

Error Recognition and Image Analysis

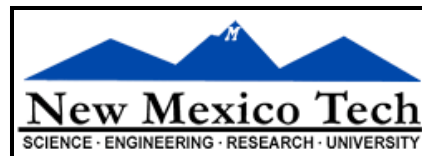
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With help from:

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Justin Linford, Ed Fomalont



Thirteenth Synthesis Imaging Workshop
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INTRODUCTION

- Why are these two topics – ‘Error Recognition’ and ‘Image Analysis’ in the same lecture?
 - **Error recognition** is used to determine defects in the (visibility) data and image during and after the ‘best’ calibration, editing, etc.
 - **Image analysis** describes the many ways in which useful insight, information and parameters can be extracted from the image.
 - **non-imaging analysis** describes how to extract information directly from the (u,v) data
- Perhaps these topics are related to the reaction one has when looking at an image after ‘good’ calibration, editing, self-calibration, etc.
- If the reaction is:

OBVIOUS IMAGE PROBLEMS

VLBA observations of SgrA* at 43 GHz

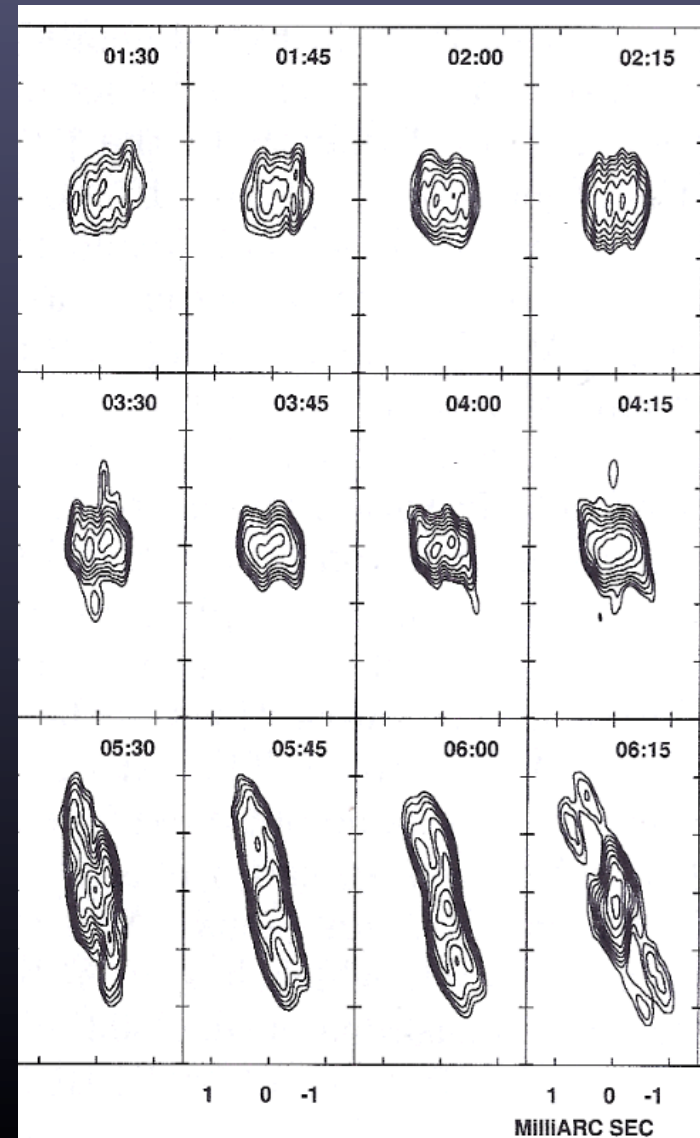
This can't be right. Either SgrA* has
bidirectional jets that nobody else
has ever seen or:

Clear signs of problems:

Image rms > expected rms

Unnatural features in the image

How can the problems be found
and corrected?



Miyoshi et al. 2005

milliarcsec

HIGH QUALITY IMAGES

Reality

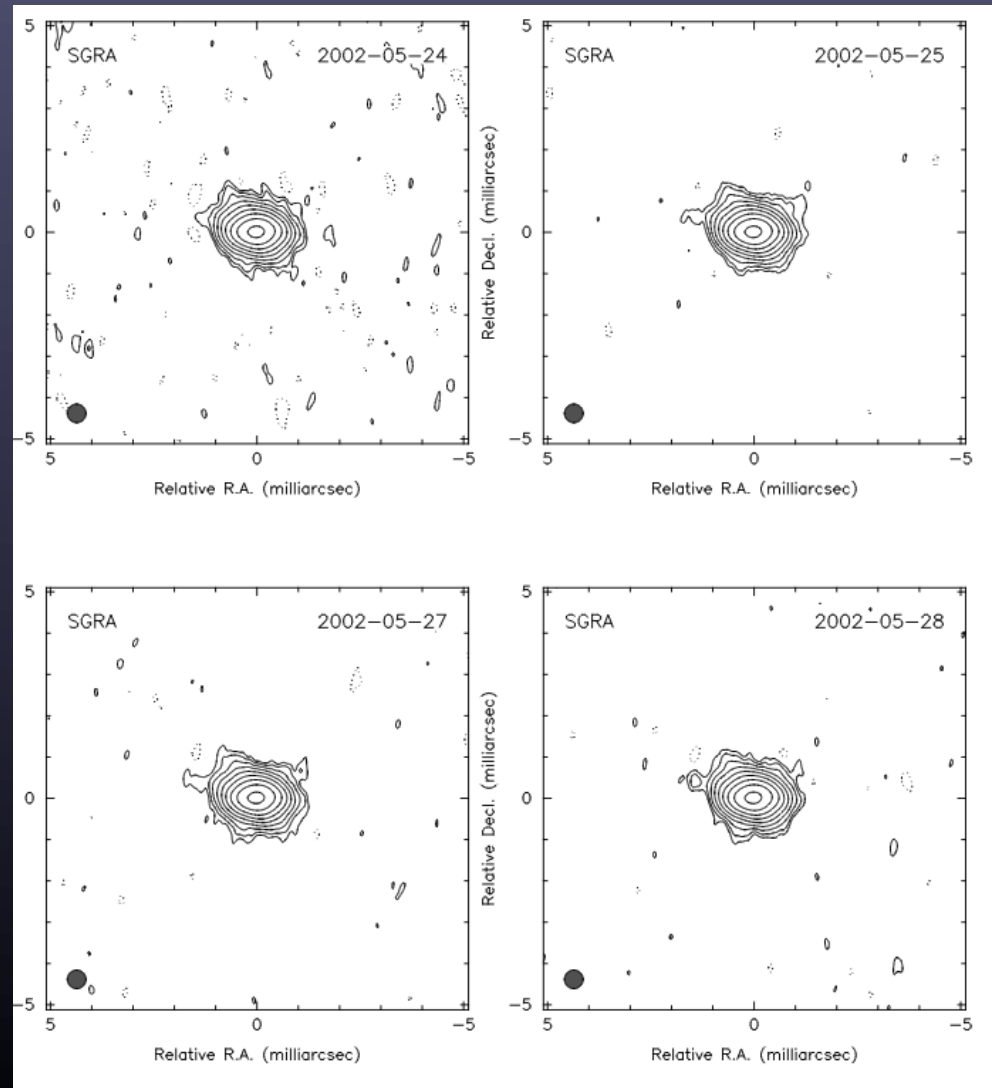
With care we can obtain good images.

What were defects?

Two antennas had ~30% calibration errors at low elevations.

This part of the lecture.

How to find the errors and remove them.



milliarcsec

GENERAL PROCEDURE

We assume that the data have been edited and calibrated reasonably successfully (earlier lectures) including self-calibration if necessary.

So, the first serious display of an image leads one—

- to inspect again and clean-up the data repeating some or all of the previous reduction steps.
 - removal of one type of problem can reveal next problem!
- once all is well, proceed to image-analysis and obtaining scientific results from the image.

But, first a digression on data and image display. First:
Images

IMAGE DISPLAYS (1)

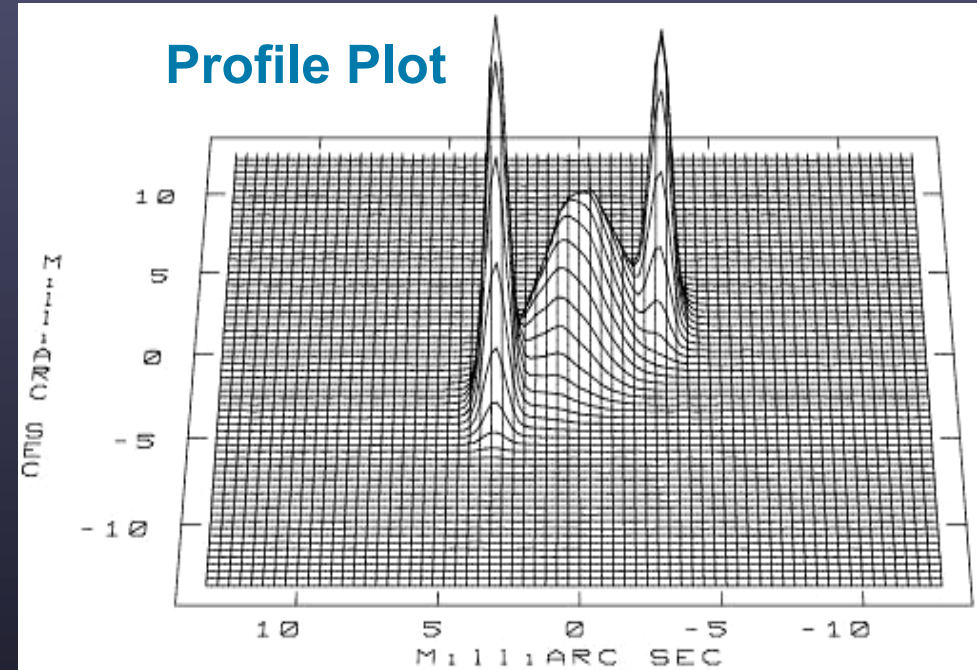
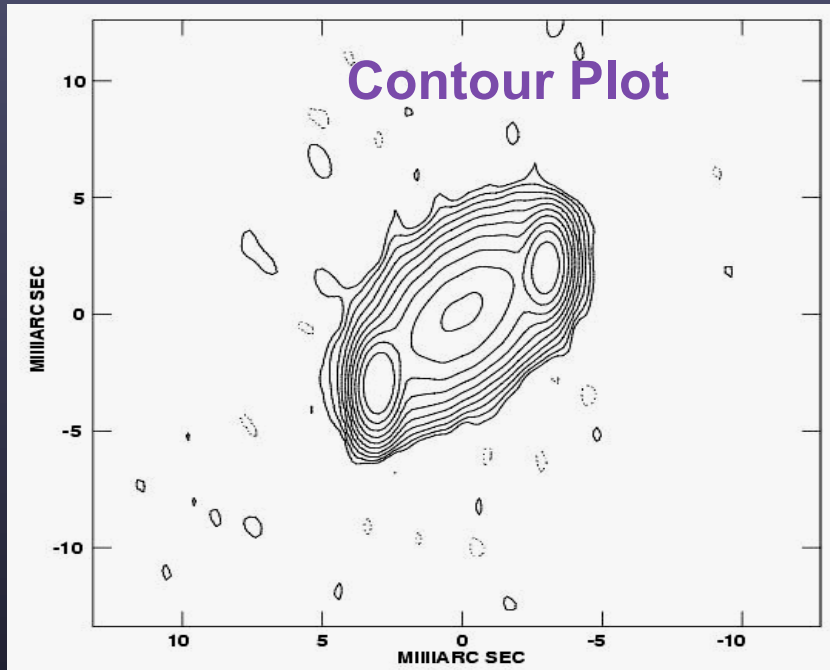
Pixel values																																		
	235						245						255						265						275									
287	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
285	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
283	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
281	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
279	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
277	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
275	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
273	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
271	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
269	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
267	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
265	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
263	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
261	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
259	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
257	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
255	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
253	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
251	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
249	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
247	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
245	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
243	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
241	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
239	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
237	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
235	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
233	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
231	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
229	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
227	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
225	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
223	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Digital image

Numbers are
proportional to
the intensity

Old School

IMAGE DISPLAYS (2)

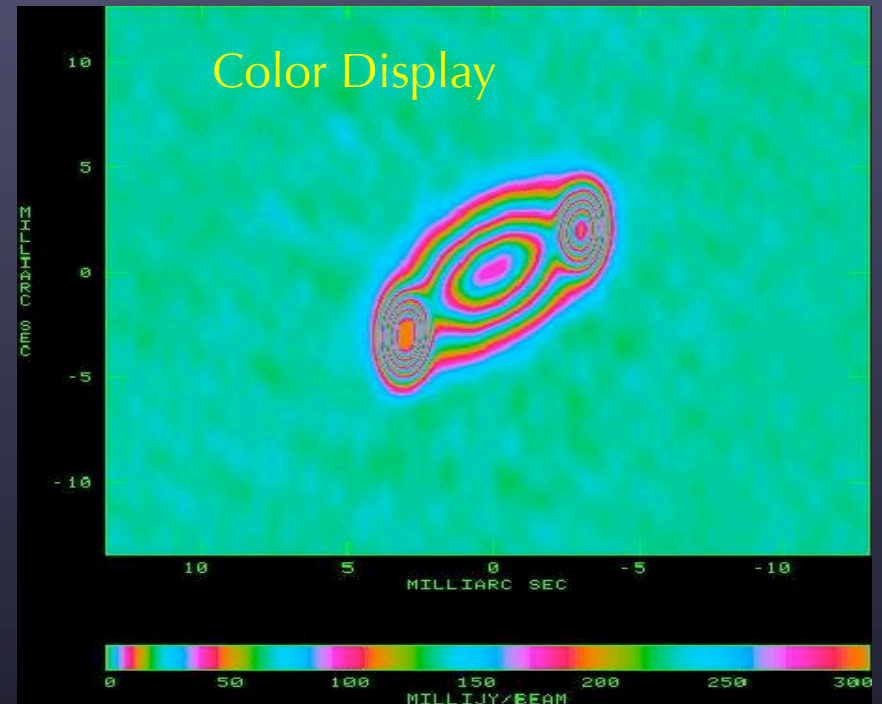
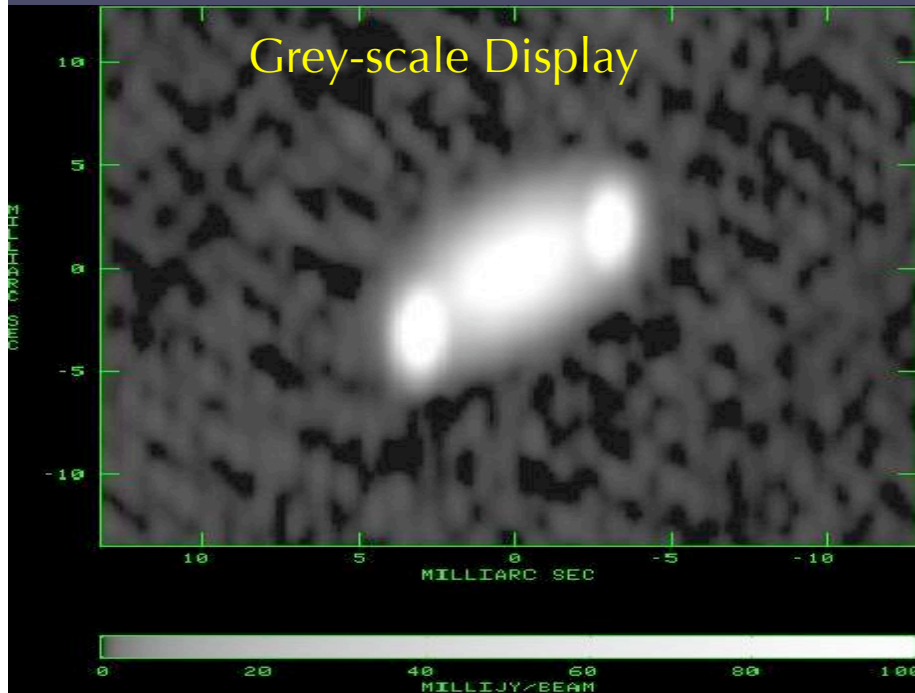


These plots are easy to reproduce and print

Contour plots give good representation of faint emission.

Profile plots give a good representation of the bright emission.

IMAGE DISPLAYS (3)



TV-based displays are most useful and interactive:

Grey-scale shows faint structure, but not good for high dynamic range and somewhat unbiased view of source
Color displays more flexible; e.g. pseudo contours

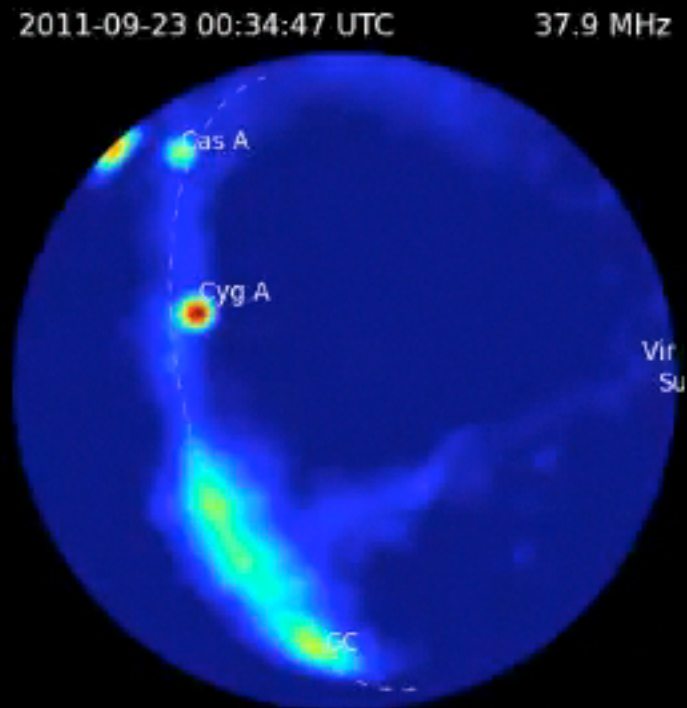
Movies and Radio Frequency Interference (RFI)

Great pressure from wireless devices
Need to "free-up" 500 MHz of spectrum
Gigabit networks
Dynamic allocation/Shared use of spectrum
Passive use is still useful!

Likely changes:

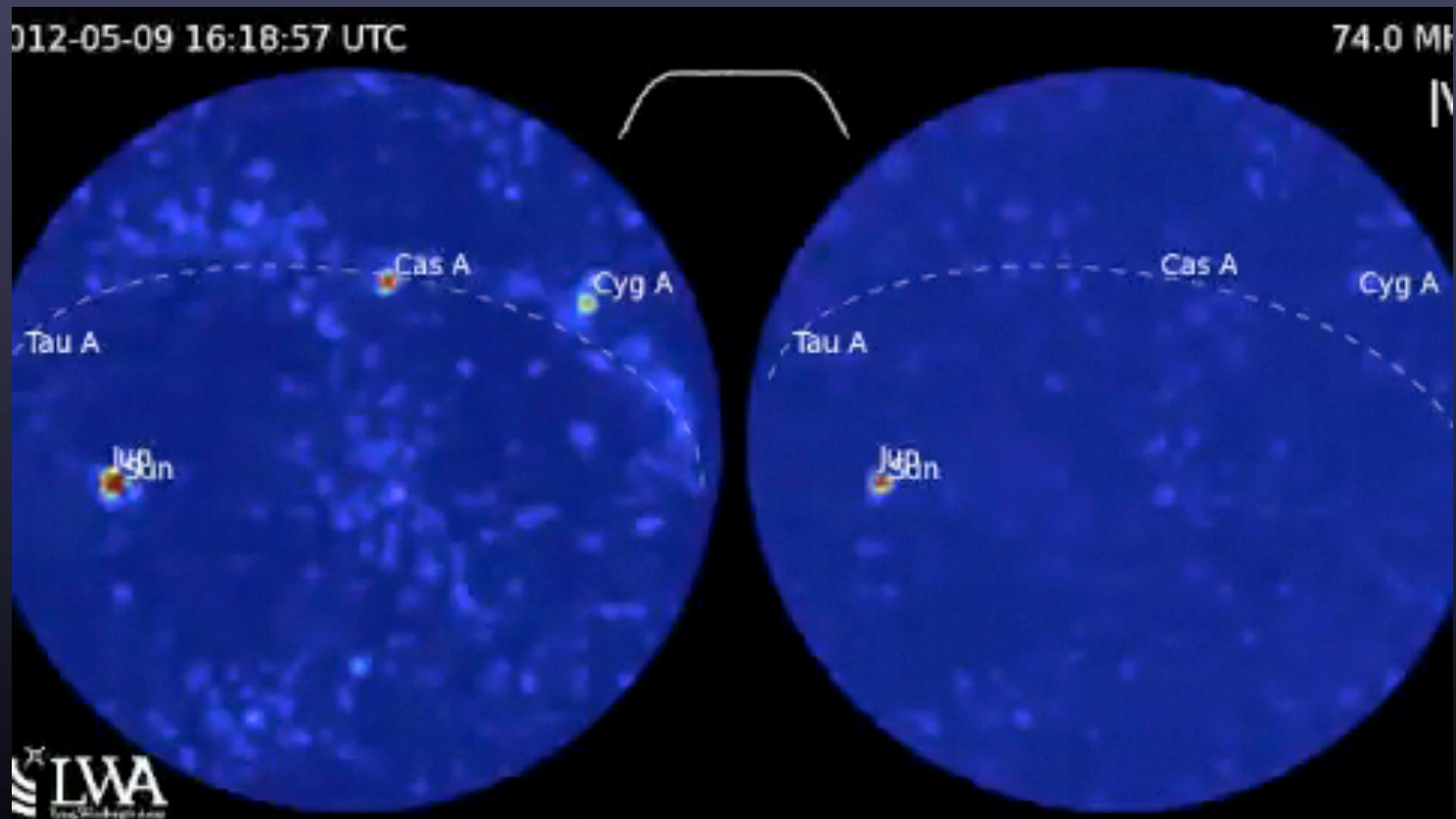
1215 – 1300 MHz mobile comm.
1675 – 1710 MHz mobile comm.
1755 – 1850 MHz mobile comm.
2155 – 2200 MHz mobile comm
4200 – 4220 MHz altimeters
4380 – 4440 MHz altimeters
5925 – 7250 level-probing-radar
14000 – 14500 air to ground
15400 – 15700 radar
76000 – 77000 automobile radar

LWA1 with ~210 antenna stands



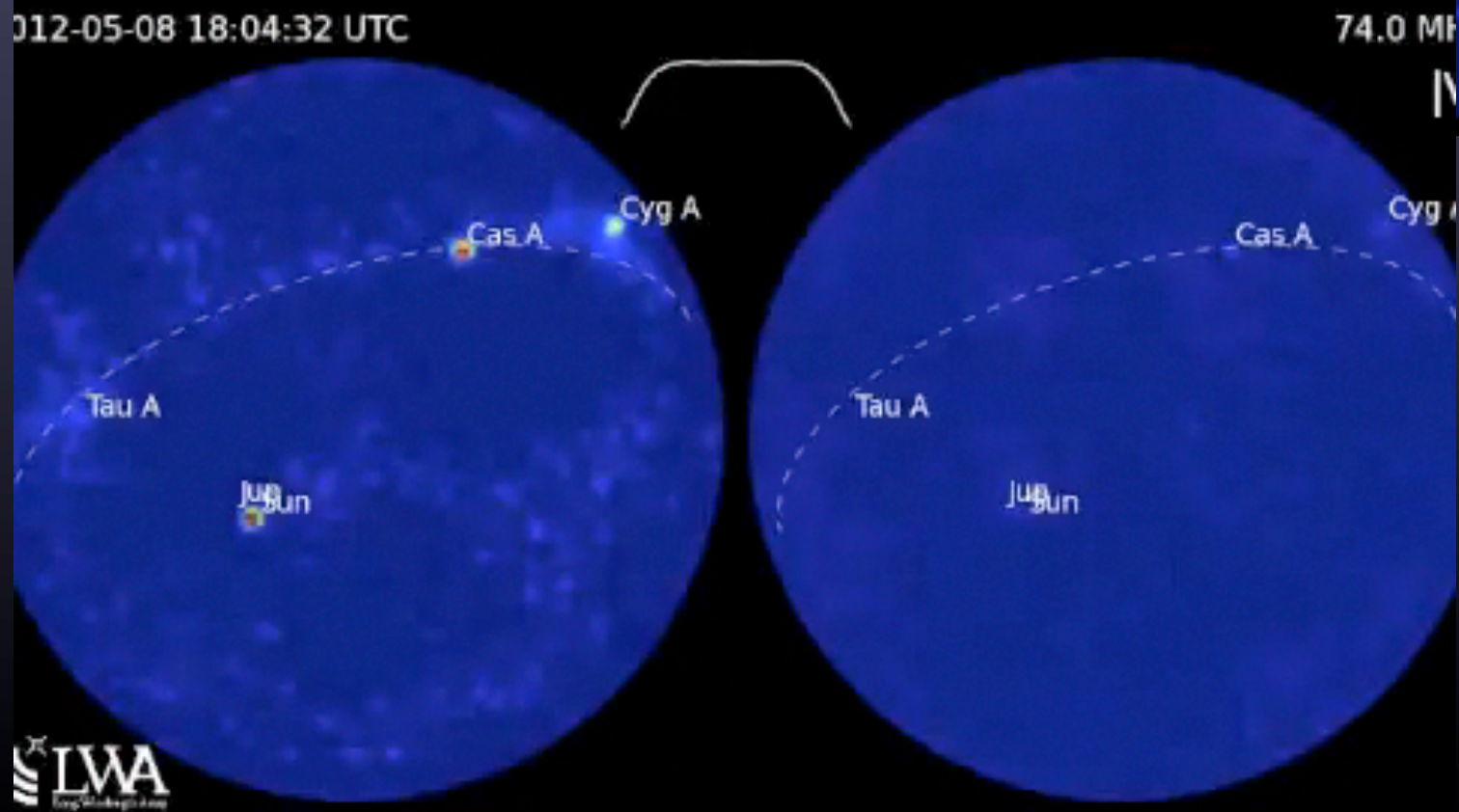
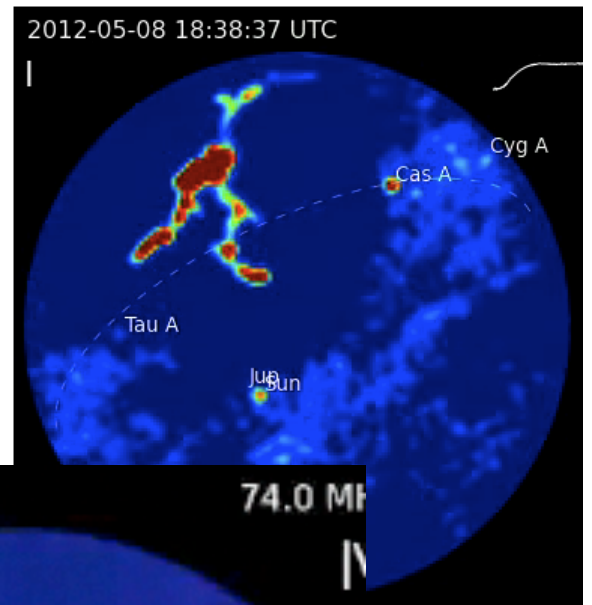
Movies and Solar Interference

Heading into Solar Maximum so watch out for the Active Sun



Lightning

Thunderstorm season on the Plains ...

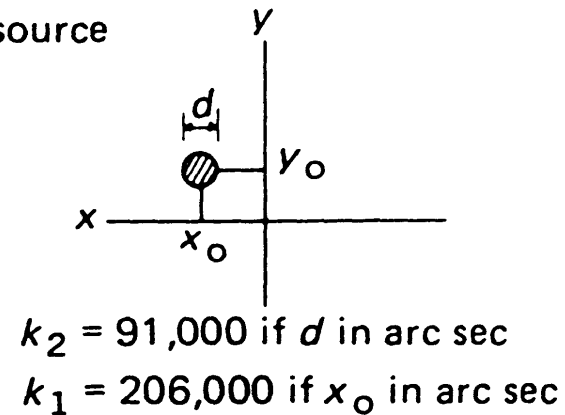
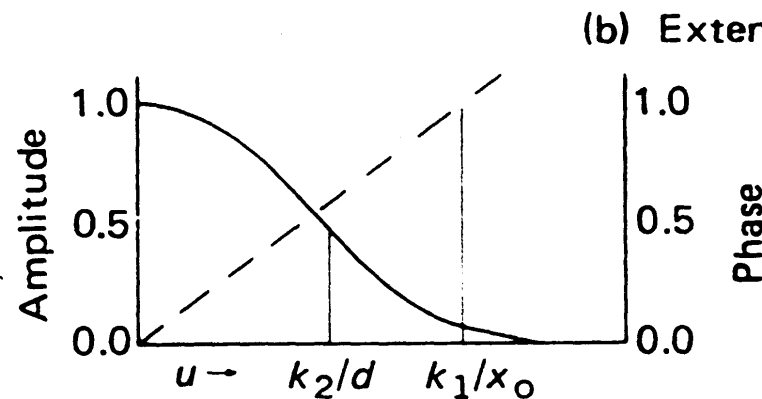
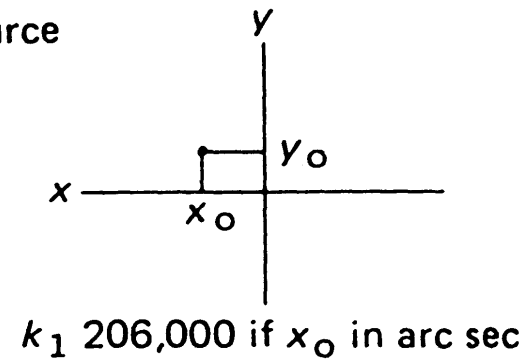
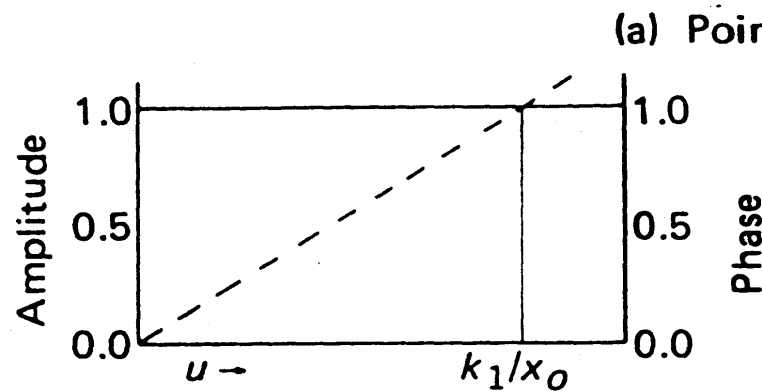


Visibility $\leftarrow F \rightarrow$ Brightness

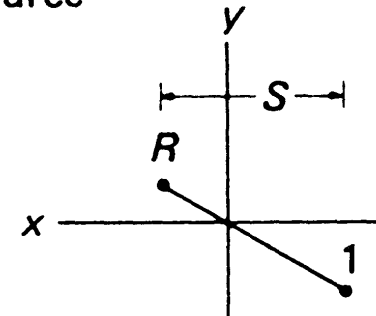
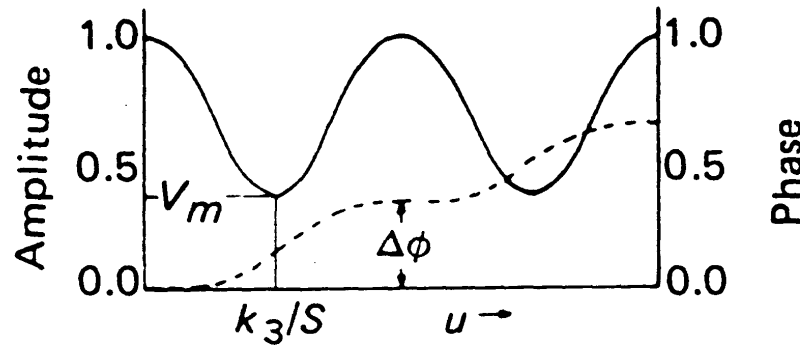
12

Visibility function

Brightness distribution



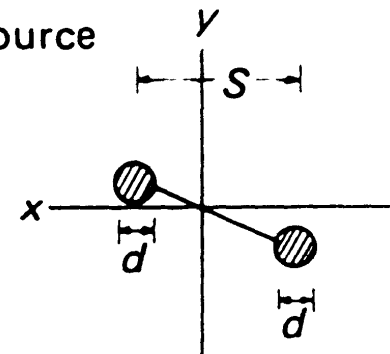
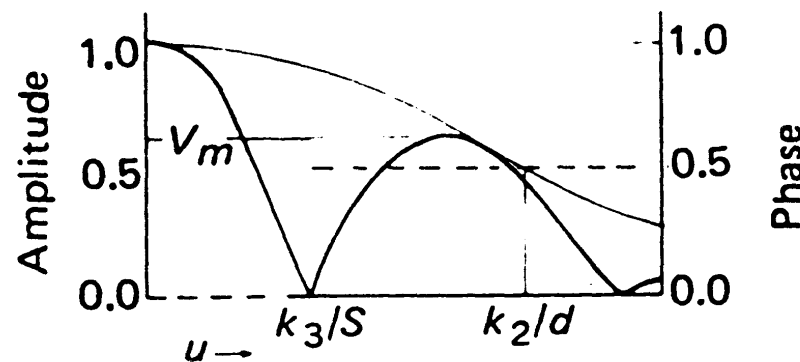
(c) Point double source



$$k_3 = 103,000 \text{ if } S \text{ in arc sec}$$

$$V_m = \frac{R - 1}{R + 1} ; \Delta\phi = \frac{1}{1 + R}$$

(d) Extended double source



$$k_3 = 103,000 \text{ if } S \text{ in arc sec}$$

$$k_2 = 91,000 \text{ if } d \text{ in arc sec}$$

$$V_m \approx \exp \left\{ -3.57 \left(\frac{d}{S} \right)^2 \right\}$$

DATA DISPLAYS(1)

List of (u,v) Data

Source= J0121+11		Freq= 8.434858511		Sort= TB			1	RR		
Vis #	IAT	Ant	Su	Fq	U(klam)	V(klam)	W(klam)	Amp	Phas	Wt
2191	0/22:35:08.22	5- 6	1	0	94220	23776	100371	0.614	-16	1.0000
3971	0/22:43:43.34	5- 6	1	0	97659	24517	96844	0.508	-13	1.0000
6431	0/23:07:05.15	5- 6	1	0	106307	26661	86632	0.154	17	1.0000
6611	0/23:07:14.98	5- 6	1	0	106364	26677	86557	0.152	17	1.0000
6791	0/23:07:24.81	5- 6	1	0	106421	26692	86483	0.150	18	1.0000
6971	0/23:07:34.64	5- 6	1	0	106477	26708	86408	0.148	19	1.0000
7151	0/23:07:44.47	5- 6	1	0	106534	26724	86333	0.146	19	1.0000
7331	0/23:07:54.30	5- 6	1	0	106591	26739	86259	0.144	20	1.0000
7511	0/23:15:06.84	5- 6	1	0	109027	27438	82930	0.101	74	1.0000
7691	0/23:15:16.67	5- 6	1	0	109081	27454	82854	0.101	75	1.0000
7871	0/23:15:26.50	5- 6	1	0	109135	27470	82777	0.102	77	1.0000
8051	0/23:15:36.33	5- 6	1	0	109189	27486	82701	0.102	78	1.0000
8231	0/23:15:46.16	5- 6	1	0	109243	27502	82624	0.103	79	1.0000
8411	0/23:15:55.99	5- 6	1	0	109297	27518	82547	0.104	81	1.0000
9701	0/23:31:02.36	5- 6	1	0	114020	29035	75322	0.260	134	1.0000
9791	0/23:31:06.29	5- 6	1	0	114040	29042	75290	0.261	134	1.0000
10301	0/23:31:29.88	5- 6	1	0	114156	29082	75098	0.266	134	1.0000
10861	0/23:39:02.08	5- 6	1	0	116320	29863	71379	0.348	139	1.0000
10951	0/23:39:06.01	5- 6	1	0	116339	29870	71346	0.348	139	1.0000
11171	0/23:39:15.84	5- 6	1	0	116384	29887	71264	0.350	139	1.0000

Very primitive display, but sometimes worth-while: e.g. , can search on e.g. Amp > 1.0, or large weight. Often need precise times in order to flag the data appropriately.

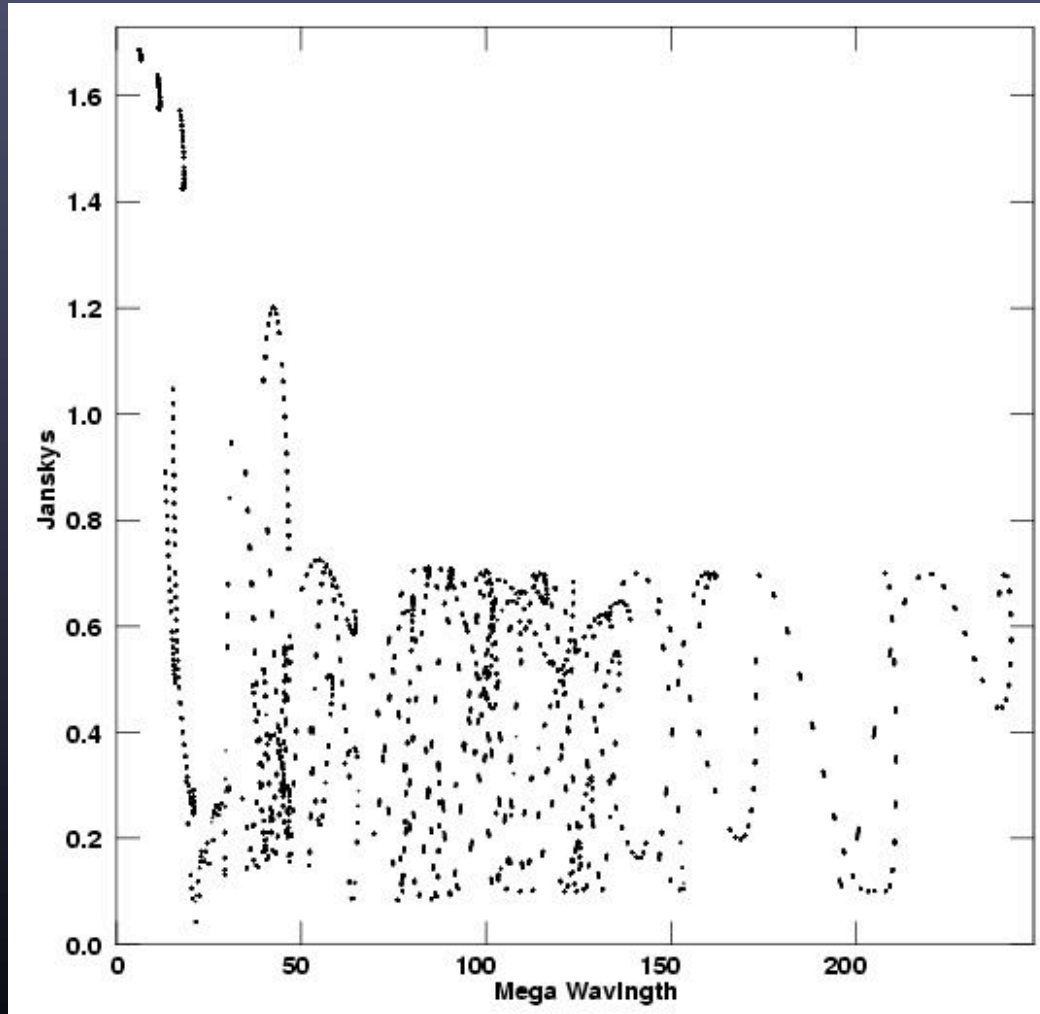
DATA DISPLAYS(2)

Visibility Amplitude versus Projected (u,v) spacing

General trend of data.
Useful for relatively strong
sources.

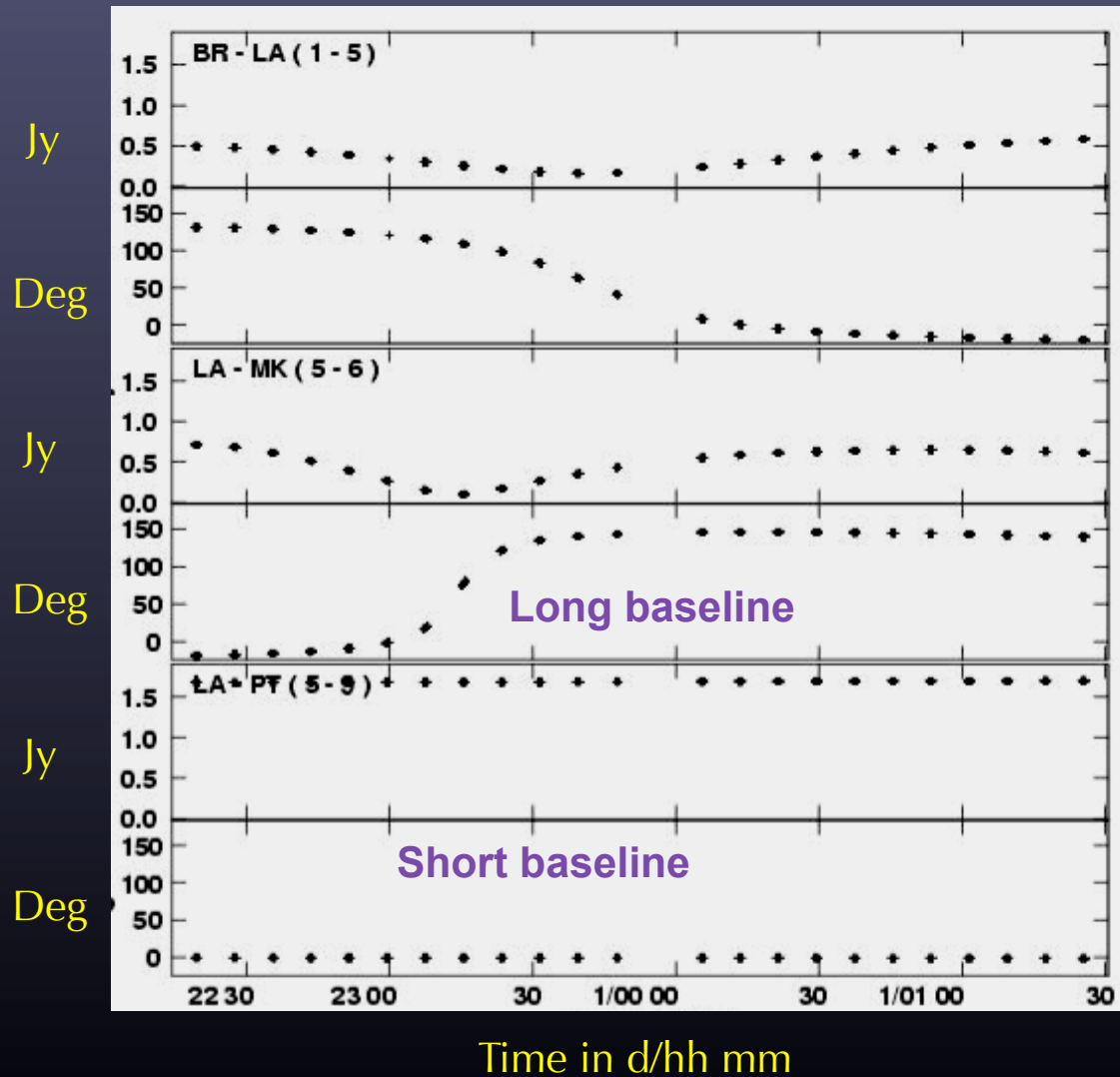
Triple source model. Large
component cause rise at
short spacings.

Oscillations at longer spacings
suggest close double.



Mega Wavelength

DATA DISPLAYS(3)



Visibility amplitude and phase versus time for various baselines

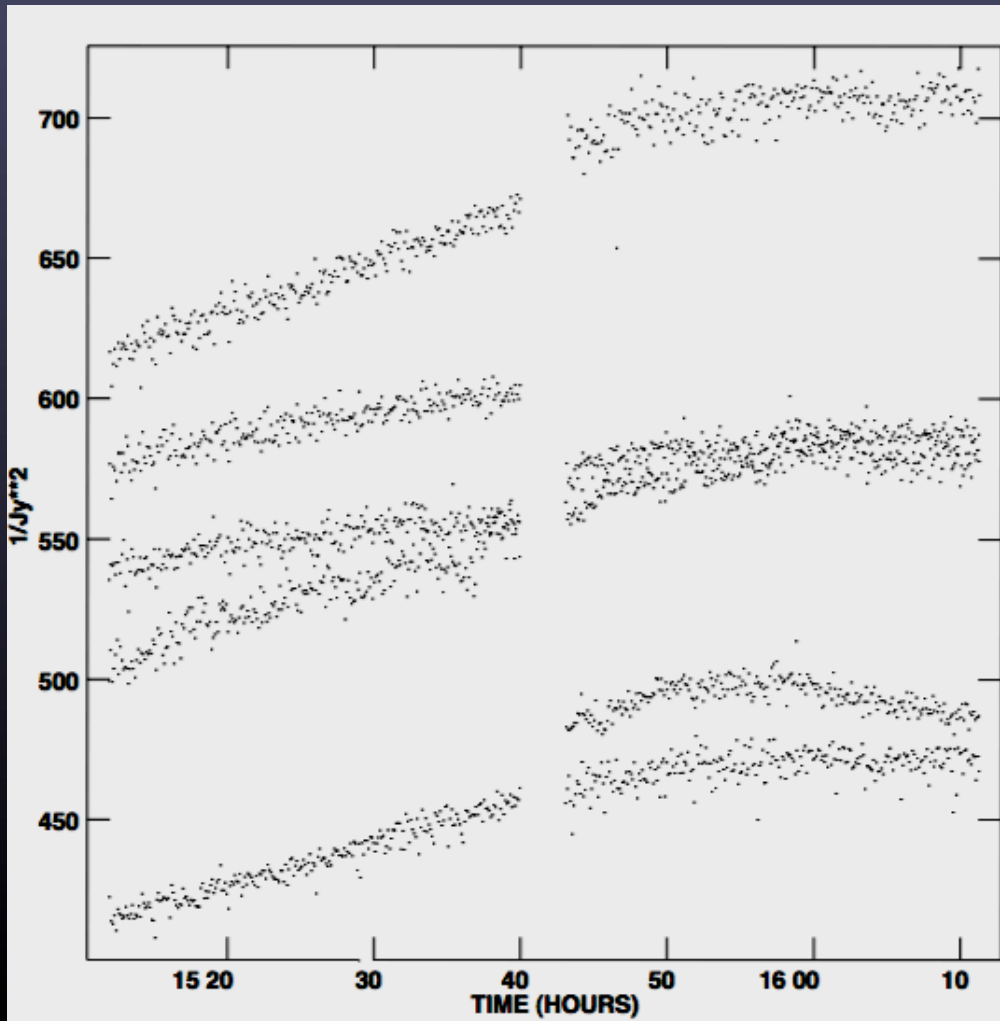
Good for determining the continuity of the data

Should be relatively smooth with time

Outliers are obvious.

DATA DISPLAYS(4)

Weights of antennas 4 with 5,6,7,8,9



All (u,v) data points have a weight. The weight depends on the antenna sensitivity, measured during the observations

The amplitude calibration values also modify the weights.

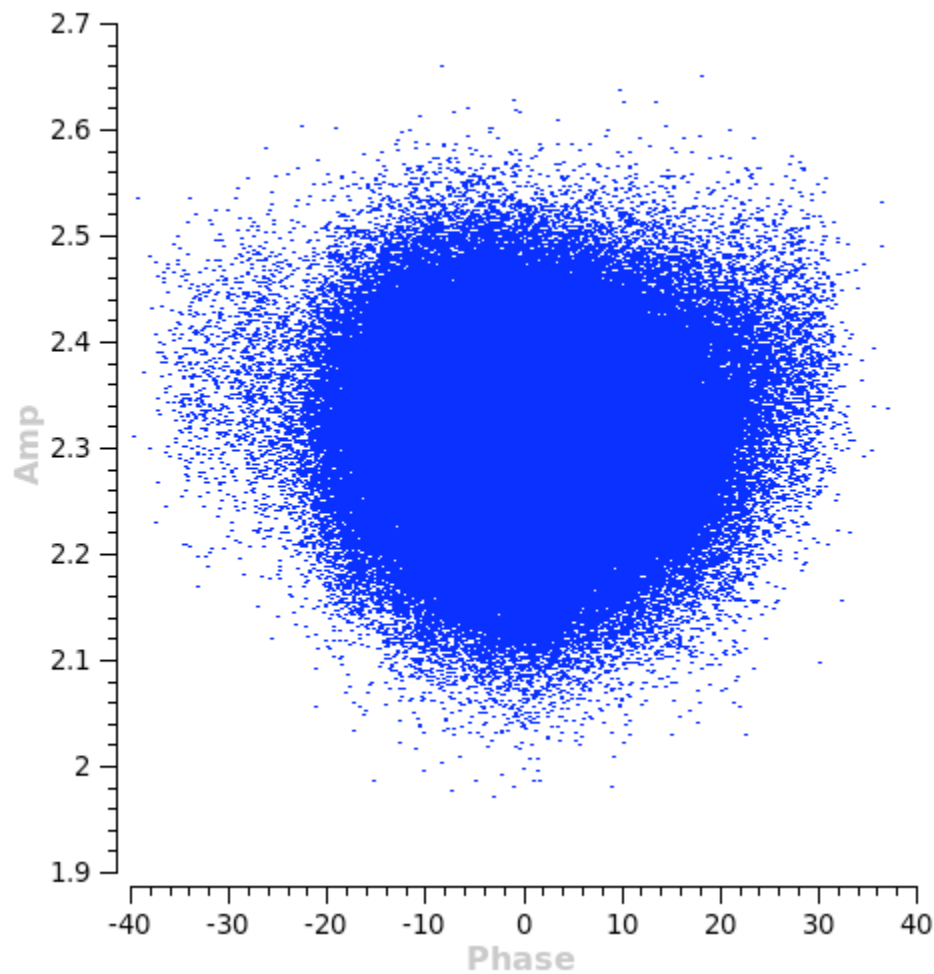
Occasionally the weight of the points become very large, often caused by subtle software bugs.

A large discrepant weight causes the same image artifacts as a large discrepant visibility value.

Please check weights to make sure they are reasonable.

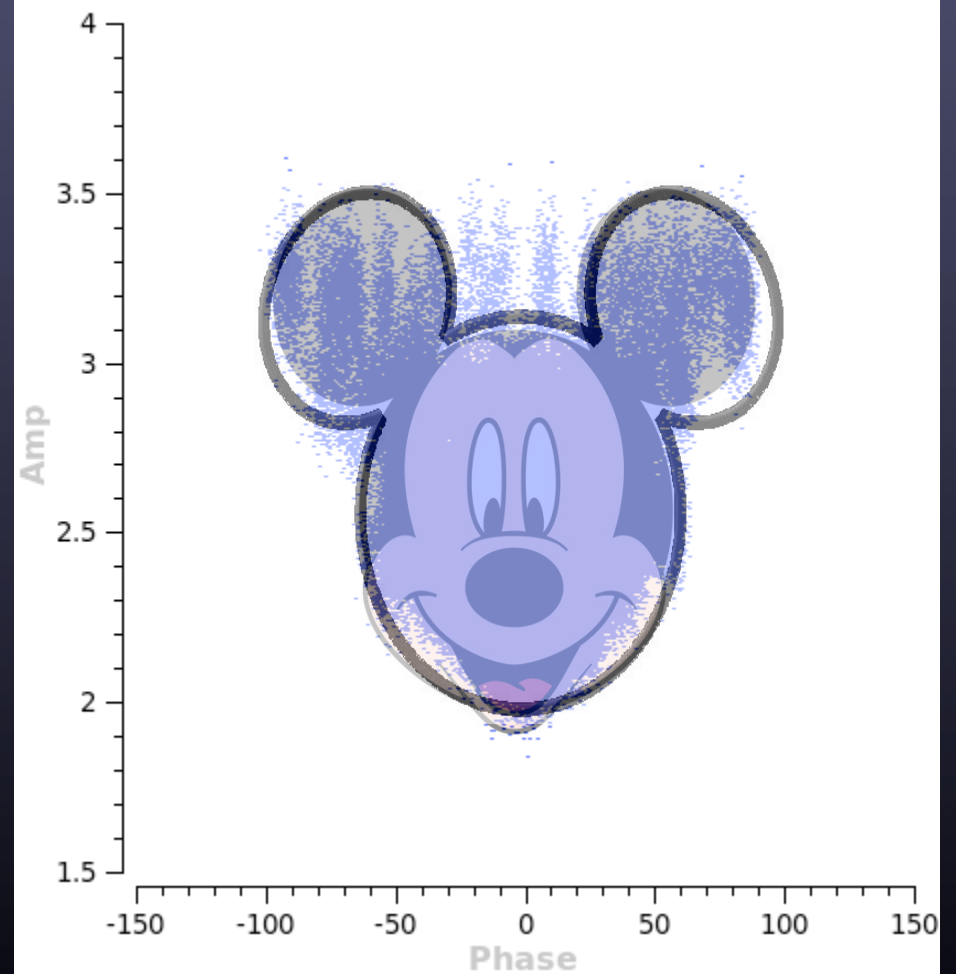
DATA DISPLAYS(5) – Amplitude vs Phase

Amp vs. Phase



Good

Amp vs. Phase Field: J0136+4751



Bad

IMAGE PLANE OR DATA (U,V) PLANE INSPECTION?

Errors obey Fourier transform relationship

Narrow feature in (u,v) plane \leftrightarrow wide feature in image plane

Wide feature in (u,v) plane \leftrightarrow narrow feature in image plane

Note: easier to spot narrow features

Data (u,v) amplitude errors \leftrightarrow symmetric image features

Data (u,v) phase errors \leftrightarrow asymmetric image features

An obvious defect may be hardly visible in the transformed plane

A small, almost invisible defect may become very obvious in the transformed plane

Noise bumps can have sidelobes!

FINDING ERRORS

---Obvious outlier data (u,v) points:

100 bad points in 100,000 data points gives an 0.1% image error
(unless the bad data points are 1 million Jy)

LOOK at DATA to find gross problem (you'd be hard pressed to find it in the image plane other than a slight increase in noise)

---Persistent small data errors:

e.g. a 5% antenna gain calibration error is difficult to see in (u,v) data (not an obvious outlier), but will produce a 1% effect in image with specific characteristics (more later).

USE IMAGE to discover problem

---Non-Data Problems:

Data ok, but algorithms chosen aren't up to the task.

ERROR RECOGNITION IN THE (u,v) PLANE

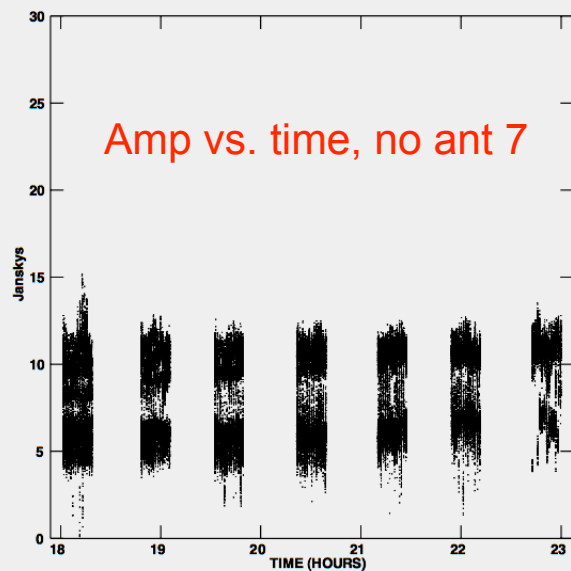
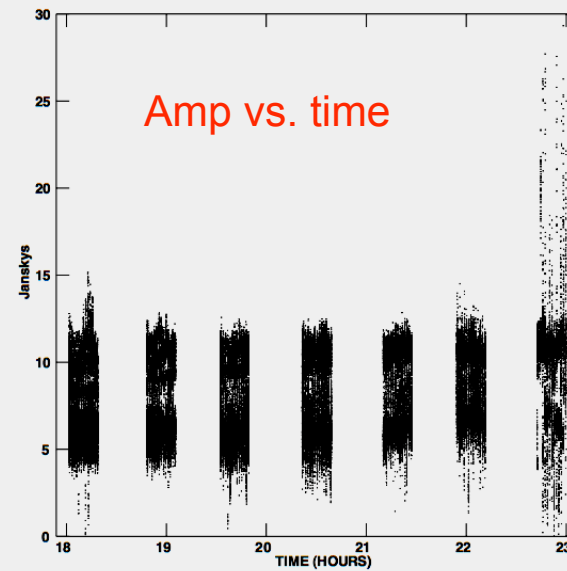
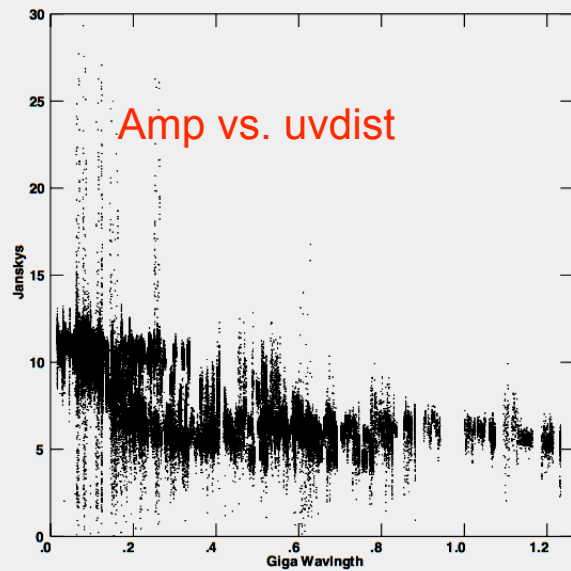
Editing obvious errors in the (u,v) plane

- Mostly consistency checks assume that the visibility cannot change much over a small change in (u,v) spacing
- Also, look at gains and phases from calibration processes. These values should be relatively stable.

See Summer school lecture notes in 2002 by Myers

See ASP Vol 180, Ekers, Lecture 15, p321

VISIBILITY AMPLITUDE PLOTS



Amp vs. uvdist shows outliers

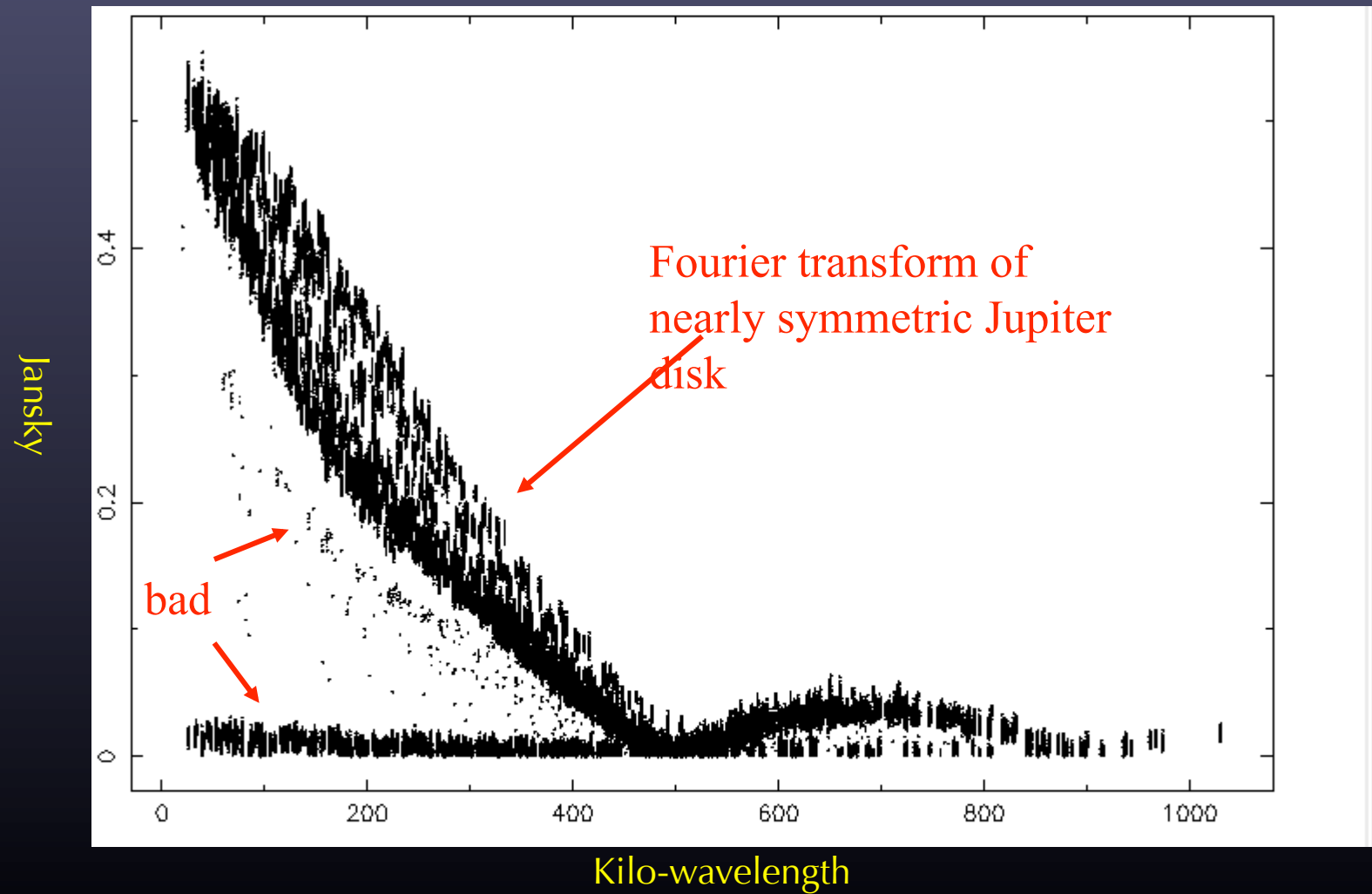
Amp vs. time shows outliers in last scan

Amp vs. time without ant 7 shows good data

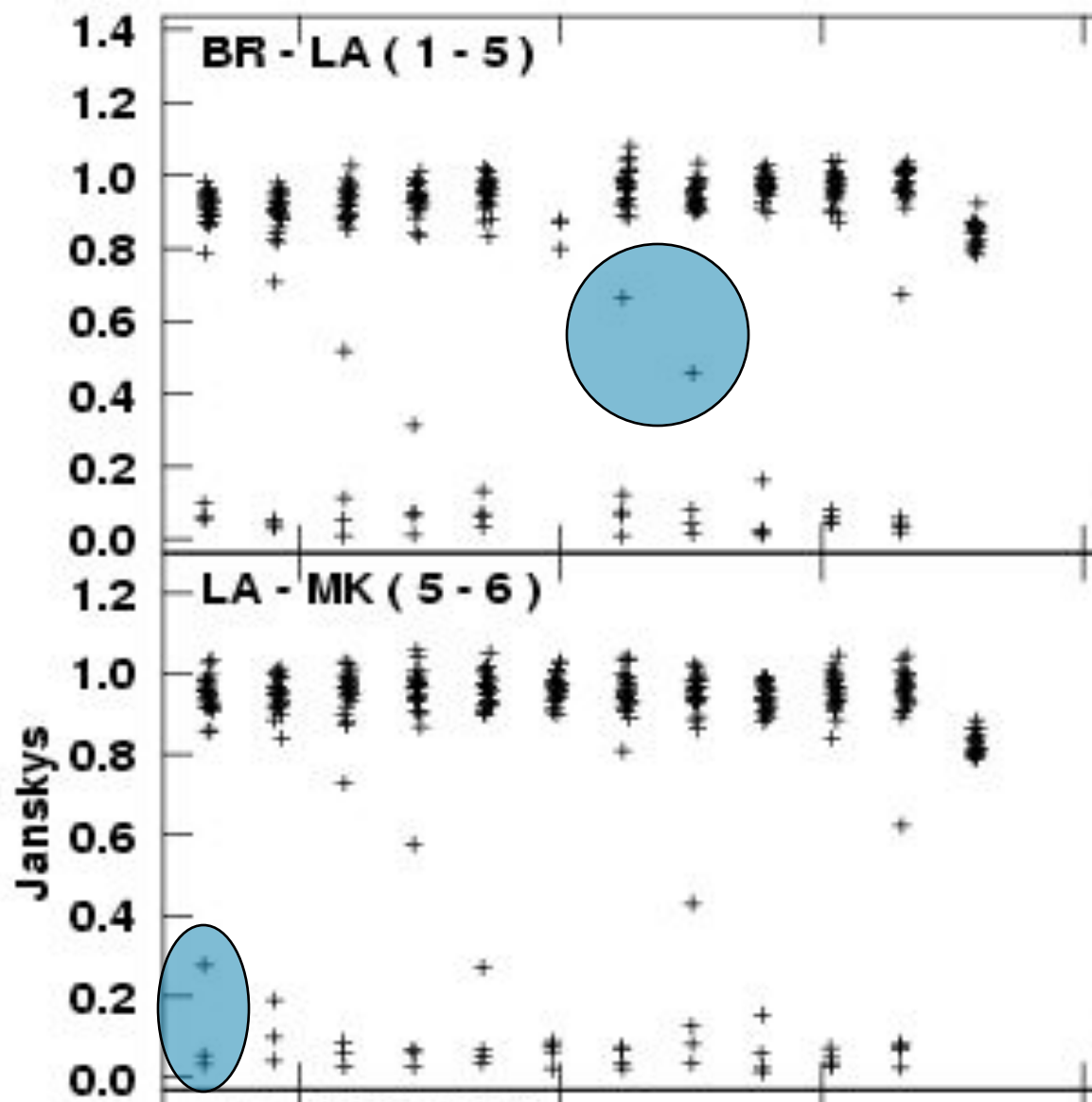
(3C279 VLBA data at 43 GHz)

Example Edit – plotms

(2)



Drop-outs at Scan Beginnings



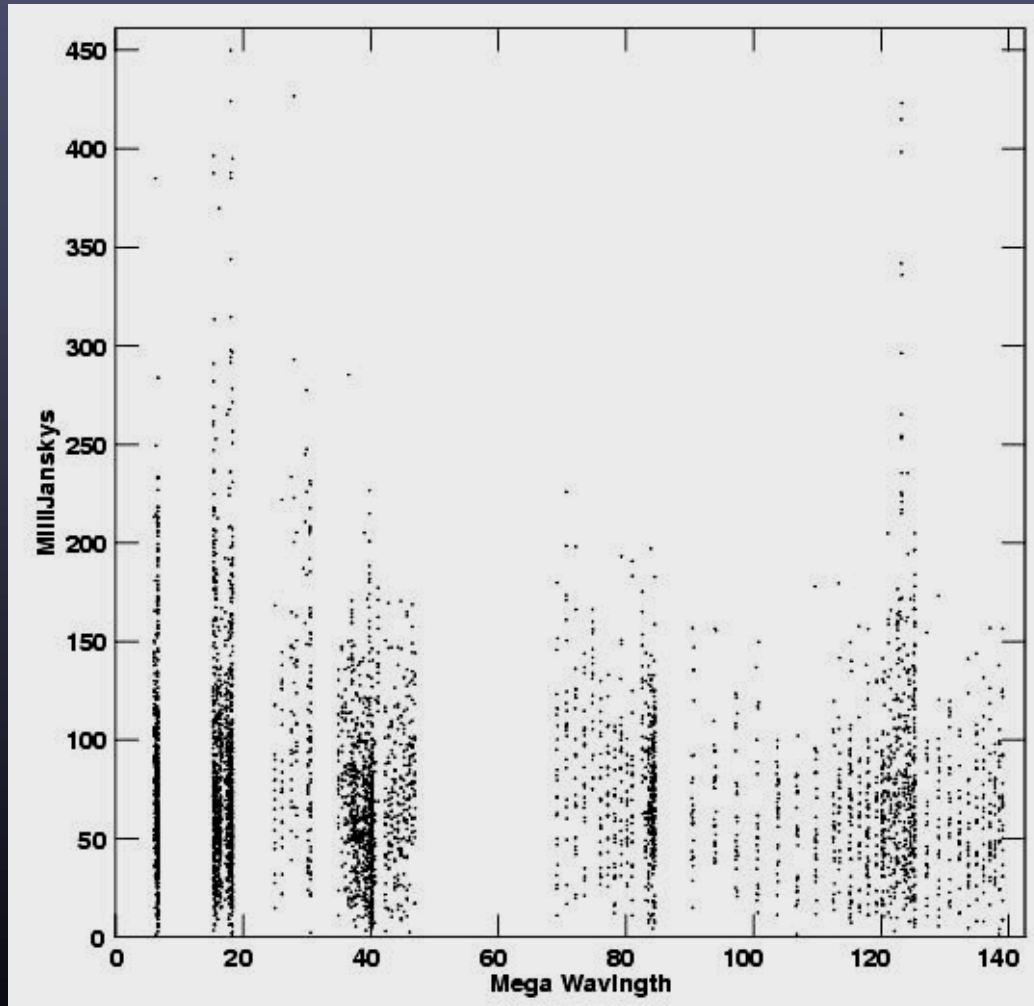
Often the first few points of a scan are low. E.g. antenna not on source.

Software can remove these points (aips, casa 'quack')

Flag extension:

Should flag all sources in the same manner even though you cannot see dropout for weak sources

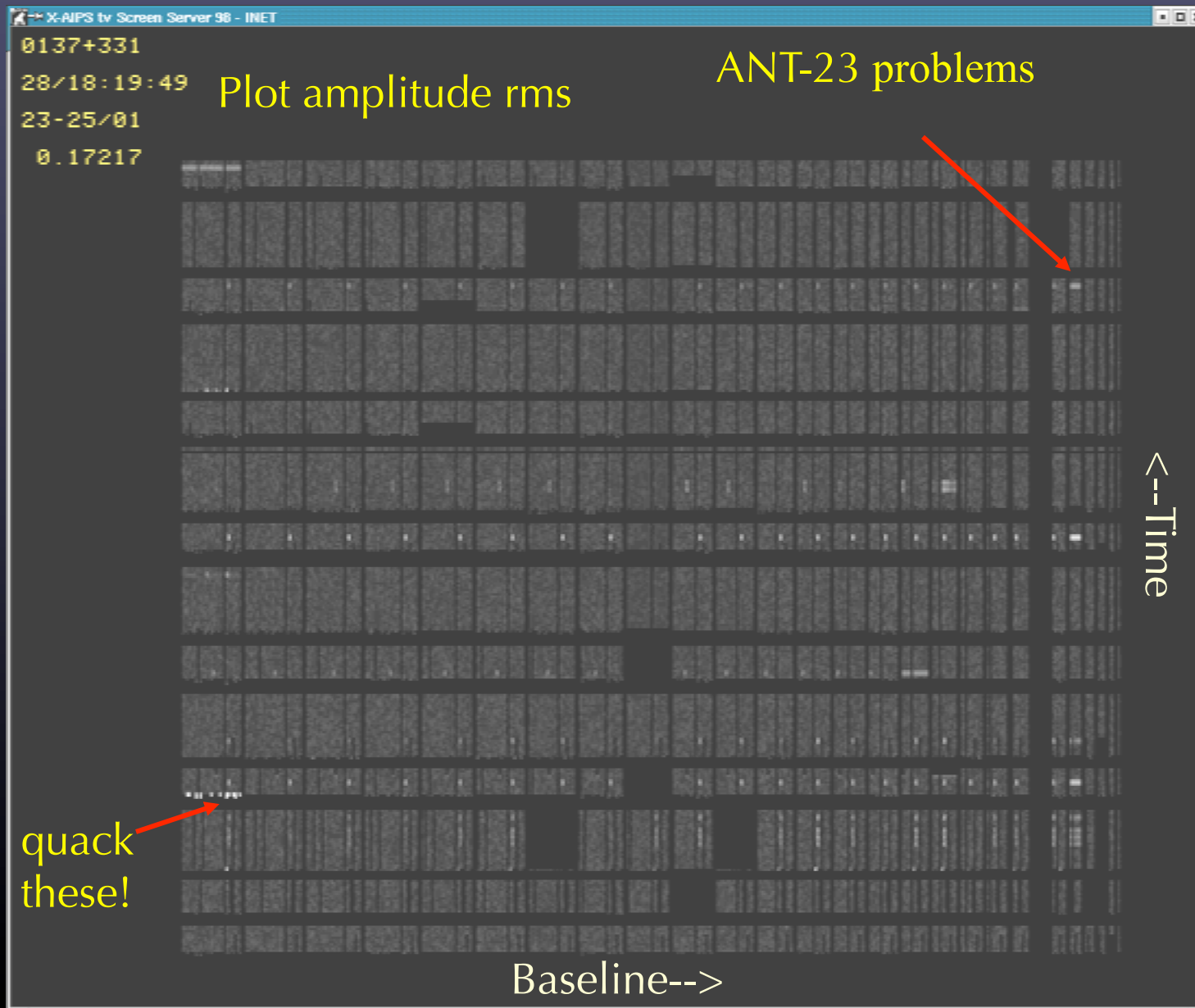
Editing Noise-dominated Sources



No source structure
information is detected.
Noise dominated.

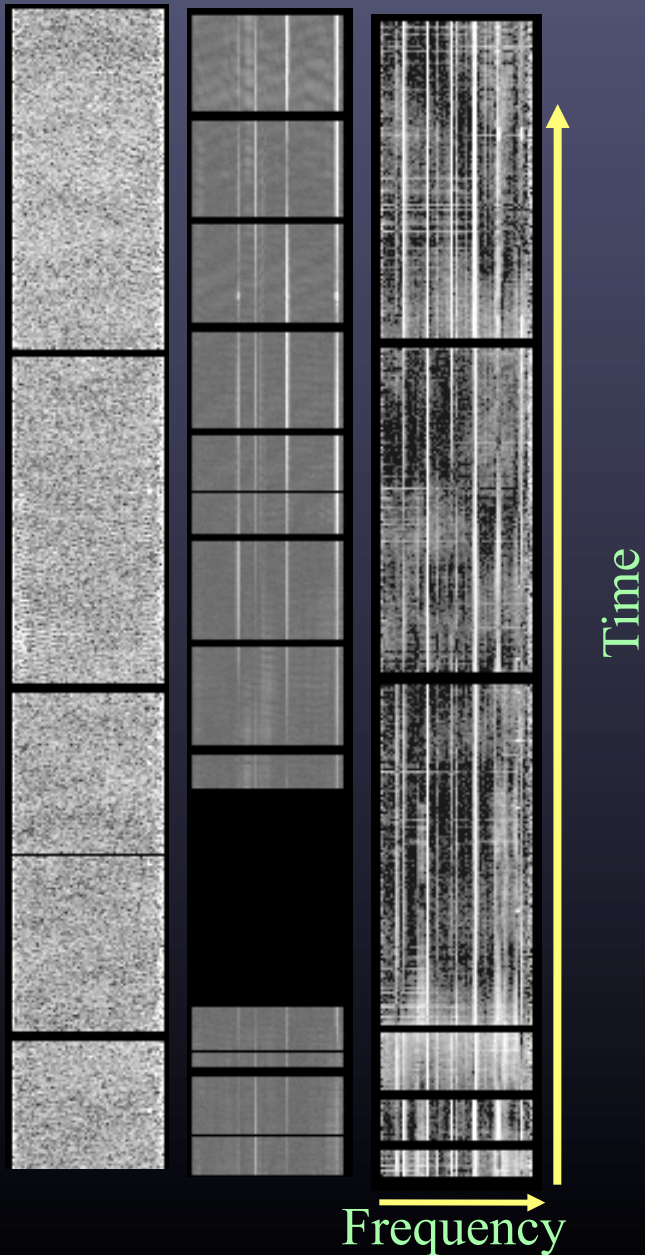
All you can do is quack and
remove outlier points
above $\sim 3\sigma$ (0.3 Jy).
Precise level not important
as long as large outliers are
removed.

USING TVFLG (VIEWER) DISPLAY on a source



RFI Excision

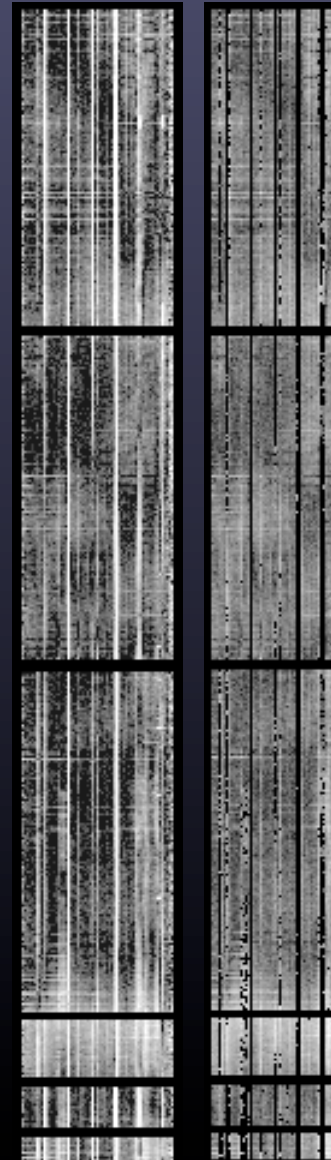
35 km 12 km 3 km baseline



AIPS: SPFLG

before

after



RFI environment worse on short baselines

Several 'types': narrow band, wandering, wideband, ...

Wideband interference hard for automated routines

AIPS tasks FLGIT, FLAGR, SPFLG and CASA flagdata, mode='rfi'

Automation is crucial for WIDAR (wide band, lots of data)

ERROR RECOGNITION IN THE IMAGE PLANE

Some Questions to ask:

Noise properties of image:

Is the rms noise about that expected from integration time?

Is the rms noise much larger near bright sources?

Are there non-random noise components (faint waves and ripples)?

Funny looking Structure:

Non-physical features; stripes, rings, symmetric or anti-symmetric

Negative features well-below 4σ noise

Does the image have characteristics that look like the dirty beam?

Image-making parameters:

Is the image big enough to cover all significant emission?

Is cell size too large or too small? ~ 4 points per beam okay

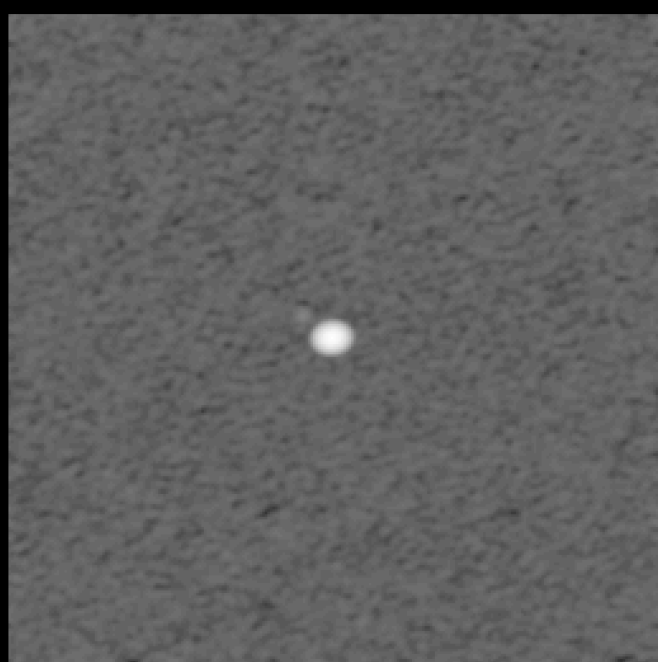
Is the resolution too high to detect most of the emission?

EXAMPLE 1

Data bad over a short period of time

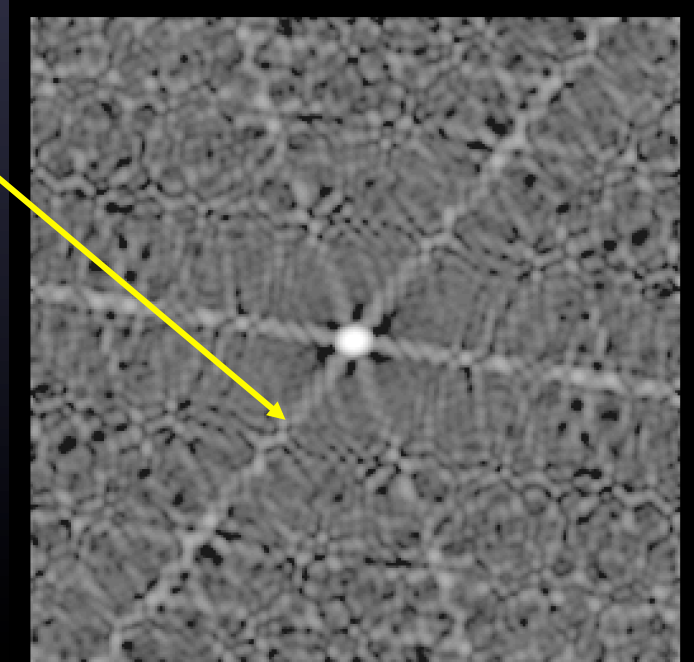
Results for a point source using VLA. 13 x 5min observation over 10 hr.
Images shown after editing, calibration and deconvolution.

no errors:
max 3.24 Jy
rms 0.11 mJy



10% amp error for all
antennas for 1 time period
rms 2.0 mJy

6-fold symmetric
pattern due to
VLA "Y".
Image has
properties of dirty
beam.

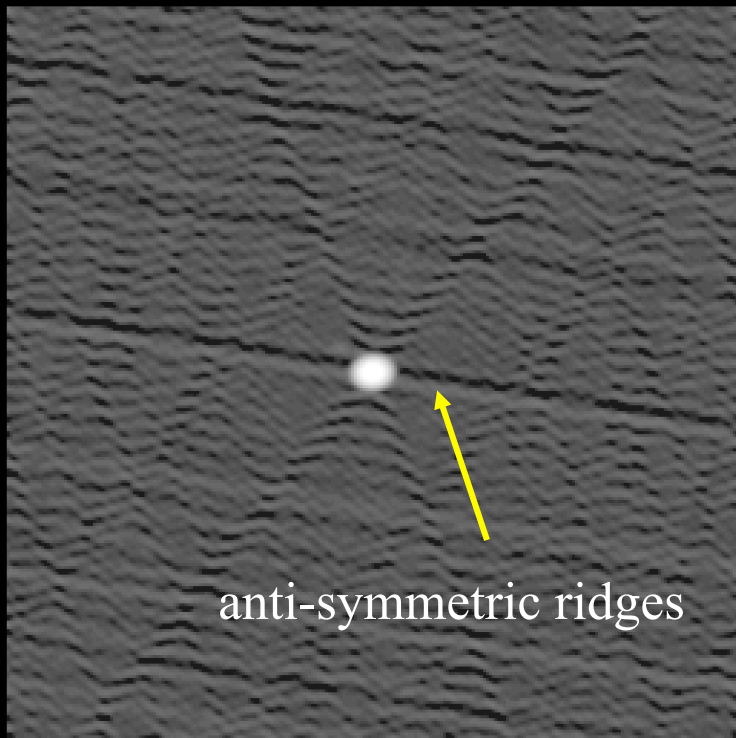


EXAMPLE 2

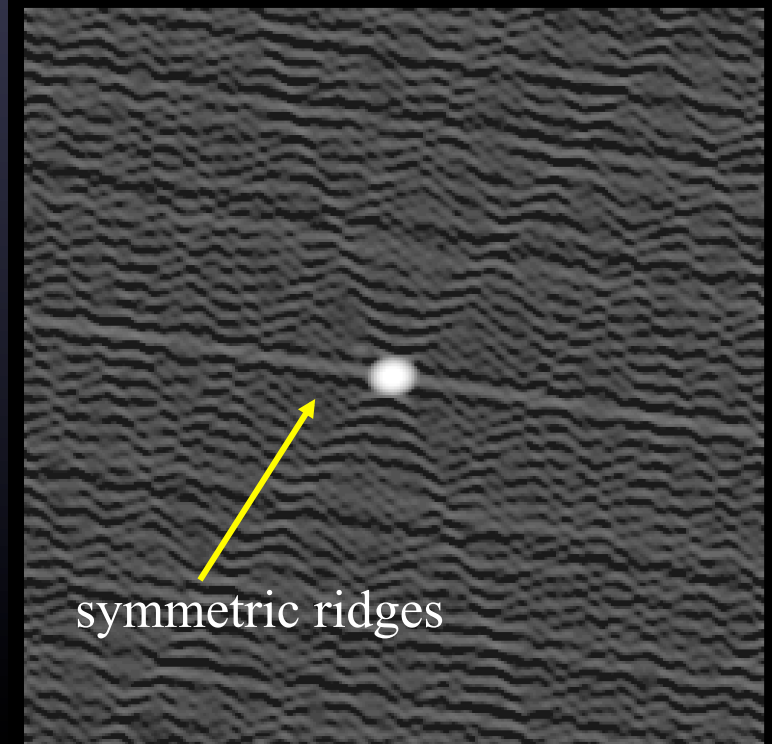
Short burst of bad data

Typical effect from one bad antenna

10 deg phase error for
one antenna at one time
rms 0.49 mJy



20% amplitude error for
one antenna at one time
rms 0.56 mJy (self-cal)



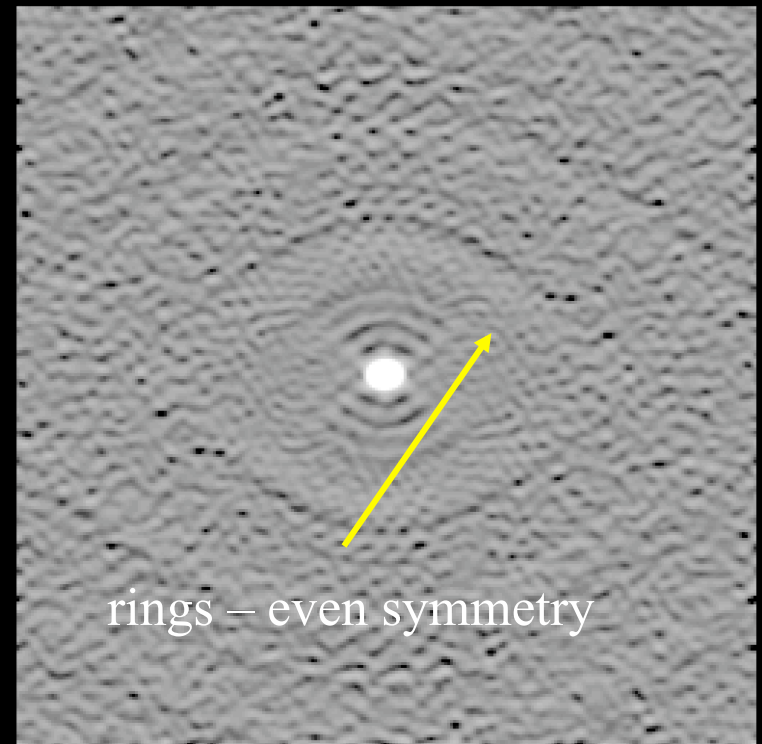
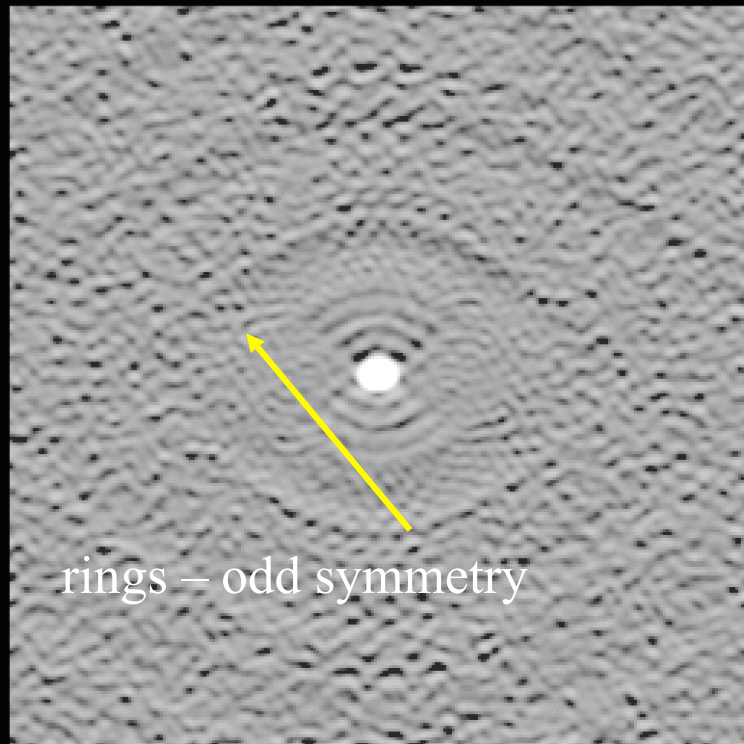
EXAMPLE 3

Persistent errors over most of observations

NOTE: 10 deg phase error to 20% amplitude error
cause similar sized artifacts

10 deg phase error for
one antenna all times
rms 2.0 mJy

20% amp error for one
antenna all times
rms 2.3 mJy



EXAMPLE 4

Spurious Correlator Offset Signals

Occasionally correlators produce ghost signals or cross talk signals
Occurred during change-over from VLA to EVLA system

Symptom: Garbage near phase center, dribbling out into image

Image with correlator offsets

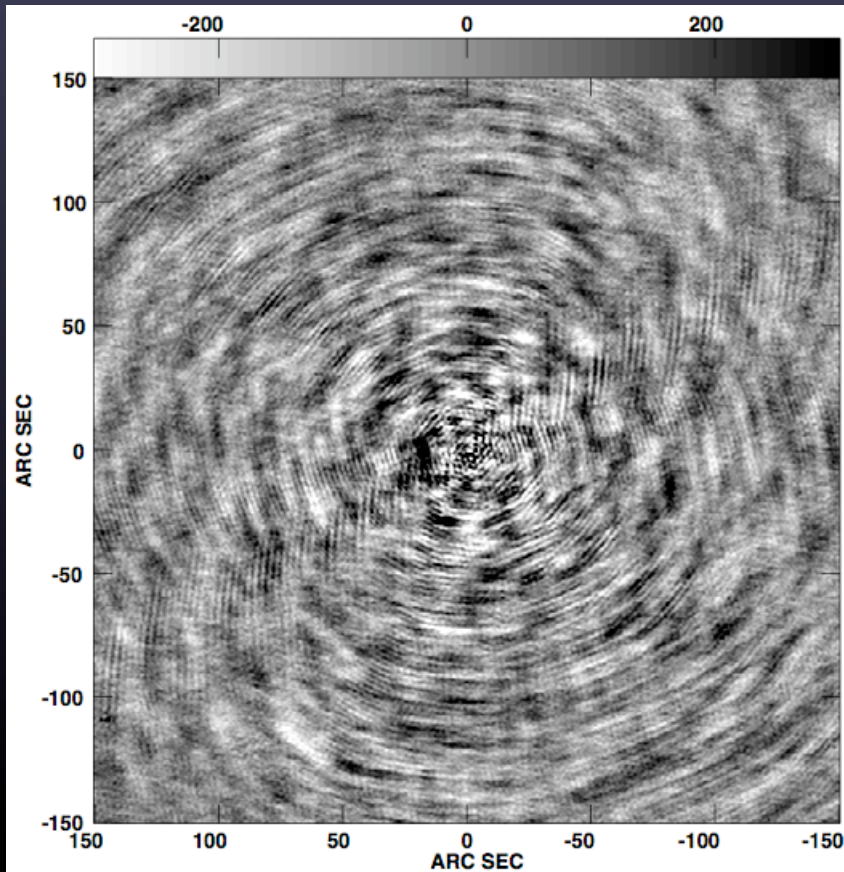
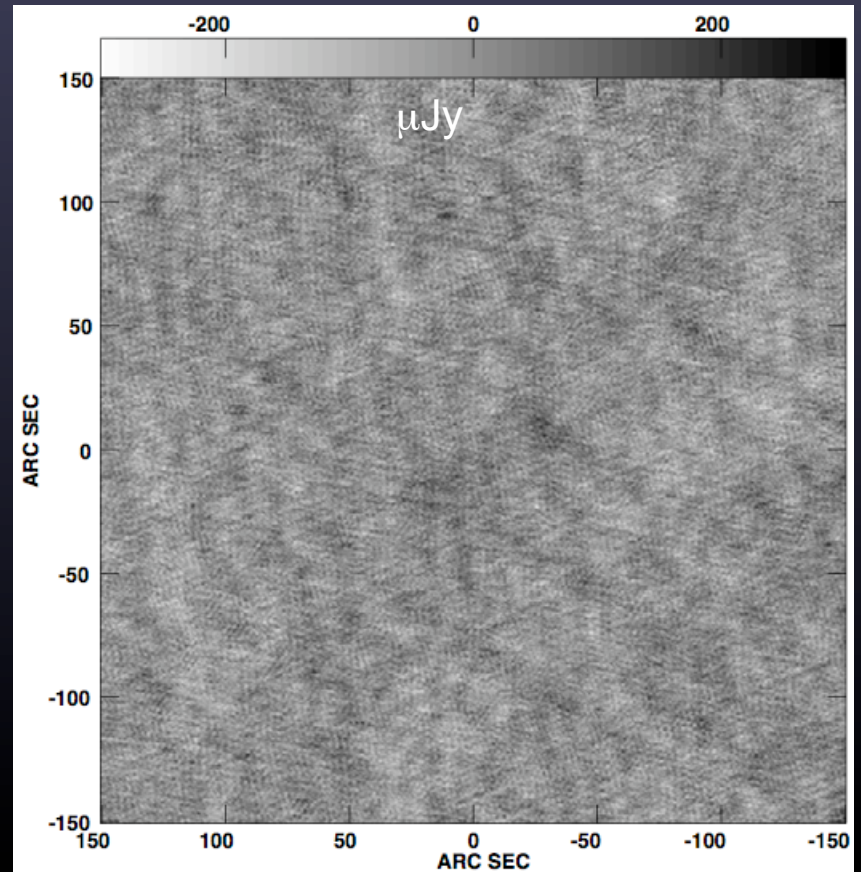
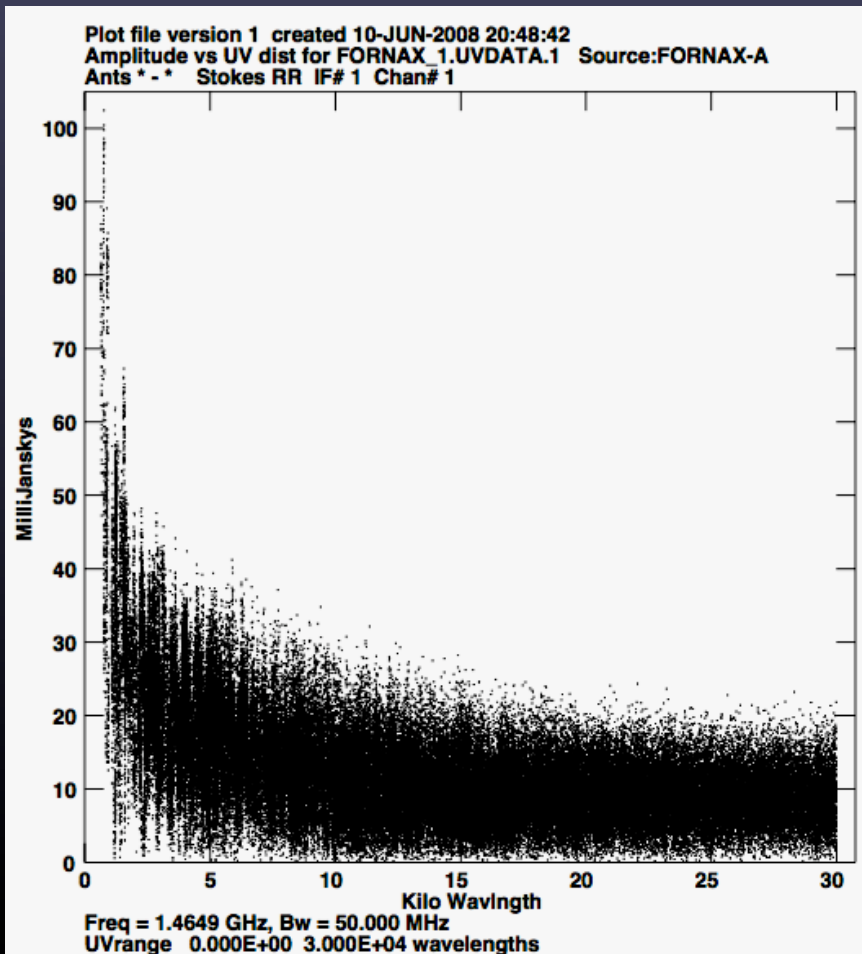


Image after correction of offsets



DECONVOLUTION ERRORS

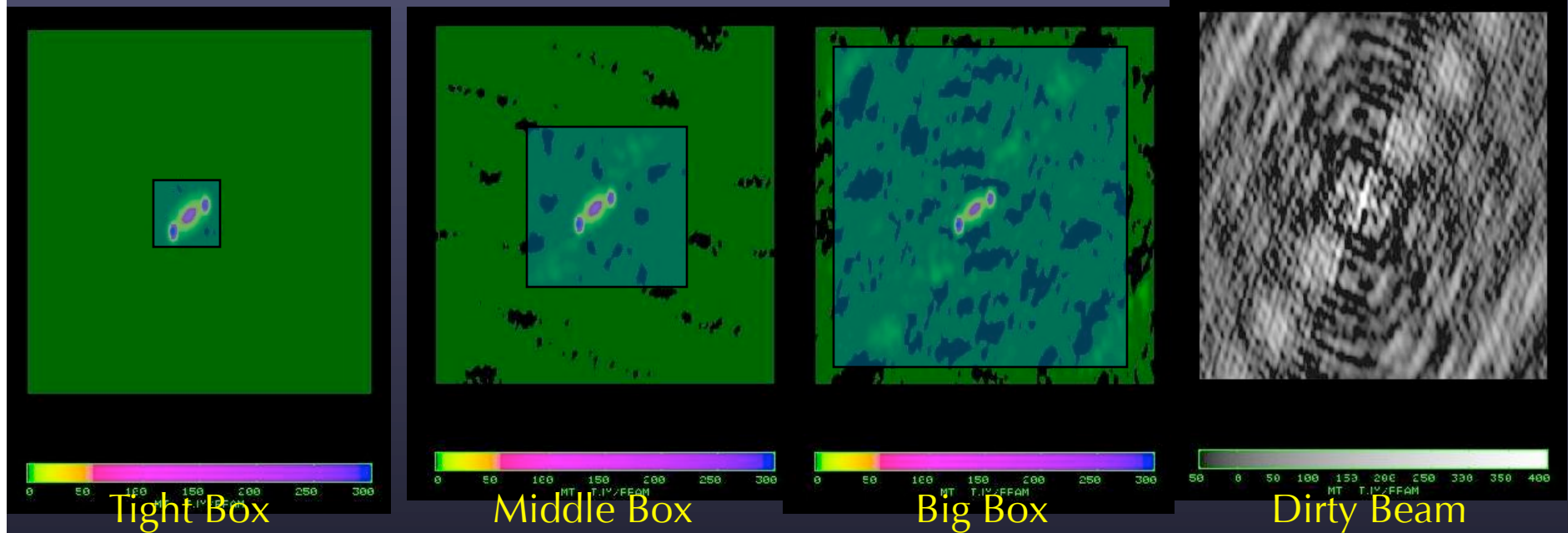
Even if the data are perfect, image errors and uncertainties will occur because the (u,v) coverage is not adequate to map the source structure.



The extreme rise of visibility at the short spacings makes it impossible to image the extended structure. You are better off imaging the source with a cutoff below about 2 kilo-wavelengths

Get shorter spacing or single-dish data

CLEANING WINDOW SENSITIVITY



One small clean
box

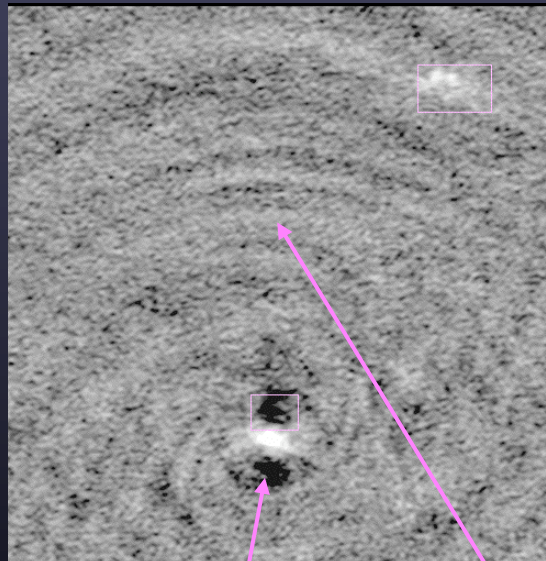
One clean box
around all emission

Clean entire
inner map quarter

*Make box as small as possible to avoid
cleaning noise interacting with sidelobes*

How Deep to Clean?

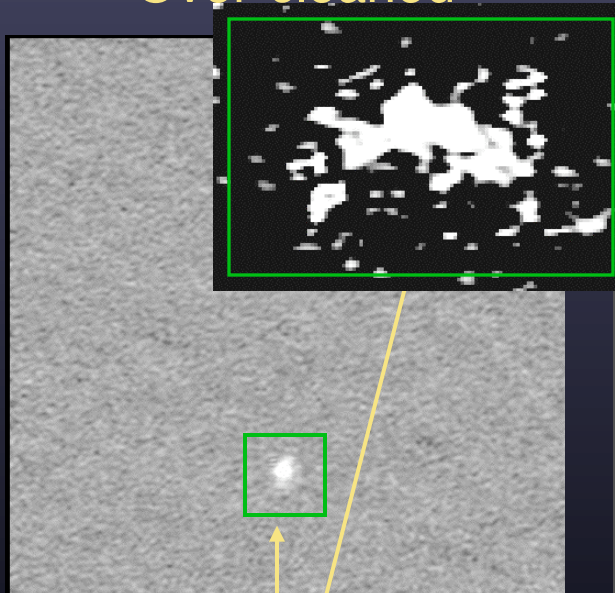
Under-cleaned



Emission from
second source sits
atop a negative "bowl"

Residual sidelobes
dominate the noise

Over-cleaned



Regions within
clean boxes
appear "mottled"

Properly cleaned

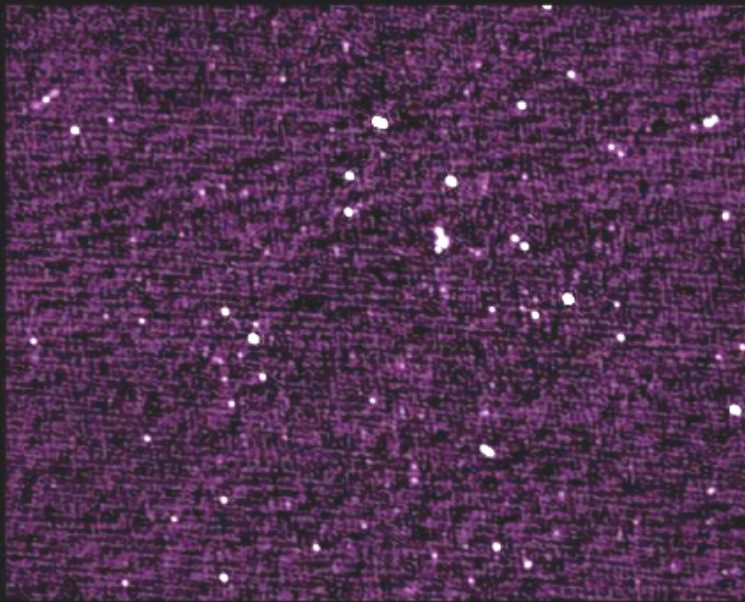


Background is thermal
noise-dominated;
no "bowls" around
sources.

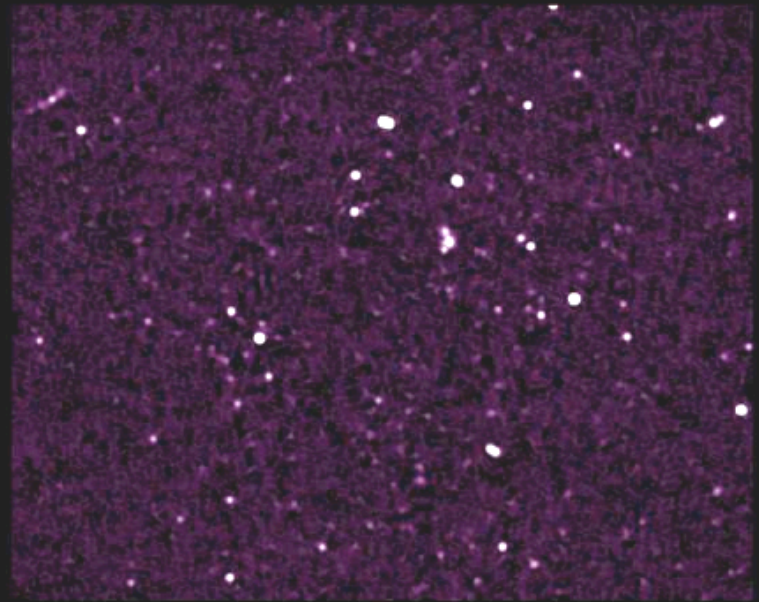
Improvement of Image

Removal of low level ripple improves detectability of faint sources

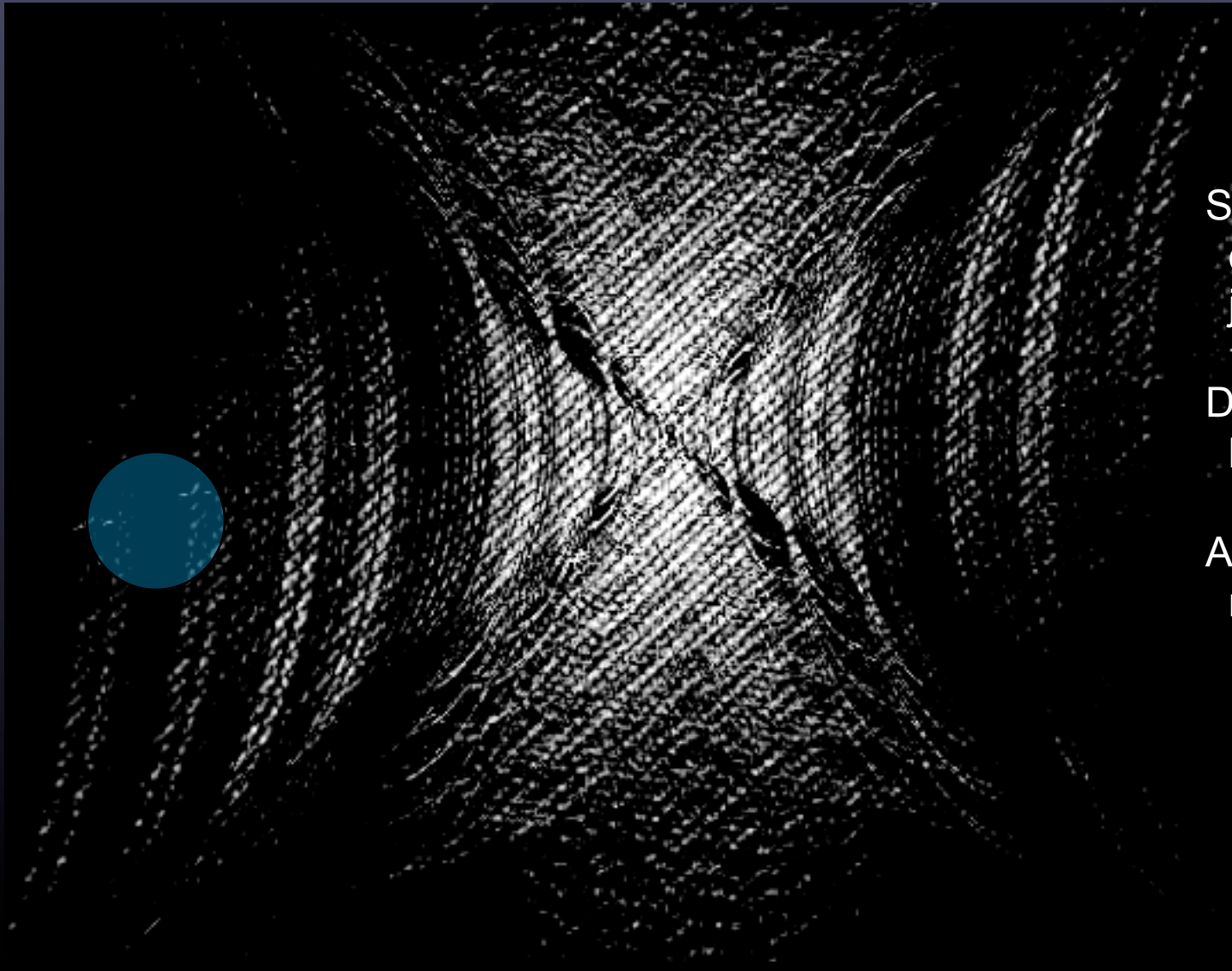
Before editing



After editing



Fourier Transform Dirty Image

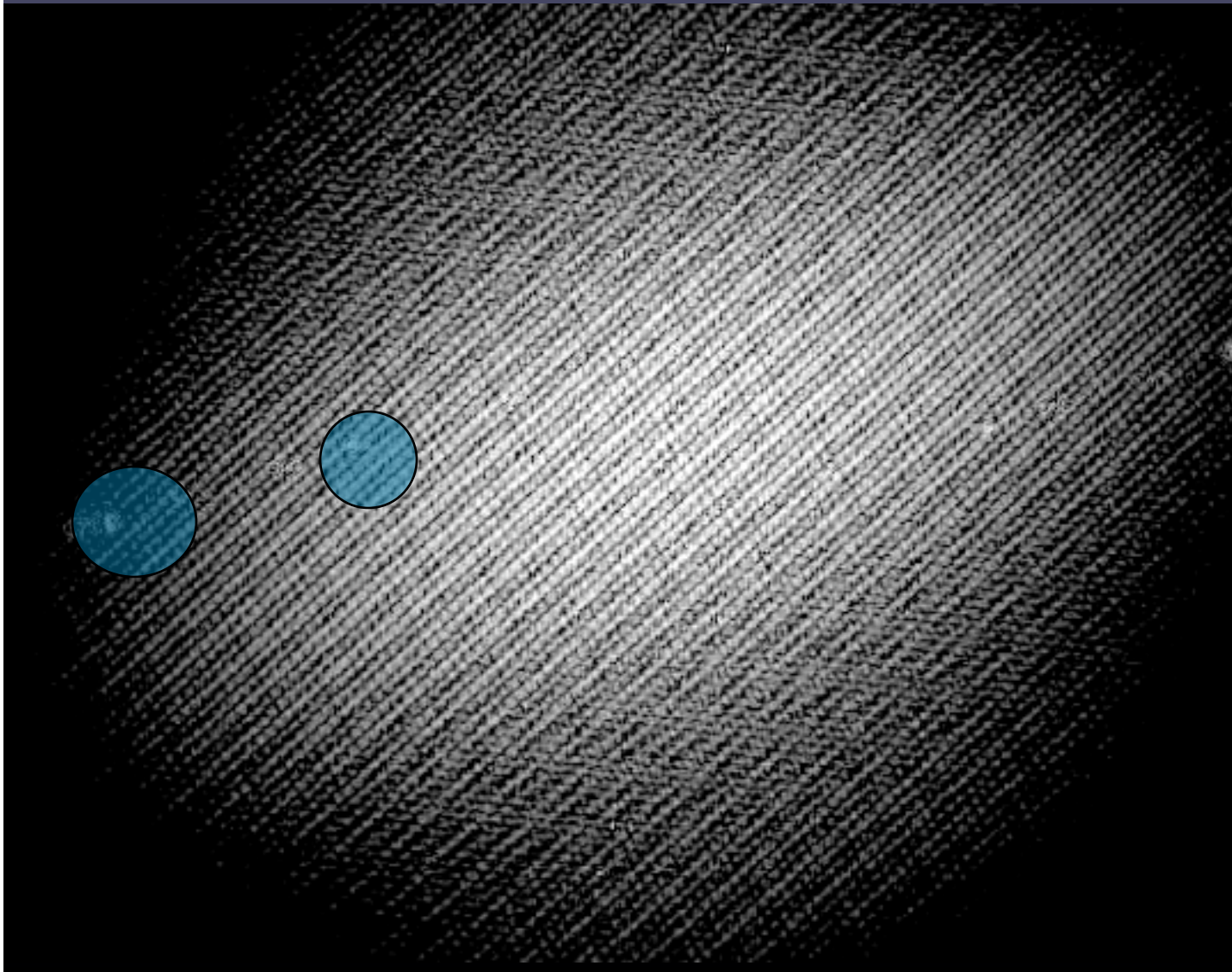


Shows the (u,v)
data as gridded
just before imaging

Diagonal lines caused
by structure in field

A few odd points are
not very noticeable

Fourier Transform Clean Image

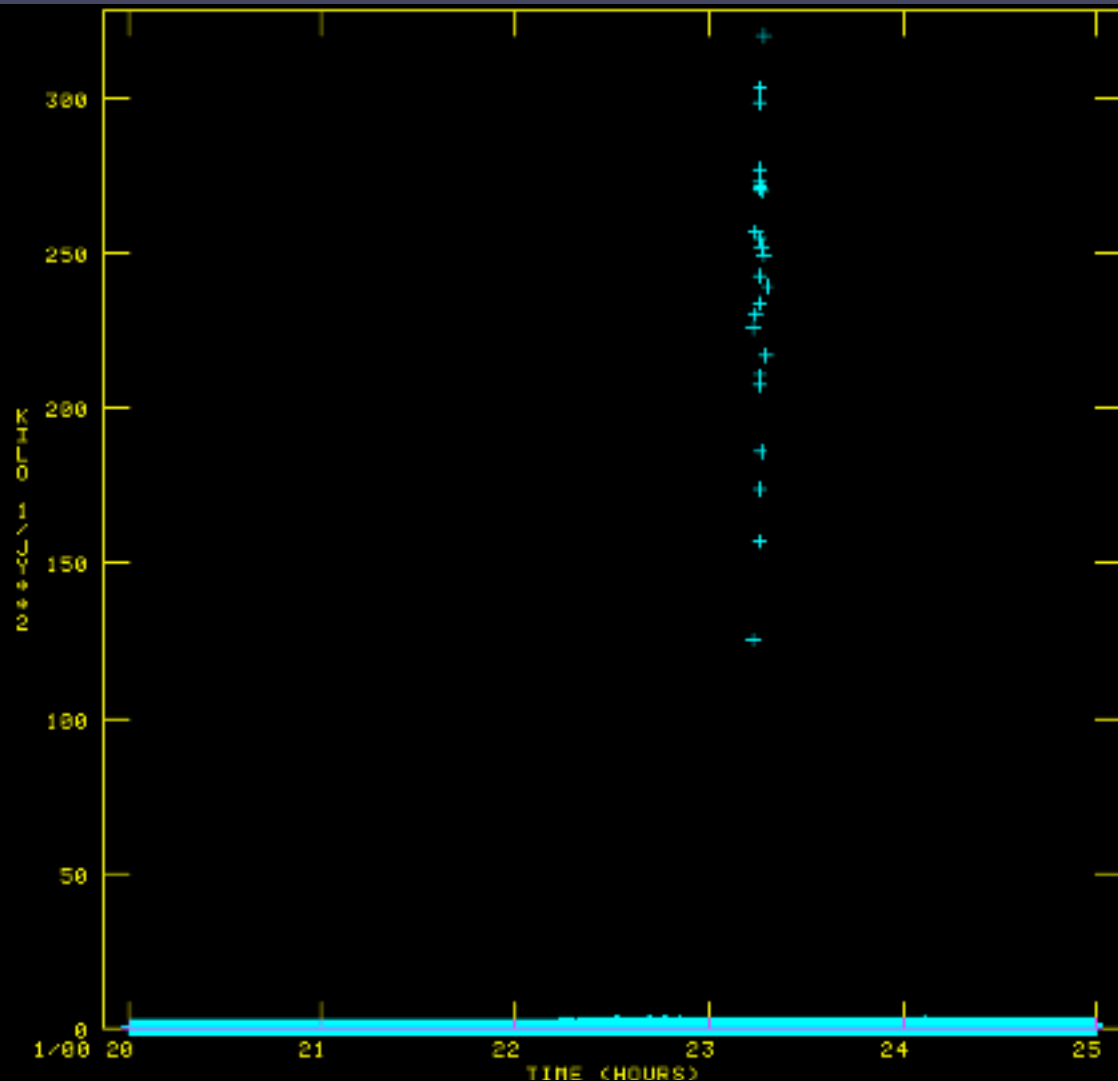


Shows the (u,v) data from clean image.

Diagonal lines still present. Notice that clean does an interpolation in the u,v plane between u,v tracks.

The odd points are smeared, but still present. These produce the low level ripples.

Bad weighting of a few (u,v) points



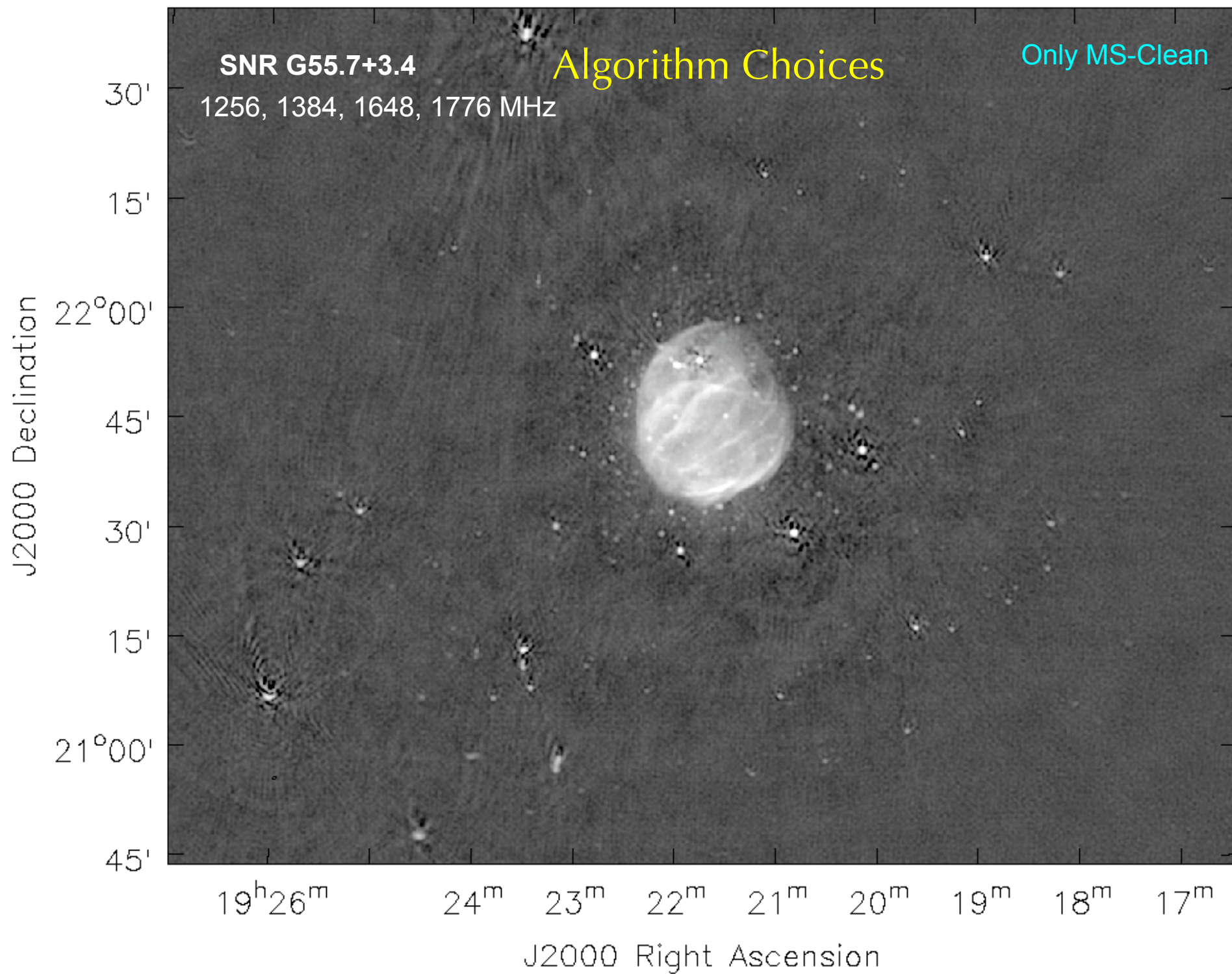
After a long search through the data, about 30 points out of 300,000 points were found to have too high of a weight by a factor of 100.

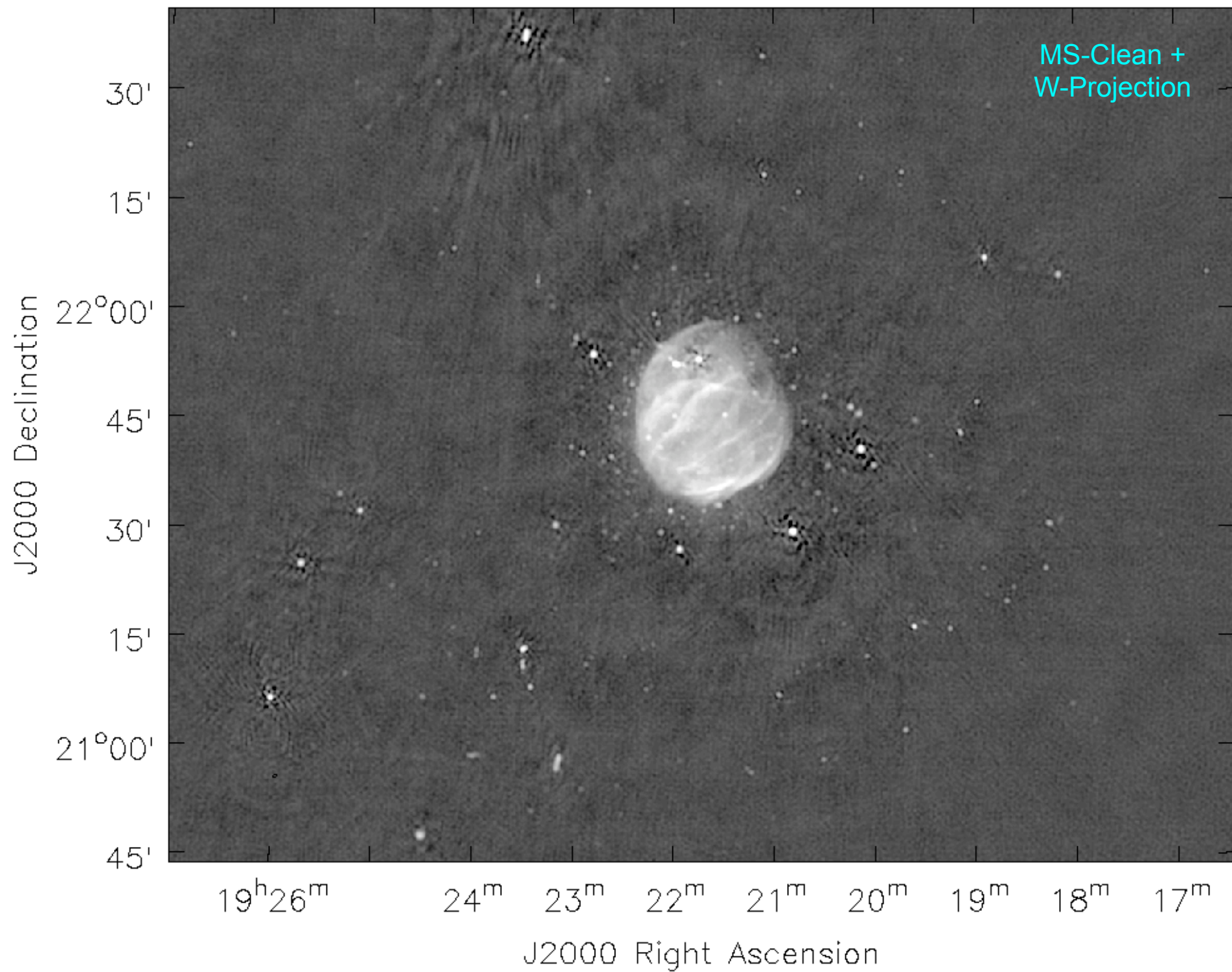
Effect is <1% in image.

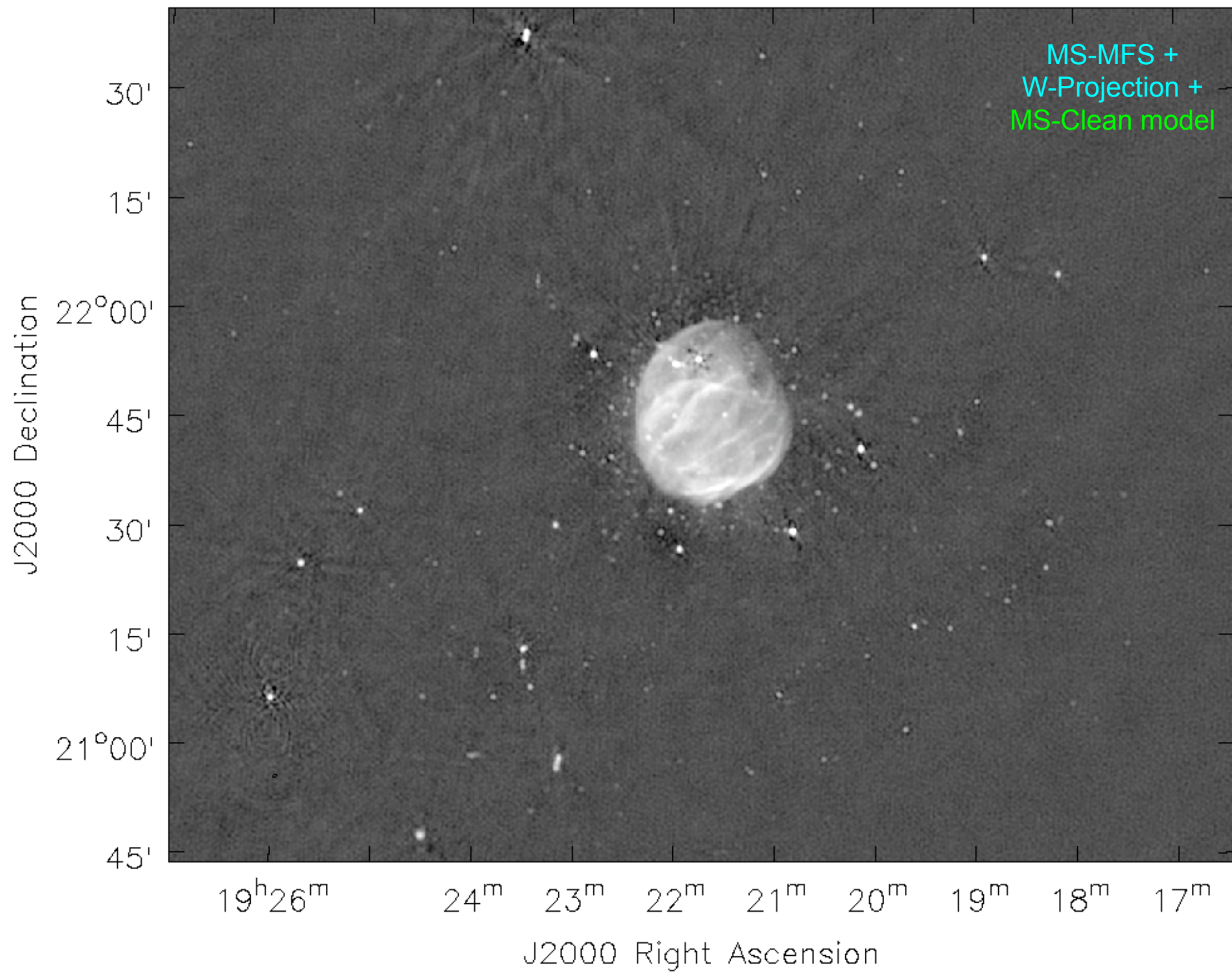
Cause??

Sometimes in applying calibration produced an incorrect weight in the data. Not present in the original data.

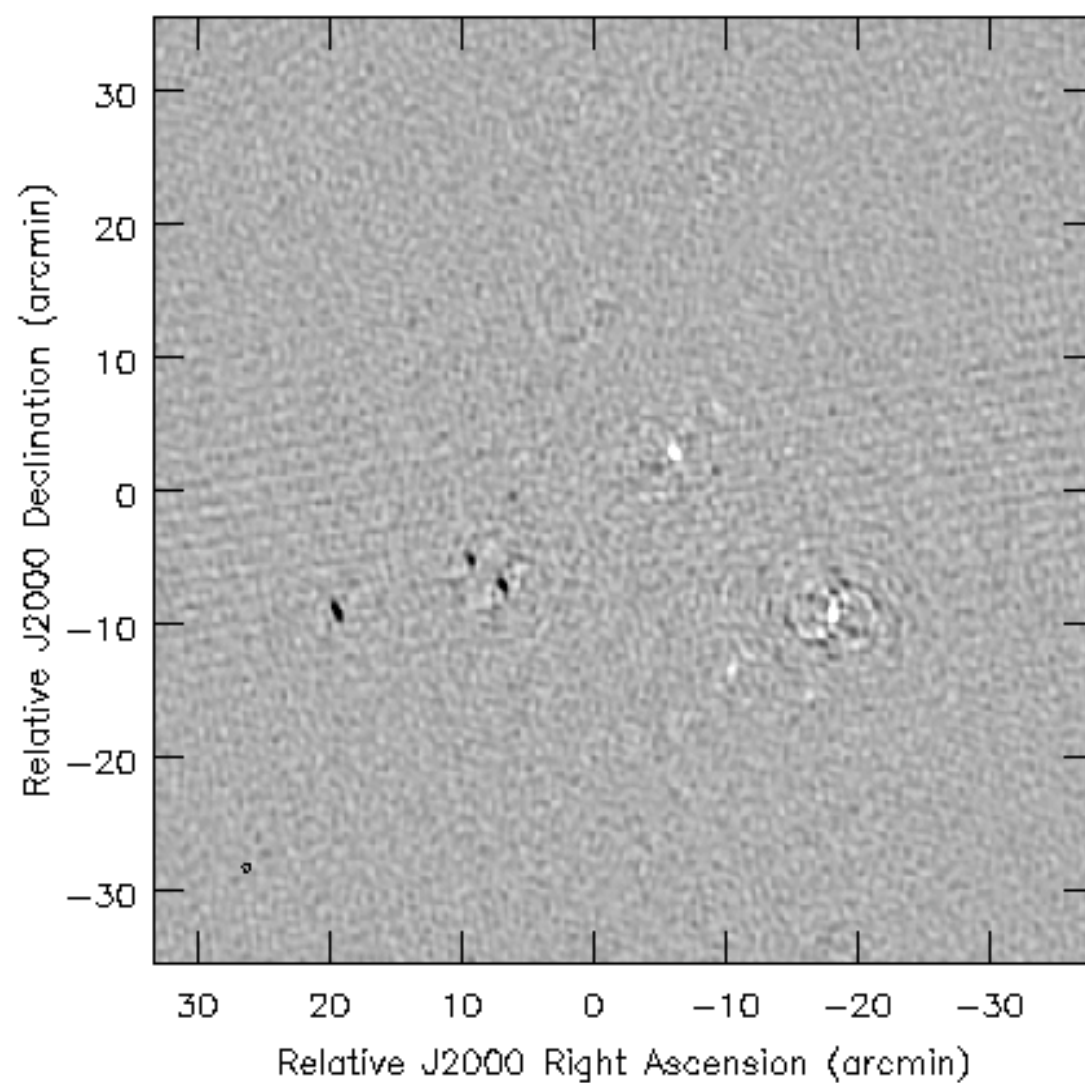
These problems can sneak up on you. Beware.







Stokes V wide-field imaging



SUMMARY OF ERROR RECOGNITION

Source structure should be 'reasonable', the rms image noise as expected, and the background featureless. If not,

(u,v) data

Look for outliers in (u,v) data using several plotting methods.
Check calibration gains and phases for instabilities.
Look at residual data (u,v data - clean components)

IMAGE plane

Do defects resemble the dirty beam?
Are defect properties related to possible data errors?
Are defects related to possible deconvolution problems?
Are other corrections/calibrations needed?
Does the field-of-view encompass all emission?

IMAGE ANALYSIS

- Input: Well-calibrated data-base producing a high quality image
- Output: Parameterization and interpretation of image or a set of images

This is very open-ended

Depends on source emission complexity

Depends on the scientific goals

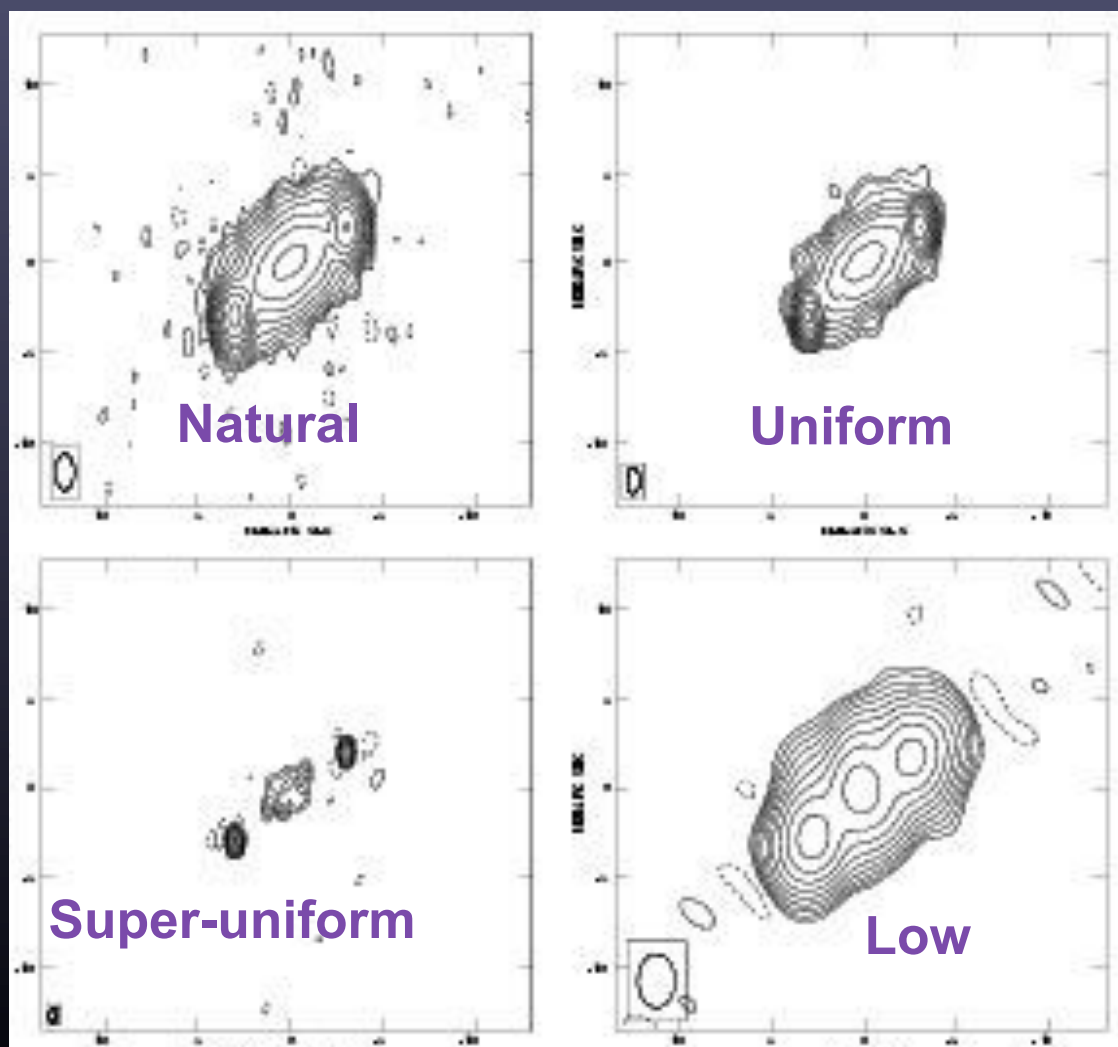
Examples and ideas are given.

Many software packages, besides AIPS and Casa (e.g.. IDL, DS-9) are available.

IMAGE ANALYSIS OUTLINE

- Multi-Resolution of radio source.
- Parameter Estimation of Discrete Components
- Image Comparisons
- Positional Registration

IMAGE AT SEVERAL RESOLUTIONS



Milli-arcsec

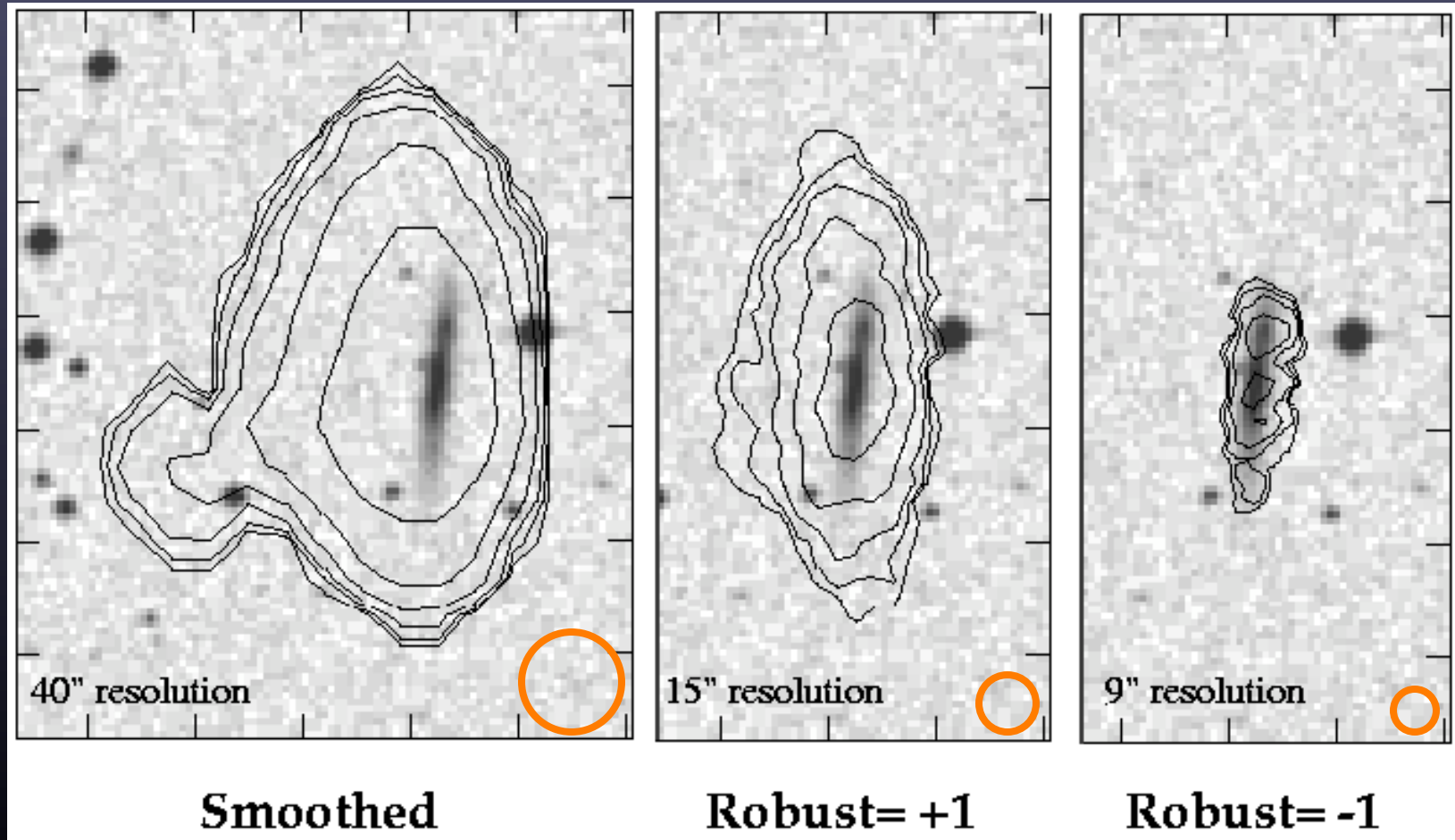
Different aspect of source structure can be seen at various resolutions, shown by the ellipse in the lower left corner of each box.

SAME DATA USED FOR ALL IMAGES

For example,
Outer components are small from SU resolution
There is no extended emission from low resolution

Imaging and Deconvolution of Spectral Line Data:

Type of weighting in imaging



HI contours overlaid on optical images of an edge-on galaxy

PARAMETER ESTIMATION

Parameters associated with discrete components

- Fitting in the image
 - Assume source components are Gaussian-shaped
 - Deep cleaning restores image intensity with Gaussian-beam
 - True size * Beam size = Image size, if Gaussian-shaped. Hence, estimate of true size is relatively simple.
- Fitting in (u,v) plane (aka model-fitting)
 - Better estimates of parameters for simple sources
 - May be possible even when imaging is not
 - Can fit to more source models (e.g. Gaussian, ring, disk)
- Error estimates of parameters
 - Simple ad-hoc error estimates
 - Estimates from fitting programs
 - Monte Carlo simulations if model-fitting

IMAGE FITTING

Component 2-Gaussian

Peak intensity = 0.104 +/- 0.005 JY/BEAM
 Integral intensity= 0.998 +/- 9.47 JANSKYS
 X-position = 255.986 +/- 0.0029 pixels
 Y-position = 257.033 +/- 0.0032 pixels
 Major ax 19.99 +/- 0.02 pixels
 Minor ax 9.98 +/- 0.03 pixels
 Pos ang 135.3 +/- 0.1 deg

Component 1-Gaussian

Peak intensity = 0.300 +/- 0.005 JY/BEAM
 Integral intensity= 0.302 +/- 0.008 JANSKYS
 X-position = 270.991 +/- 0.001 pixels
 Y-position = 267.018 +/- 0.001 pixels
 Major ax 0.53 +/- 0.01 pixels
 Minor ax 0.00 +/- 0.05 pixels
 Pos ang 21.6 +/- 1.1 deg

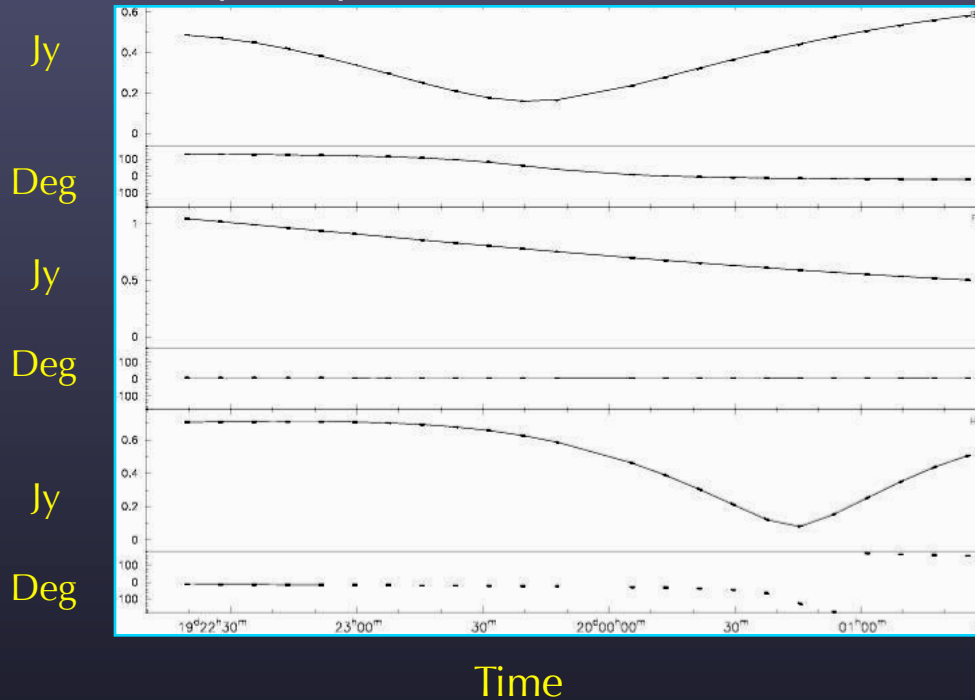
Component 3-Gaussian

Peak intensity = 0.393 +/- 0.004 JY/BEAM
 Integral intensity= 0.403 +/- 0.008 JANSKYS
 X-position = 241.007 +/- 0.001 pixels
 Y-position = 241.988 +/- 0.001 pixels
 Major ax 1.54 +/- 0.01 pixels
 Minor ax 0.21 +/- 0.01 pixels
 Pos ang 3.6 +/- 0.2 deg

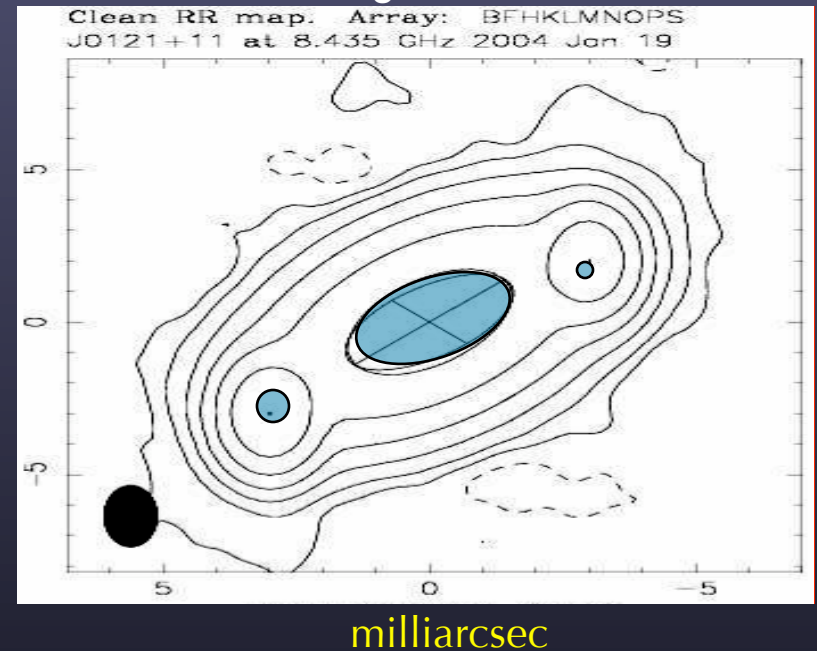
AIPS task: JMFIT
 Casa tool
 imfit

(u,v) DATA FITTING

Amp and phase vs. time for three baselines



Contour image with model fits



DIFMAP has good (u,v) fitting algorithm

Fit model directly to (u,v) data

Compare model to data

Contour display of image

Ellipses show true component size. (SNR dependent resolution)

COMPONENT ERROR ESTIMATES

P = Component Peak Flux Density

σ = Image rms noise

P/σ = signal/noise = S

B = Synthesized beam size

θ_i = Component image size

ΔP = Peak error = σ

ΔX = Position error = $B / 2S$

$\Delta \theta_i$ = Component image size error = $B / 2S$

θ_t = True component size = $(\theta_i^2 - B^2)^{1/2}$

$\Delta \theta_t$ = Minimum component size = $B / S^{1/2}$

eg. $S=100$ means can determine size of $B/10$



Comparison and Combination of Images of Many Types

FORNAX-A Radio/Optical field

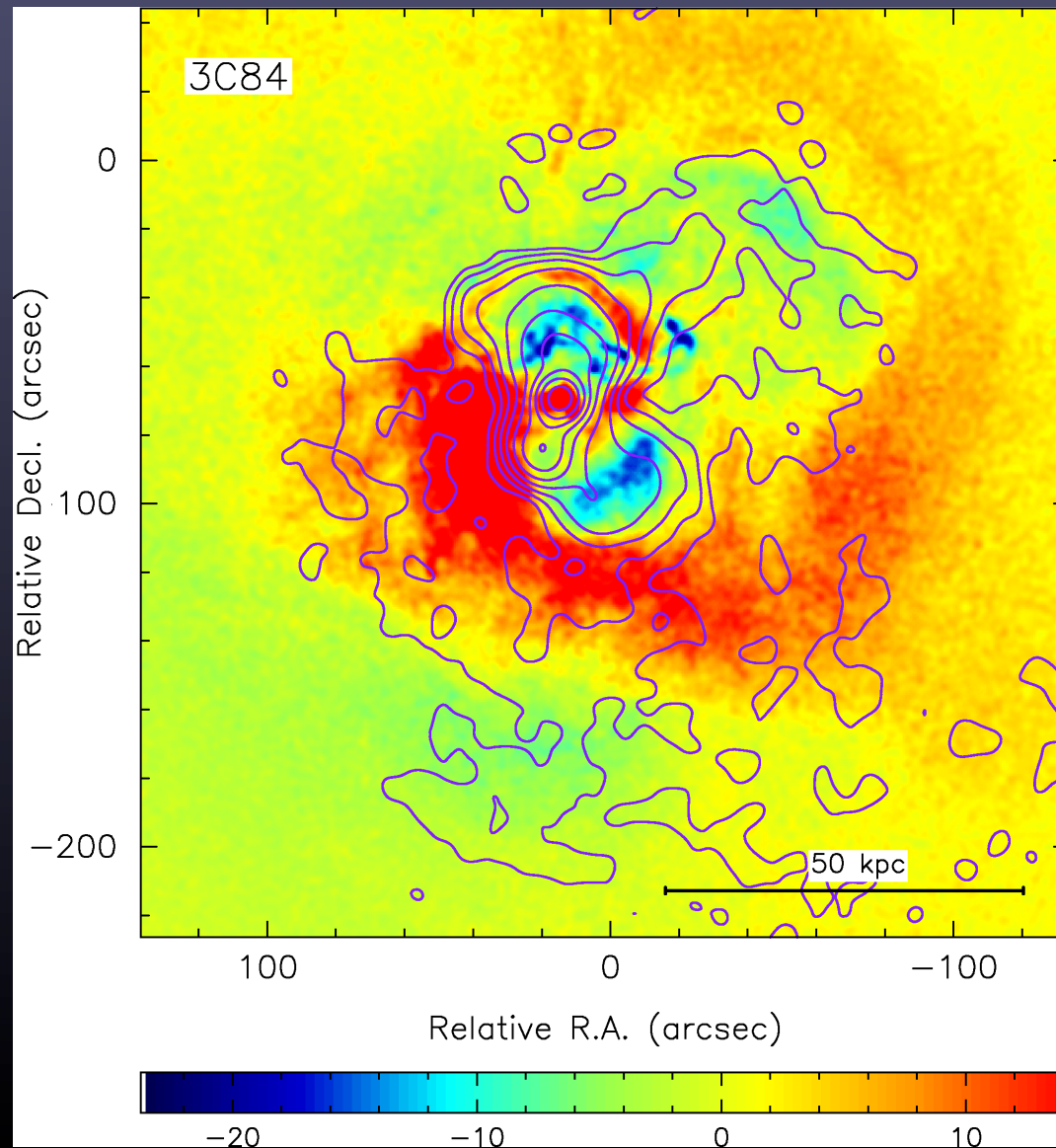
Radio is red
Faint radio core
in center of
NGC1316

Optical in
blue-white

Frame size is
60' x 40'



COMPARISON OF RADIO/X-RAY IMAGES



Contours of radio intensity at
1.4 GHz

Color intensity represents X-
ray intensity smoothed to
radio resolution

IMAGE REGISTRATION AND ACCURACY

- Separation Accuracy of Components on One Image due to residual phase errors, regardless of signal/noise:

Limited to 1% of resolution

Position errors of 1:10000 for wide fields, i.e. 0.1" over 1.4 GHz PB

- Images at Different Frequencies:

Multi-frequency. Use same calibrator for all frequencies.

Watch out at frequencies < 2 GHz when ionosphere can produce displacement. Minimize calibrator-target separation

- Images at Different Times (different configuration):

Use same calibrator for all observations. Daily troposphere changes can produce position changes up to 25% of the resolution.

- Radio versus non-Radio Images:

Header-information of non-radio images often much less accurate than for radio. For accuracy $< 1''$, often have to align using coincident objects.

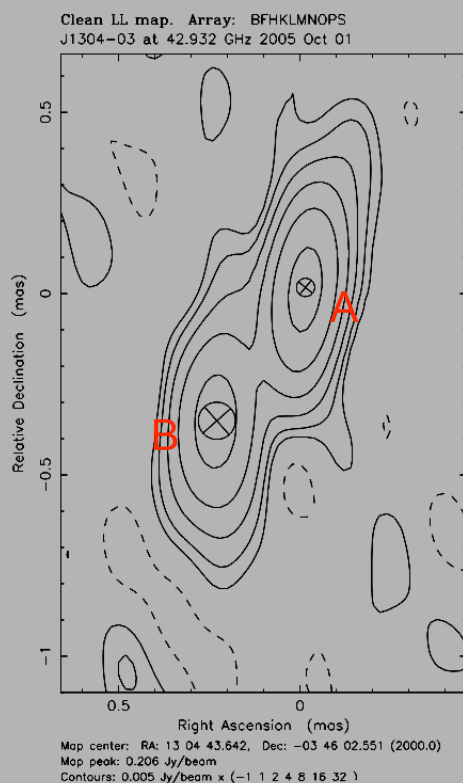
Radio Source Alignment at Different Frequencies

Self-calibration at each frequency aligns maximum at (0,0) point

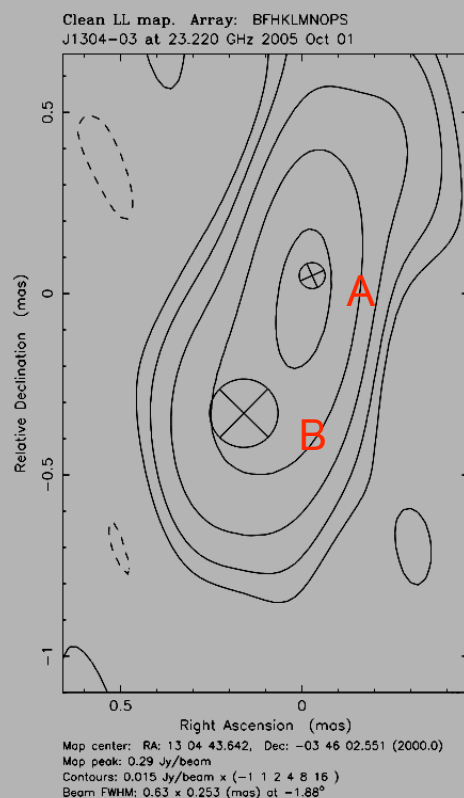
Frequency-dependent structure causes relative position of maximum to change

Fitting of image with components can often lead to proper registration

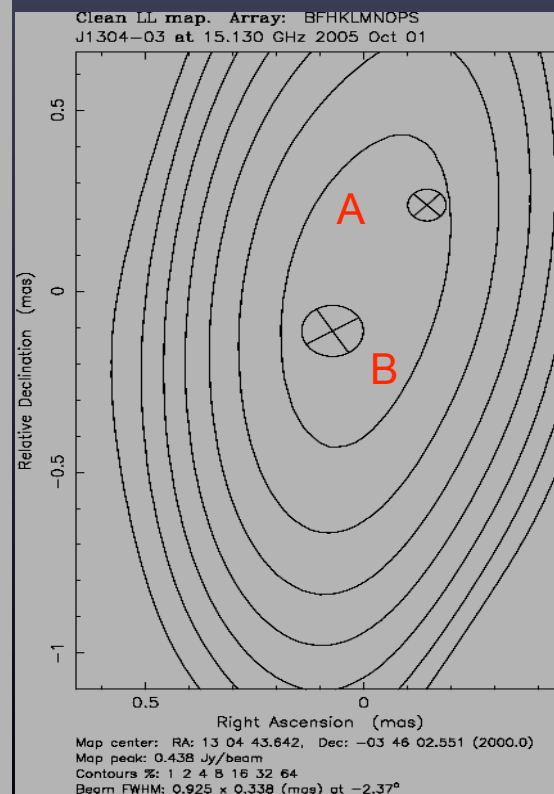
43 GHz: res = 0.3 mas



23 GHz: res = 0.6 mas



15 GHz: res = 0.8 mas



ANALYSIS: SUMMARY

- Analyze and display data in several ways
 - Adjust resolution to illuminate desired interpretation, analysis
- Parameter fitting useful, but be careful of error estimates
 - Fitting in u,v plane and/or image plane
- Registration of a field at different frequencies or wave-bands can be subtle.
 - Whenever possible use the same calibrator
 - May be able to align using 'known' counterparts

Further Reading

- <http://www.nrao.edu/whatisra/>
- www.nrao.edu
- 2010 Lecture on Non-Imaging Analysis
- Synthesis Imaging in Radio Astronomy
- ASP Vol 180, eds Taylor, Carilli & Perley
- Numerical Recipes, Press et al. 1992