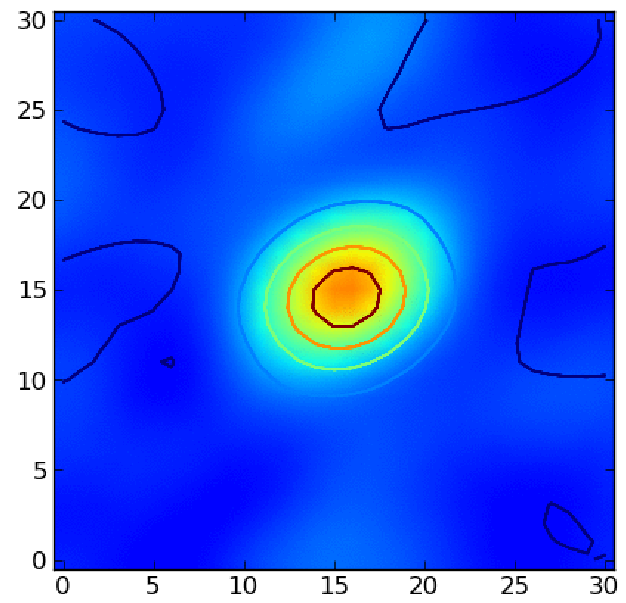
Radio interferometric imaging of spatial structure that varies with time and frequency





Urvashi Rau

National Radio Astronomy Observatory, USA

9th SKA Calibration and Imaging Workshop, Socorro, NM, USA

11 Oct 2016

Time Domain Science

- **SKA Key Science Goal** : “Exploration of the Unknown : The Dynamic Radio Sky”

- **US Decadal Survey** : Time Domain Astronomy = Science Frontier Discovery Area

- **VLA ‘RealFast’** program funded : Real Time Imaging to find and track transients.

- **VLASS** goals include Time Domain Science (repeated mapping of large volumes)

Types of variable sources : very short single events to long term variability

GRB afterglows, coalescing neutron stars, exoplanetary magnetospheric bursts, X-ray binaries, giant pulses, compact cores of AGN, tidal disruption events, flaring stars (including our Sun), novae, extreme scattering events, etc

It is expected that improved sensitivities of all (new) radio telescopes will allow the detection and study of far more sources than has so far been done.

Weaker sources : More processing and more complex algorithms
Often need more than snapshots for better fidelity

When the sky brightness varies with time (within an observation)

(1) A nuisance (artifacts preventing good imaging of a weaker target)

(image per timstep and uv-sub or stacking, dd-cals + peeling)

(2) Something to be detected (perhaps within a large f-o-v survey)

(image shorter and shorter time intervals, ignoring imaging fidelity)

(3) Something to be modeled for study.

(Image each timestep separately and model on the time-cube)

The above are all fine when there is enough uv-coverage and SNR and you can spare the extra processing to image every snapshot.

Imaging accuracy is often limited when small subsets of the data are used.

- How much of the 'variability' is real ?

(variable PSF, clean bias, reconstruction uncertainty for resolved structure, un-modeled PB effects, etc)

One option – Also model the time variability during reconstruction

This problem is very similar to that of wideband modeling for MFS.

[Aperture synthesis : Earth-Rotation and Multi-Frequency Synthesis]

MT-MFS models the frequency dependence of each source with a polynomial
[Sault & Wieringa, 1994, Rau & Cornwell, 2011]

=> with a very small change in basis function, we can model
time variability too (on its own and along with spectra).

TV-Imager : Uses polynomials to model time variability per component
(this assumes smoothness).

A CLEAN-based approach, using L2 minimization as the overall framework with constraints applied during the update step.

TV-Imaging is easily combined with both multi-scale and wideband imaging
[Rau, 2012 (SPIE Proc)]

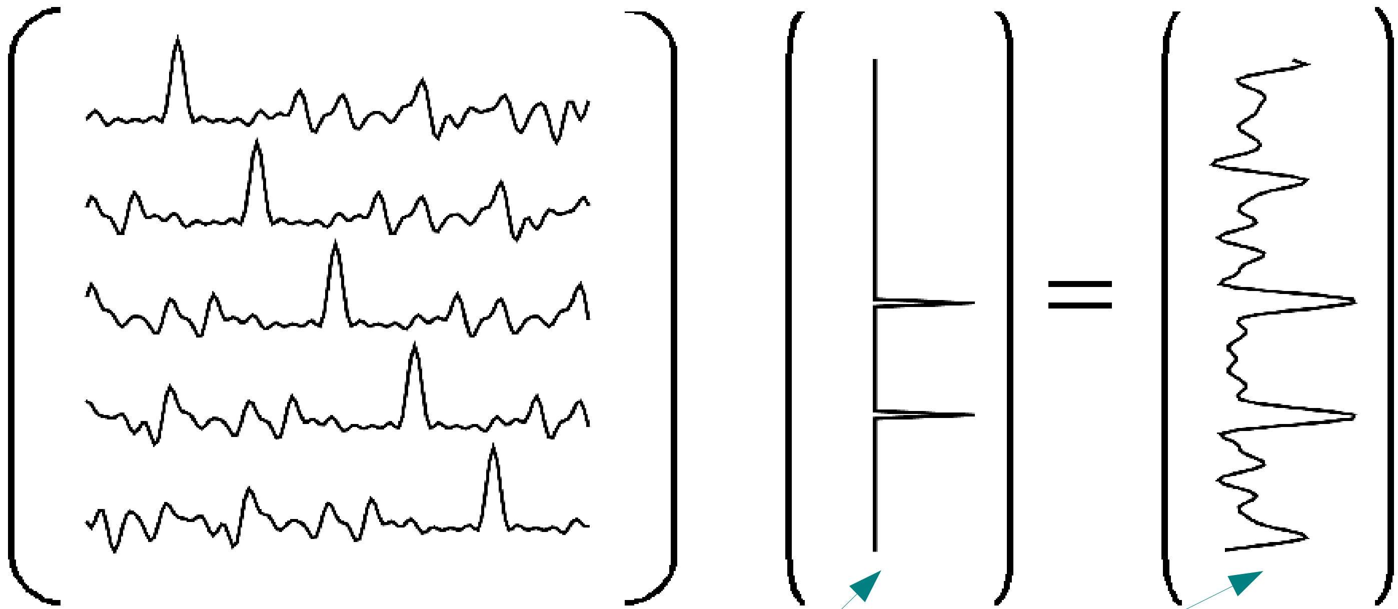
Basic L2 Image Reconstruction - CLEAN

χ^2 minimization of the M.Eqn.

$$[A] I^m = V^{obs}$$

where

$$[A] \approx [S][F]$$



Normal Equations : $[A^T W A] I^m = [A^T W] V^{obs}$

→ This describes an image-domain convolution $I^{psf} * I^m = I^{dirty}$

Iterative Solution :

$$\underbrace{I_{i+1}^m = I_i^m + g [A^T W A]^+}_{\text{Deconvolution}} \left(A^T W \left(V^{obs} - A I_i^m \right) \right)$$

Deconvolution

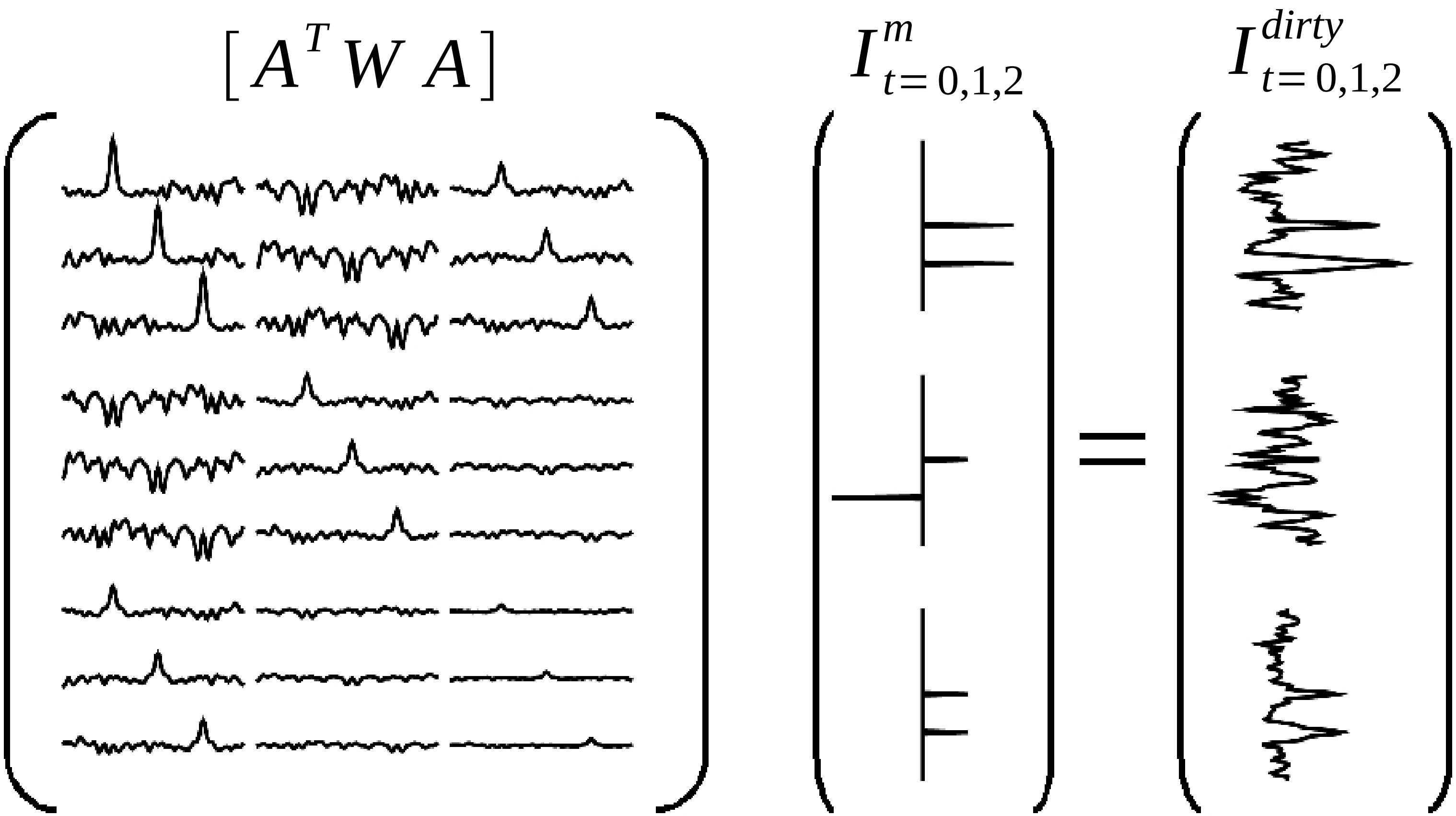
Imaging (Gridding + iFT)

Prediction (FT + de-Gridding)

Multi-Term CLEAN (wide-band or time-variable or multi-scale)

Model the sky signal in a sparse basis

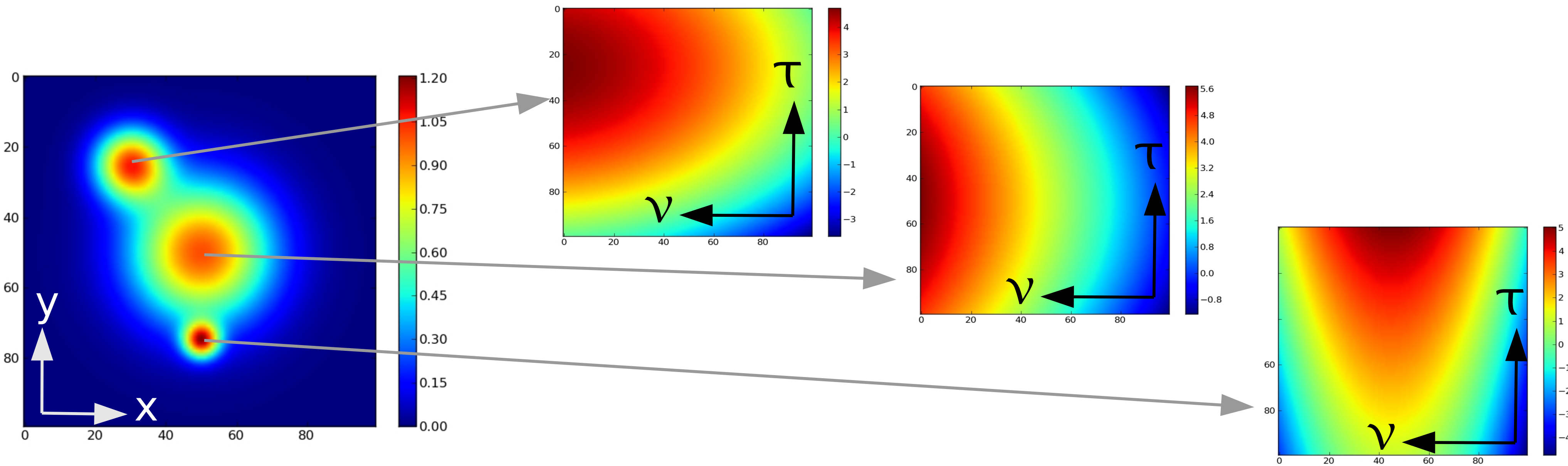
Use polynomial coefficients for smooth spectra or time series.
Use multi-scale atoms as a sparse representation of extended emission.



Multi-Scale, Multi-Frequency, Time-Variable Sky model

Multi-scale flux-components whose amplitudes follow dynamic spectra

$$I^{model}_{\nu,t} = \sum_s I^{shp}_s * \left[I^{sky}_0 + \sum_{p=1}^{N_p-1} I^{sky}_p \left(\frac{\nu - \nu_0}{\nu_0} \right)^p + \sum_{q=1}^{N_q-1} I^{sky}_{q+N_p-1} \left(\frac{t - t_{mid}}{t_{max} - t_{min}} \right)^q \right]_s$$



Sparse representation
of extended structure :
Atom position and shape

Sparse representation of dynamic spectrum of each component (or atom):

Coefficients of polynomials in time/frequency

Two Examples

(1) Dynamic 3D Coronal Magnetogram

Data : VLA Simulations between 5 – 15 GHz.

Goal : Reconstruct wideband time varying extended structure

(2) Orion Nebula Cluster

Data : VLA A-Config C-Band observations

Goal : Measure and characterize variability
of compact structures (some resolved, some not)
embedded in complicated extended structure

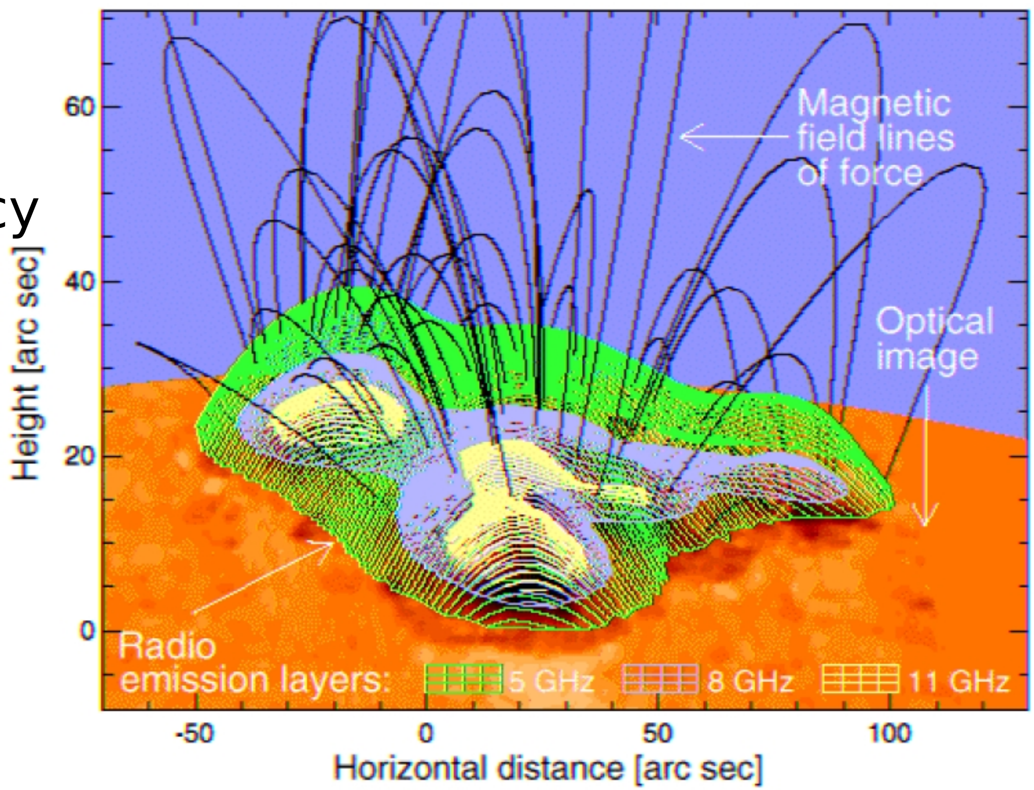
Solar Coronal Magnetography – 3D structures (Flares + Sunspots)

Sunspots : Regions of high B-fields

For a given B-field, radio emission peaks at the gyro-resonance frequency

$$\nu_B = \frac{eB}{2\pi mc}$$

The brightness distribution at a given observing frequency relates to the electron temperature on an isogauss surface.



Magnetic field strength (generally) decreases with height from the base of the active region.

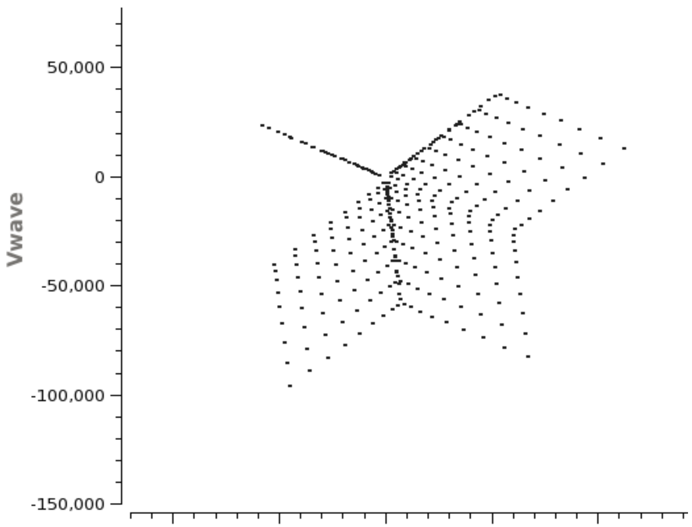
=> Multi-frequency observations (1-20 GHz) trace 3D structures in the solar corona.

+ These structures evolve with time

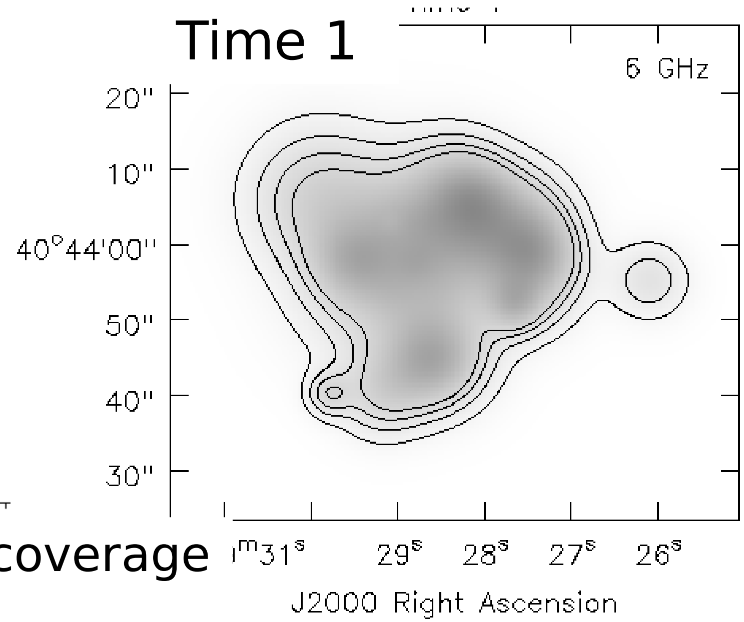
Gary,2001

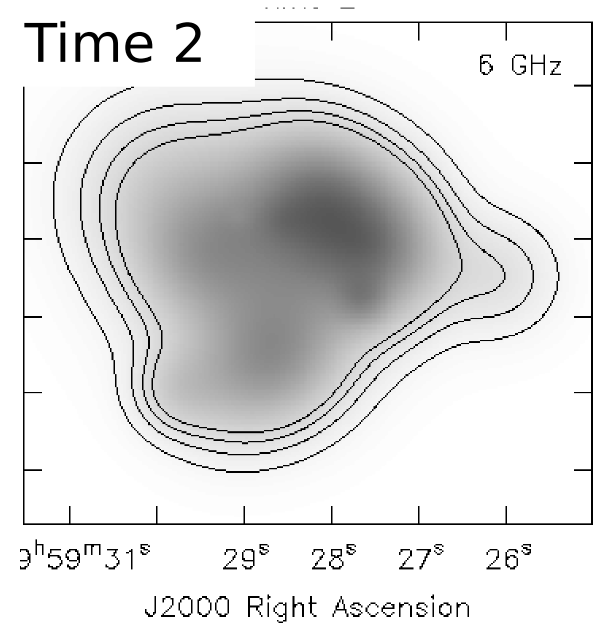
Dynamic Coronal Magnetogram : Simulation (VLA : 27 elements, 4 hrs)

Snapshot + Single-frequency UV-coverage



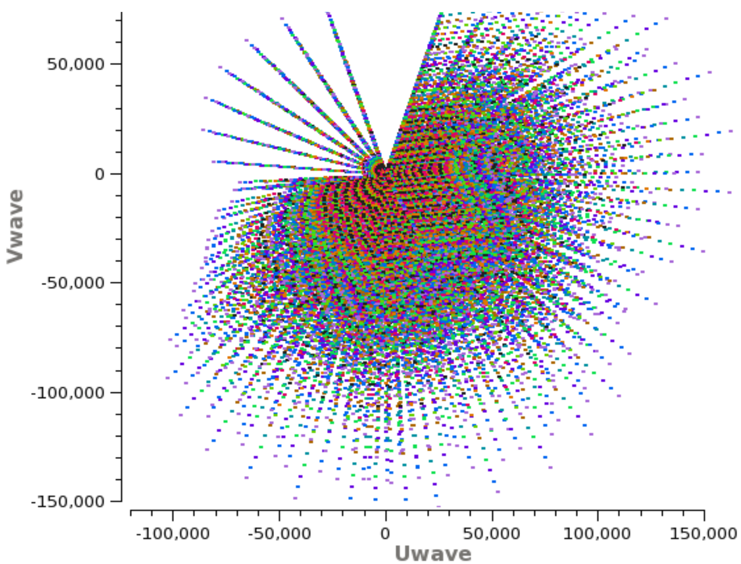
Model (6, 8, 10,12, 14 GHz)





1 arcmin

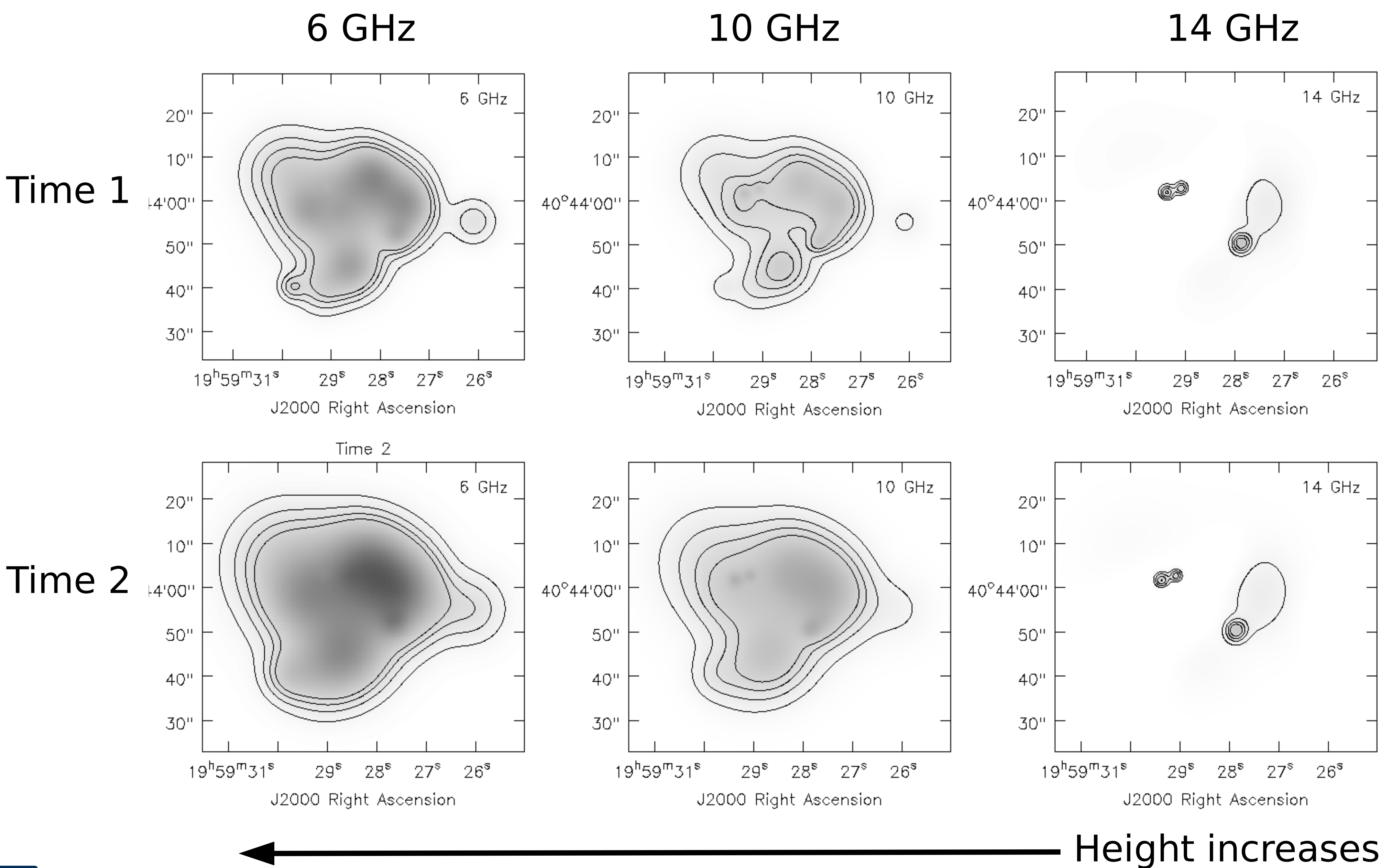
4-hour, Multi-frequency UV-coverage



Array : 27 elements, max baseline of 3km

Frequencies :	5 GHz	–	15 GHz
Angular resolution :	4 arcsec	–	1 arcsec
Largest spatial scale :	6 arcmin	–	2 arcmin

Dynamic Coronal Magnetogram : (True) Time-varying 3D structure

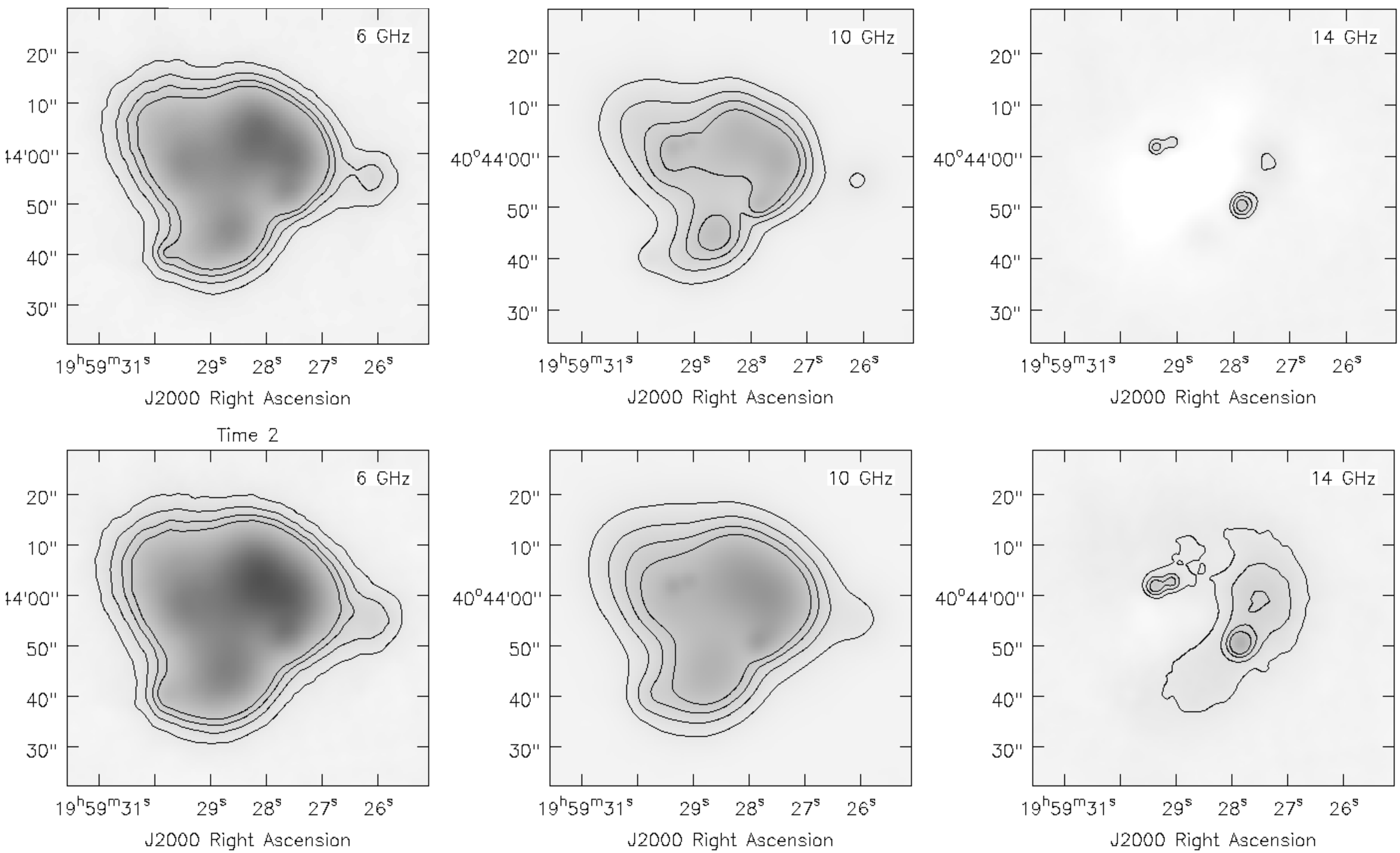


Dynamic Coronal Magnetogram : Reconstruction

6 GHz | 10 GHz | 14 GHz

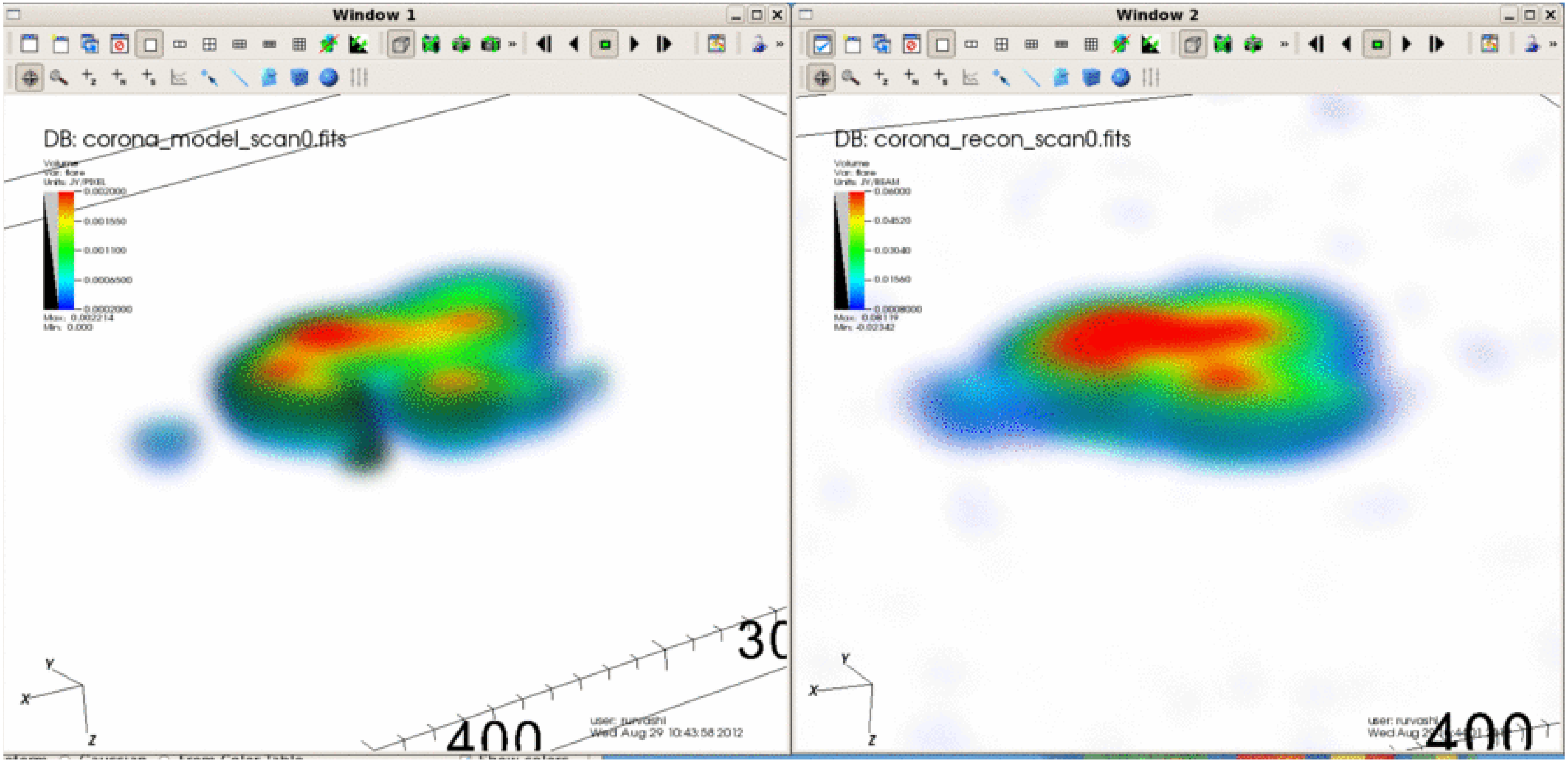
Time 1

Time 2



Dominant Errors : Frequency dependent structure at the largest spatial scales.

Dynamic Coronal Magnetogram : Reconstruction



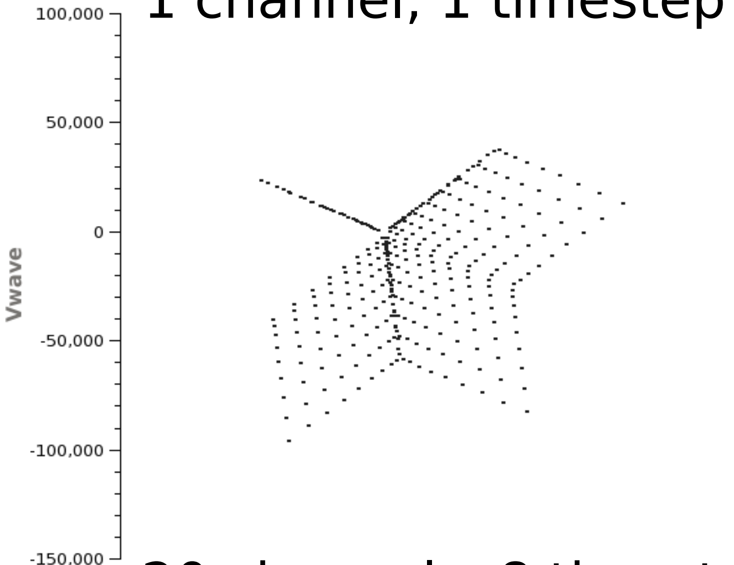
Reconstruction from 8 VLA C-config snapshots over 4 hours between 5-15 GHz

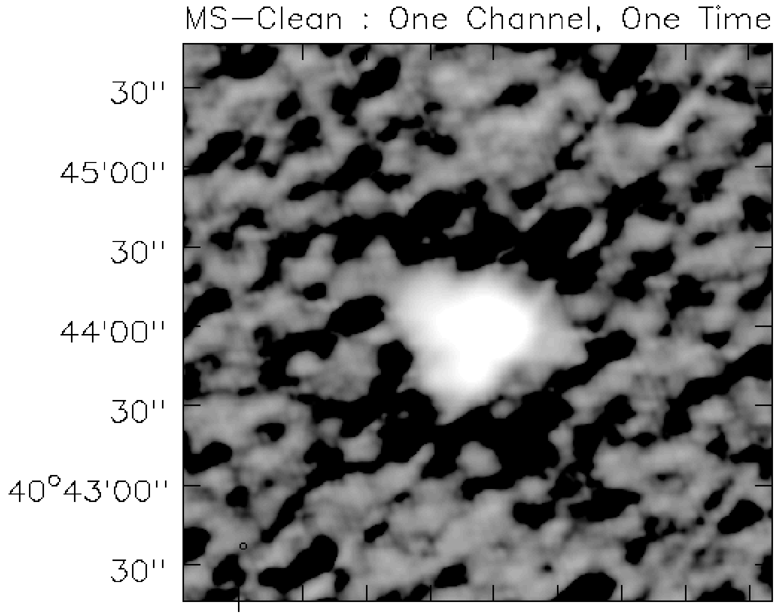
- 6 spatial scales [0,10,20,40,60,80], linear spectral and time variation

(*at the time of this run, a bug was present in how cross-terms were computed)

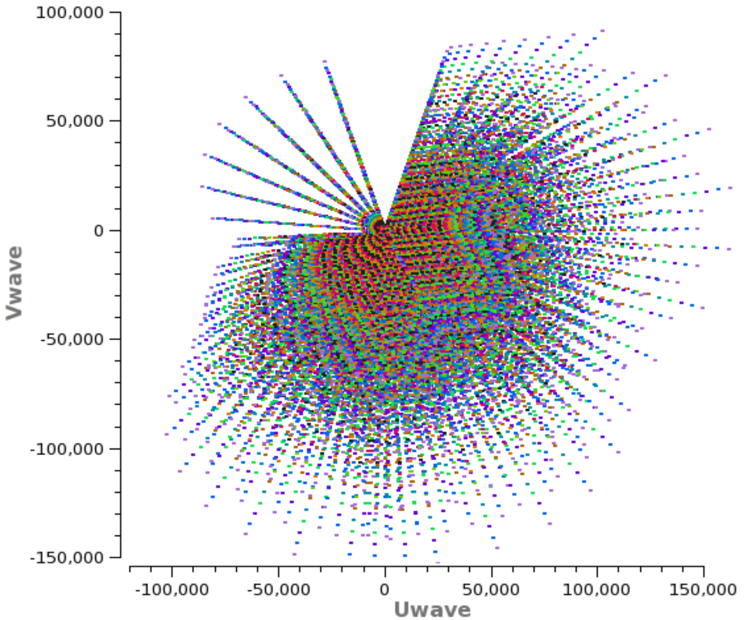
Dynamic Coronal Magnetogram : Imaging the average intensity

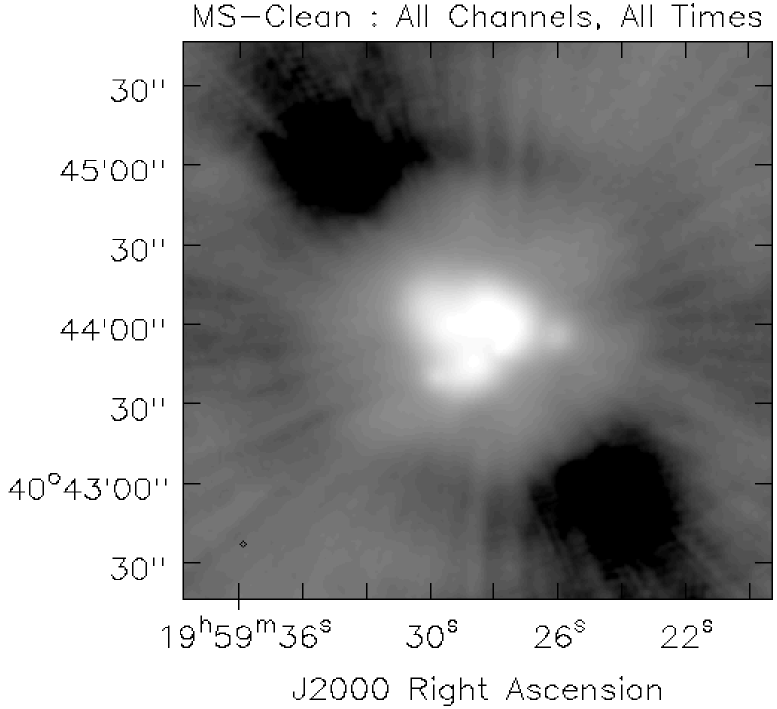
1 channel, 1 timestep





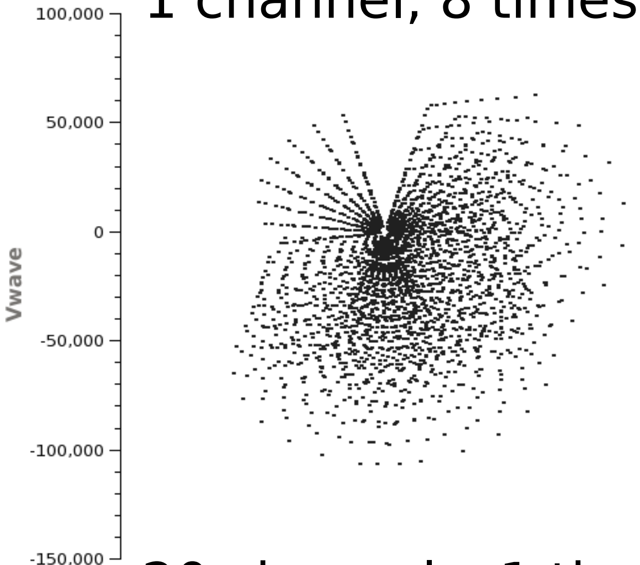
20 channels, 8 timesteps

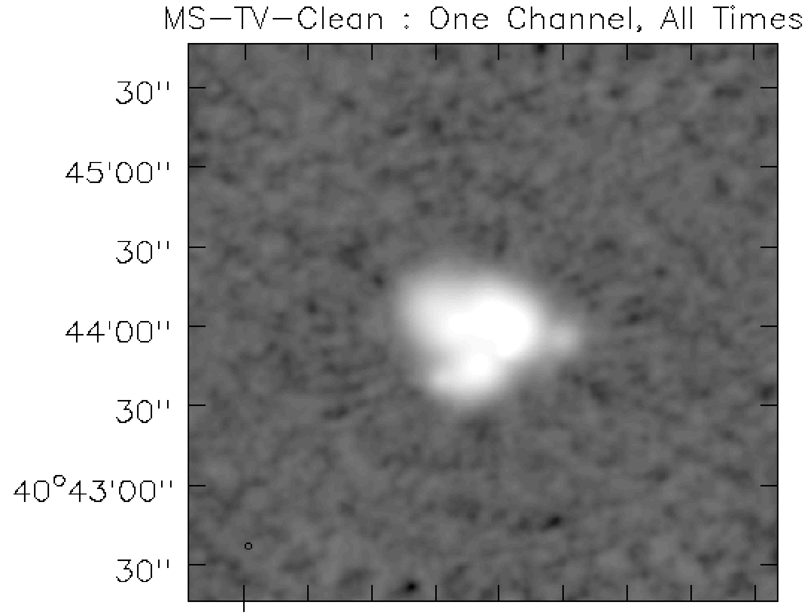




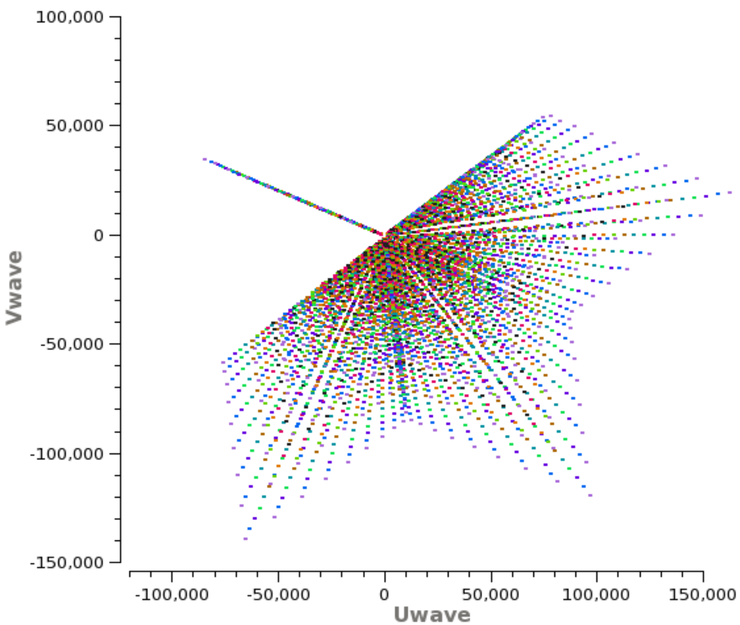
Dynamic Coronal Magnetogram : Imaging the average intensity

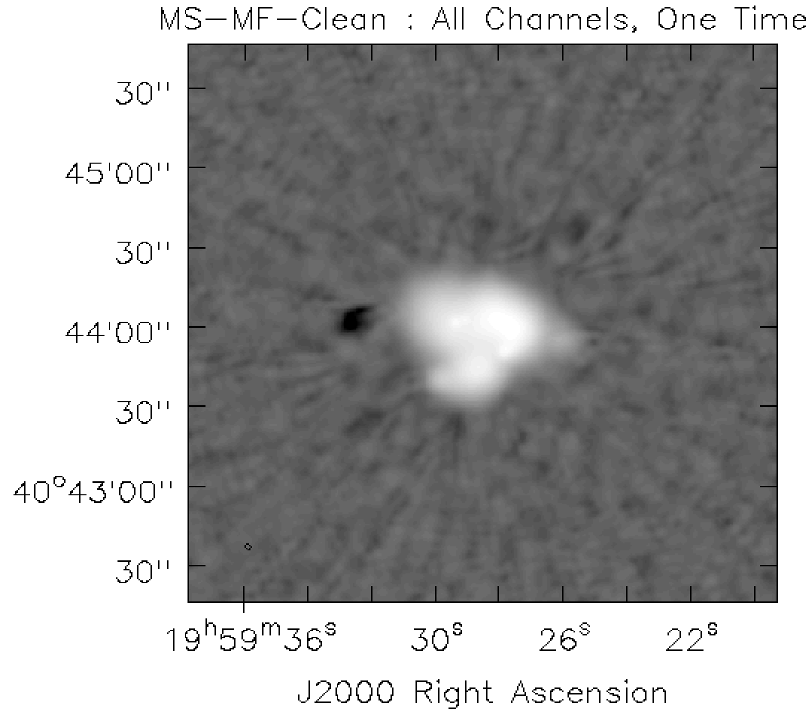
1 channel, 8 timesteps





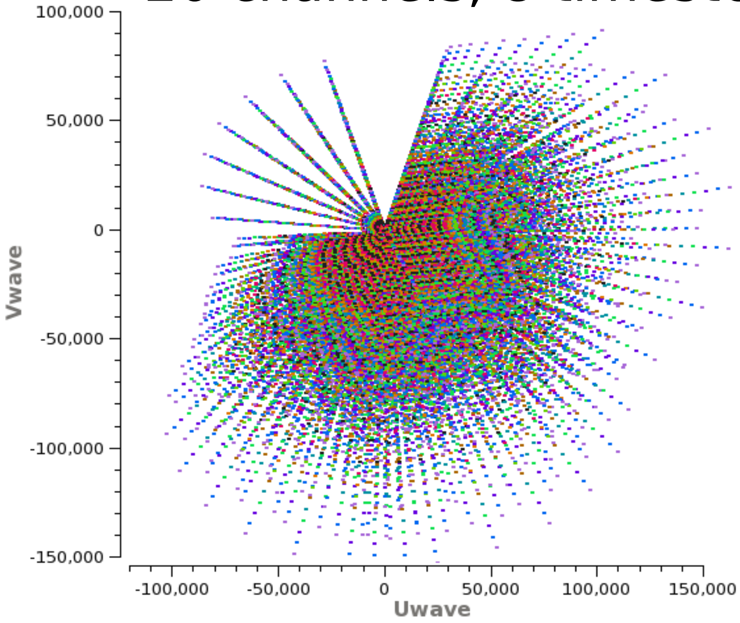
20 channels, 1 timestep

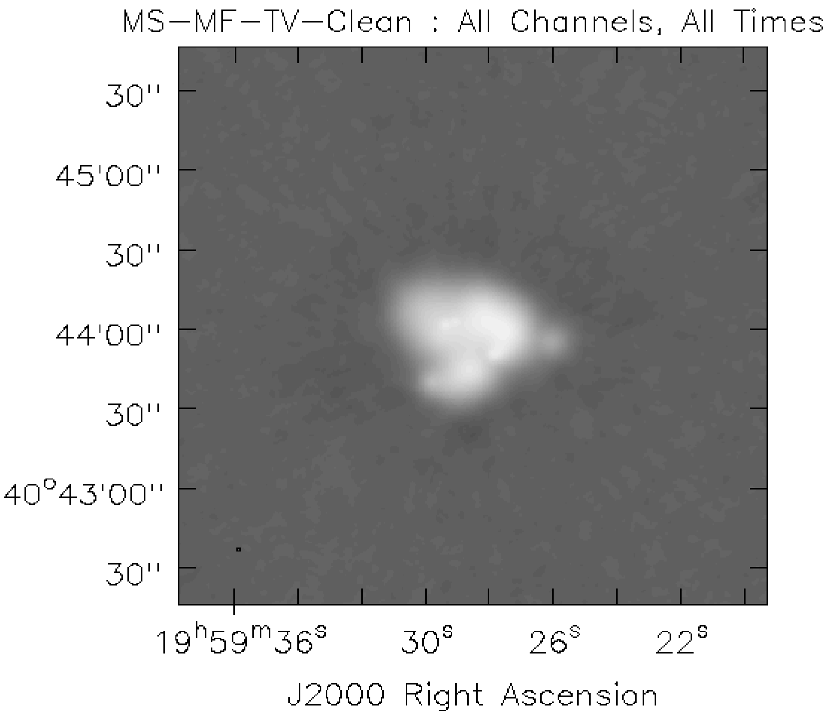




Dynamic Coronal Magnetogram : Imaging the average intensity

20 channels, 8 timesteps





The model separates the varying and invariant parts of the signal.

=> Useful for reconstructing invariant (average) structure

=> (In some cases) you can reconstruct the frequency-structure and time-variability accurately enough for astrophysical interpretation.

Variable Radio Sources in the Orion Nebula Cluster

VLA A-config, 1GHz chunks
centered at 4.7 and 7.3 GHz

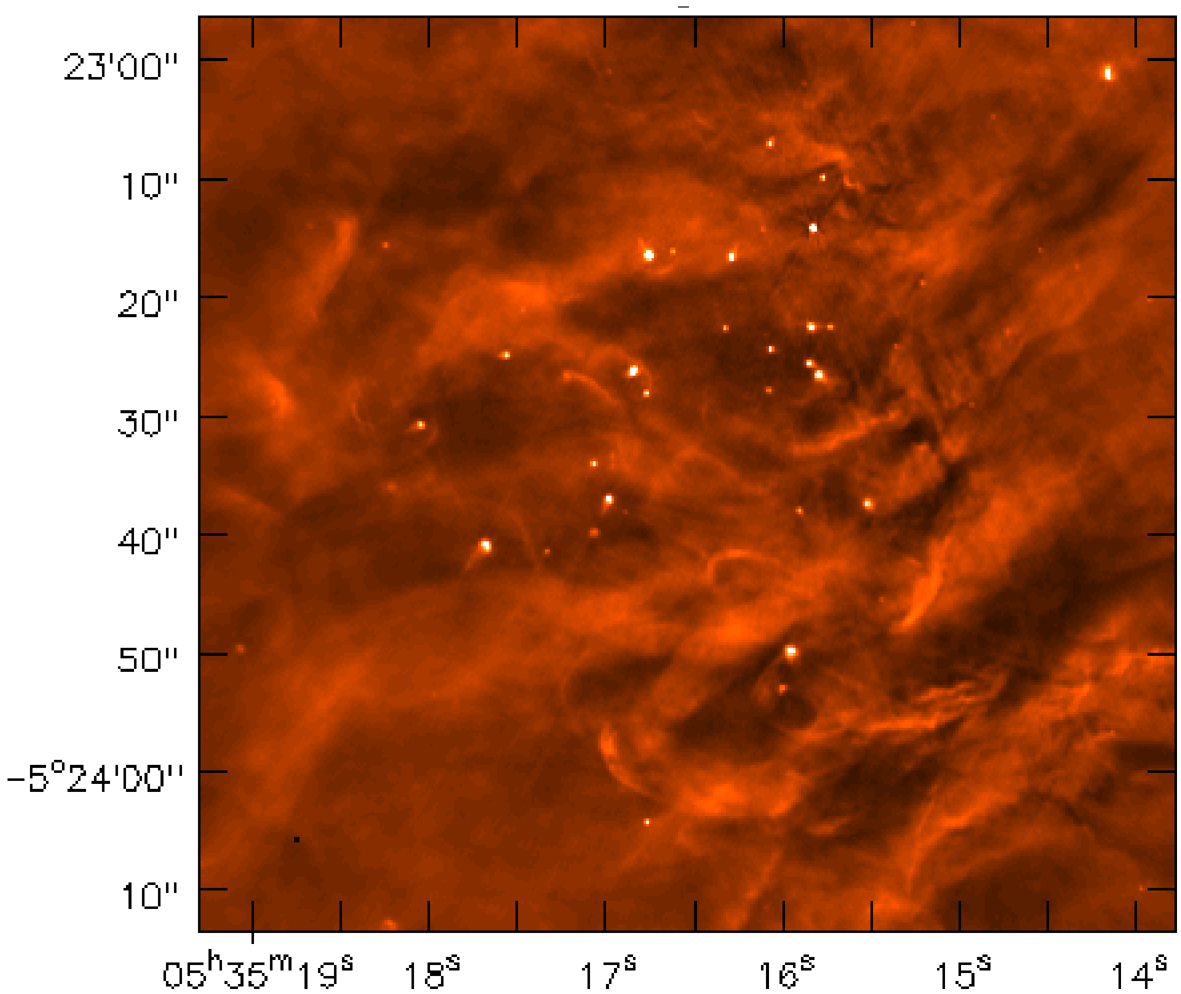
5 epochs, a day or so apart
6hrs per epoch.

Forbrich et al, ApJ, 2016,
Forbrich et al (in prep).

Variability seen across epochs, as
well as within each epoch

Few 10s of % to several times.

How much of this is real ?



- Imaging fidelity limits (from subsets of the data + MS-Clean) ?
- PB-rotation effects ?
- Few artifacts around strong sources... can be improved ?

=> Compare imaging in time-slices with TV-Imager

Variable Radio Sources in the Orion Nebula Cluster

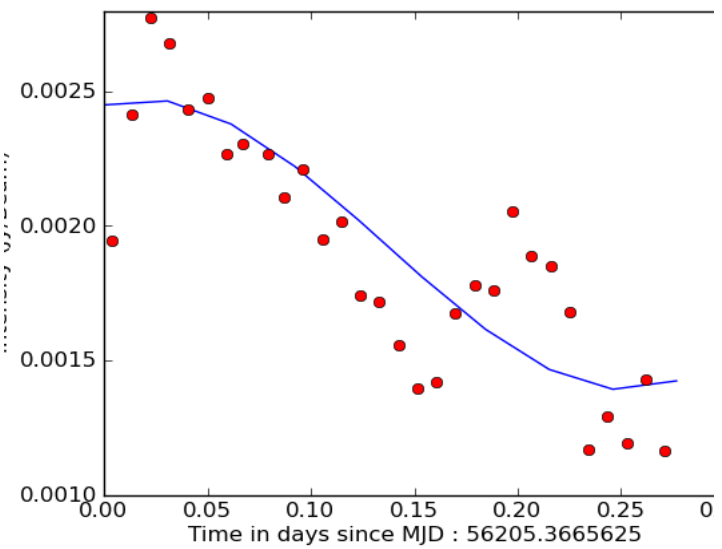
Un-Resolved sources, within 1 epoch.

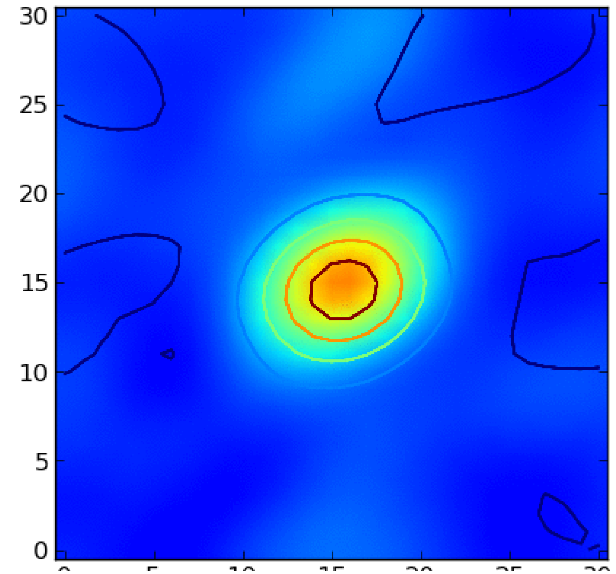
Imaging 'Noise' ?

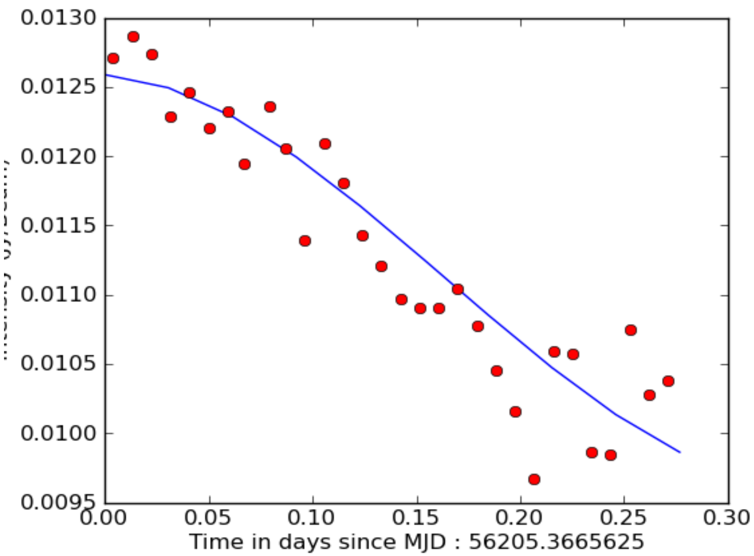
+

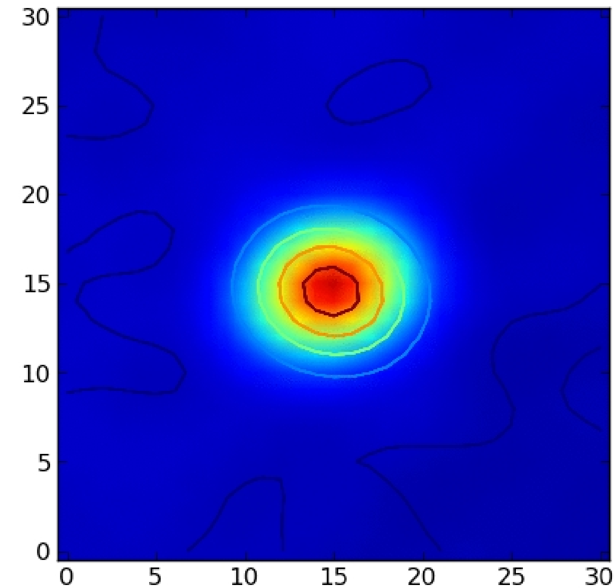
Time Variability Signal

(Real variability -vs- that due to PB rotation ?)









Variable Radio Sources in the Orion Nebula Cluster

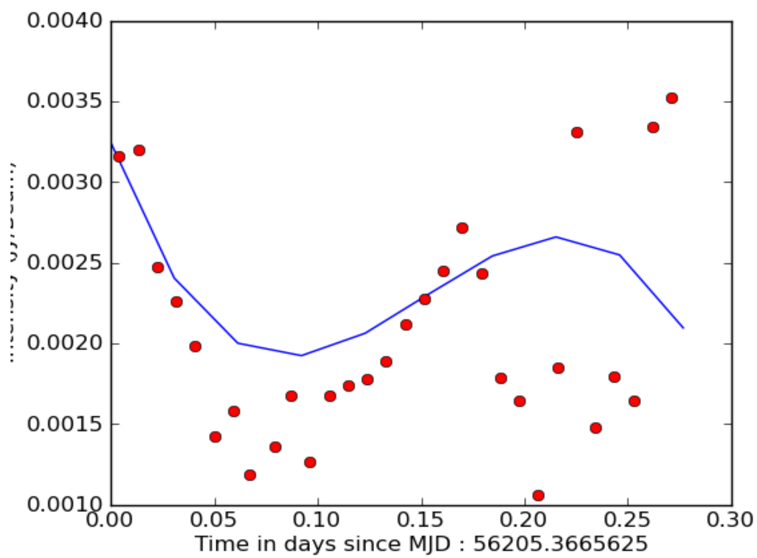
Resolved sources, within 1 epoch.

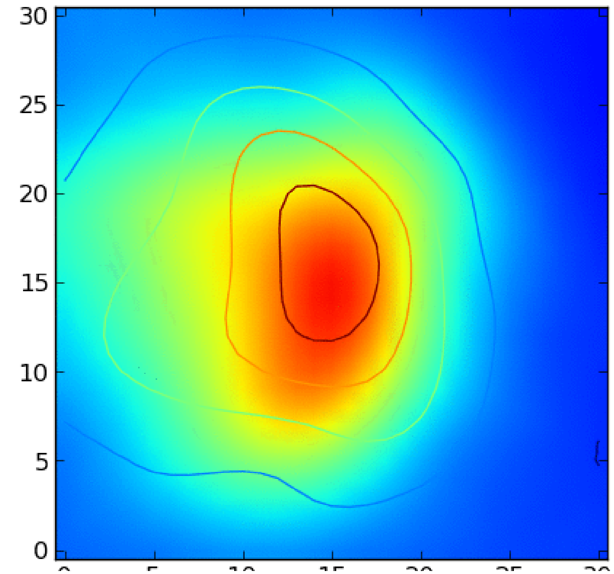
Shape changes

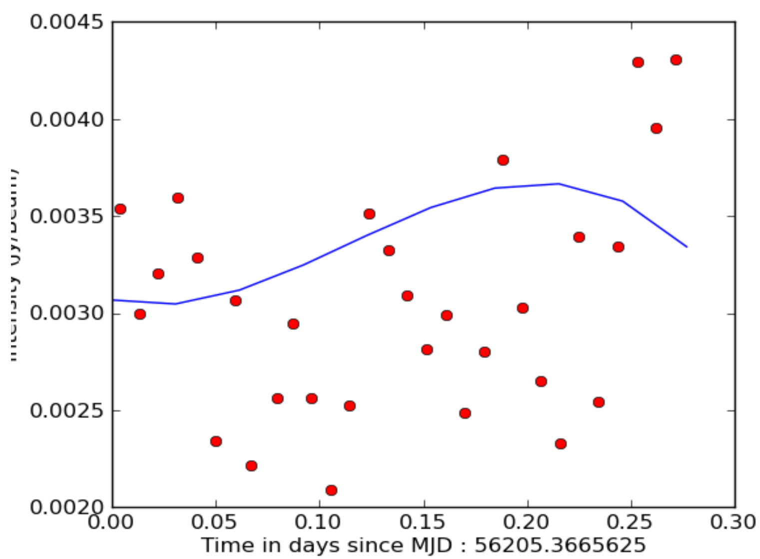
Real or Not ?

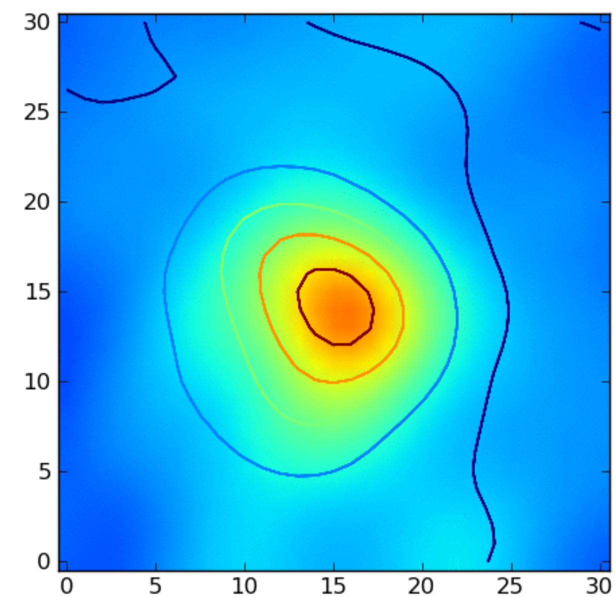
Compact sources embedded in rich extended structure

=> short scans may have insufficient uv-coverage for perfect imaging







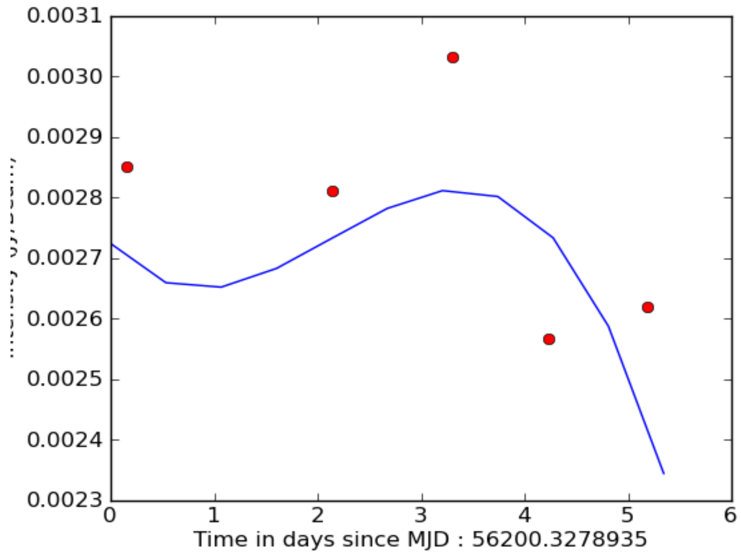


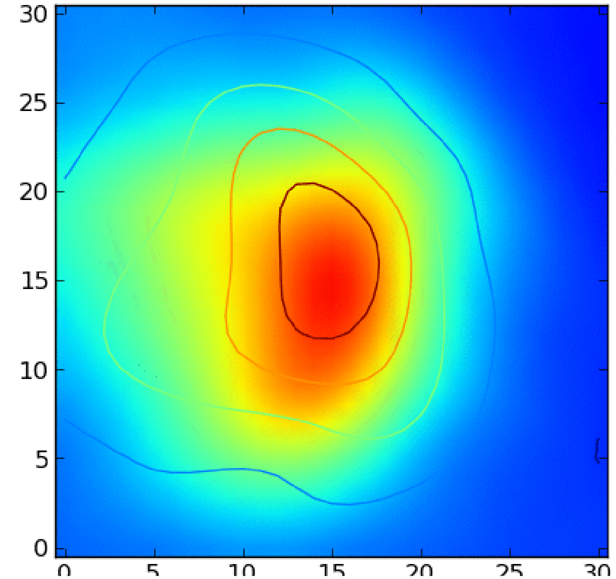
Variable Radio Sources in the Orion Nebula Cluster

Variability across epochs (days)

Variability can be detected from higher order term Images.

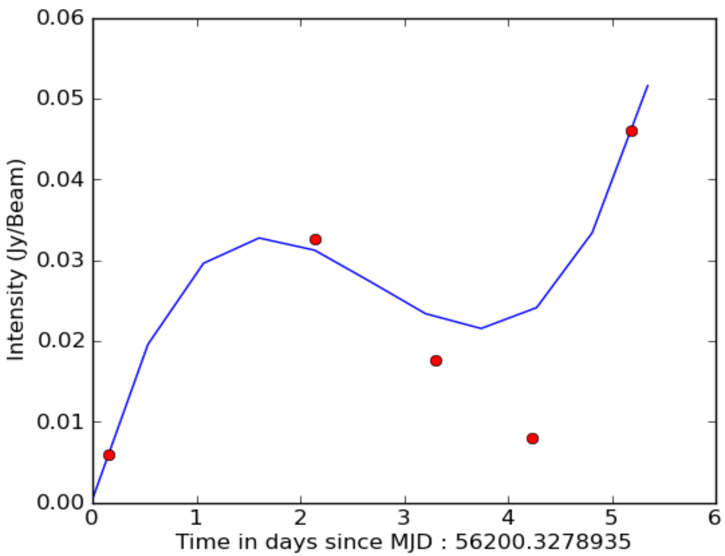
(Need more terms to truly model it and fix artifacts.)

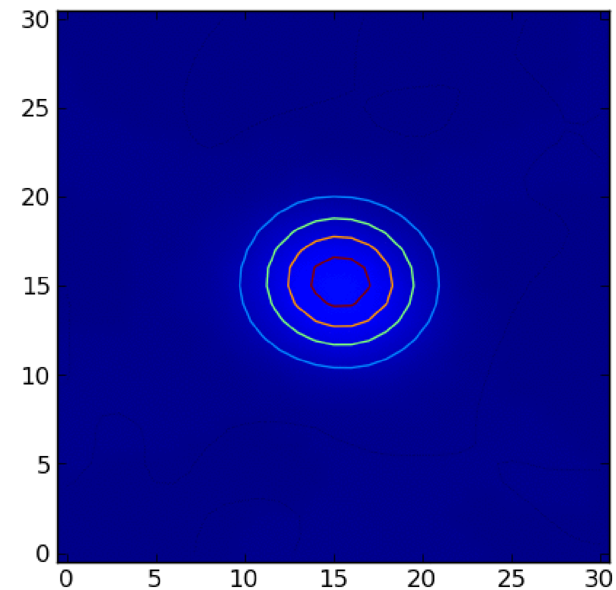




For this dataset, only the compact sources showed variability (as expected)

=> Algorithm does not produce fake variability





Variable Radio Sources in the Orion Nebula Cluster

→ Detecting variability : Imaging uncertainty (vs) actual variability

→ What timescales over which to trust variability ?

→ Depends on field and uv-cov and algorithm...
→ Try something better than MS-Clean with snapshot uv-coverage

→ A joint method 'ties' together timesteps via the parameterized model

→ Do artifacts go down ?

→ Yes, but only when all the variability is modeled with high order terms.

→ Noise everywhere goes up due to overfitting for most sources.
→ Can use location-dependent nterms (but how to automate?)

→ Apply joint wideband and time-variability reconstruction (after fixing bug).

→ Need A-Projection gridding to account for instrumental variability before imaging for TV (especially for far-out sources and Stokes V).

→ TV-Imager will not handle spiky transients , but other ideas exist (Wenger et al, 2014).

Summary

→ Time Domain Science is increasing in popularity.

→ Traditional methods of imaging at short timescales are unlikely to suffice for weaker source populations and complicated structures

(Justification is similar to why it's good to use a joint wideband sky model for continuum image reconstruction)

→ With multi-term algorithms, it will be possible to

→ Detect variability while benefiting from the combined data

→ Reduce (and eliminate) artifacts if all the structure is modeled

→ Solve for spectral and time-variability information together

→ Achieve this with less computing than the traditional methods

→ Eliminate instrumental sources of variation (PB effects) via A-Projection gridding before doing the model reconstruction

A note about software – Refactored CASA Imager

- Re-write of the application layer and interfaces (i.e. the plumbing)
- Gridders and Image domain deconvolvers are the same as before.
- Synchronized controls across algorithms and modes
- Parallelization of the major cycle (for continuum and cube imaging)

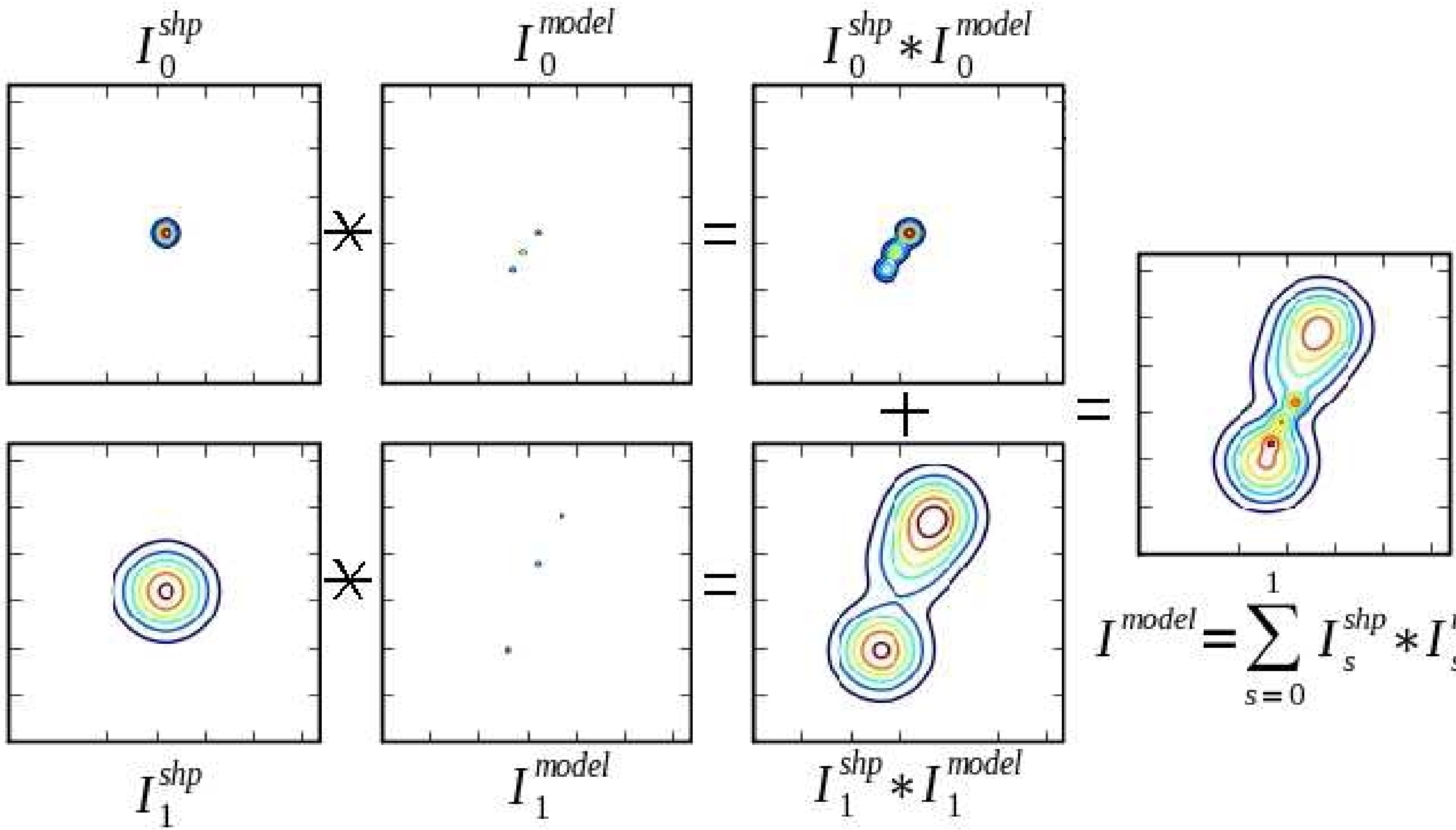
```
paramList = ImagerParameters(vis=”xx”,imagename=”yy”,...... )

imager = PySynthesisImager(params=paramList)
          # or   PyParallelContSynthesisImager(params=paramList)

imager.initializeImagers()
imager.initializeNormalizers()
imager.setWeighting()
imager.initializeDeconvolvers()
imager.initializeIterationControl()

imager.makePSF()                         # grid weights to make psf
imager.runMajorCycle()                   # grid data to make dirty image

while ( not imager.hasConverged() ):
    imager.runMinorCycle()               # run image reconstruction algorithm
    imager.runMajorCycle()               # compute residual image

imager.restoreImages()
```

[Available in CASA v4.6 and later]

Extended emission : Multi-Scale CLEAN

Multi-Scale Sky Model : Linear combination of atoms at different scale sizes

$I^{sky} = \sum_s \left[I_s^{shp} * I_s^m \right]$ where I_s^{shp} is a blob of size 's' and $I_s^m = \sum_i a_{s,i} \delta(l - l_{s,i})$



$$I^{model} = \sum_{s=0}^{1} I_s^{shp} * I_s^{model}$$