Multi-λ Paris Summer School 2009

Images from Interferometry

Katherine Blundell
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David Wilmer
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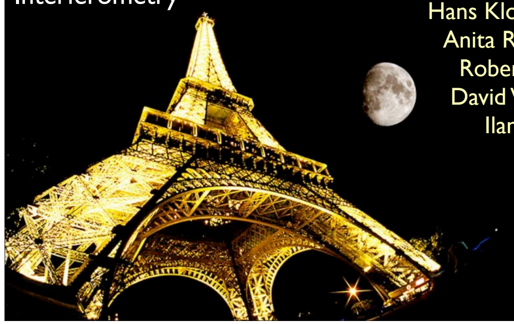
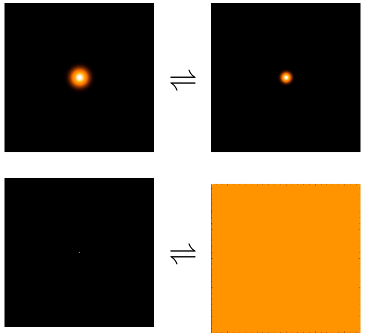


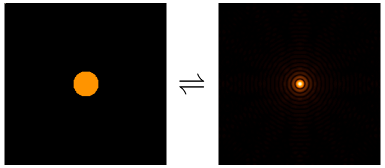
Fourier transforms are at the heart of interferometry

Jean Baptiste Joseph Fourier buried 3.5 km from where we are now



A gaussian transforms to a gaussian

A delta-function transforms to a constant

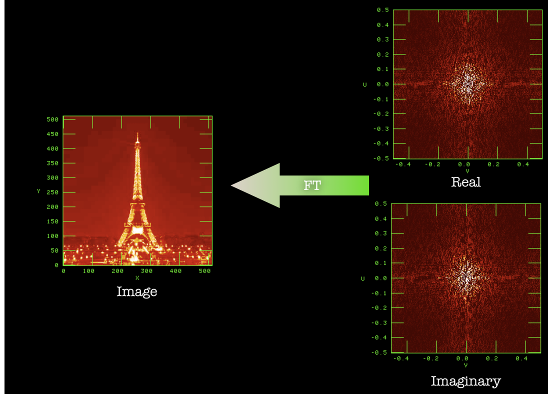


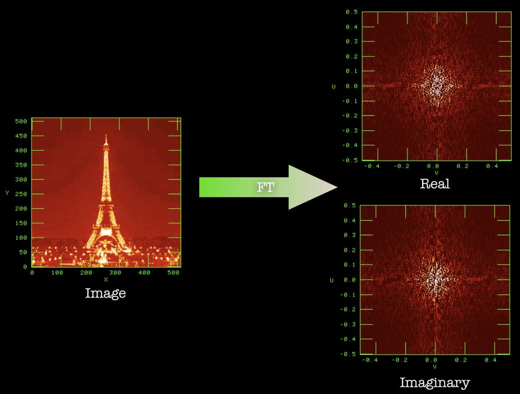
A disc transforms to a Bessel function

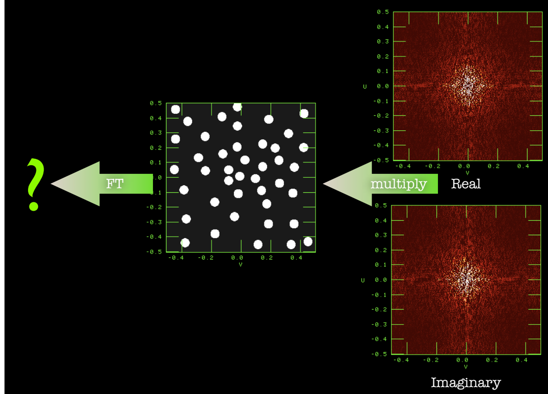
Sharp edges result in many high spatial frequencies

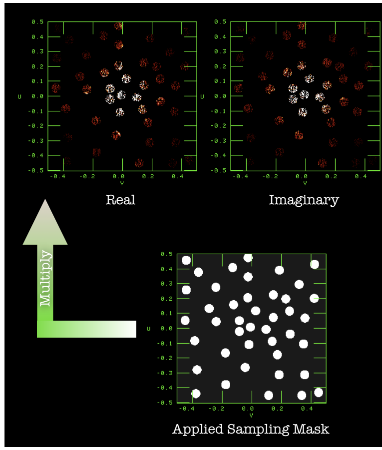
FT relationships	$f(x) \rightleftharpoons F(s)$
scaling	$f(\alpha x) = \alpha^{-1} F(s/\alpha)$
shifting	$f(x - x_0) = F(s) e^{i2\pi x_0 s}$
convolution/ multiplication	$g(x) = f(x) \otimes h(x); \quad G(s) = F(s)H(s)$

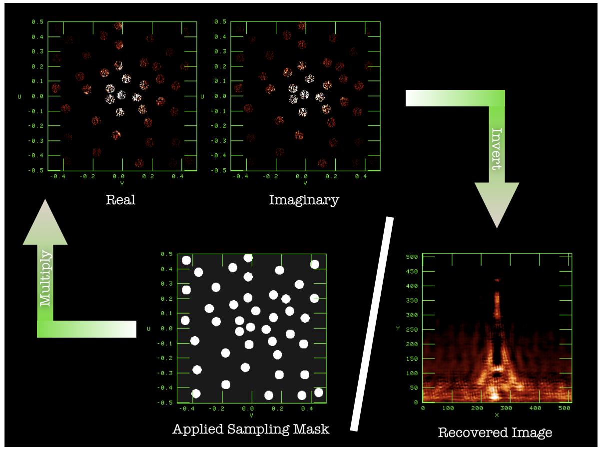
Thompson, Moran & Swenson (2001)

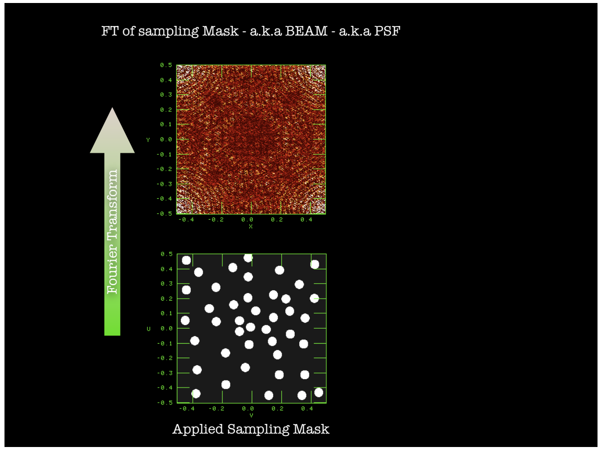


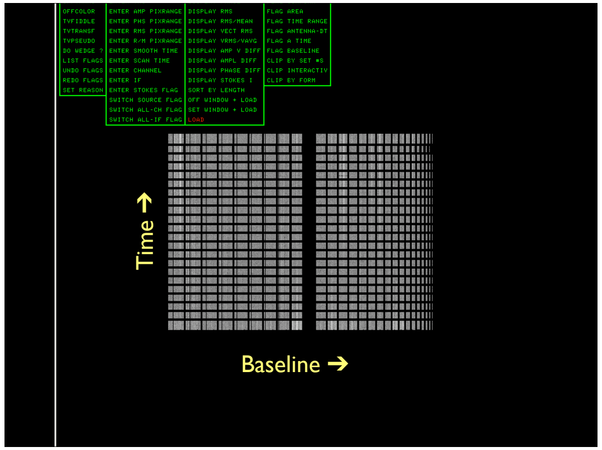


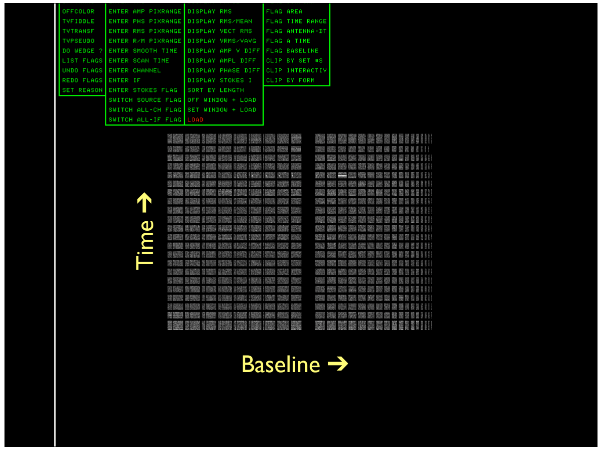


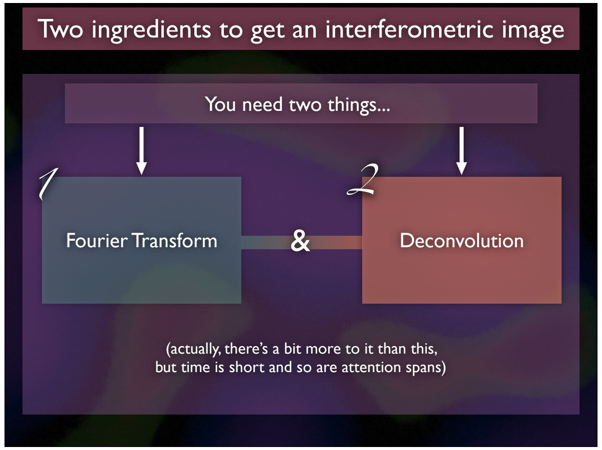


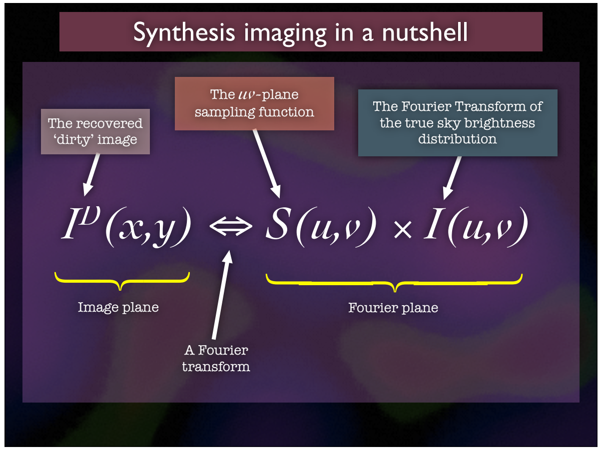


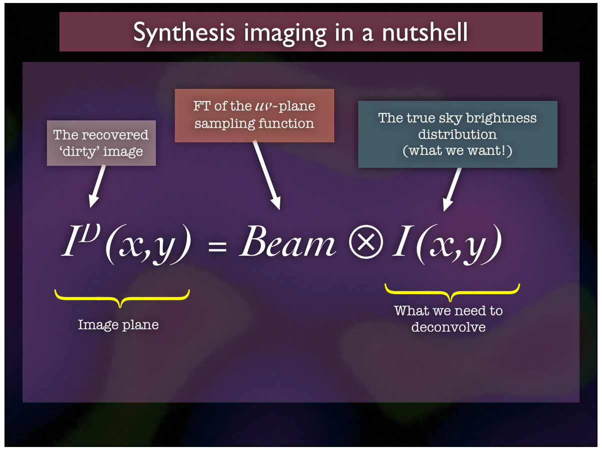






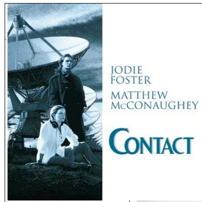


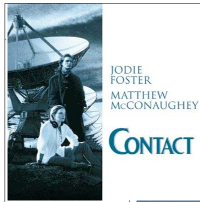




Parlez-vous interferometry?

Beam	what the image you want is *convolved with, i.e. the* **PSF**
(FT pair) UV-plane (coverage)	How you have sampled the FT of what you want to observe
Baseline	**Single antenna pair** (at one instant, corresponds to one sampling of UV-plane)
Flux calibrator (or primary)	Object of **known structure**, so we know what its amplitude & phase *should* be
Phase calibrator (or secondary)	A nearby, **point source**

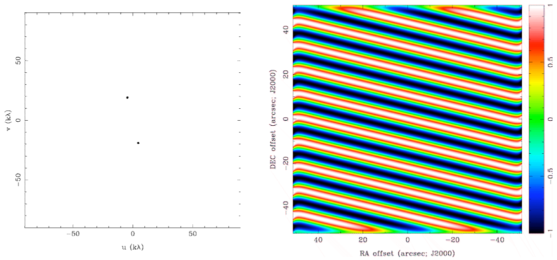




The separation of the VLA antennas is altered every ~4 months.
Most extended: A Most compact: D

Dirty Beam Shape and N Antennas

2 Antennas



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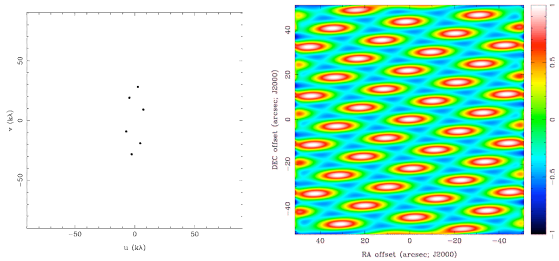
Dirty Beam Shape and N Antennas

3 Antennas



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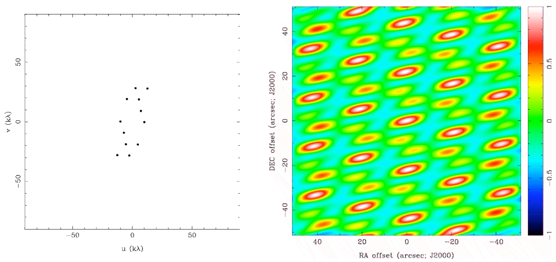
Dirty Beam Shape and N Antennas

4 Antennas



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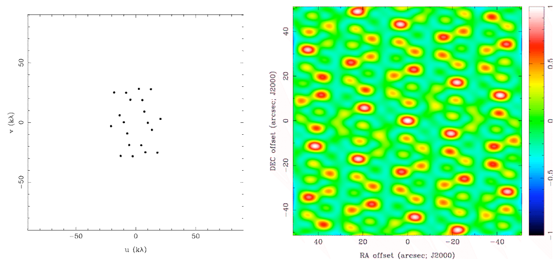
Dirty Beam Shape and N Antennas

5 Antennas



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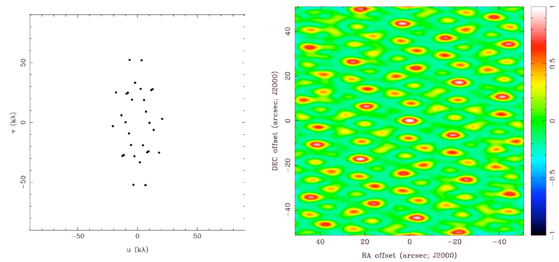
Dirty Beam Shape and N Antennas

6 Antennas



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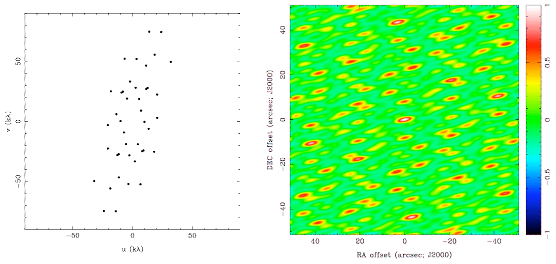
Dirty Beam Shape and N Antennas

7 Antennas



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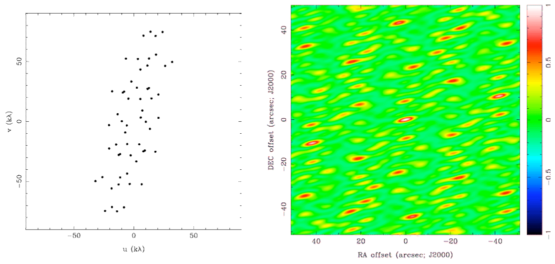
Dirty Beam Shape and N Antennas

8 Antennas



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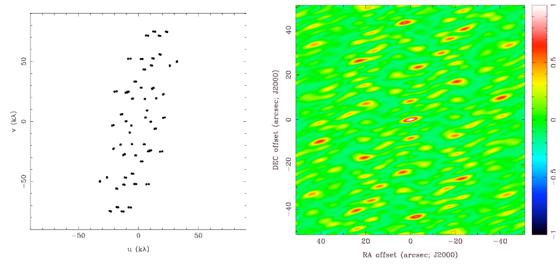
Dirty Beam Shape and Super Synthesis

8 Antennas x 2 samples



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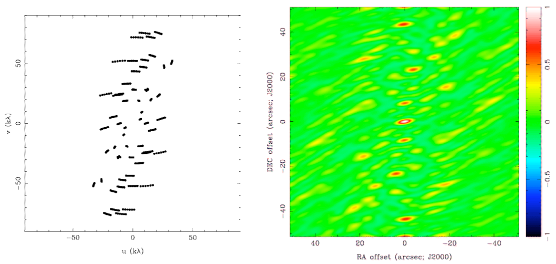
Dirty Beam Shape and Super Synthesis

8 Antennas x 6 samples



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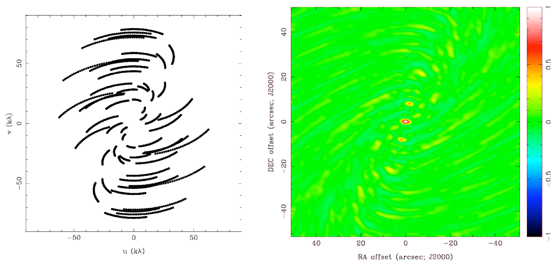
Dirty Beam Shape and Super Synthesis

8 Antennas x 30 samples



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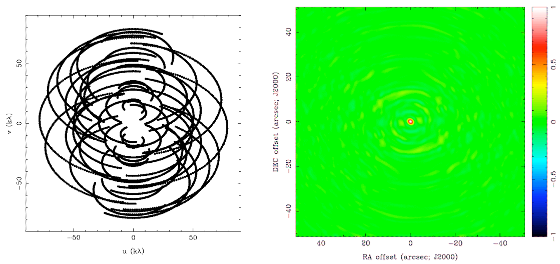
Dirty Beam Shape and Super Synthesis

8 Antennas x 107 samples



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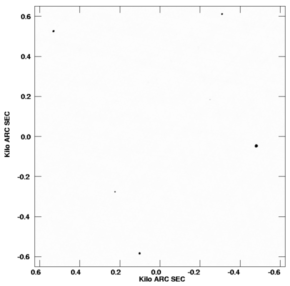
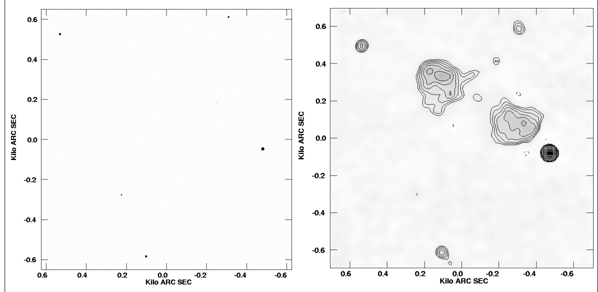


a 200 second observation with the VLA

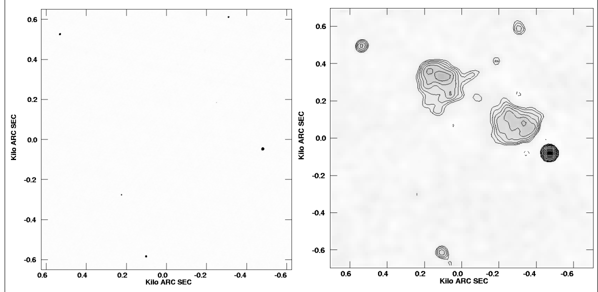


a 200 second observation with the VLA

a 23 second observation with the VLA

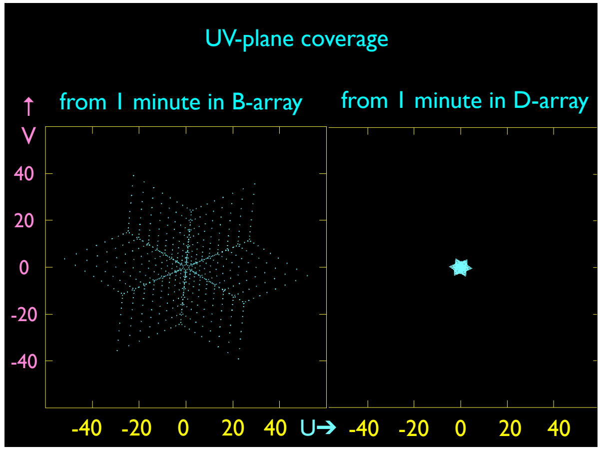
Blundell 2003 (astro-ph/0306110)

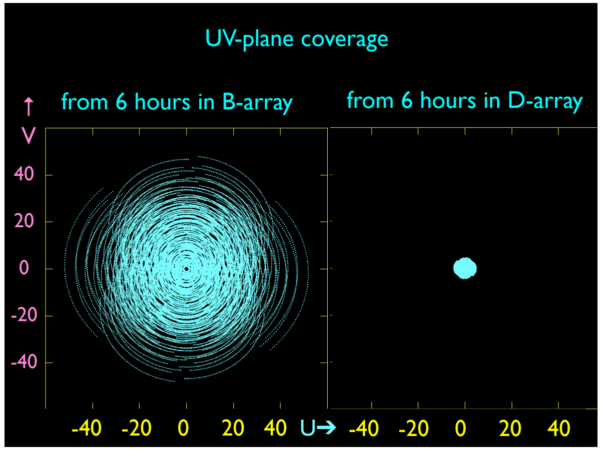
sans short baselines **avec short baselines**

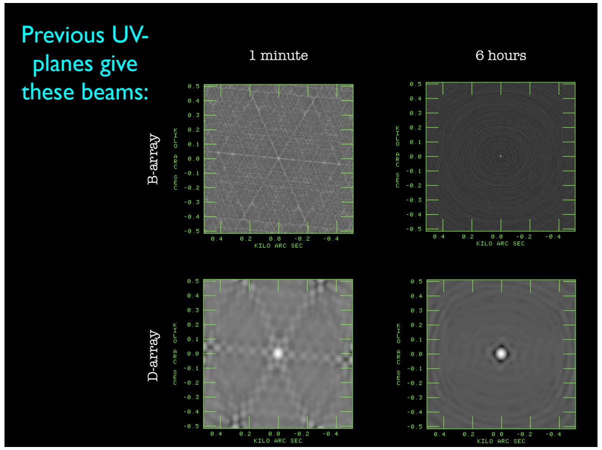


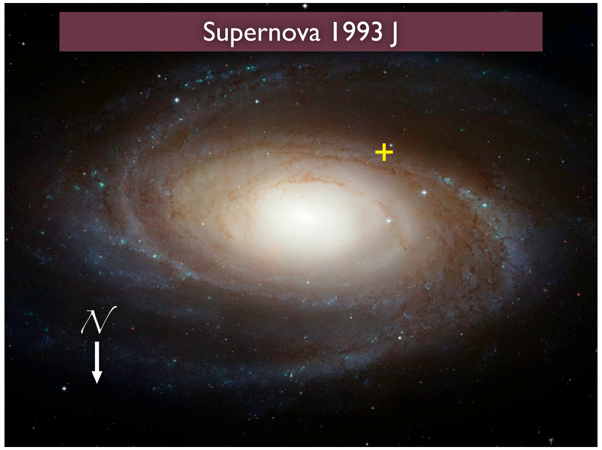
a 200 second observation with the VLA in B-array

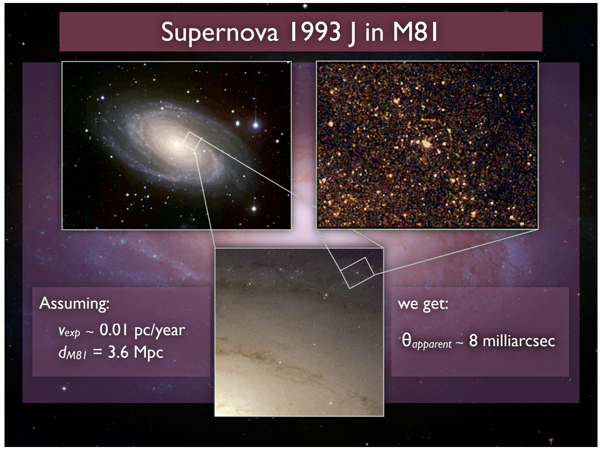
a 23 second observation with the VLA in D-array

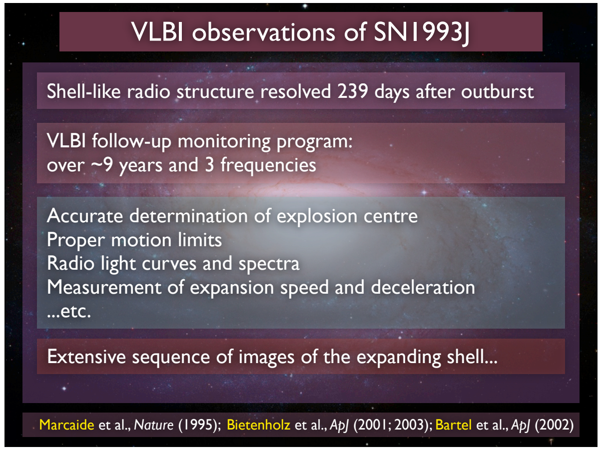

UV-plane coverage
from 1 minute in B-array
from 1 minute in D-array
V
40
20
0
-20
-40
-40 -20 0 20 40 U→ -40 -20 0 20 40

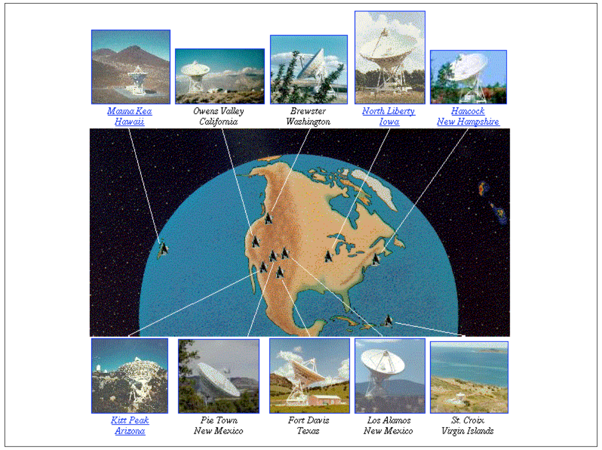

UV-plane coverage
from 6 hours in B-array
from 6 hours in D-array
V
40
20
0
-20
-40
-40 -20 0 20 40 U→ -40 -20 0 20 40

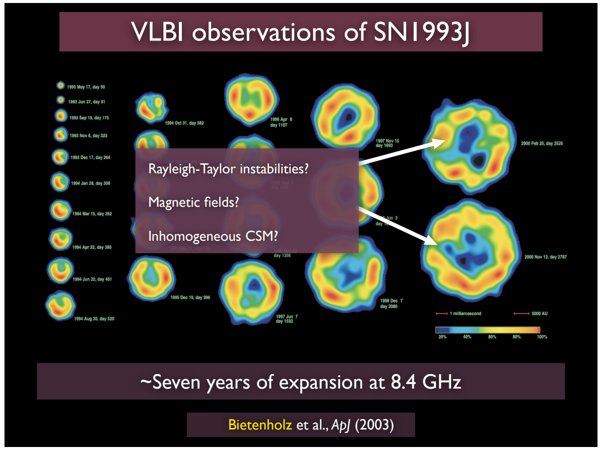

Previous UV-planes give these beams:
1 minute
6 hours
B-array
D-array
KILO ARC SEC

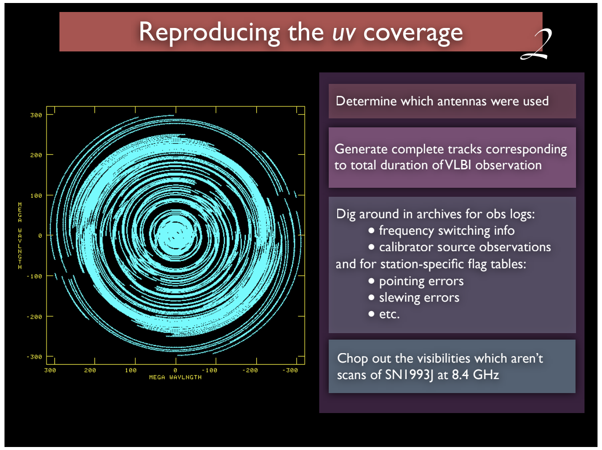

Supernova 1993 J
N


Supernova 1993 J in M81
Assuming:
v_{exp} ~ 0.01 pc/year
d_{M81} = 3.6 Mpc
we get:
$\theta_{apparent}$ ~ 8 milliarcsec

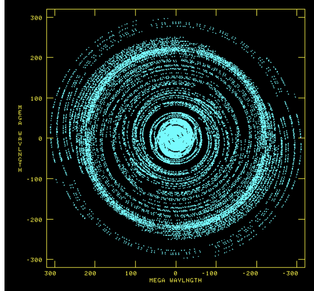

VLBI observations of SN1993J
Shell-like radio structure resolved 239 days after outburst
VLBI follow-up monitoring program:
over ~9 years and 3 frequencies
Accurate determination of explosion centre
Proper motion limits
Radio light curves and spectra
Measurement of expansion speed and deceleration
...etc.
Extensive sequence of images of the expanding shell...
Marcaide et al., Nature (1995); Bietenholz et al., ApJ (2001; 2003); Bartel et al., ApJ (2002)


Mauna Kea Hawaii
Owens Valley California
Brewster Washington
North Liberty Iowa
Hancock New Hampshire
Kitt Peak Arizona
Pie Town New Mexico
Fort Davis Texas
Los Alamos New Mexico
St. Croix Virgin Islands


VLBI observations of SN1993J
Rayleigh-Taylor instabilities?
Magnetic fields?
Inhomogeneous CSM?
~Seven years of expansion at 8.4 GHz
Bietenholz et al., ApJ (2003)


Reproducing the uv coverage
Determine which antennas were used
Generate complete tracks corresponding to total duration of VLBI observation
Dig around in archives for obs logs:
• frequency switching info
• calibrator source observations
and for station-specific flag tables:
• pointing errors
• slewing errors
• etc.
Chop out the visibilities which aren't scans of SN1993J at 8.4 GHz
MEGA WAVLNGTH

Reproducing the *uv* coverage



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and for station-specific flag tables:
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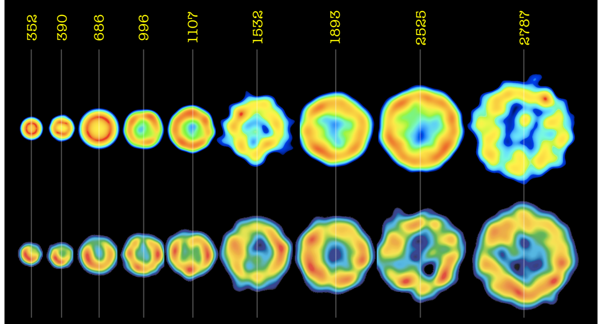
- etc.

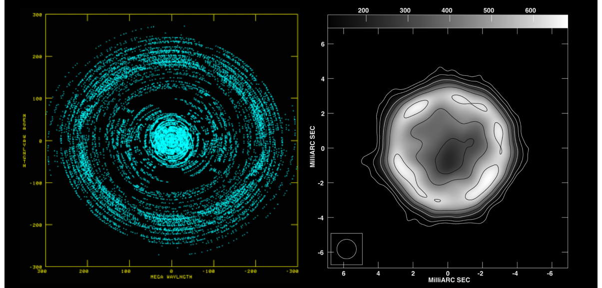
Chop out the visibilities which aren't scans of SN1993J at 8.4 GHz

Simulated VLBI images



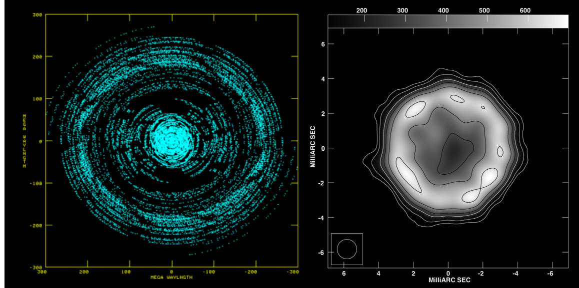
A few more illustrative simulations

Structural evolution via flagging



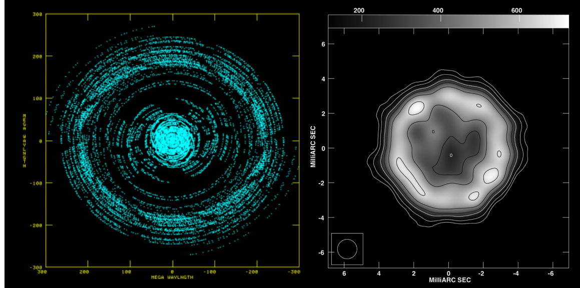
Day 2525: *uv* coverage and simulated image...

Structural evolution via flagging



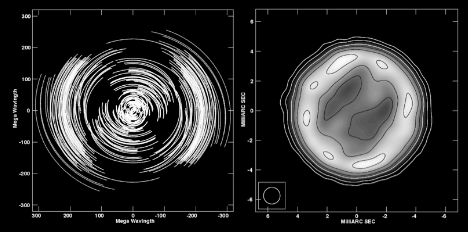
...35 degree elevation flag on Mauna Kea station...

Structural evolution via flagging



...complete removal of St. Croix station

Apparent rotation



Hour angle range: 00:00 - 06:00

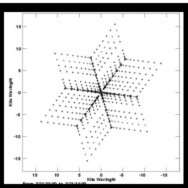
Day 2787: six-hour continuous track;
full figures & detailed examples in **Heywood et al 2009**

Incomplete sampling of the Fourier plane can impart false, complex structure to a morphologically simple source

These effects are certainly partially, and potentially fully responsible for the evolving complex structure in SN1993J

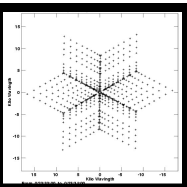
If SN1993J has genuine clumpy structure, and it is *not* a smooth sphere (it probably isn't), the VLBI observations cannot tell the difference between these two cases

Mitigation: simulations in parallel with observations
Full description in **Heywood et al (2009)**

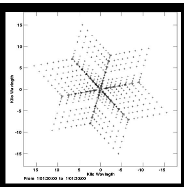


Snapshot observation 2 hours before transit

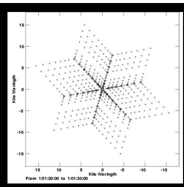
Snapshot observation at transit



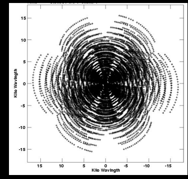
Snapshot observation 2 hours after transit



Snapshot observation 2 hours after transit



Conveniently, the earth rotates!



Continuous observation for total 4 hours

ASKAP CSIRO

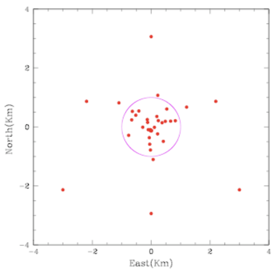
Slides courtesy Ilana Feain

Number of dishes	36
Dish diameter	12 m
Collecting Area	4070 m²
Max baseline	6km
Resolution	~10"
Observing frequency	700 – 1800 MHz
Field of View	***30 deg²*** (ν independent)
Processed Bandwidth	300 MHz
Channels	16 384
System Temperature	35-50K

+ Infrastructure for new SKA-ready observatory Murchison Radio Observatory (MRO)

ASKAP Australian SKA Pathfinder

Initial Array Configuration 36 antennas

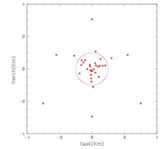


Gupta et al. 2008, ATNF ASKAP Memo 21

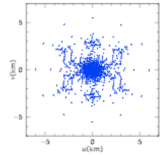
ASKAP CSIRO

UV coverage & beam sizes

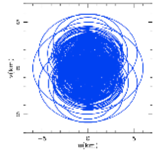
Declination (deg)	Snapshot beam (arcsec x arcsec)	10 hr beam (arcsec x arcsec)
−50	19.1 x 15.4	19.4 x 15.9
−30	17.6 x 15.2	18.9 x 17.5
−10	17.9 x 15.3	19.6 x 18.2
0	18.4 x 15.3	19.5 x 19.3
+10	21.5 x 15.1	20.1 x 19.2



Snapshot (12mins)



Synthesis (10hrs)



Gupta et al. 2008, ATNF ASKAP Memo 21

ALMA

- Atacama Large Millimetre/submillimetre Array
- Aperture synthesis array optimised for millimetre and sub-millimetre wavelengths
- High, dry site, Chajnantor Plateau, Chile (5000m)
- North America (NRAO) + Europe (ESO) + Japan (NAOJ) + Chile
- Fifty 12-m dishes, baselines from 15 m to 14 km
  - few arcsec to 5 milli-arcsec resolution
- ALMA Compact Array 12x7-m dishes, + total power
  - providing sensitivity to larger structures
- 8-GHz bandwidth, 1 mJy in 1 second at 350 GHz!
  - spectral resolution down to tens m/s

ALMA A M S Richards EVLA May 2009 p Printed: 22/06/09 MERLIN

ALMA

Key performance numbers

- Baseline range 15m – 14.5 km + ACA + single dish
- Primary beam / arcsec ≈ 17 (λ/mm) [12m dish]
- Resolution/ arcsec ≈ 0.2(λ/mm)/(max baseline/km)

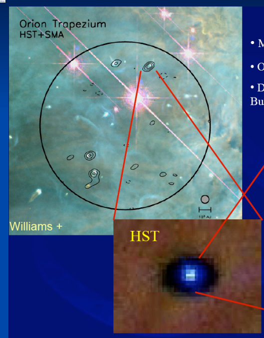
  0.04 arcsec at 100 GHz, 14.5 km baseline

  0.005 arcsec at 900 GHz, 14.5 km baseline
- Wide bandwidth (8 GHz/polarization), low noise temperatures, good site and antennas, … → excellent continuum sensitivity and wide spectral coverage
- Full polarization

Robert Laing
European ALMA Instrument Scientist
Heidelberg, June 10th 2009

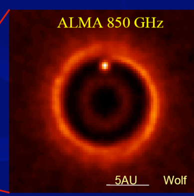
ALMA

Protoplanetary discs with ALMA



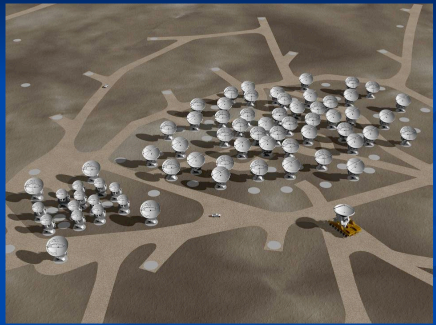
Birth of planets

- $M_{planet} / M_{star} = 1.0 M_{Jup} / .5 M_{sun}$
- Orbital radius: 5AU at 50pc distance
- Disk mass = circumstellar disk around the Butterfly Star in Taurus



Robert Laing
European ALMA Instrument Scientist
Heidelberg, June 10th 2009

Simulation of compact configuration and ACA



Robert Laing
European ALMA Instrument Scientist
Heidelberg, June 10th 2009

Continuous reconfiguration

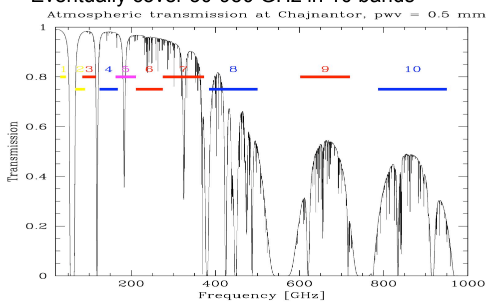
Robert Laing
European ALMA Instrument Scientist
Heidelberg, June 10th 2009

Prototype interferometer

Robert Laing
European ALMA Instrument Scientist
Heidelberg, June 10th 2009

Atmospheric windows

- Eventually cover 30-950 GHz in 10 bands



A M S Richards EVLA May 2009 p Printed: 22/06/09

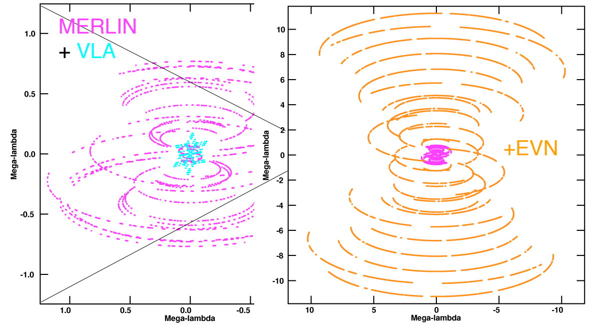
e -MERLIN capabilities

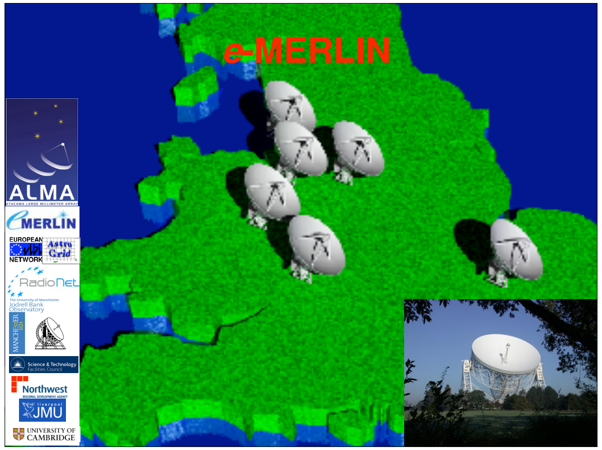
- Resolution matches HST/JWST/ALMA
  - Sub-mas ICRF astrometry, in-beam calibration
  - Full polarization
- 6 mJy 3-s sensitivity in 12 hr at 4-8 GHz (2-GHz bw)
  - 40-mas resolution, up to 8-arcmin field of view
- ~15 mJy continuum sensitivity at other frequencies
- Spectral line sensitivity 7-20 mJy in 0.1 km/s
- Early science later this year, full operations 2010
  - Open access via UK PATT peer review
  - Joint observations with EVN/ Global VLBI
- http://www.merlin.ac.uk

A M S Richards EVLA May 2009 p Printed: 22/06/09

e-MERLIN complements EVLA, VLBI

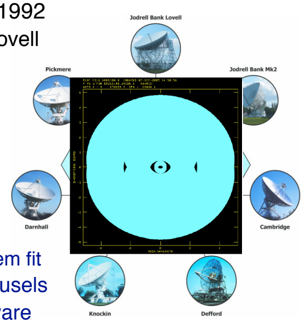
- Spectral line *uv* coverage at 1.6 GHz





What is e-MERLIN?

- MERLIN operating since 1992
  - 6 dedicated antennas + Lovell
  - Baselines 10-217 km
- 2 GHz opt fibre b/w
- WIDAR correlator
- Lovell upgrade
  - 10-30x sensitivity
  - 3 E-systems + Ca 32 m
    - On-axis Rx carousel
    - L-band lenses to make them fit
  - Mk2, De prime focus carousels
  - New receivers, hard/software



e -MERLIN capabilities

- Sub-mas ICRF astrometry (in-beam calibration)
- Full polarization
- Resolution matches HST/JWST, ALMA
- VO access to customised archive products
- RadioNet, NRAO software collaborations

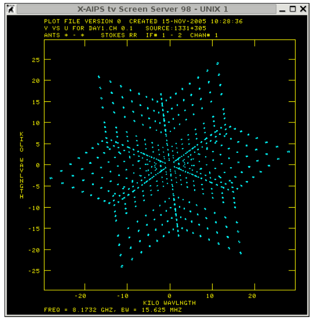
	L-band	C-band	K-band
GHz/cm	1.3-1.725 / 23-17.4	4.2-7.8 / 7.1-3.8	21.5-24.5 / 1.4-1.2
Ang. resol'n	220 - 110 mas	70 - 30 mas	13 - 8 mas
FoV	13 - 30 arcmin	4 - 7 arcmin	2 arcmin
Continuum	sensitivity /beam (max Dn /subband)	sensitivity /beam (max Dn /subband)	sensitivity /beam (max Dn /subband)
3s 12 hr / 4 hr	14 mJy / 25 mJy	6 mJy / 10 mJy	15 mJy / 26 mJy

Spectral capabilities

- Spectral resolution dn≧ 2 Hz (l/dl ≦ 7x10^8 @ 21cm)
  - No more jumping about to cover high velocity sources!
  - Transfer calibration between lines and continuum
  - Almost always a good, close calibrator
    - Achieve optimal sensitivity even if line too weak to self-cal
- Easy to match spectral configs with EVLA or VLBI

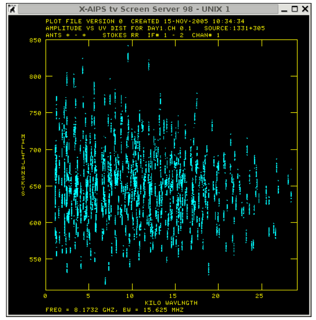
Spectral	L-band	C-band	K-band
3s 12 hr / 4 h Lines:	sensitivity /beam (per channel)	sensitivity /beam (per channel)	sensitivity /beam (per channel)
0.05 km/s	23 mJy / 40 mJy	10 mJy / 17 mJy	32 mJy / 55 mJy
3 km/s	2.9 mJy / 5 mJy	1.3 mJy / 2.2 mJy	4 mJy / 7 mJy
Continuum	(max Dn /subband)	(max Dn /subband)	(max Dn /subband)
12 subbands	17 mJy / 30 mJy	8 mJy / 14 mJy	17 mJy / 30 mJy

Looking at UV-data: U versus V



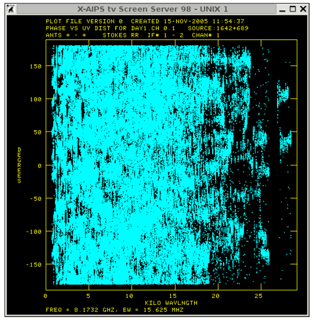
task 'UVPLT'; bparm 6,7

Looking at UV-data: Amplitude versus baseline length



task 'UVPLT'; bparm 0,0

Looking at UV-data: Phase versus baseline length



task 'UVPLT'; bparm 0,2

Pixel size and image size

- Pixel size
  - should satisfy sampling theorem for longest baselines, $\Delta x < 1/2\ u_{max}$, $\Delta y < 1/2\ v_{max}$
  - In practice, use 3-5 pixels across dirty beam
- Image size
  - Image size 2 x primary beam
  - Sometimes larger

Deconvolution via CLEAN

- Identify strongest feature in dirty image
- Add a fraction g (loop gain) of this point source to the "clean components" list
- Subtract *this fraction multiplied by the beam* from the dirty image
- Repeat...
- Finally, convolve clean component list with clean beam and add back to (cleaned) dirty image to give restored image

Remarkably important tip regarding CLEAN

- Well worth taking the time to centre the brightest point on the dirty image on the centre of a pixel.

$$V_{ij}(t) = g_i(t) g_j^*(t) V^{\mathrm{true}}(t) + \epsilon_{ij}(t)$$

Complex gain of antenna *i*

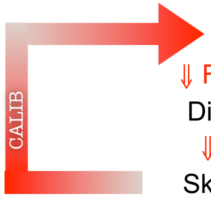
Additive noise

Visibility measured between antennas *i* and *j*

True visibility (but use model)

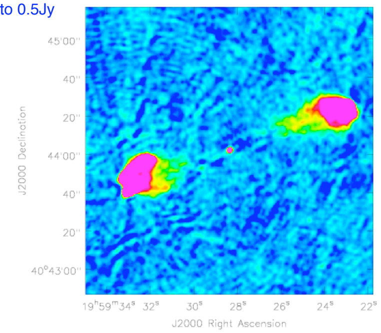
Self-calibration

- a priori calibration not perfect
  - calibration solutions from a different time, different direction from target
- Self-cal aims to find antenna-based errors (N complex gains) while making use of model of your target. N(N-1)/2 visibilities.
- Absolute positional information is preserved IF model has correct initial position
- Dangerous if target is complex, and/or signal-to-noise is low
- Iterative technique: start with conservative model, improve...

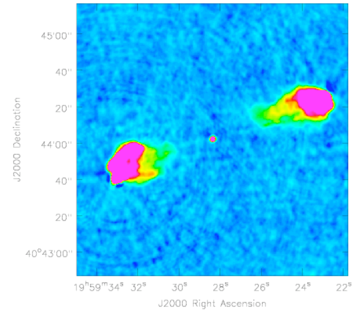


Calibrated Visibilities
⇓ Fourier Transform [IMAGR]
Dirty Beam and Dirty Image
⇓ Deconvolution [IMAGR]
Sky Model, “restored” Image

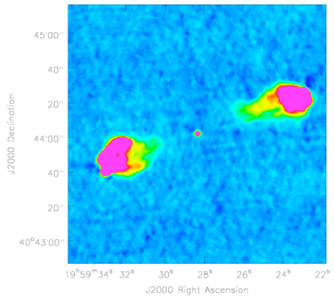
Phase calibration using nearby source observed every 20 minutes
Peak ~ 22Jy
Display shows -0.05Jy to 0.5Jy

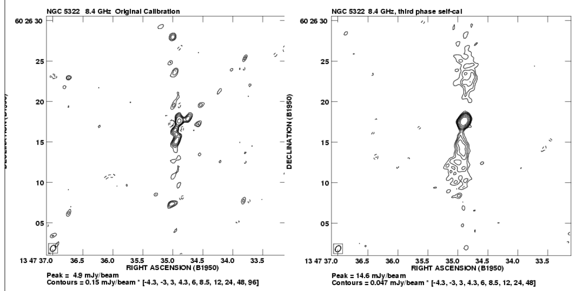


Phase self-cal
every 10 seconds



Then after 1 amp+ phase self-cal





Rules of thumb for self-cal

- Start with phase self-cal. (Meaning no amplitude self-cal)
- Short solution interval (~30 seconds)
- As final(ish) step: amplitude+phase self-cal (~20 minutes)
- Only include baselines in model if their flux is included

When self-calibration is risky / impossible

When your target source is too weak and feeble to self-calibrate, then need to use phase-referencing technique (extreme form of which is fast-switching).