NORTH AMERICAN ARC
ALMA Regional Center

North American
ALMA Science
Center

Interferometry Basics for ALMA Community Days

NAASC Memo #104

Nuria.Marcelino

ABSTRACT

These Interferometry Basics slides were included as part of the NA ALMA mm considerations presentation prepared by T. Hunter and C. Brogan. They include material from the NRAO Synthesis Imaging School, as well as from presentations of other ALMA Community Days, in particular the one at Caltech. The attached version is the presentation used in the ALMA Early Science Proposal Preparation Tutorial held in Charlottesville (Apr 26-27, 2011). Further updated versions of this presentation can be found at: https://sites.google.com/site/almacommunityoutreach/community-day-agendas/cde-powerpoint-slides.

Interferometry Basics and MM Observing Considerations

Nuria Marcelino

North American ALMA Science Center

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

Overview of Talk

- **Perspective:** Getting time on ALMA will be competitive!
  - The math: only ~600 hours for ES cycle 0
    at ~6 hours per project ➔ ~100 projects split over the world

- **Motivation:** While ALMA is for everyone, a technical justification is required for each proposal, so you need to know some of the details of how the instrument works

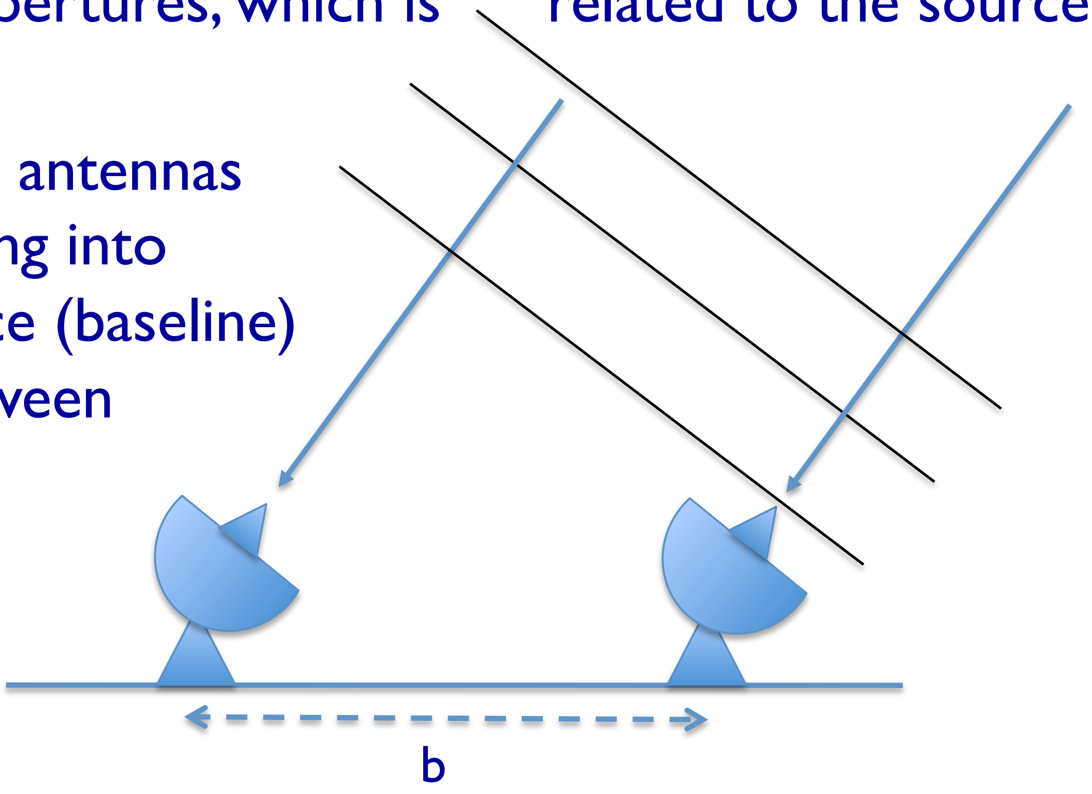
- **Goal:** Do the best job you can to match your science to ALMA's capabilities

- Angular resolution
- Sensitivity
- Spectral resolution
- Image quality: UV coverage
- Source characteristics
- Calibration

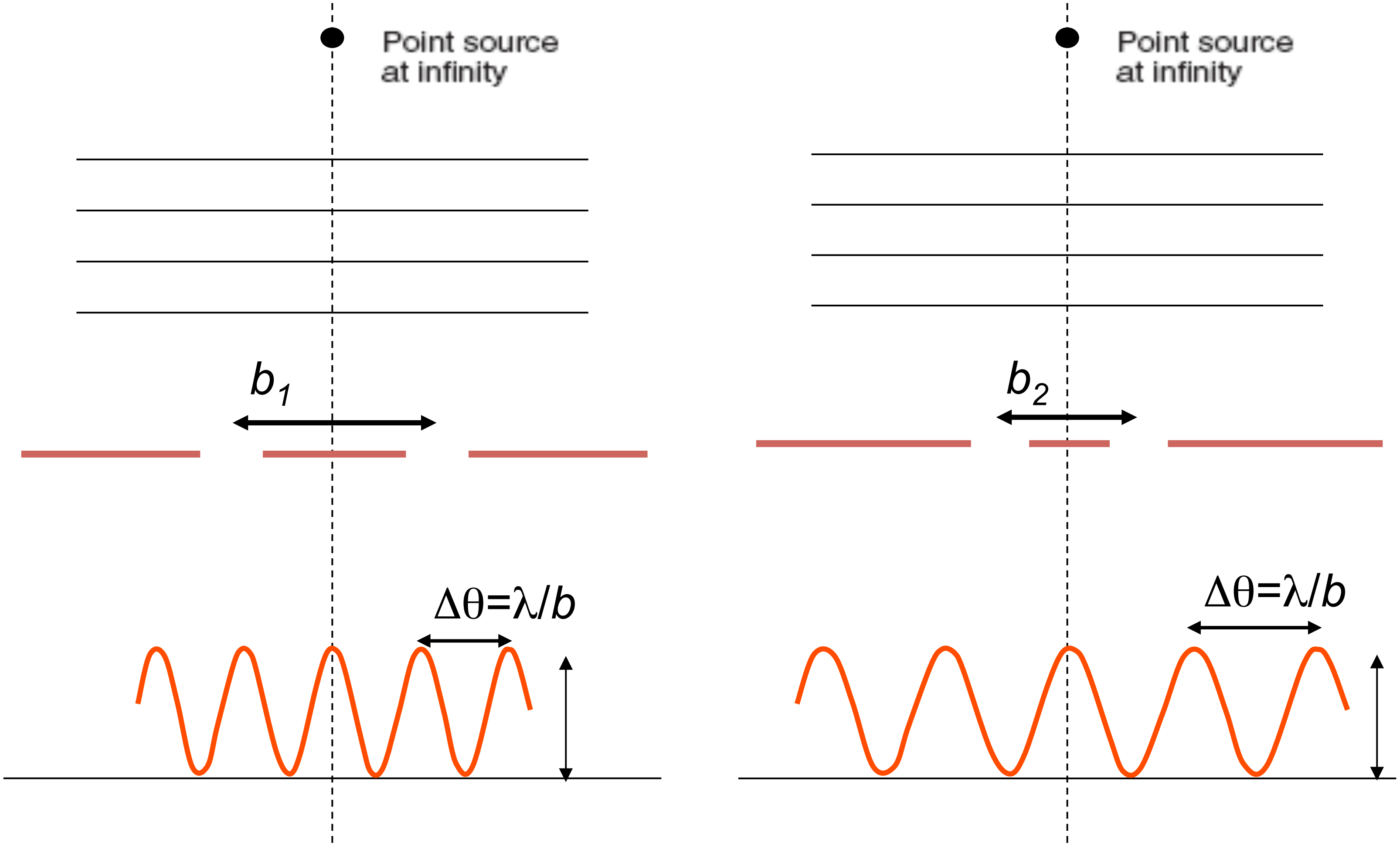
- **Angular resolution**
  - Single-dish: ~ λ / D
  - Interferometer: ~ λ / D_{max}
- Sensitivity
- Spectral resolution
- Image quality: UV coverage
- Source characteristics
- Calibration

Interferometers: the basics

- Interferometry: a method to 'synthesize' a large aperture by combining signals collected by separated small apertures
- An Interferometer measures the interference pattern produced by two apertures, which is related to the source brightness.
- The signals from all antennas are correlated, taking into account the distance (baseline) and time delay between pairs of antennas

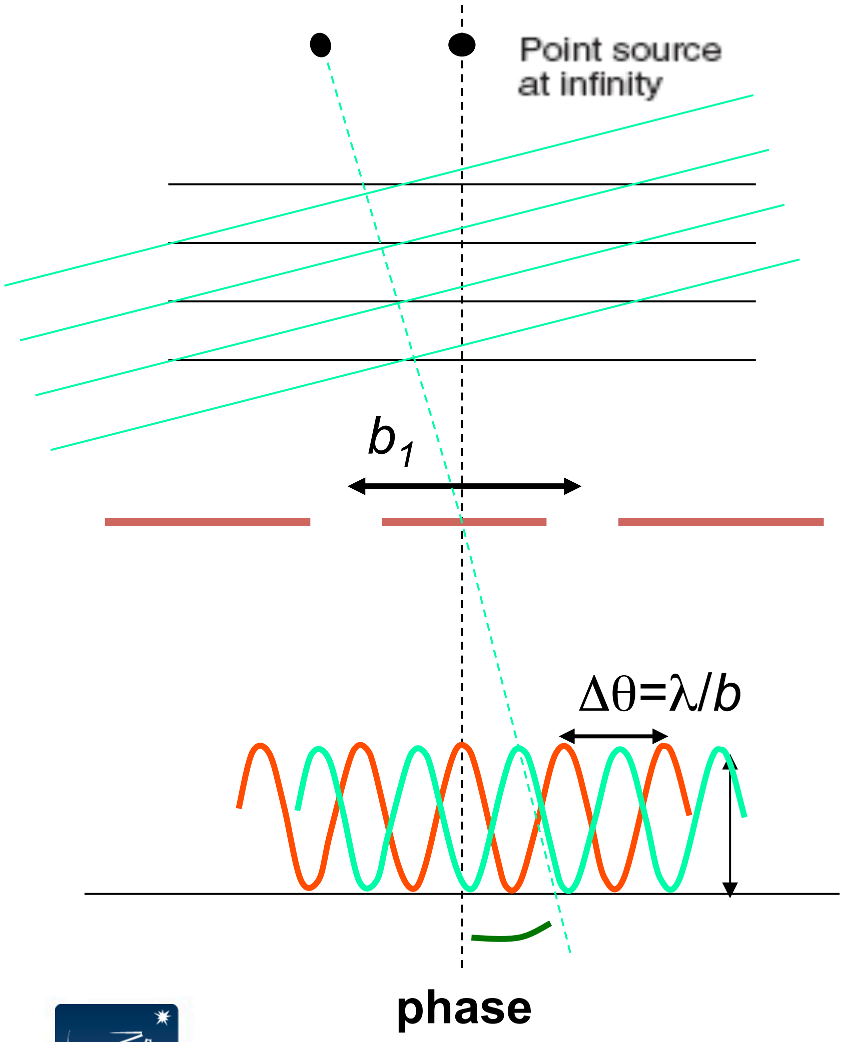


Interferometers: the basics

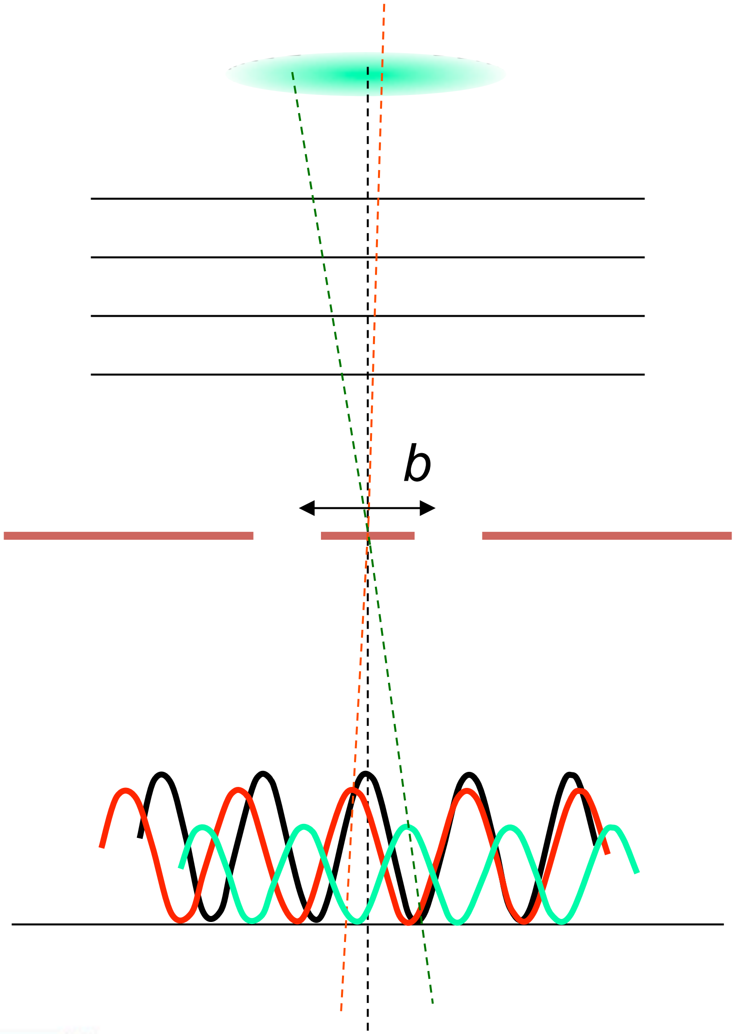


(based on CalTech CDE talk by A. Isella)

Interferometers: the basics



Interferometers: the basics



- Amplitude tells "how much" of a certain frequency component
- Phase tells "where" this component is located

↓

Visibility

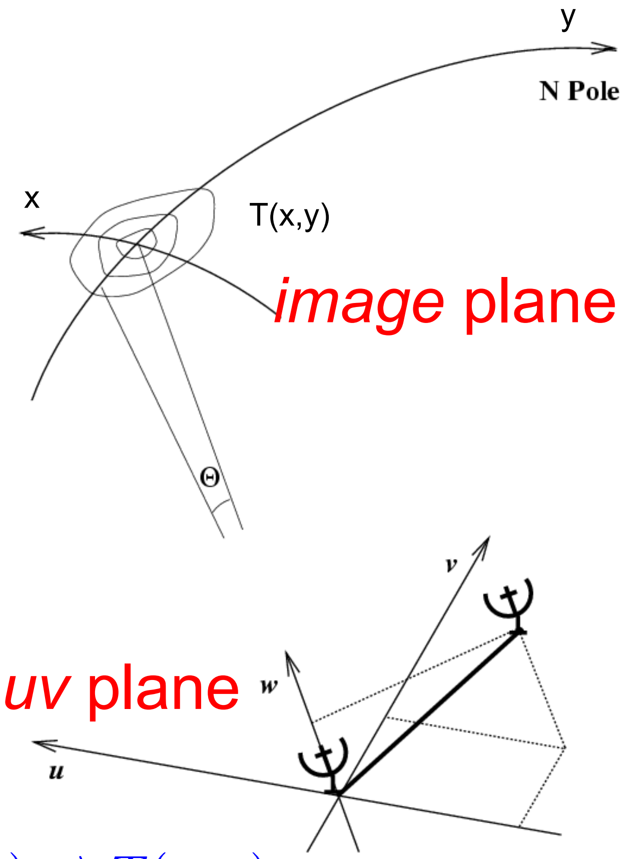
Visibility and Sky Brightness

For small fields of view: the complex visibility, V(u,v), is the 2D Fourier transform of the brightness on the sky, T(x,y)

$$V(u,v) = \int \int T(x,y) e^{2\pi i(ux+vy)} dxdy$$

$$T(x,y) = \int \int V(u,v) e^{-2\pi i(ux+vy)} dudv$$

- u,v (wavelengths) are spatial frequencies in E-W and N-S directions, i.e. the baseline lengths
- x,y (rad) are angles in tangent plane relative to a reference position in the E-W and N-S directions



$$V(u,v) \rightleftharpoons T(x,y)$$

2D Fourier Transforms

(from Summer School lecture by D. Wilner)

T(x,y)

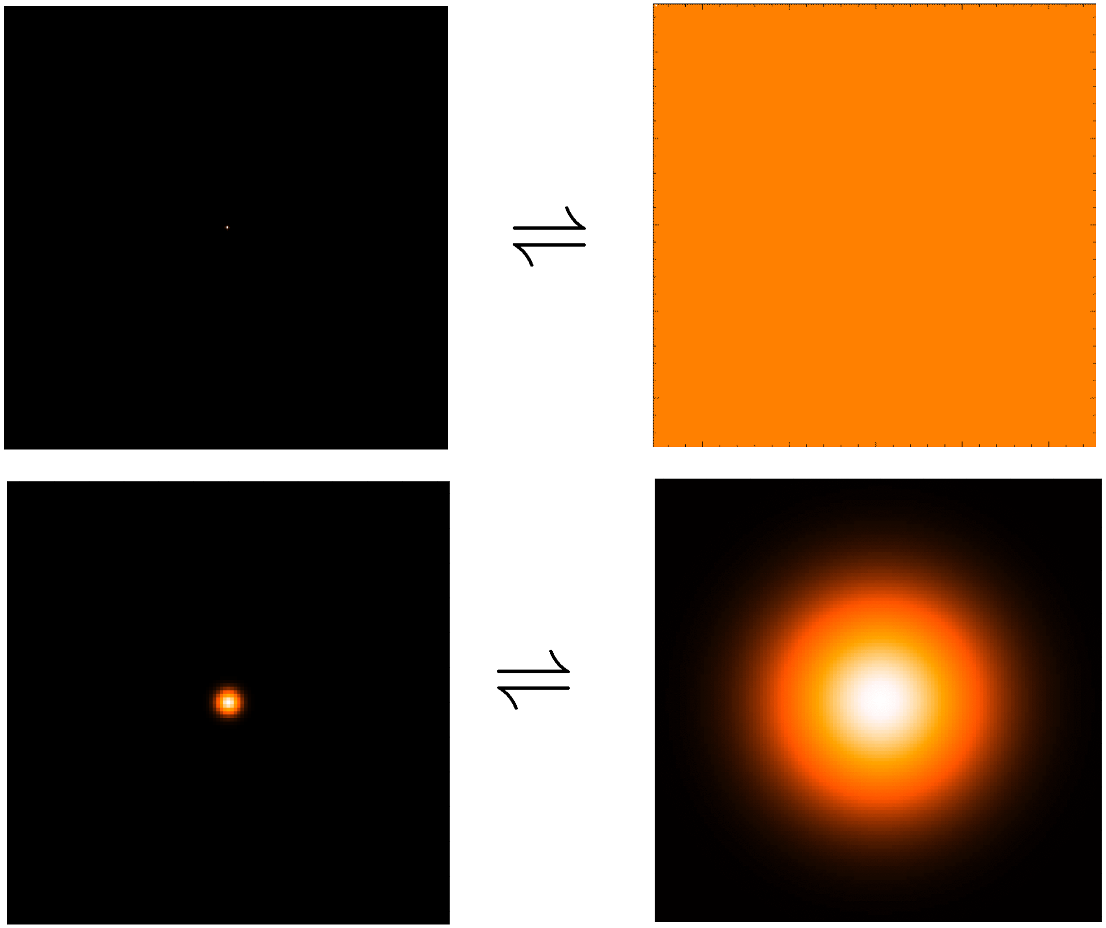
Amp{V(u,v)}

δ Function

Constant

Gaussian

Gaussian

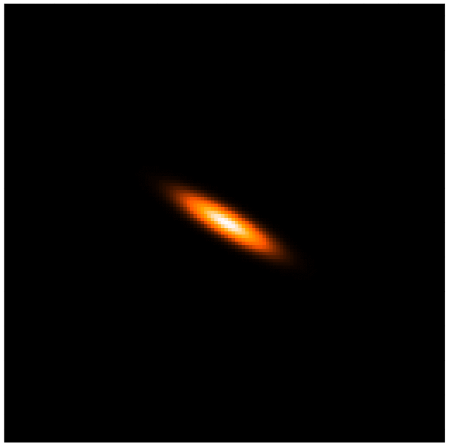


narrow features transform to wide features (and vice-versa)

2D Fourier Transforms

T(x,y)

elliptical
Gaussian



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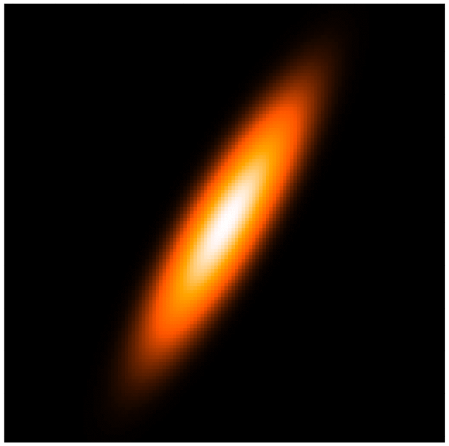
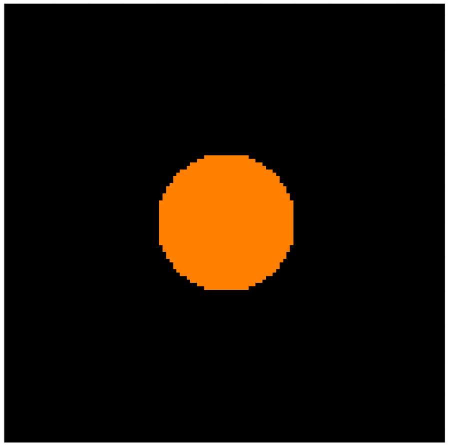


Amp{V(u,v)}

elliptical
Gaussian

Disk



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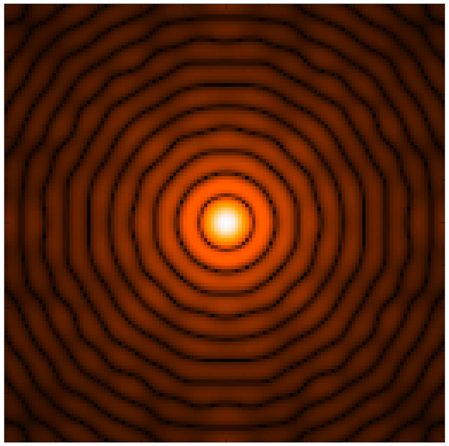
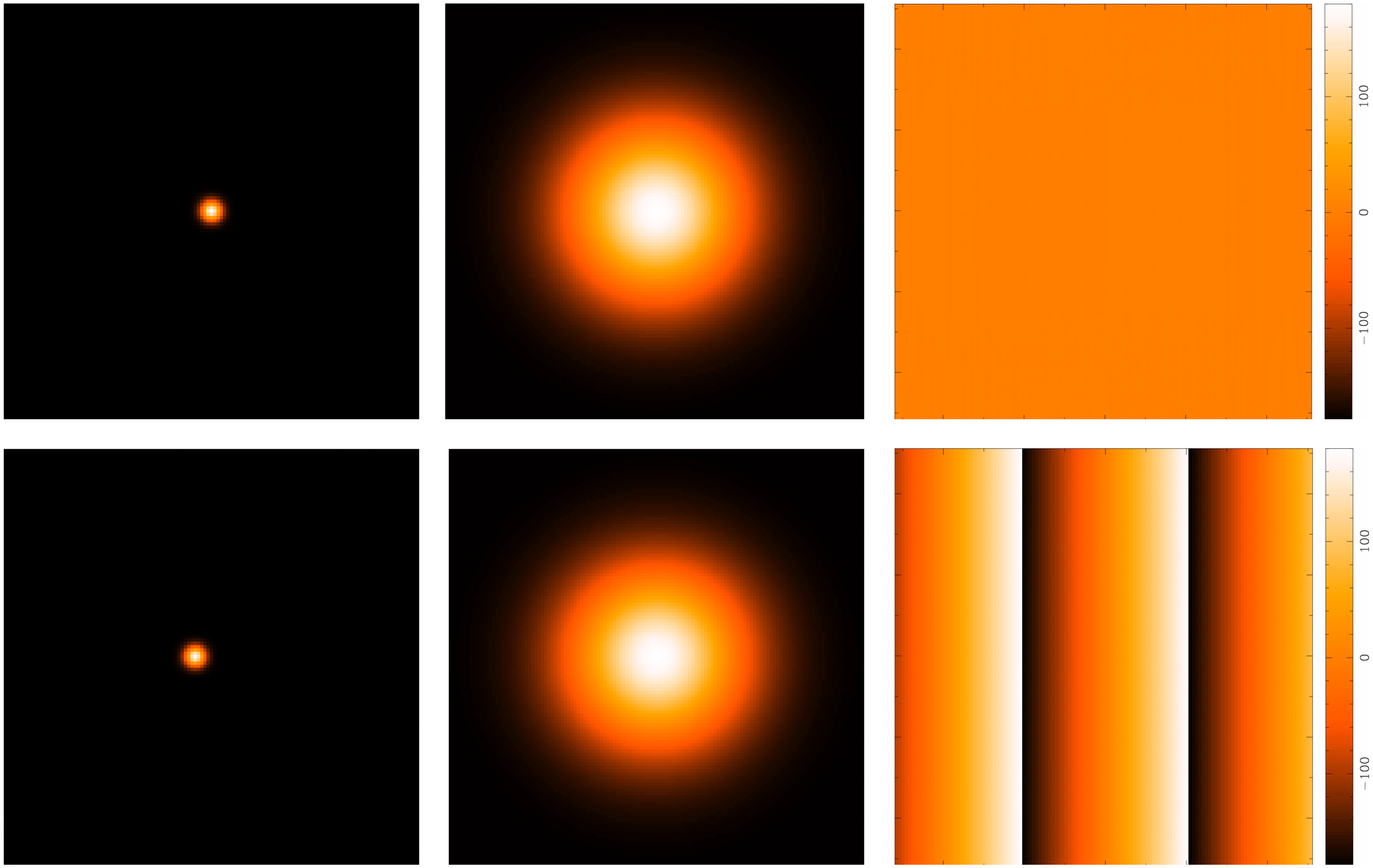


Bessel

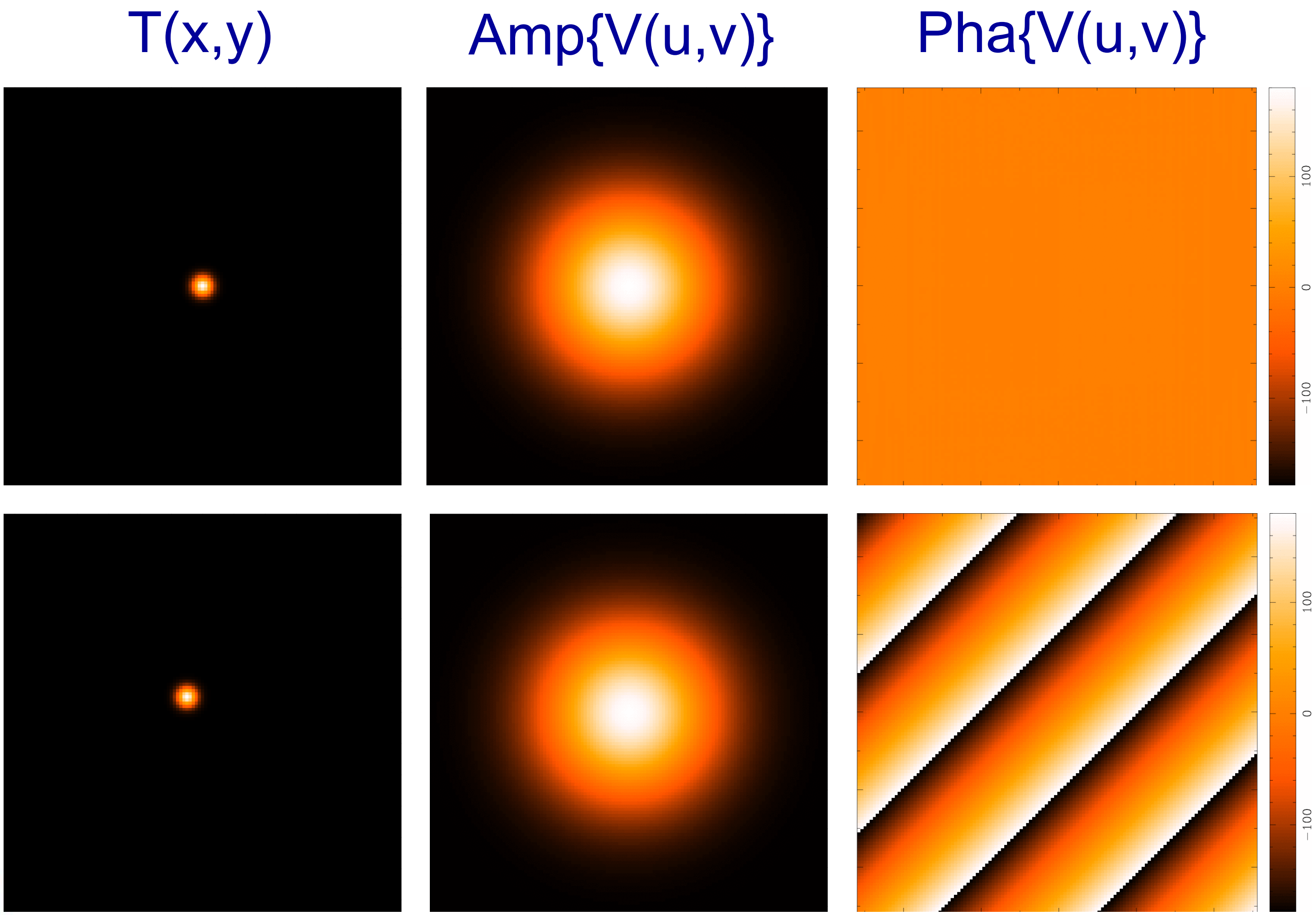
sharp edges result in many high spatial frequencies

Visibility: Amplitude and Phase

T(x,y)   Amp{V(u,v)}   Pha{V(u,v)}



Visibility: Amplitude and Phase

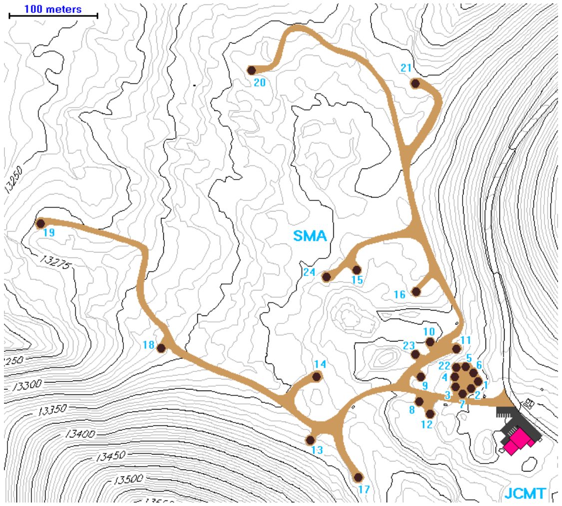

T(x,y)

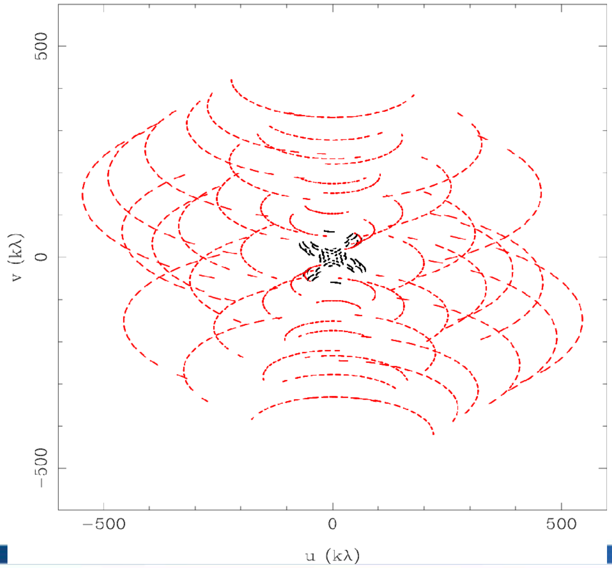
Amp{V(u,v)}

Pha{V(u,v)}

Aperture Synthesis

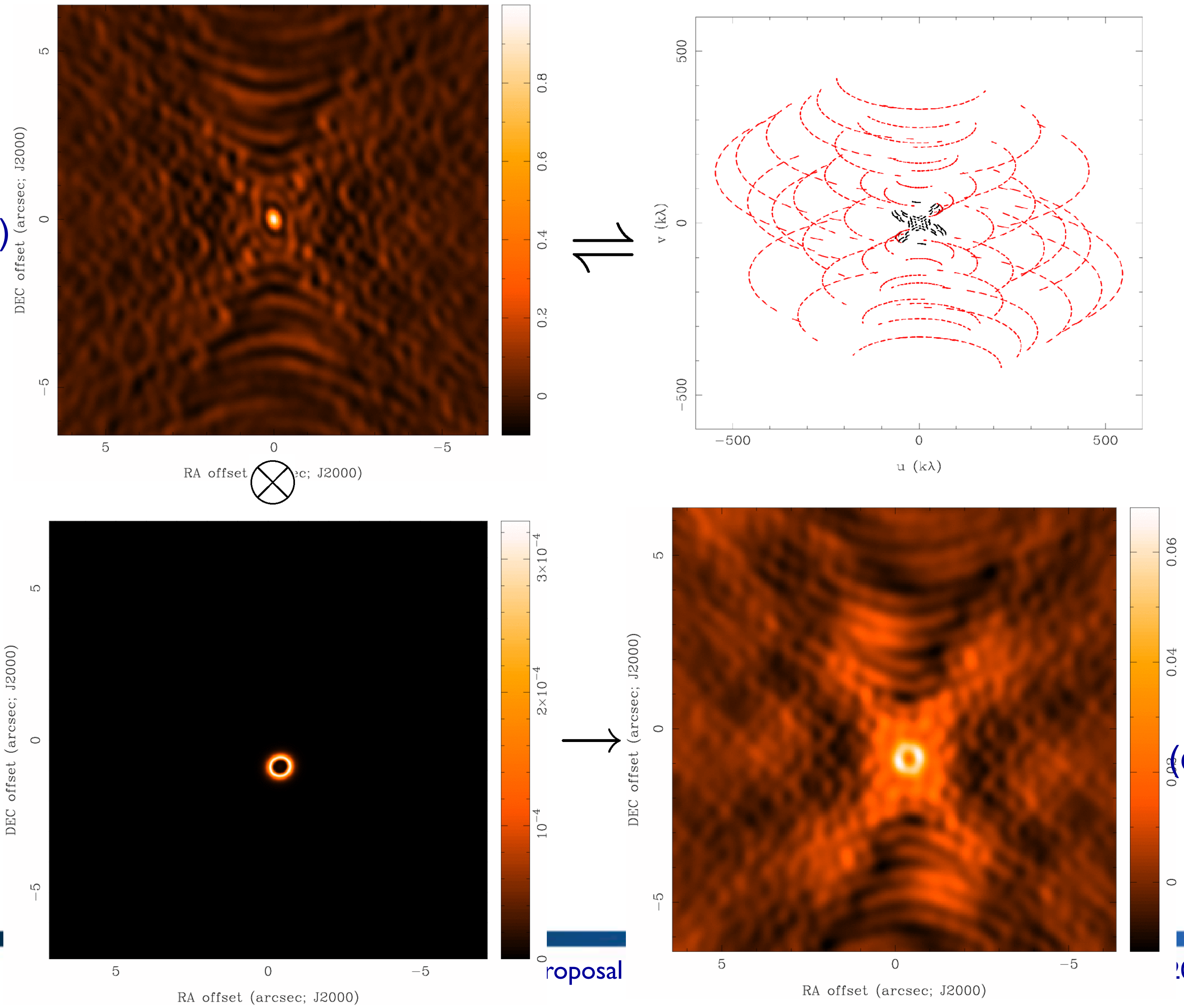
- Sample V(u,v) at enough points to synthesis the equivalent large aperture of size (u_{max},v_{max})
  - 1 pair of telescopes → 1 (u,v) sample at a time
  - N telescopes → number of samples = N(N-1)/2 (“snapshot”)
- A good image quality requires a good coverage of the uv plane
  - fill in (u,v) plane by making use of Earth rotation (“track”)
  - reconfigure physical layout of N telescopes





2 configurations
of 8 SMA antennas
345 GHz
Dec = -24 deg

Dirty Beam and Dirty Image



b(x,y)
(dirty beam)

B(u,v)

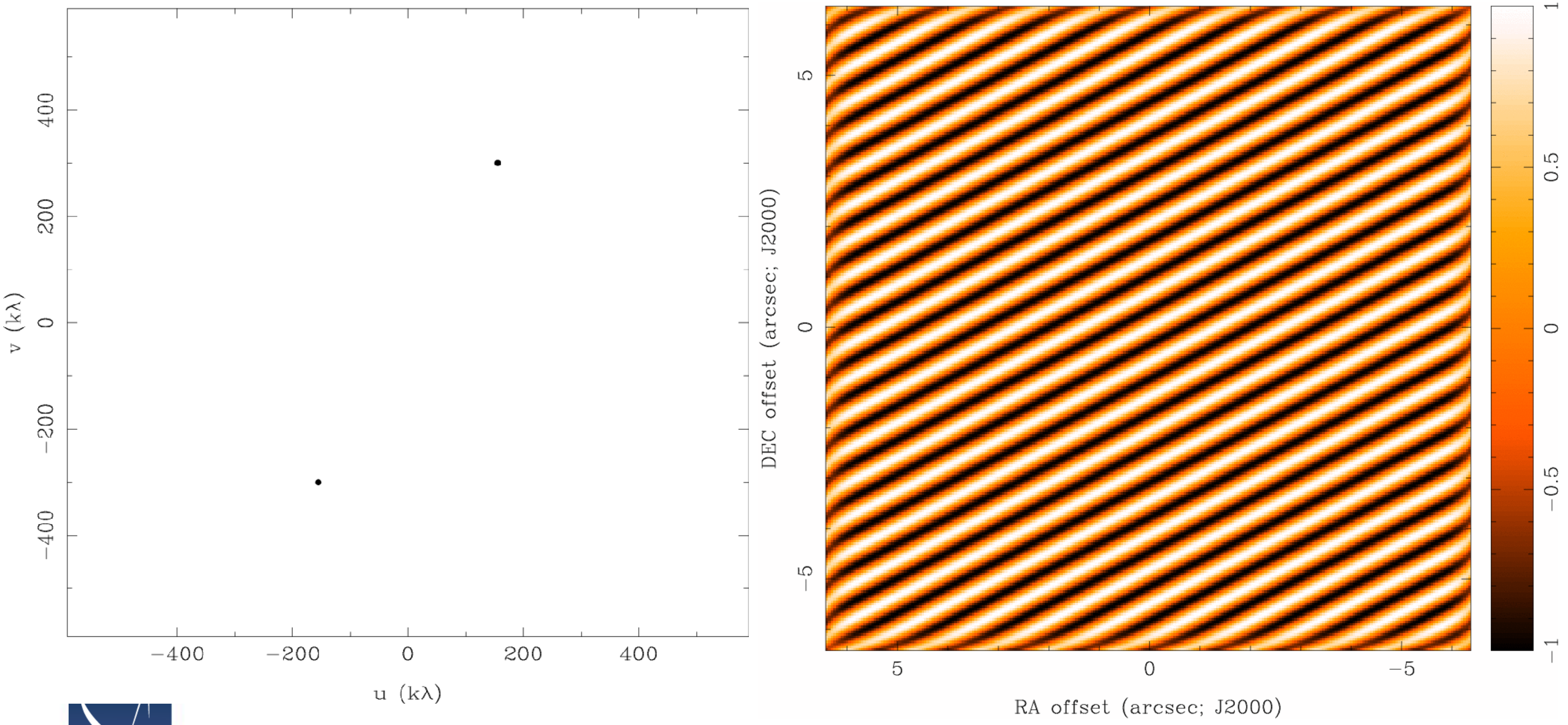
T(x,y)

$T^D(x,y)$
(dirty image)

Dirty Beam Shape and N Antennas

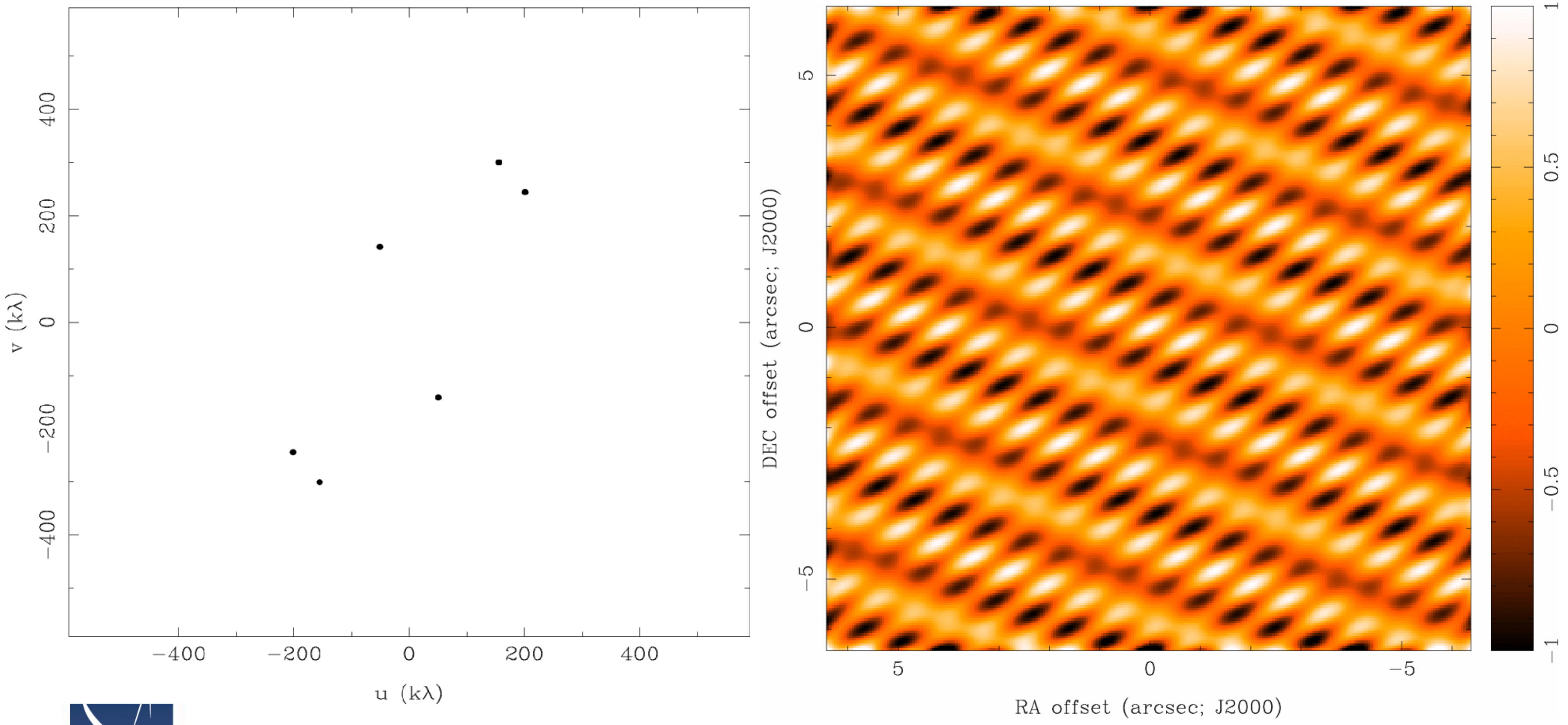
(Image sequence taken from Summer School lecture by D.Wilner)

2 Antennas



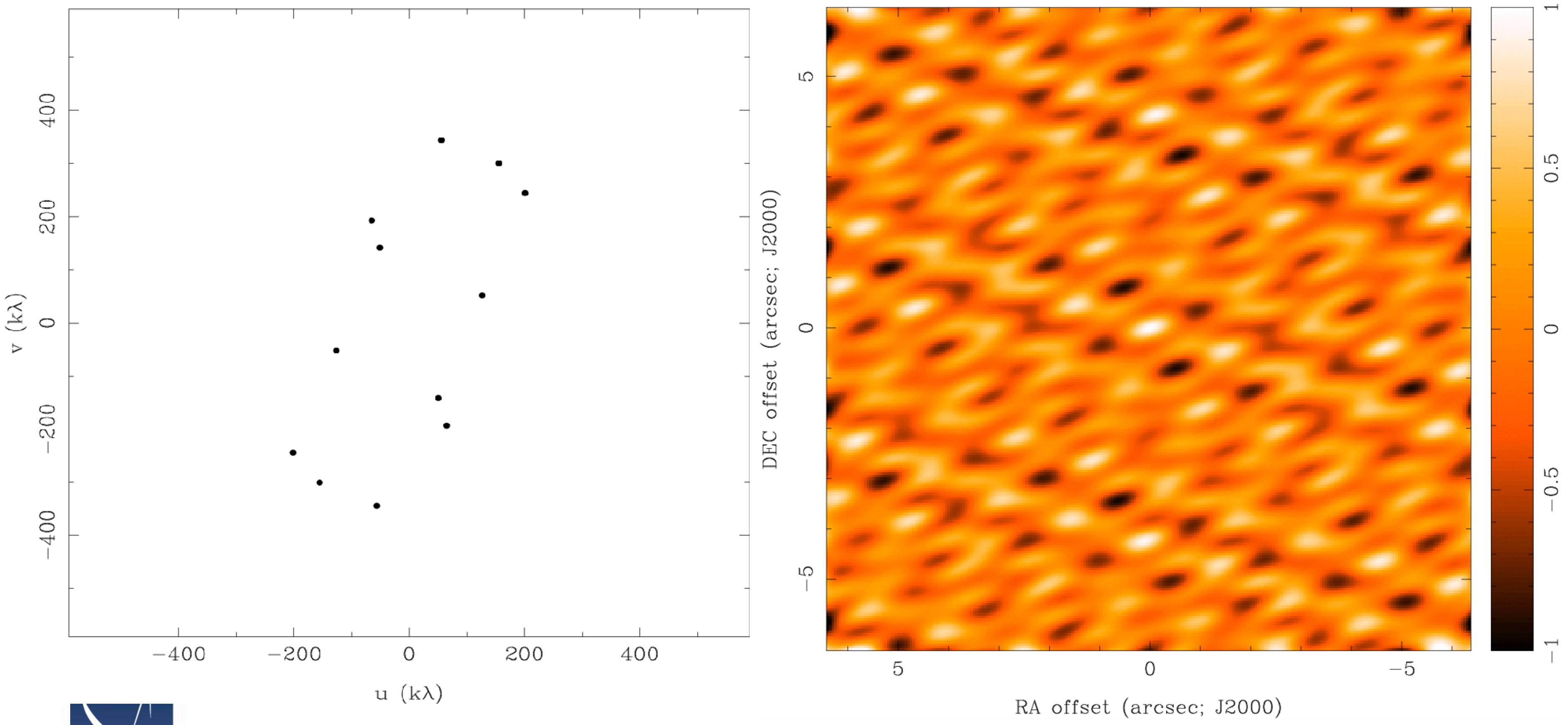
Dirty Beam Shape and N Antennas

3 Antennas



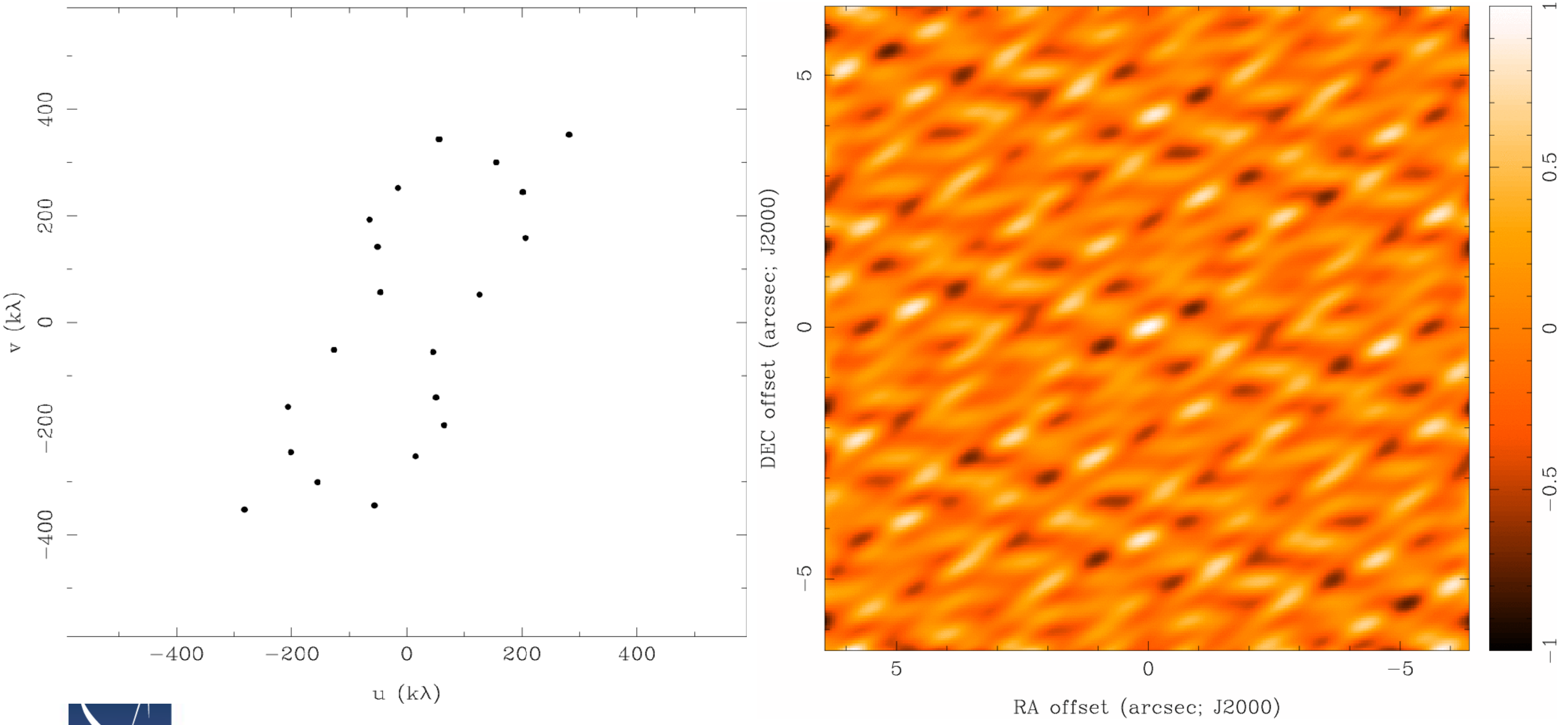
Dirty Beam Shape and N Antennas

4 Antennas



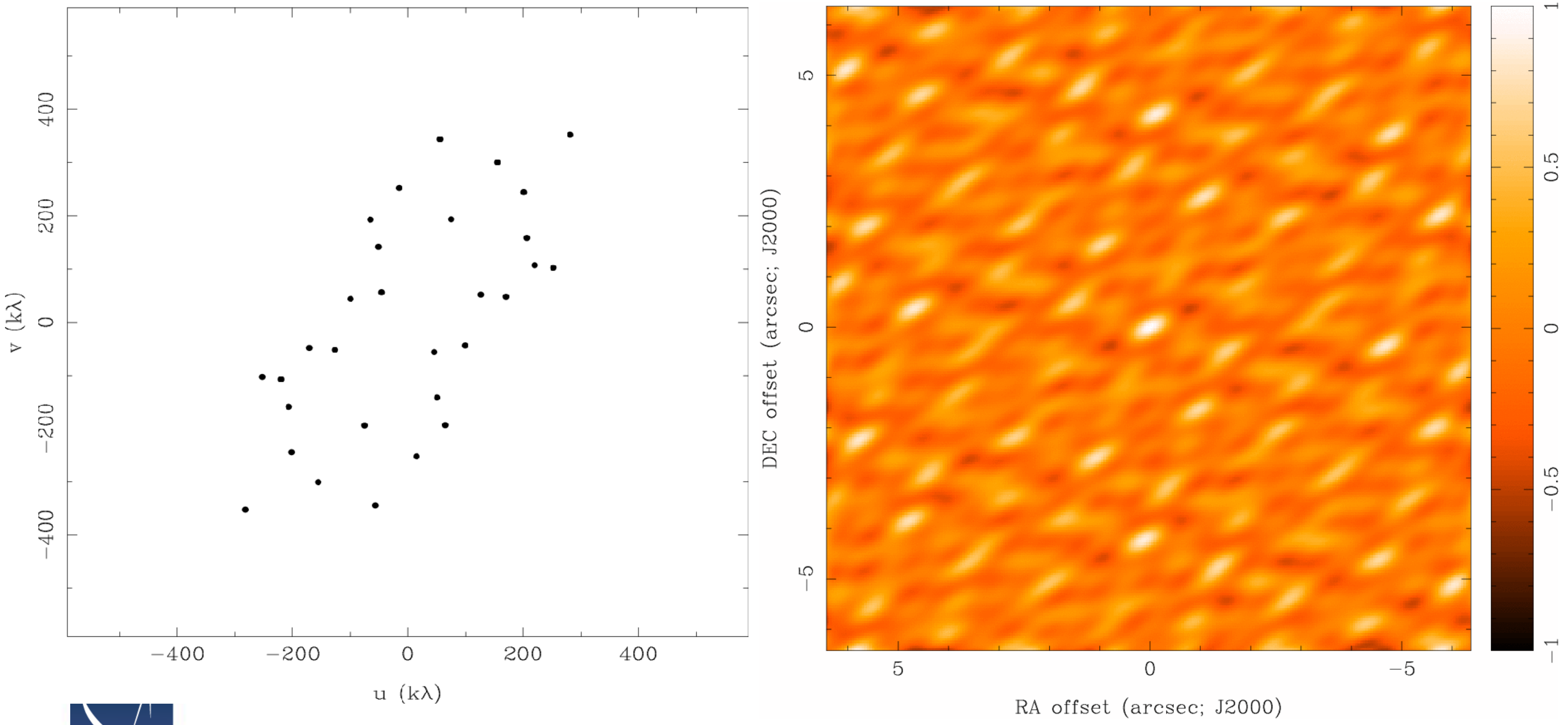
Dirty Beam Shape and N Antennas

5 Antennas



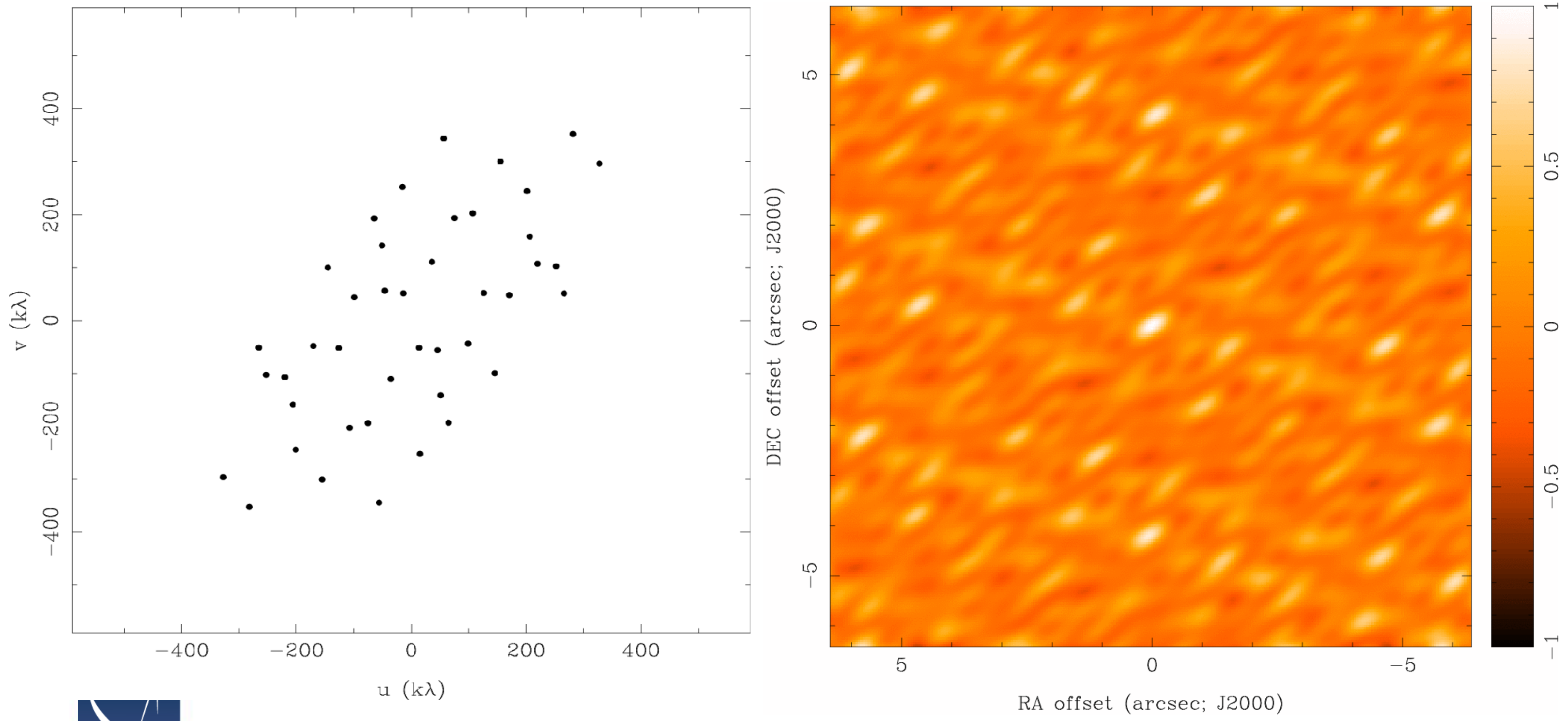
Dirty Beam Shape and N Antennas

6 Antennas



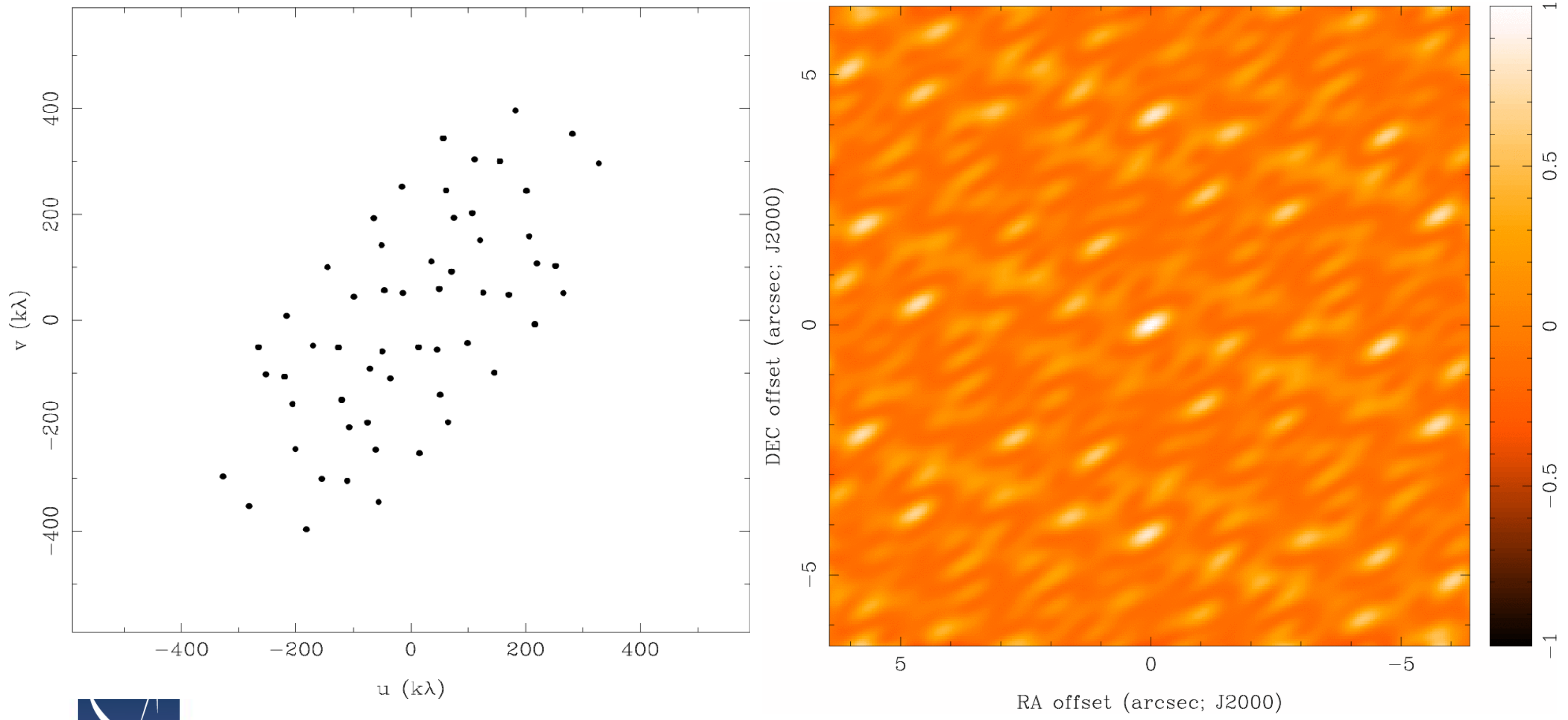
Dirty Beam Shape and N Antennas

7 Antennas



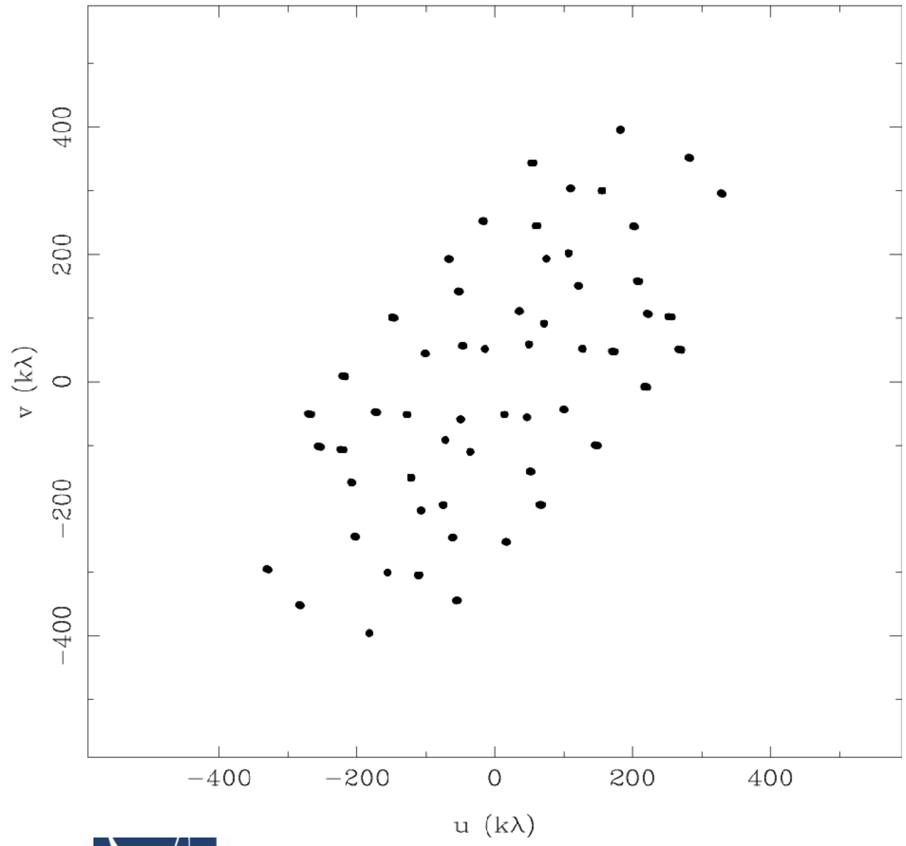
Dirty Beam Shape and N Antennas

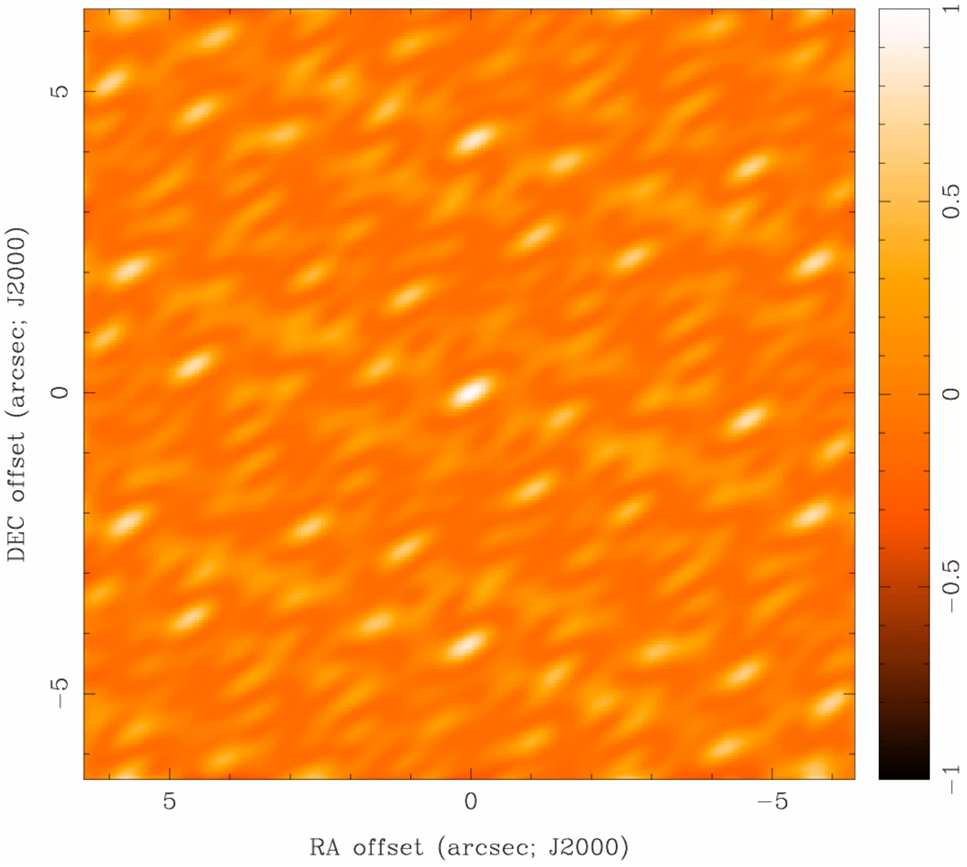
8 Antennas



Dirty Beam Shape and N Antennas

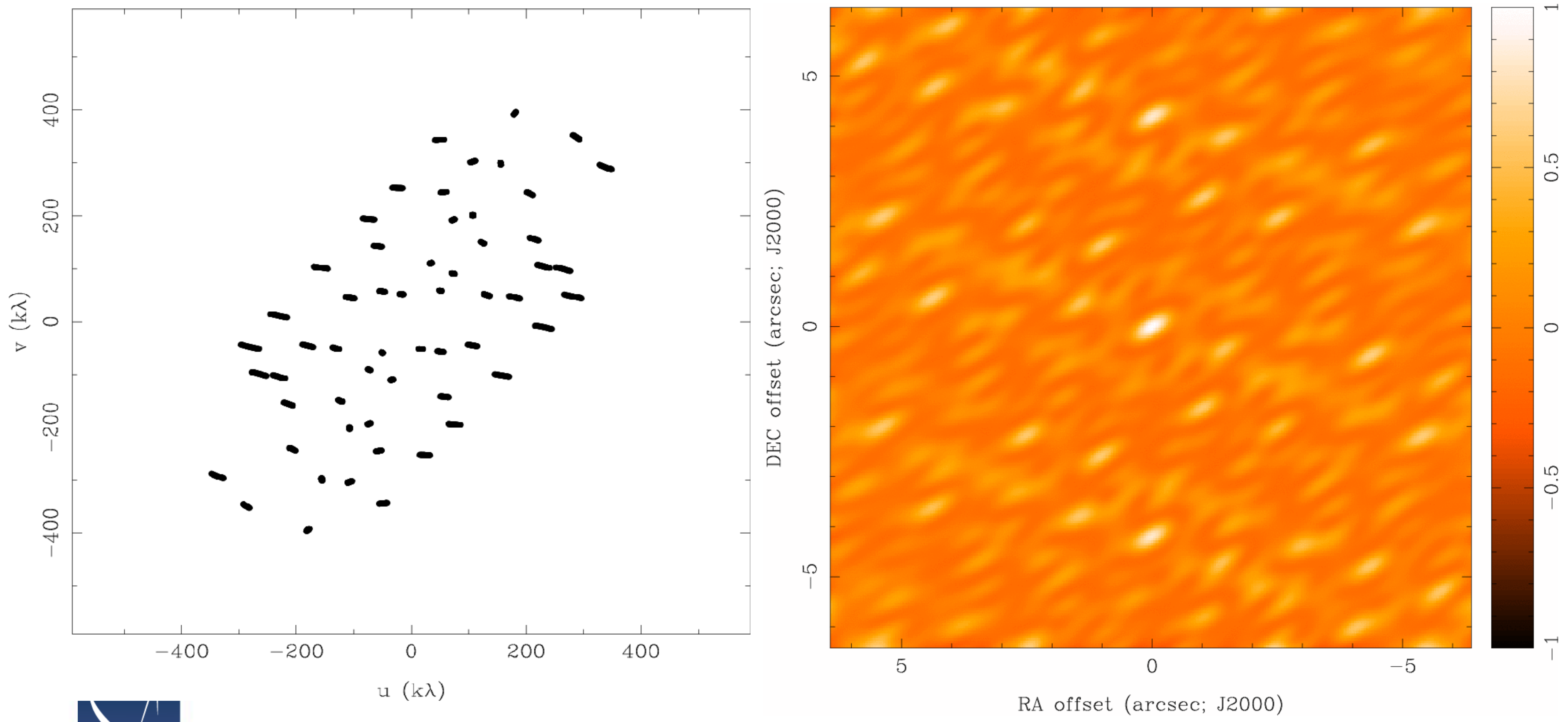
8 Antennas x 6 Samples





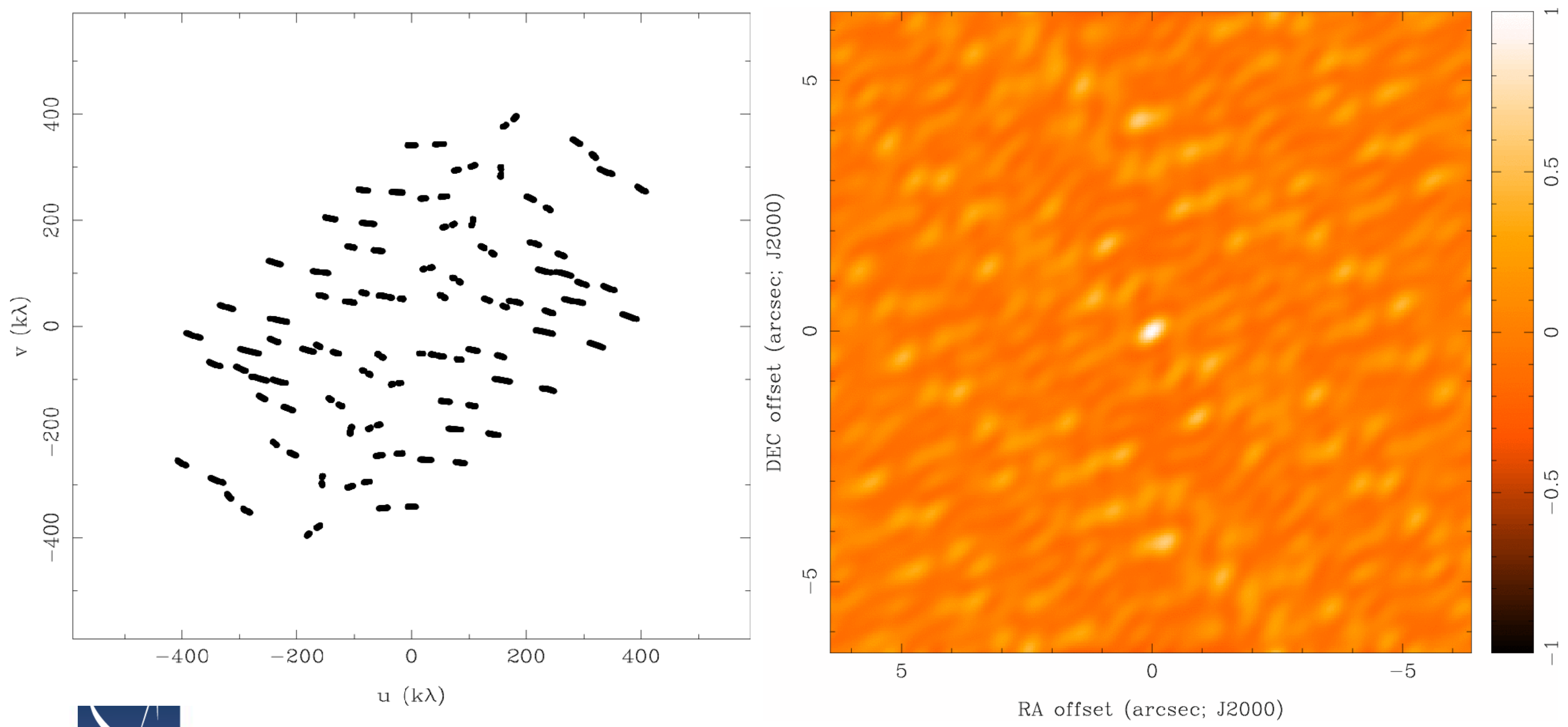
Dirty Beam Shape and N Antennas

8 Antennas x 30 Samples



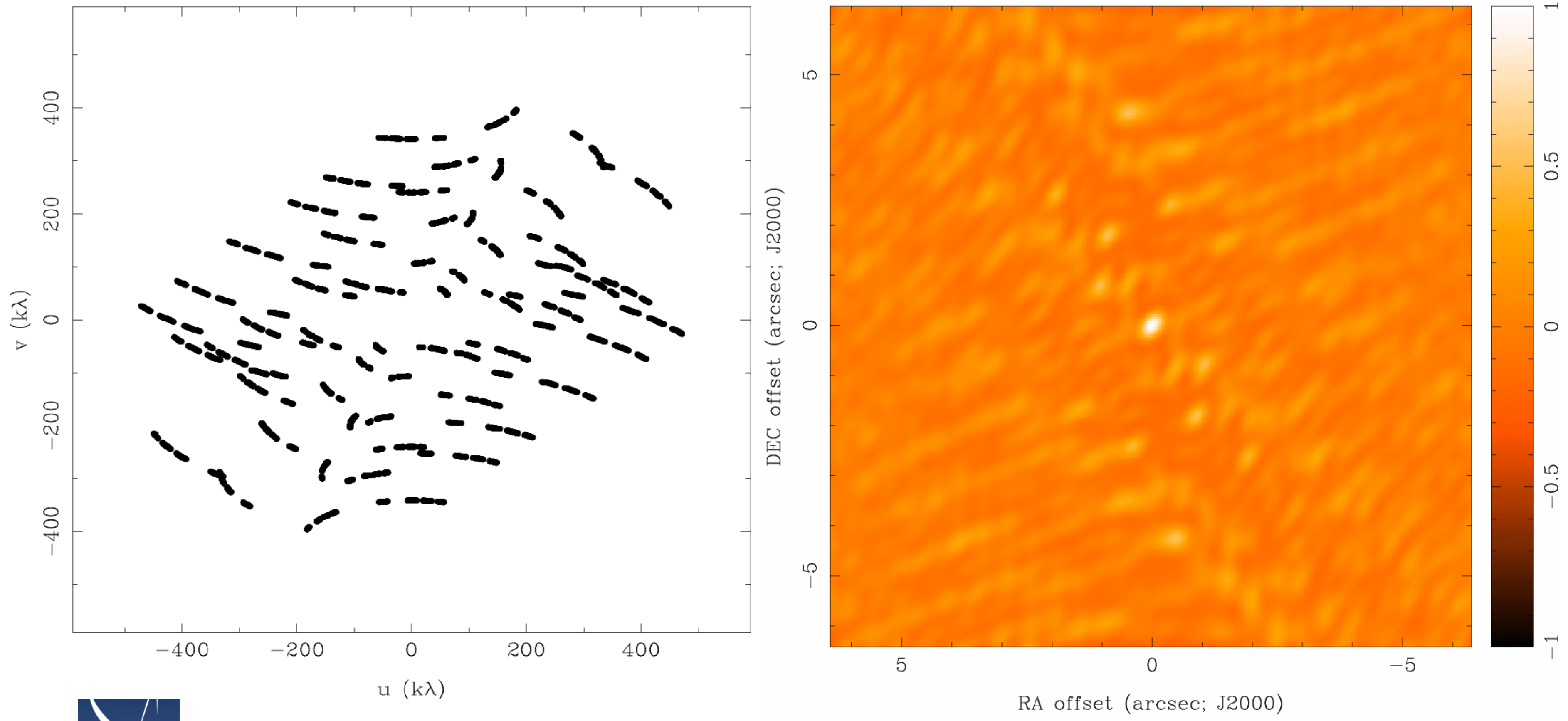
Dirty Beam Shape and N Antennas

8 Antennas x 60 Samples



Dirty Beam Shape and N Antennas

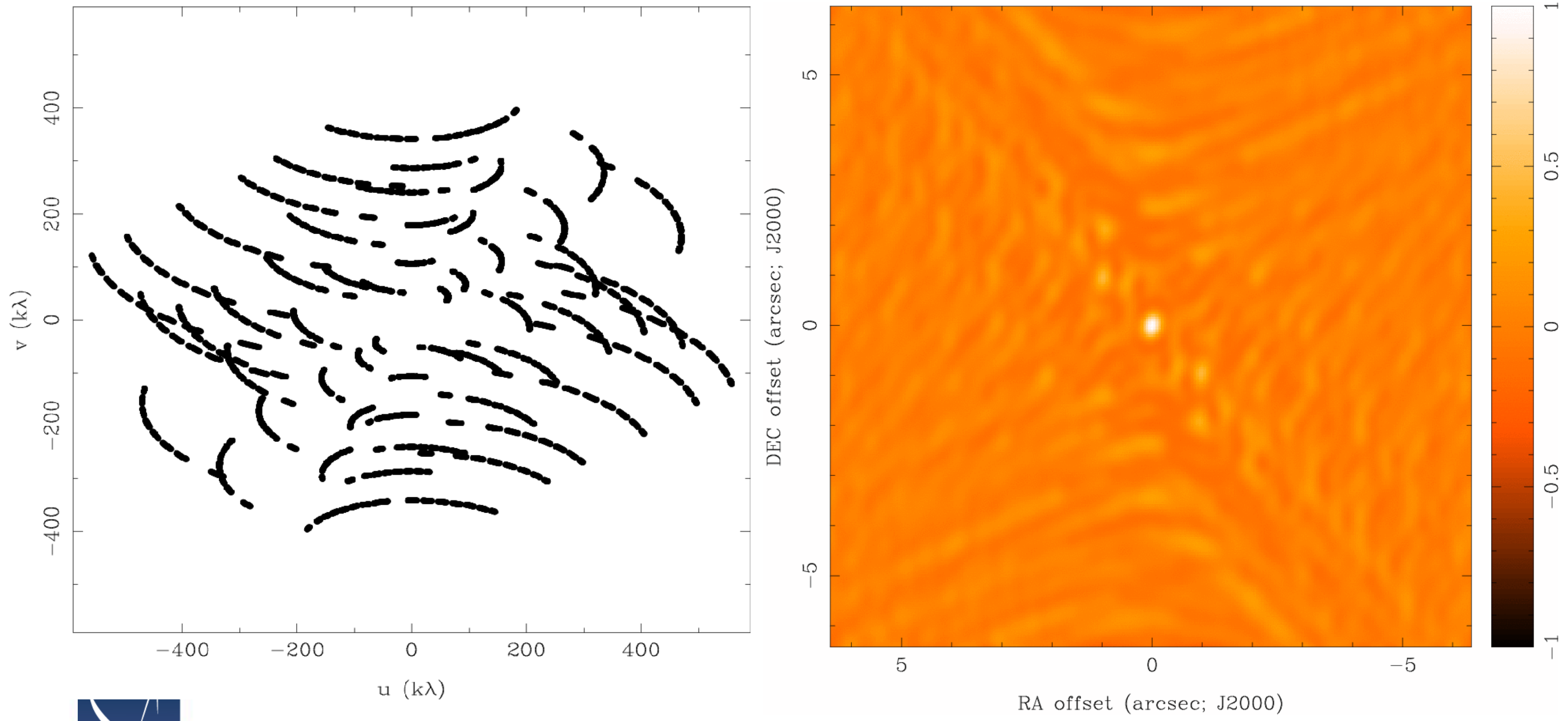
8 Antennas x 120 Samples



Dirty Beam Shape and N Antennas

ALMA

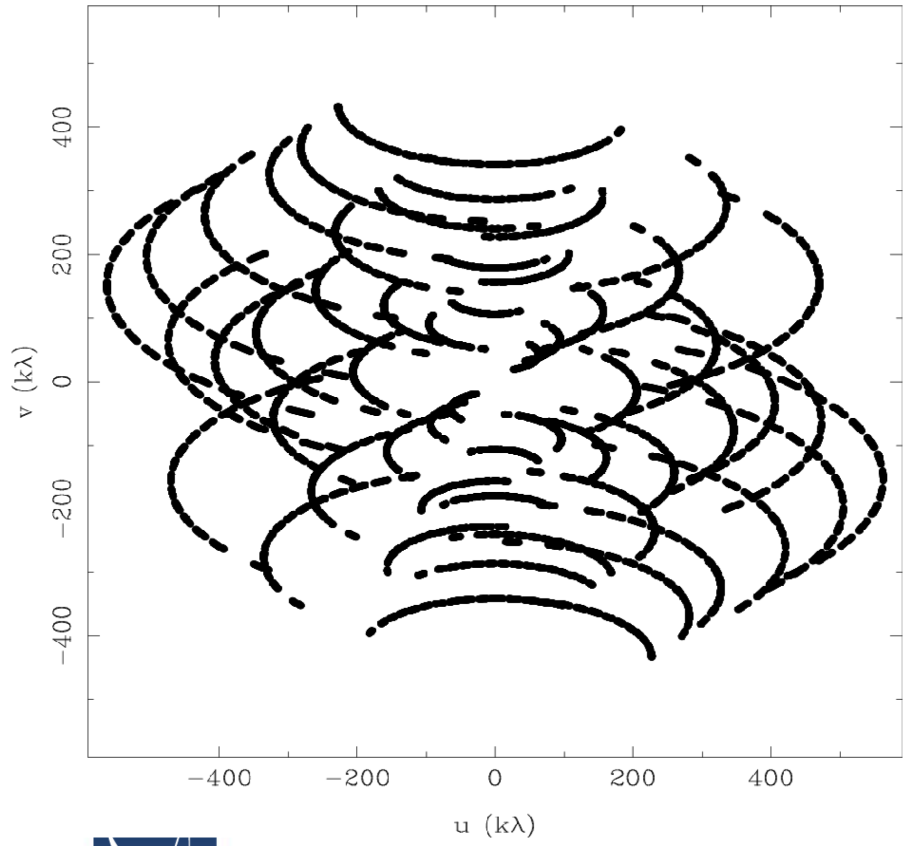
8 Antennas x 240 Samples

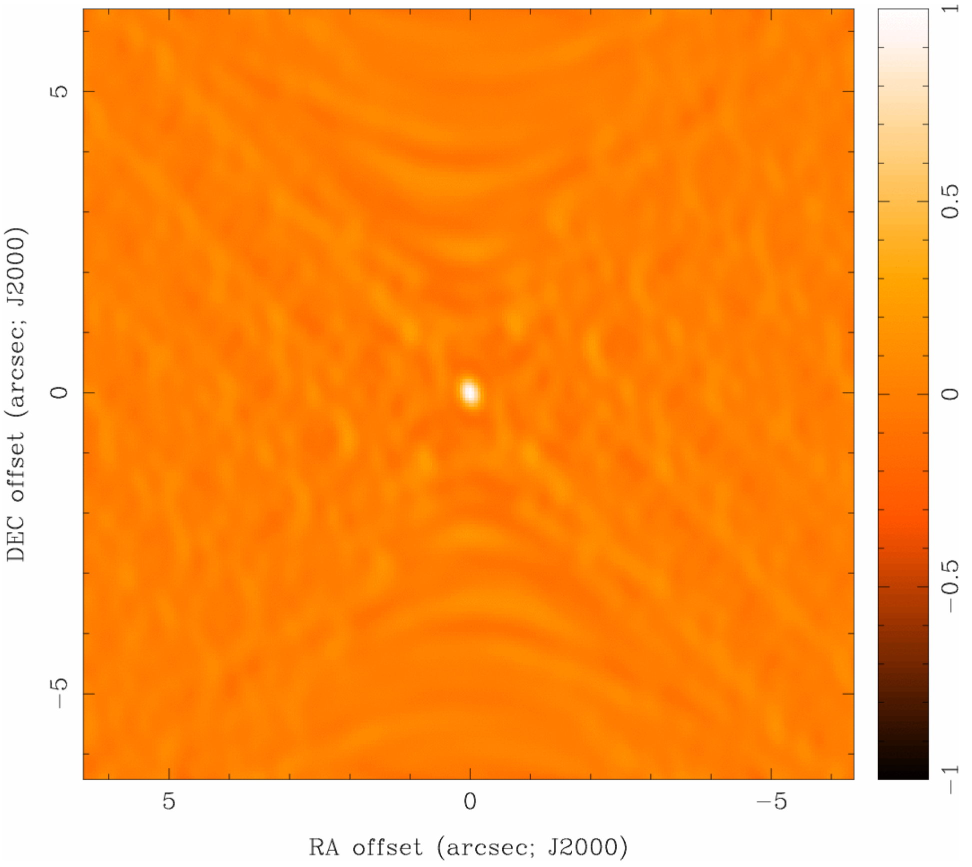


NRAO

Dirty Beam Shape and N Antennas

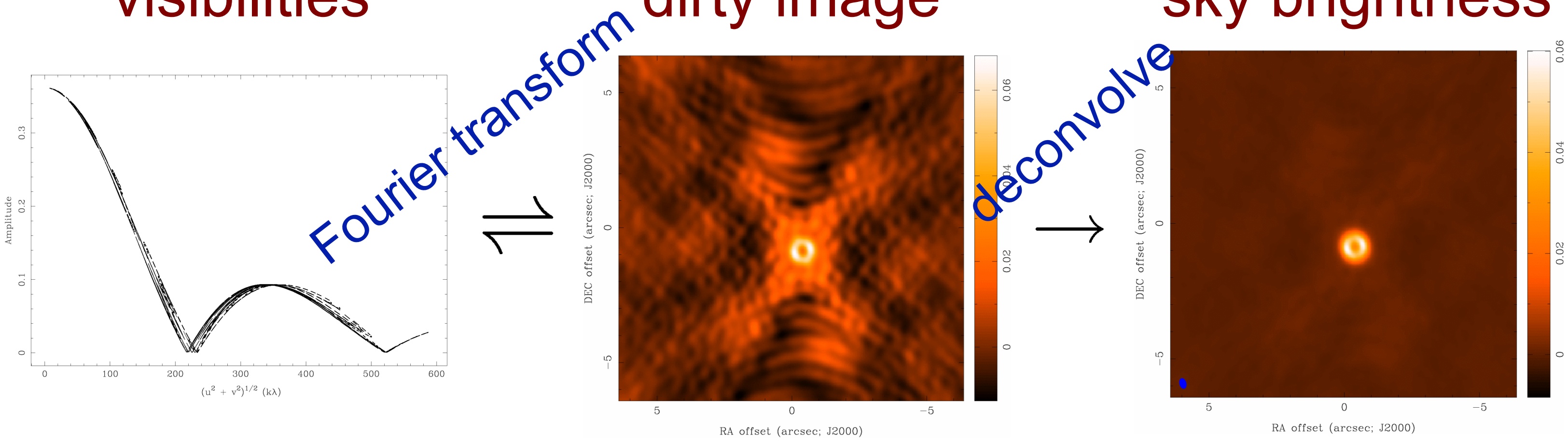
8 Antennas x 480 Samples





From Visibilities to Images

- Fourier transform of the measured V(u,v) to the image plane → $T^D(x,y)$
- But difficult to do science on dirty image
- To determine (model of) T(x,y) we need to deconvolve b(x,y) from $T^D(x,y)$ → “clean” image



visibilities

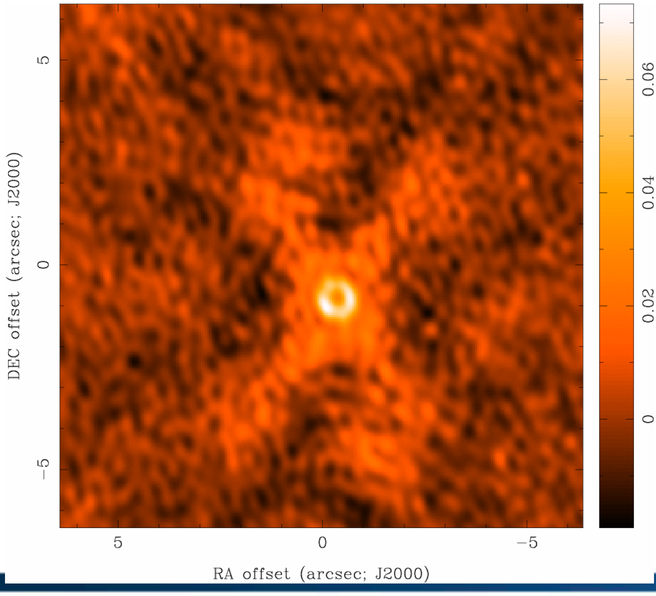
dirty image

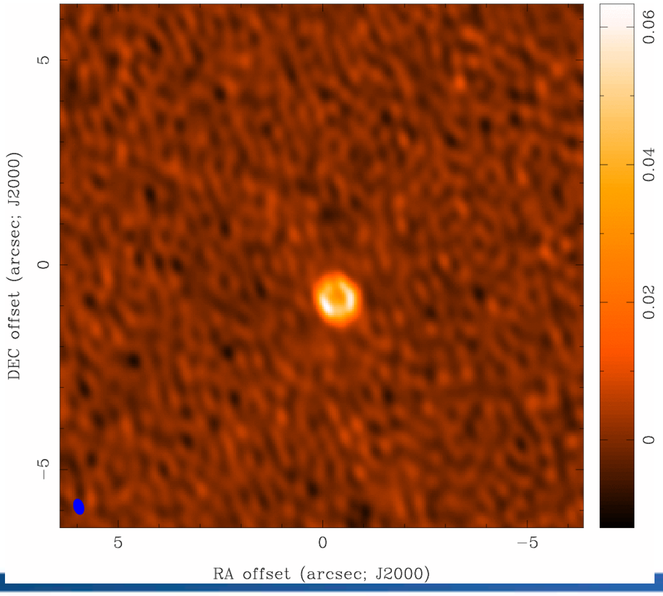
sky brightness

Deconvolution

- Aims to find a **sensible** model of T(x,y) compatible with data without sidelobes
- Uses non-linear techniques to interpolate/extrapolate samples of V(u,v) into unsampled regions of the (u,v) plane
- Requires knowledge of beam shape and *a priori* assumptions about T(x,y)
- One of the most common algorithms in radio astronomy is the algorithm CLEAN (Hogbom 1974)

"dirty" image





"CLEAN" image

- Angular resolution
- **Sensitivity**
- Spectral resolution
- Image quality: UV coverage
- Source characteristics
- Calibration

Sensitivity calculator

https://almascience.nrao.edu/call-for-proposals/sensitivity-calculator

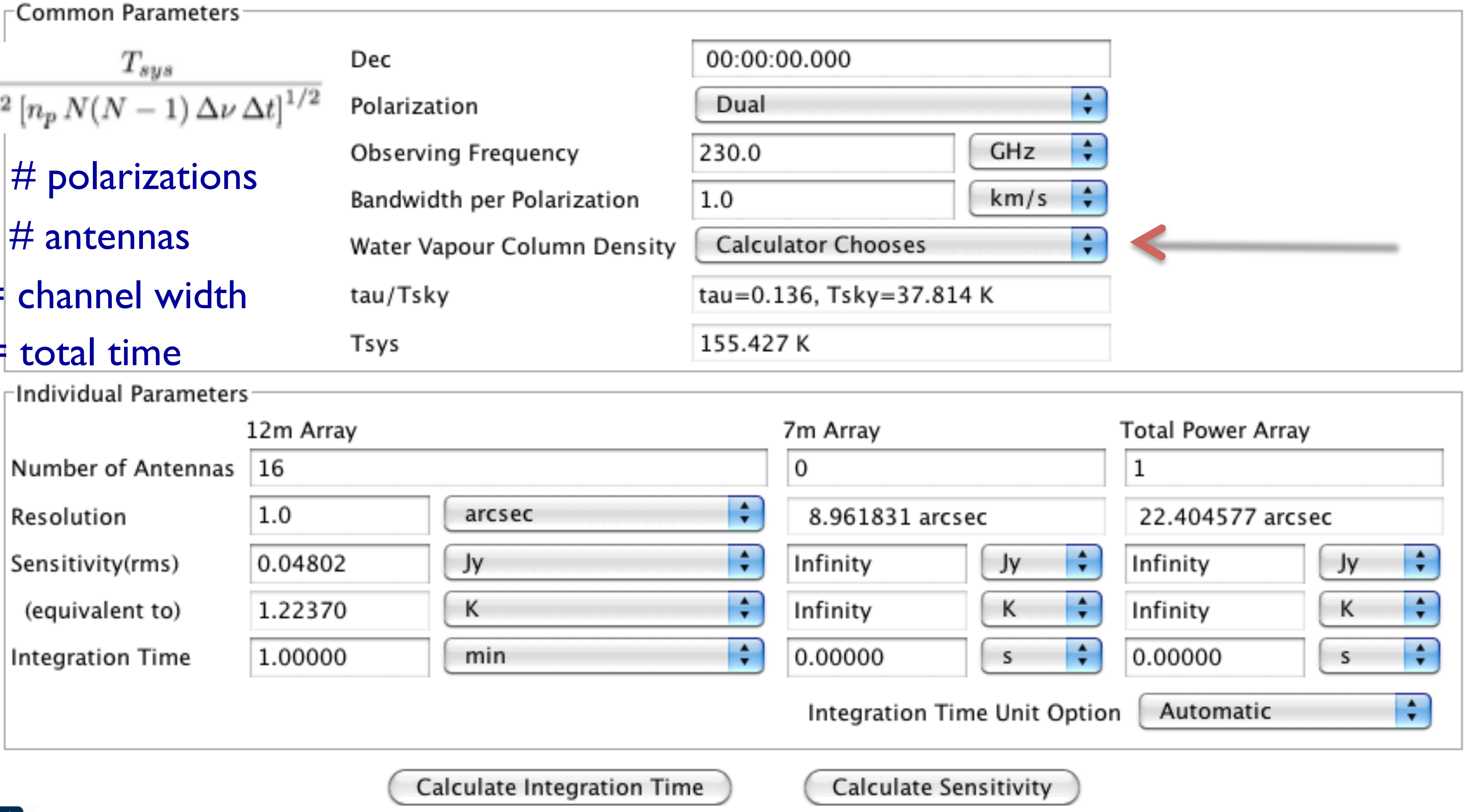
$$\Delta S \propto \frac{T_{sys}}{D^2 \left[n_p\, N(N-1)\, \Delta\nu\, \Delta t\right]^{1/2}}$$

n_p = # polarizations

N = # antennas

$\Delta\nu$ = channel width

Δt = total time



Common Parameters

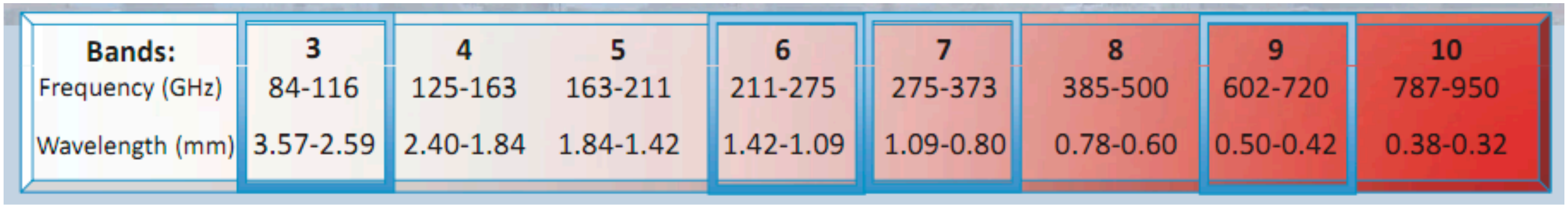
Dec	00:00:00.000
Polarization	Dual
Observing Frequency	230.0 GHz
Bandwidth per Polarization	1.0 km/s
Water Vapour Column Density	Calculator Chooses
tau/Tsky	tau=0.136, Tsky=37.814 K
Tsys	155.427 K

Individual Parameters

	12m Array		7m Array		Total Power Array	
Number of Antennas	16		0		1	
Resolution	1.0	arcsec	8.961831 arcsec		22.404577 arcsec	
Sensitivity(rms)	0.04802	Jy	Infinity	Jy	Infinity	Jy
(equivalent to)	1.22370	K	Infinity	K	Infinity	K
Integration Time	1.00000	min	0.00000	s	0.00000	s

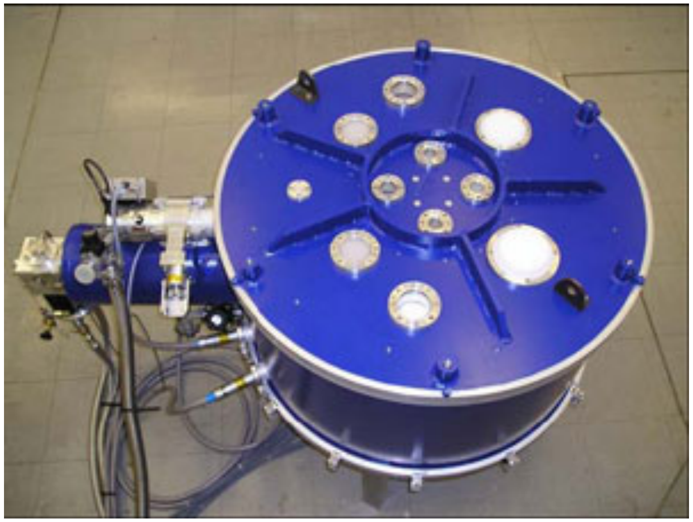
Integration Time Unit Option: Automatic

Receiver Bands Available



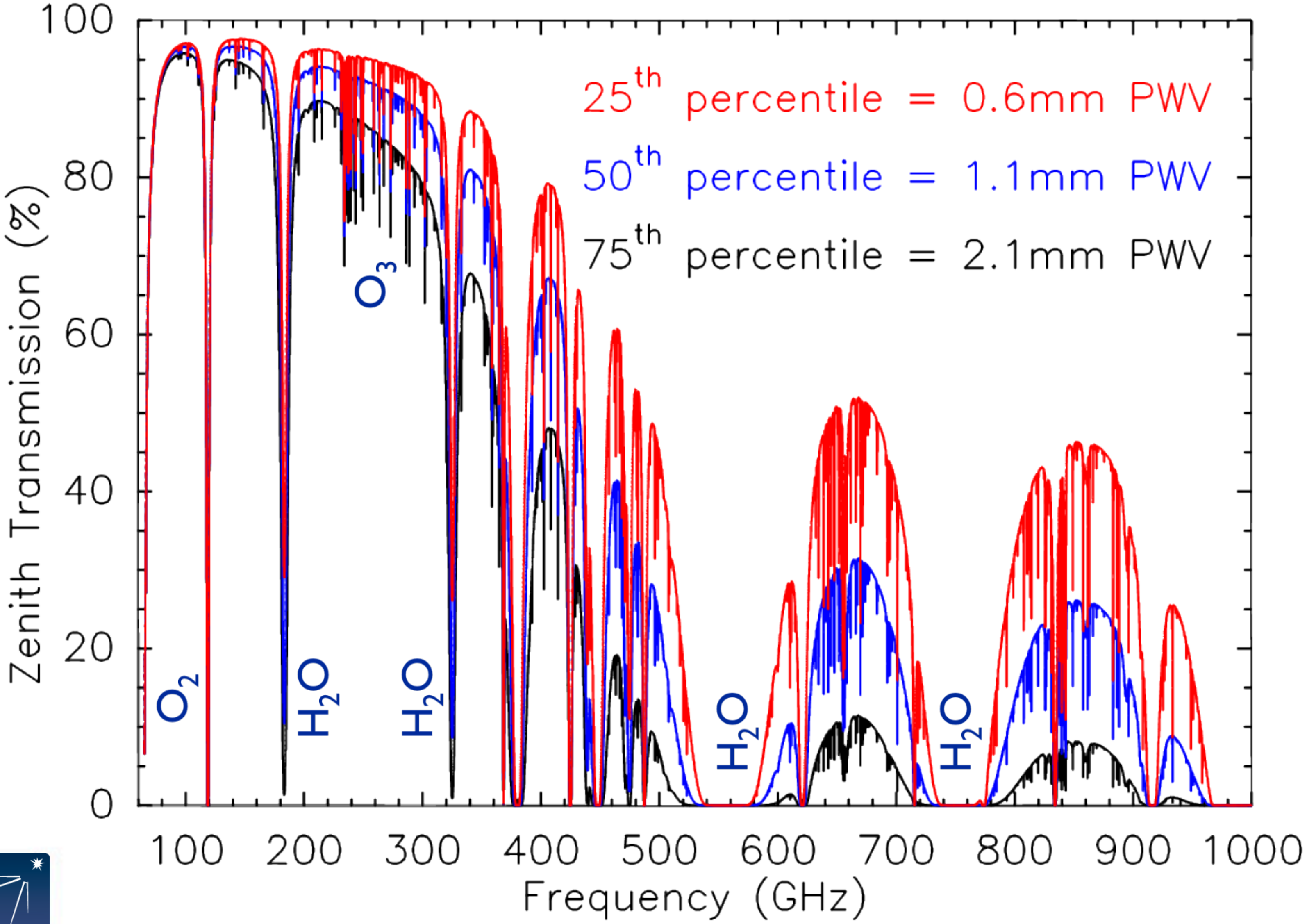
Bands:	3	4	5	6	7	8	9	10
Frequency (GHz)	84-116	125-163	163-211	211-275	275-373	385-500	602-720	787-950
Wavelength (mm)	3.57-2.59	2.40-1.84	1.84-1.42	1.42-1.09	1.09-0.80	0.78-0.60	0.50-0.42	0.38-0.32

3 mm **1.3 mm** **0.87 mm** **0.45 mm**



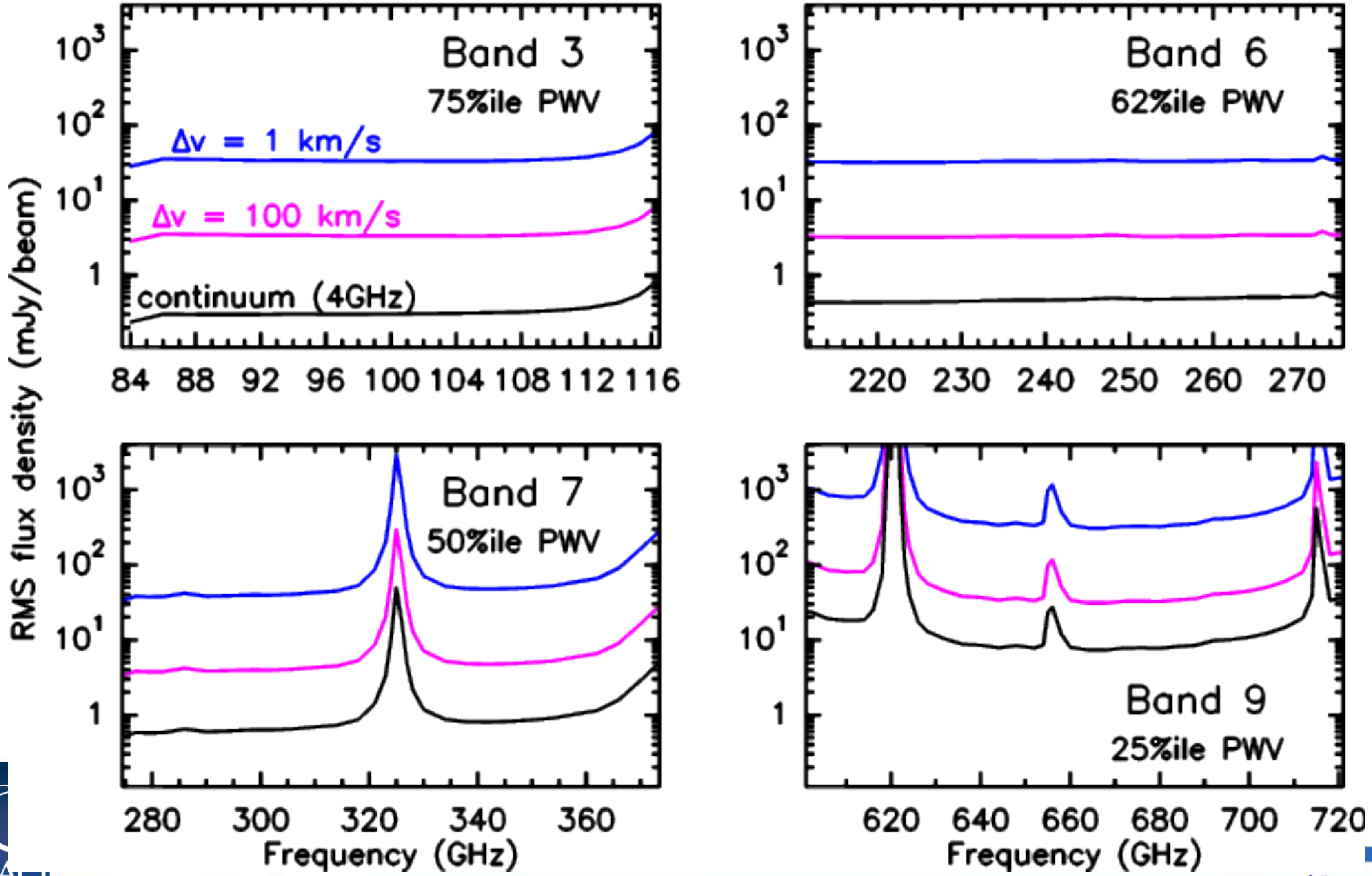
- Only 4 of 8 bands are available for Early Science, all with dual linear polarization feeds
- Only 3 receiver bands can be "ready" at one time (i.e. amplifiers powered on and stable temperature achieved). Required lead time to stabilize a new band is about 20 minutes.
- With configurations of ~125m and ~400m, approximately matched resolution is possible between Bands 3 and 7, or between Bands 6 and 9
  - Matched resolution can be critical, for example to measure the SEDs of resolved sources.

Atmospheric Opacity
(PWV = Precipitable Water Vapor)



Choosing your bands
(constructed from sensitivity calculator)

Early Science Sensitivities in 1 minute (dual−pol, 16 antennas)

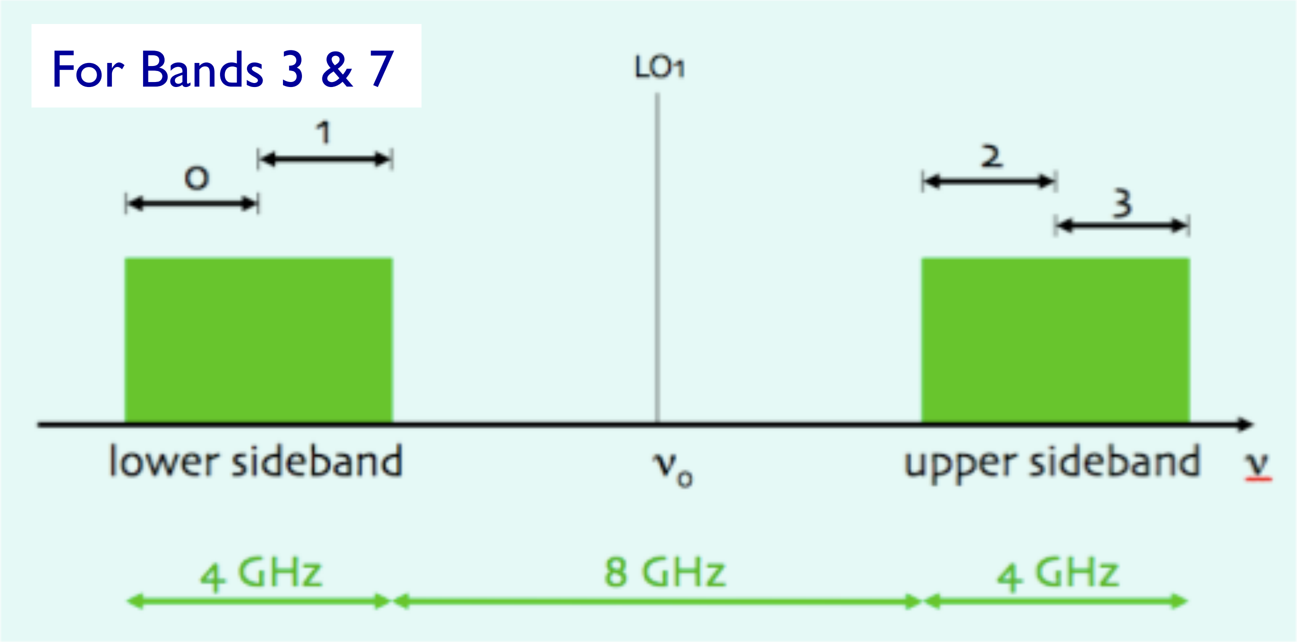


NOTE: For 8 GHz continuum bandwidth divide by √2

- Angular resolution
- Sensitivity
- **Spectral resolution**
- Image quality: UV coverage
- Source characteristics
- Calibration

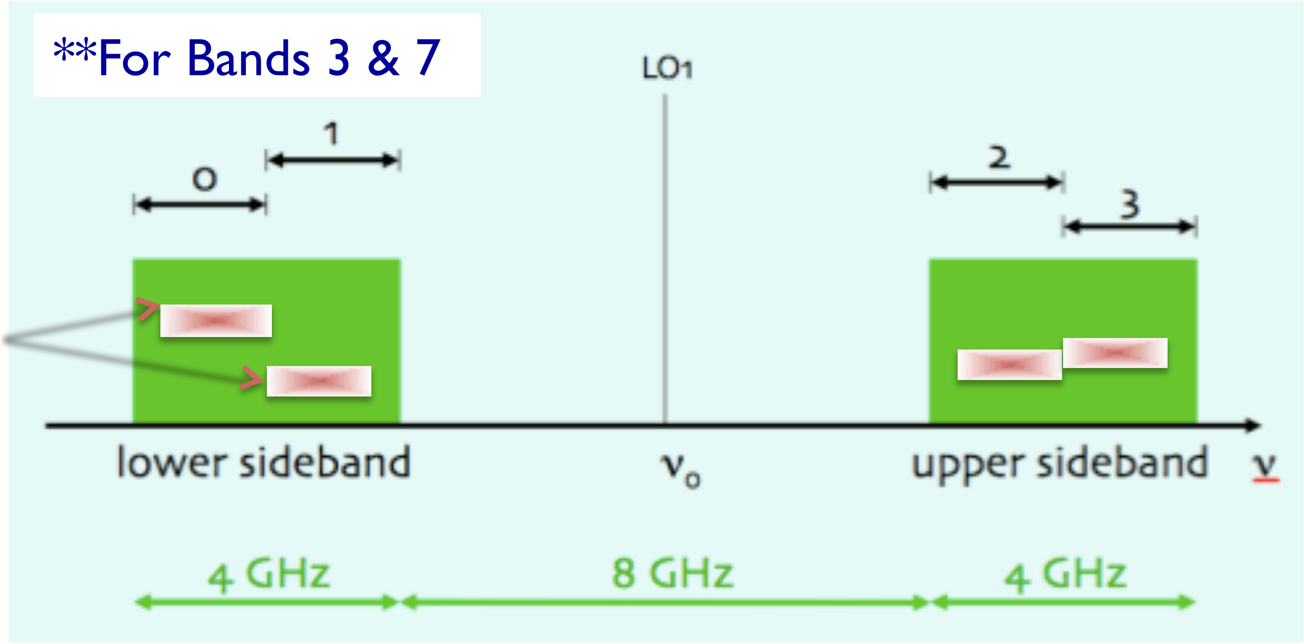
Correlator Modes, Spectral Resolution, Spectral Coverage - I

- Receivers are sensitive to two separate ranges of sky frequency: **sidebands**
- Each antenna has 4 digitizers which can each sample 2 GHz of bandwidth
- These 2 GHz chunks are termed **basebands**, and can be distributed among the sidebands (in ES: either all four in one, or two in both as shown below)



(NOTE: In Band 9, you can also have 1 or 3 basebands in a sideband.)

Correlator Modes, Spectral Resolution, Spectral Coverage - II


**For Bands 3 & 7

Spectral windows

- In order to collect data, you need to set up a spectral window within one (or more) basebands.
- In Early Science, only 4 spectral windows are available, i.e. one per baseband, and all must have the same resolution and bandwidth
- **Note: exact spacing between sidebands and sideband widths vary from band to band – OT will show correct one for each band

Correlator Modes and Spectral Resolution

Typical purposes:

Spectral scans

Targeted imaging of moderately narrow lines: cold clouds / protoplanetary disks

"Continuum" or broad lines

Mode	Polari-zation	Bandwidth per baseband (MHz)	Number of channels per baseband	Channel Spacing (MHz)	Velocity width at 300 GHz (km/s)
7	Dual	1875	3840	0.488	0.48
8	Dual	938	3840	0.244	0.24
9	Dual	469	3840	0.122	0.12
10	Dual	234	3840	0.061	0.06
11	Dual	117	3840	0.0305	0.03
12	Dual	58.6	3840	0.0153	0.015
6	Single	58.6	7680	0.00763	0.008
69	Dual	2000	128	15.625	15.6
71	Single	2000	256	7.8125	7.8

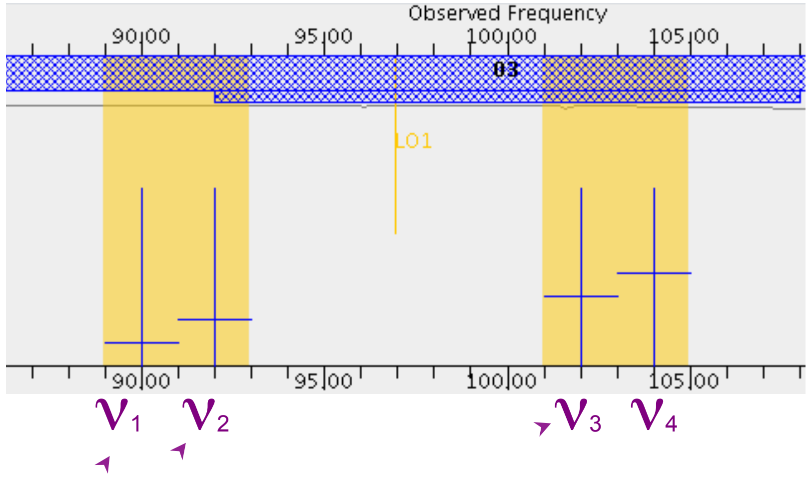
- These numbers are per baseband (you can use up to 4 basebands)
- Usually want to have several channels across narrowest line
- **Note that the resolution is ~ 2*channel width (Hanning)**
- The required spectral resolution typically needs to be justified as does the number of desired spectral windows

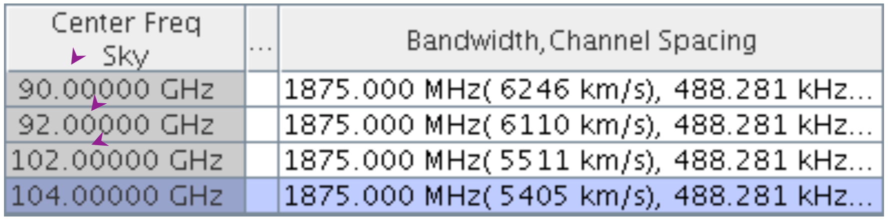
Correlator Setup
line vs. continuum

- “continuum mode”: automatically place 4 spectral windows, with the largest bandwidth, across the sidebands

Band 3 (or 7)

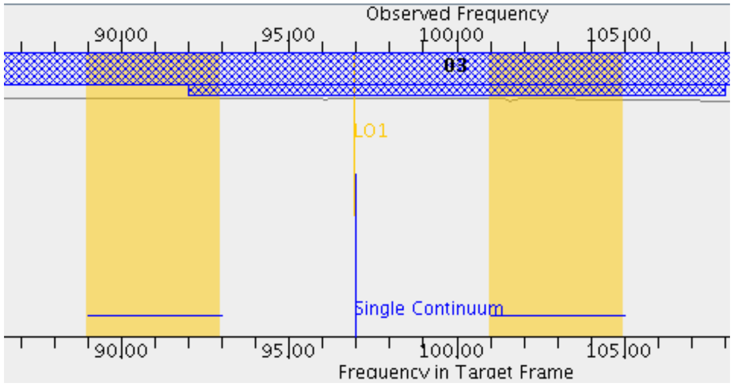
Spectral line mode:



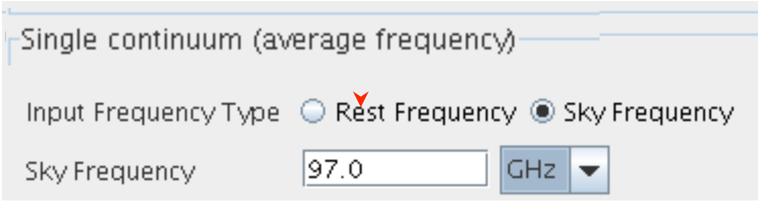


Center Freq Sky	...	Bandwidth, Channel Spacing
90.00000 GHz		1875.000 MHz(6246 km/s), 488.281 kHz...
92.00000 GHz		1875.000 MHz(6110 km/s), 488.281 kHz...
102.00000 GHz		1875.000 MHz(5511 km/s), 488.281 kHz...
104.00000 GHz		1875.000 MHz(5405 km/s), 488.281 kHz...

Continuum mode:



2000 MHz bandwidth, ν_{sky}
15.625 MHz resolution



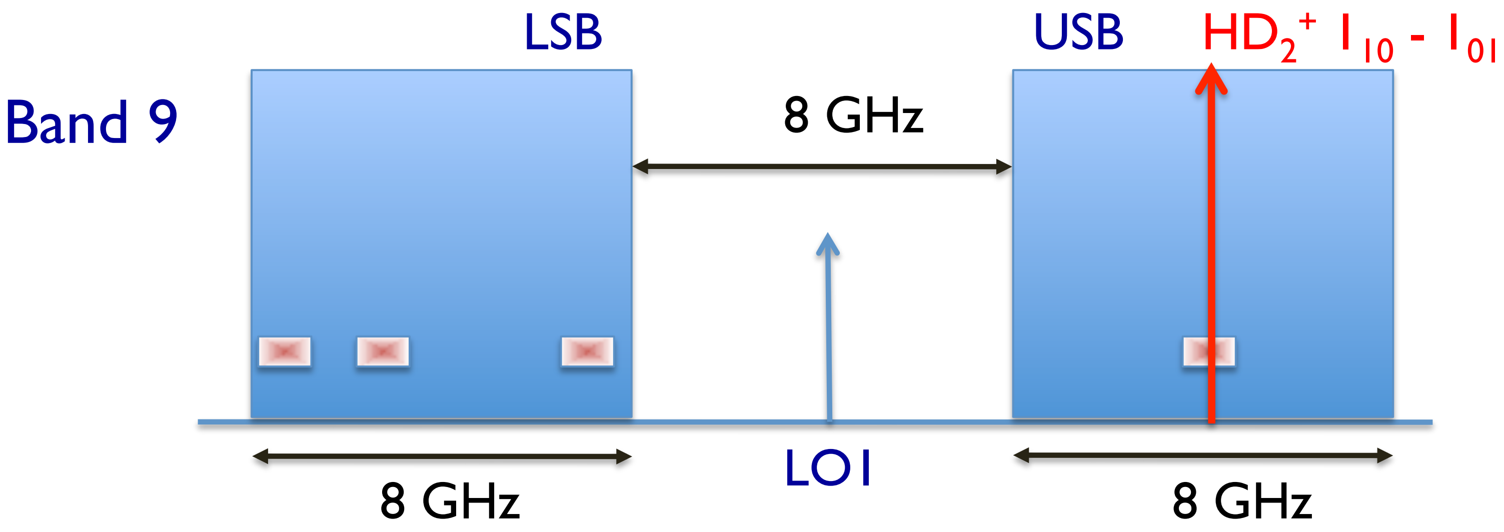
Single continuum (average frequency)

Input Frequency Type ○ Rest Frequency ● Sky Frequency

Sky Frequency 97.0 GHz

Correlator Setup

Example: Spectral Lines in Band 9

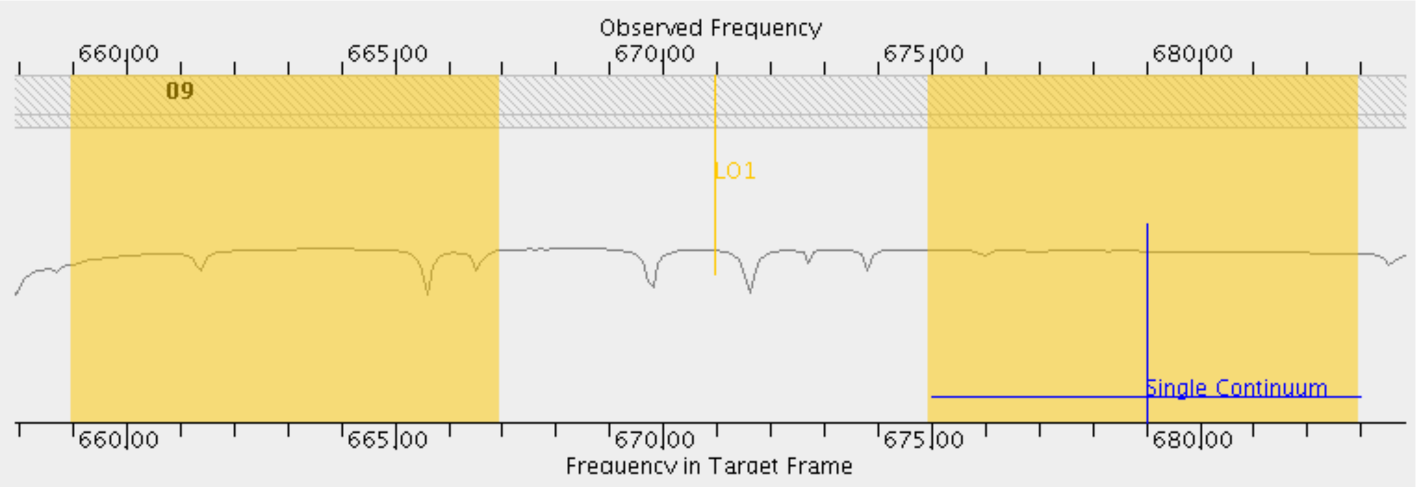


- in Cycle 0, **only one sideband** per spectral window will be correlated
- for Band 9, there is full flexibility in that **each baseband can be connected to either one or the other sideband**
    - e.g. observe HD_2^+ at 691.66 GHz with one spectral window
    - can place 3 additional windows in USB or LSB

Correlator Setup

- Band 9: 8 GHz continuum in a single side-band

Continuum placement in Band 9



8 GHz

ν_{sky}

- Angular resolution
- Sensitivity
- Spectral resolution
- **Image quality: UV coverage**
- Source characteristics
- Calibration

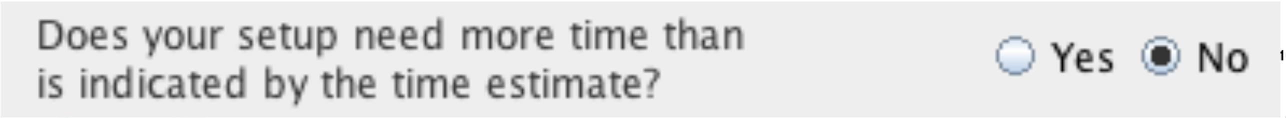
Image Quality

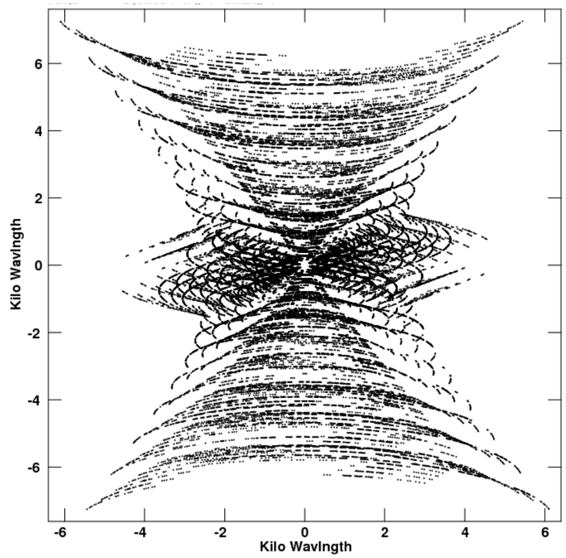
Sensitivity is not enough! Image quality also depends on *UV* coverage and density of *UV* samples

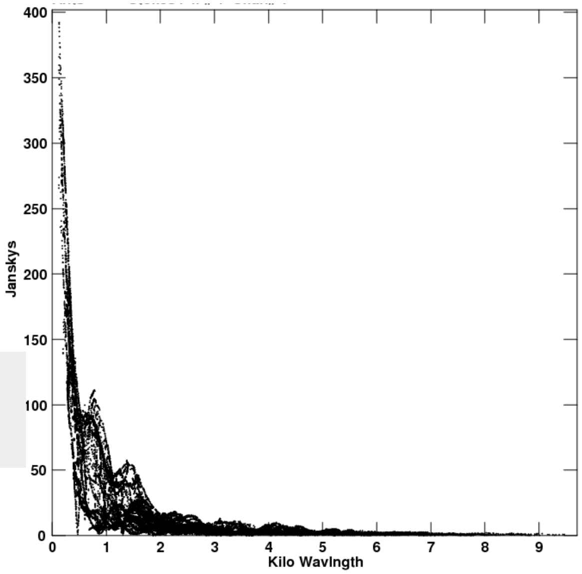
Image fidelity is improved when high density regions of UV coverage are well matched to source brightness distribution

→The required DYNAMIC RANGE can be more important than sensitivity

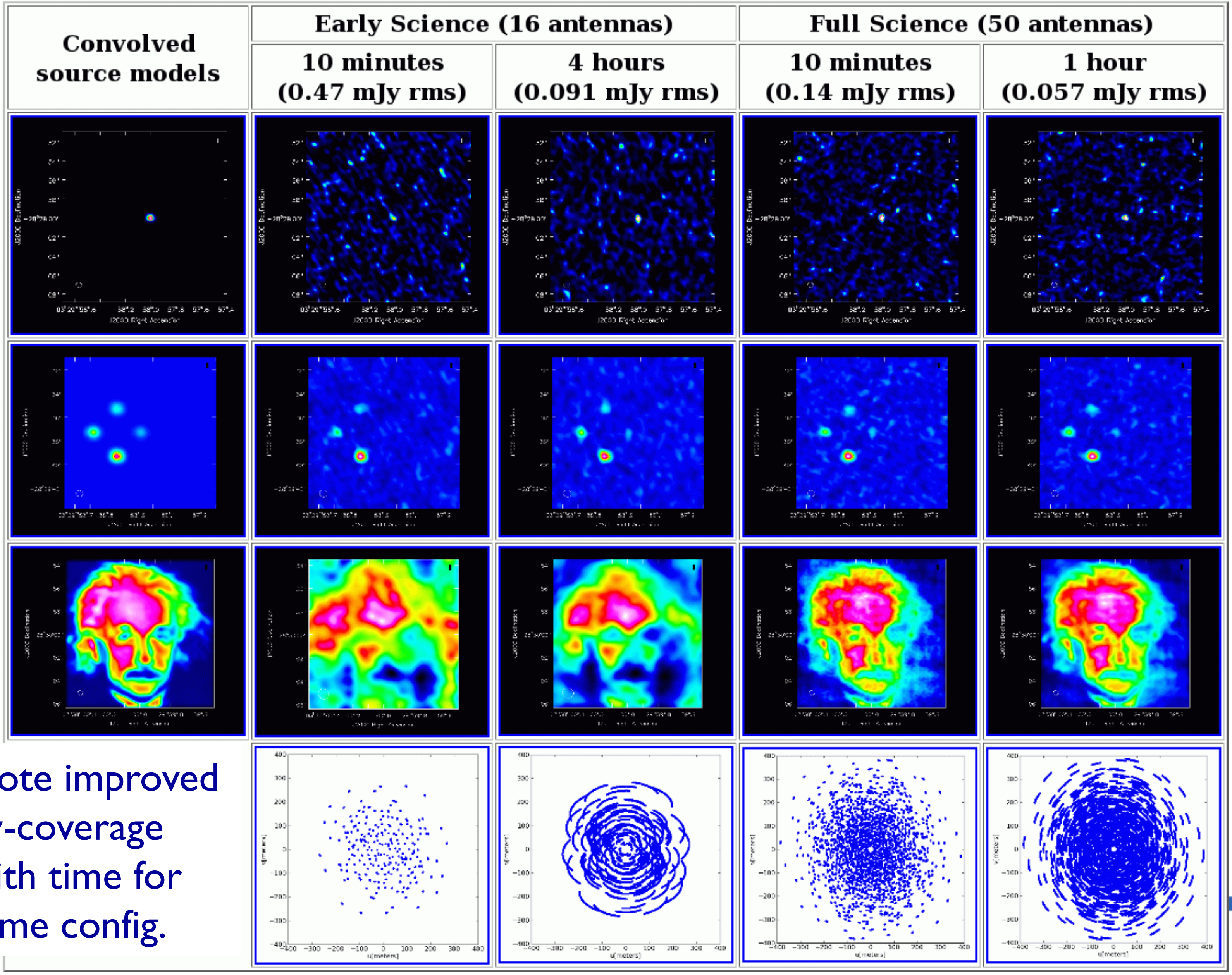
→ALMA OT currently has no way to specify required image quality, but you can request more time in the Technical Justification


Does your setup need more time than is indicated by the time estimate? ○ Yes ● No





Effects of UV Coverage



Convolved source models	Early Science (16 antennas)		Full Science (50 antennas)	
	10 minutes (0.47 mJy rms)	4 hours (0.091 mJy rms)	10 minutes (0.14 mJy rms)	1 hour (0.057 mJy rms)

5σ

5σ
10σ
15σ
20σ

Note improved uv-coverage with time for same config.

- Angular resolution
- Sensitivity
- Spectral resolution
- Image quality: UV coverage
- **Source characteristics**
- Calibration

Sky coverage available

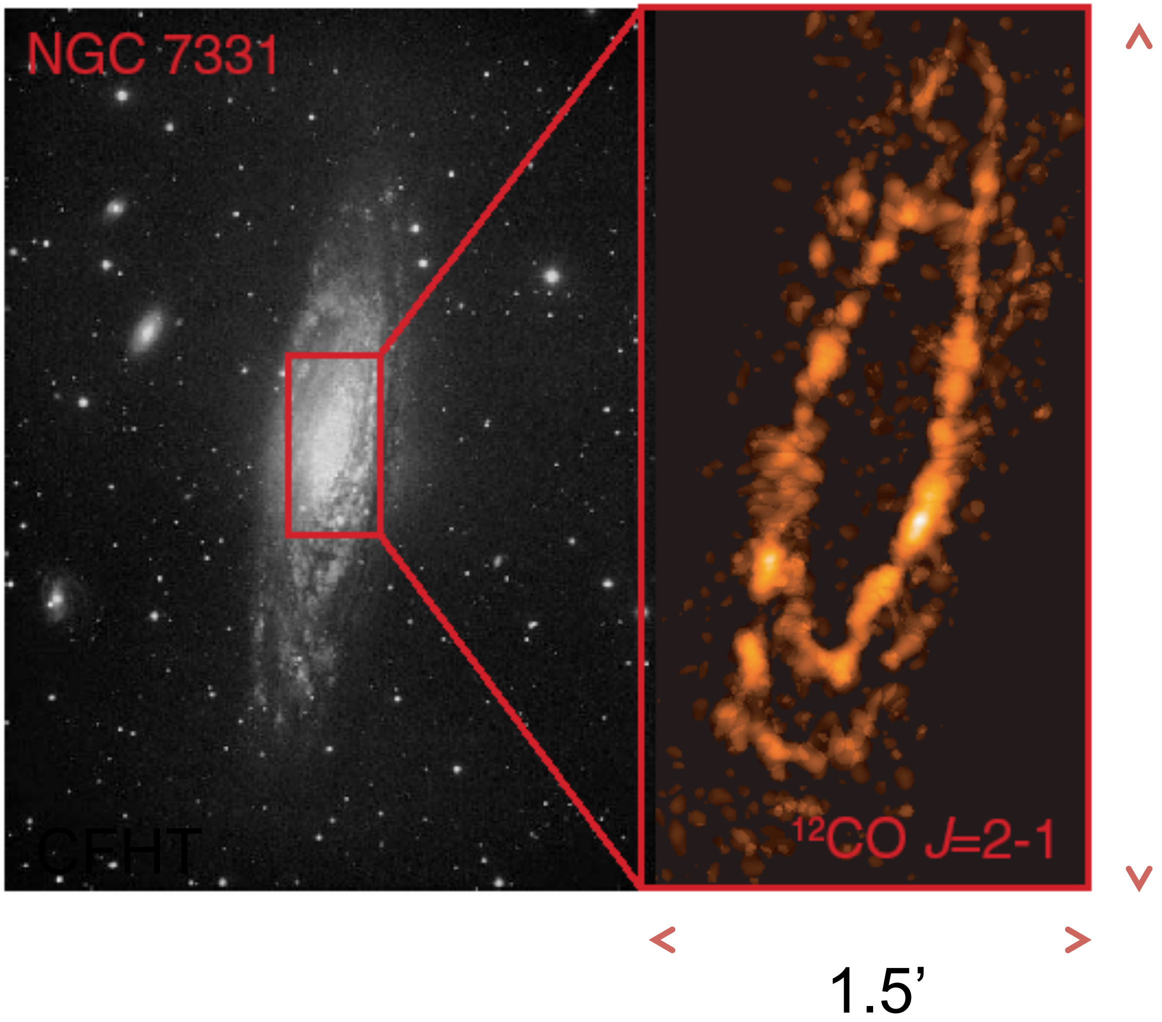
- ALMA is at a latitude of -23 degrees ➔ Southern sky!
- Antenna elevation limit is technically 3 degrees
- But in practice, atmospheric opacity will cause significant degradation with lower elevation ➔ most severe at higher frequencies

Maximum length of observation for Northern sources (hrs)

Dec	Elev > 15°	Elev > 20°	Elev > 30°
+50	2.5	-	-
+40	5.8	**4.3**	-
+30	7.3	6.3	3.9
+20	8.4	7.5	5.7

Note: This table does not account for shadowing, which further impedes low elevation observations in compact configurations.

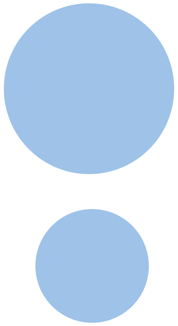
Choose Single Field or Mosaic



Petitpas et al.

Example: SMA 1.3 mm observations: 5 pointings

- Primary beam ~1’
- Resolution ~3”



ALMA 1.3mm PB

ALMA 0.85mm PB

In ES, the number of pointings will <= 50.

Maximum Angular Scale

Band	Frequency (GHz)	Primary beam (“)	Maximum Angular Scale (“)	
			Compact	Extended
3	84-116	72 - 52	20	10
6	211-275	29 - 22	9	4.5
7	275-373	22 - 16	6	3
9	602-720	10 – 8.5	3	1.5

- **Smooth** structures larger than MAS are completely resolved out
- Begin to lose total recovered flux for objects on the order of half MAS

→ Need additional observations with a single-dish or a more compact array with smaller antennas

Sensitivity and Brightness Temperature

- There will be a factor of 10 difference in brightness temperature sensitivity between the 2 configurations offered in Early Science. Very important to take into account for resolved sources.

The conversion from brightness temperature T to flux S_ν with synthesized beam solid angle Ω_s is

$$S_\nu = \frac{2\,\nu^2\,k\,T}{c^2}\Omega_s.$$

An alternate formula that is often useful is

$$\left(\frac{T}{1K}\right) = \left(\frac{S_\nu}{1\ \mathrm{Jy\ beam}^{-1}}\right)\left[13.6\left(\frac{300\ \mathrm{GHz}}{\nu}\right)^2\left(\frac{1''}{\theta_{max}}\right)\left(\frac{1''}{\theta_{min}}\right)\right]$$

Example: 1 minute integration at 230 GHz with 1 km/sec channels:

Configuration	Angular resolution	Flux density Sensitivity	Brightness sensitivity
125 m	3”	32 mJy/beam	0.09 K
400 m	1”		0.82 K

→ It is harder to detect extended line emission at high angular resolution !

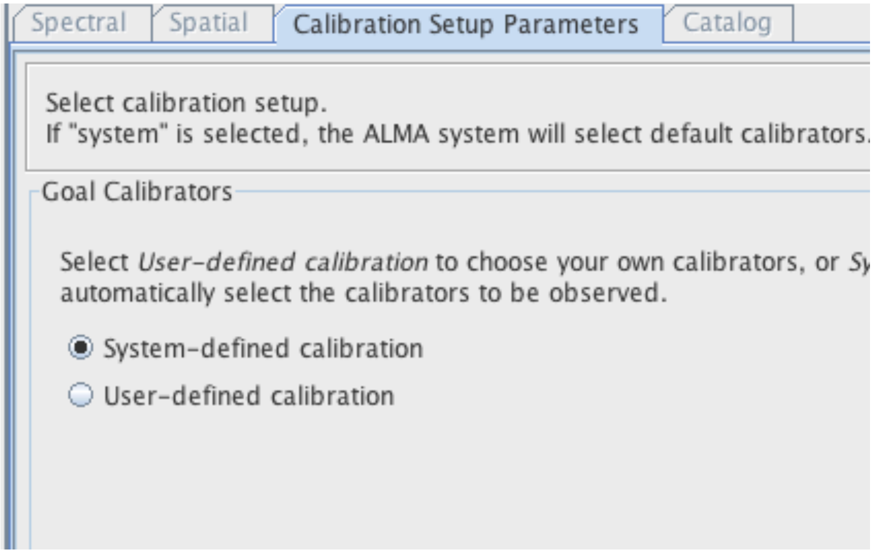
- Angular resolution
- Sensitivity
- Spectral resolution
- Image quality: UV coverage
- Source characteristics
- **Calibration**

Observatory Default Calibration

- Need to measure and remove the (time-dependent and frequency-dependent) atmospheric and instrumental variations.

- Set calibration to **system-defined calibration** unless you have very specific requirements for calibration (which then must be explained in the Technical Justification). Defaults include (suitable calibrators are chosen at observation time):

1. Pointing, focus, and delay calibration
2. Phase and amplitude gain calibration
3. Absolute flux calibration
4. Bandpass calibration
5. System Temperature calibration
6. Water-vapor radiometry correction



Select calibration setup.
If "system" is selected, the ALMA system will select default calibrators

Select *User-defined calibration* to choose your own calibrators, or Sy
automatically select the calibrators to be observed.

● System-defined calibration
○ User-defined calibration

Future Capabilities

ALMA

- **Better sensitivity and image fidelity:**
  - Imaging fidelity ~10x better, Sensitivity > 3x better
  - Fantastic "snapshot" uv-coverage (50 x 12m antennas = 1225 baselines)
- **Higher angular resolution**:
- baselines ~15km, matched beams possible in all bands
- **Better imaging** of resolved objects and mosaics
  - TPA: four additional 12m antennas with subreflector nutators
  - ACA: Atacama Compact configuration 12 x 7m antennas
  - "On-the-Fly" mosaics: quickly cover larger areas of sky
- **More receiver bands**: 4, 8, 10 (2mm, 0.7mm, 0.35mm)
- **Polarization:** magnetic fields and very high dynamic range imaging
- **"Mixed" correlator modes** (simultaneous wide & narrow, see A&A 462, 801)
- **ALMA development program ➔** studies just beginning
  - mm VLBI, more receiver bands
  - Higher data rates

ALMA

ATACAMA LARGE MILLIMETER ARRAY

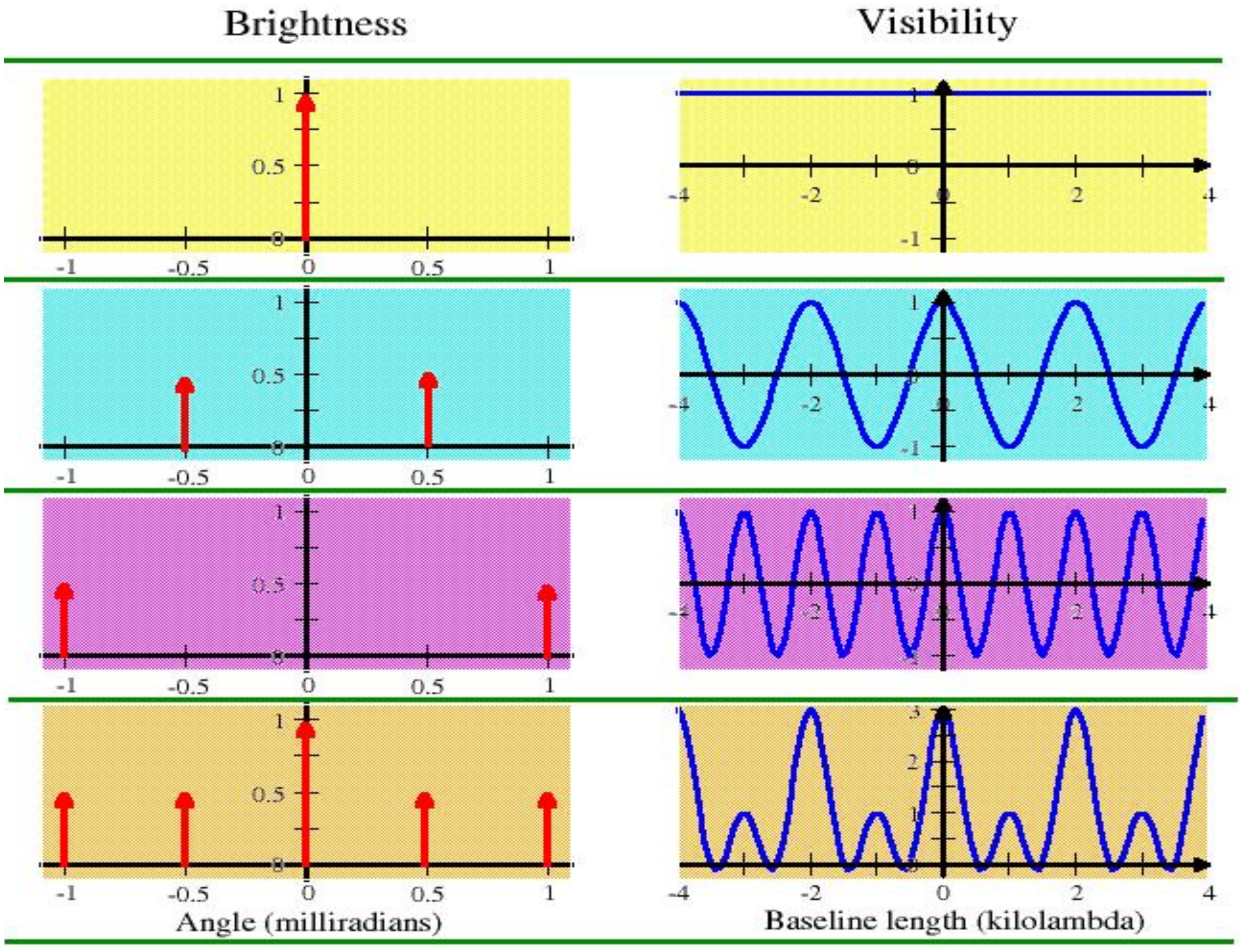
www.almaobservatory.org

The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership among Europe, Japan and North America, in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere, in Japan by the National Institutes of Natural Sciences (NINS) in cooperation with the Academia Sinica in Taiwan and in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC). ALMA construction and operations are led on behalf of Europe by ESO, on behalf of Japan by the National Astronomical Observatory of Japan (NAOJ) and on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI).

Visibility and Sky Brightness

- The Visibility is a complex quantity, which is the Fourier transform of the source Brightness

- Some simple and illustrative examples make use of 'delta functions' – sources of infinitely small extent, but finite total flux.



(from Summer School lecture by R. Perley)

Synthesized beam

Discrete sampling: $T'(x,y) = \iint W(u,v)V(u,v)e^{2\pi i(uv+vy)}dudv$

The **weighting function W(u,v)** is 0 where V is not sampled

T'(x,y) is FT of the product of W and V, which is the convolution of the FT of V and W:

$$T'(x,y) = B(x,y) \otimes T(x,y)$$

$$B(x,y) = \iint W(u,v)e^{2\pi i(uv+vy)}dudv$$

B(x,y) is the synthesized beam, analogous of the point-spread function in an optical telescope.

(from CalTech CDE talk by A. Isella)

Weighting function

ALMA

Measured flux: $T'(x,y) = B(x,y) \otimes T(x,y)$

Synthesized beam: $B(x,y) = \iint W(u,v) e^{2\pi i(uv+vy)} du dv$

You can change the angular resolution and sensitivity of the final image by changing the weighting function W(u,v)

(from CalTech CDE talk by A. Isella)

NRAO

Weighting function

ALMA

- **“Natural”** weighting: $W(u,v) = 1/\sigma^2(u,v)$, where $\sigma^2(u,v)$ is the noise variance of the (u,v) sample
Advantage: gives the lowest noise in the final image, highlight extended structures.
Disadvantage: generally gives more weights to the short baseline (where there are more measurements of V) degrading the resolution

- **“Uniform”** weighting: W(u,v) is inversely proportional to the local density of (u,v) points. It generally gives more weights to the long baseline therefore leading to higher angular resolution.
Advantage: better resolution and lower sidelobes
Disadvantage: higher noise in the final map

- **“Robust”** (Briggs) weighting: W(u,v) depends on a given threshold value S, so that a large S gives natural weighting and a small S gives uniform weighting.
Advantage: continuous variation of the angular resolution.

NRAO

(from CalTech CDE talk by A. Isella)

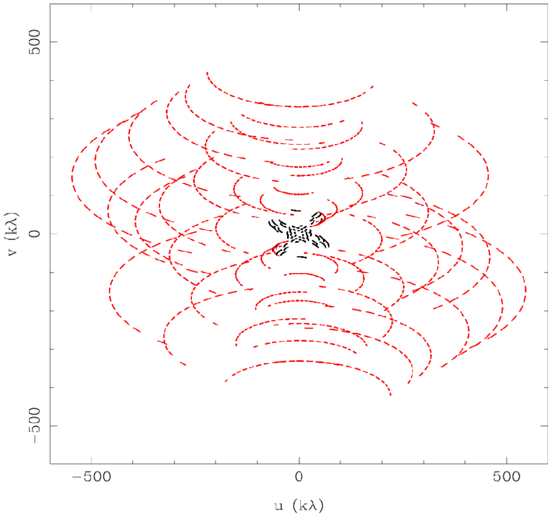
Dirty Beam Shape and Weighting

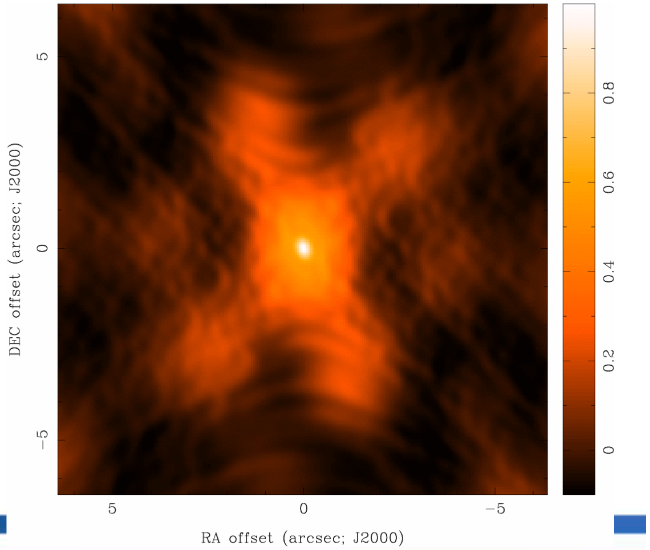
- introduce weighting function W(u,v)

  $$b(x,y) = FT^{-1}\{W(u,v)B(u,v)\}$$

  - W modifies sidelobes of dirty beam (W is also gridded for FFT)

- "Natural" weighting
  - $W(u,v) = 1/\sigma^2(u,v)$ at points with data and zero elsewhere, where $\sigma^2(u,v)$ is the noise variance of the (u,v) sample
  - maximizes point source sensitivity (lowest rms in image)
  - generally more weight to short baselines (large spatial scales), degrades resolution

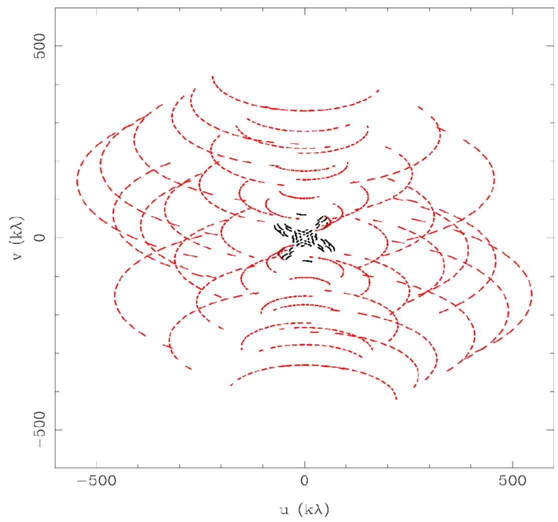


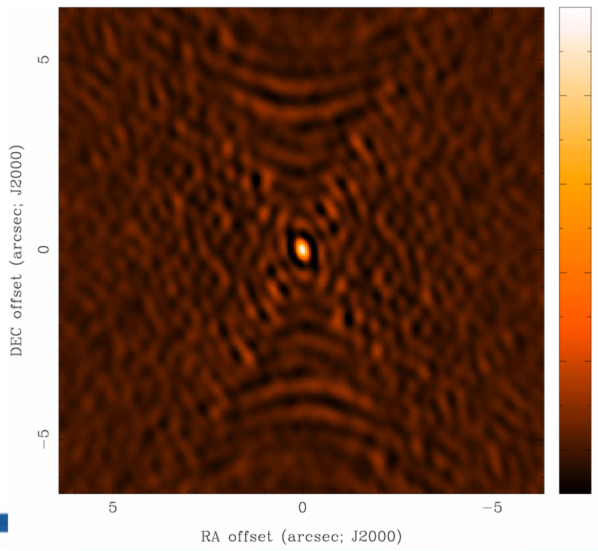


(from Summer School lecture by D.Wilner)

Dirty Beam Shape and Weighting

- “Uniform” weighting
  - W(u,v) is inversely proportional to local density of (u,v) points, so sum of weights in a (u,v) cell is a constant (or zero)
  - fills (u,v) plane more uniformly, so (outer) sidelobes are lower
  - gives more weight to long baselines and therefore higher angular resolution
  - degrades point source sensitivity (higher rms in image)
  - can be trouble with sparse sampling: cells with few data points have same weight as cells with many data points





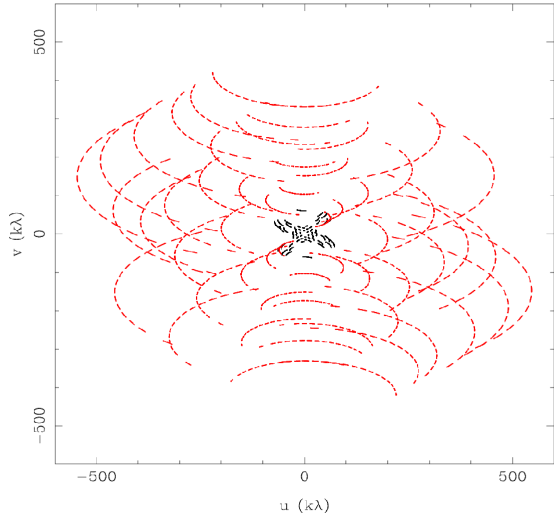
(from Summer School lecture by D.Wilner)

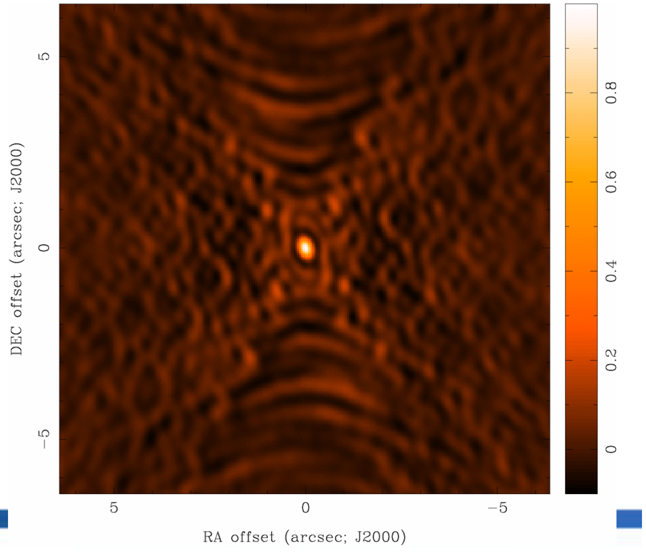
Dirty Beam Shape and Weighting

- "Robust" (Briggs) weighting
  - variant of "uniform" that avoids giving too much weight to cell with low natural weight
  - implementations differ, e.g. S_N is natural weight of a cell, S_t is a threshold

$$W(u,v) = \frac{1}{\sqrt{1+S_N^2/S_{thresh}^2}}$$

  - large threshold → natural weighting
  - small threshold → uniform weighting
  - an adjustable parameter that allows for continuous variation between highest angular resolution and optimal point source sensitivity





(from Summer School lecture by D.Wilner)

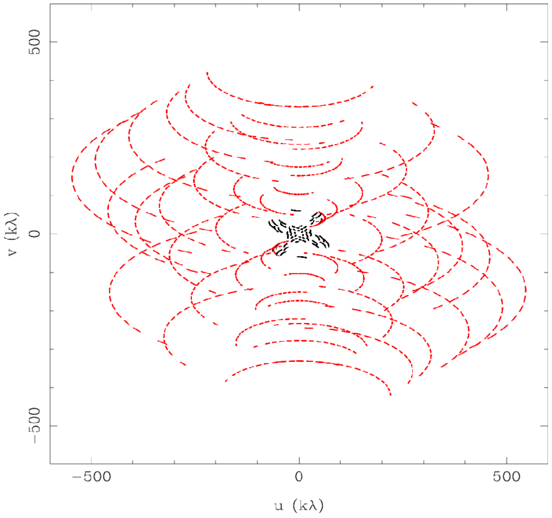
Dirty Beam Shape and Weighting

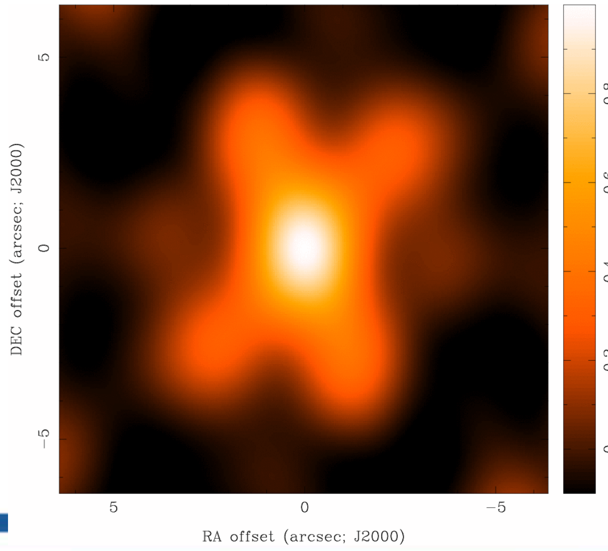
- "Tapering"
  - apodize the (u,v) sampling by a Gaussian

$$W(u,v) = exp\left\{-\frac{(u^2+v^2)}{t^2}\right\}$$

t = tapering parameter (in kλ; arcsec)

  - like smoothing in the image plane (convolution by a Gaussian)
  - gives more weight to short baselines, degrades angular resolution
  - degrades point source sensitivity but can improve sensitivity to extended structure
  - could use elliptical Gaussian, other function
  - limits to usefulness

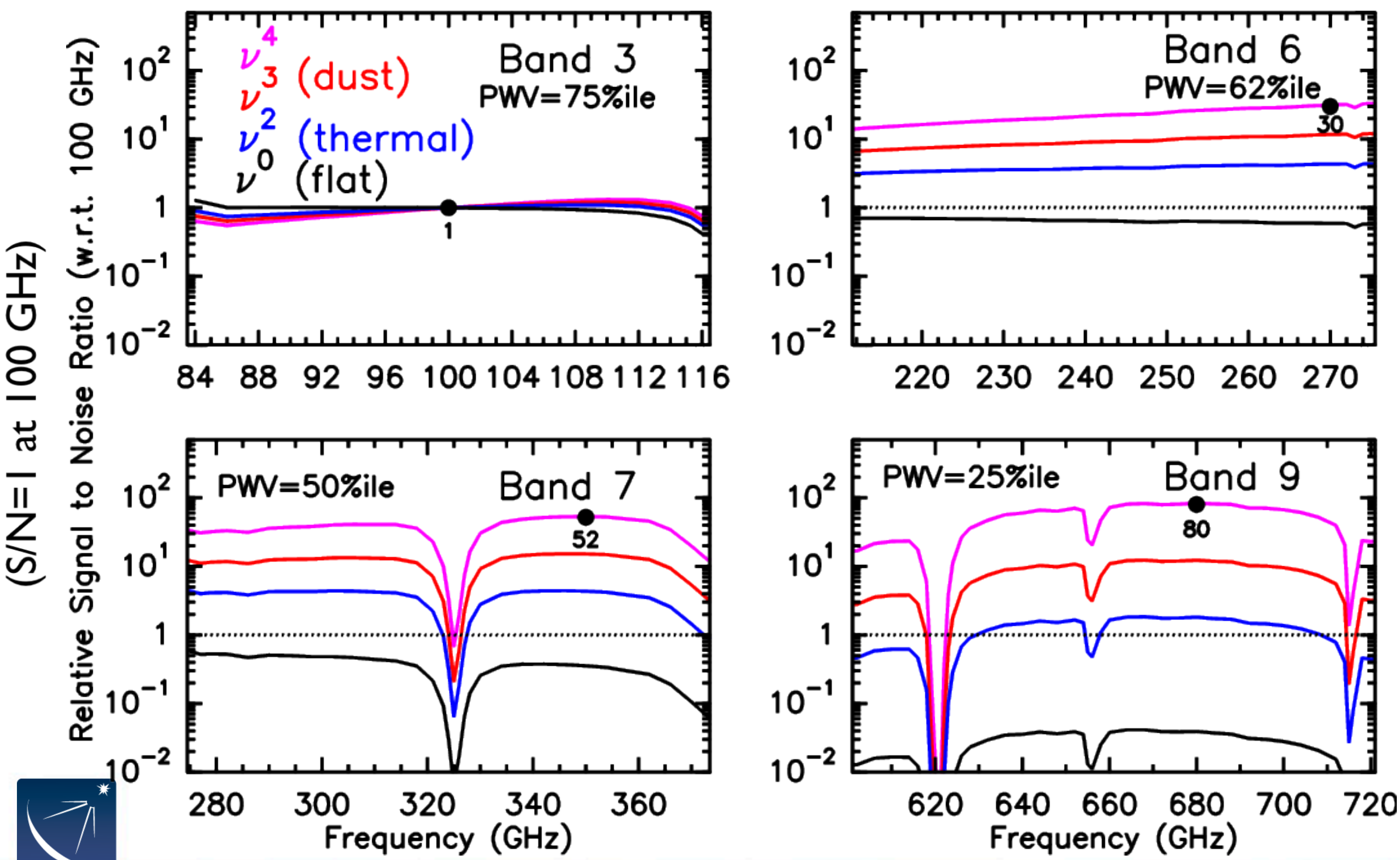




(from Summer School lecture by D.Wilner)

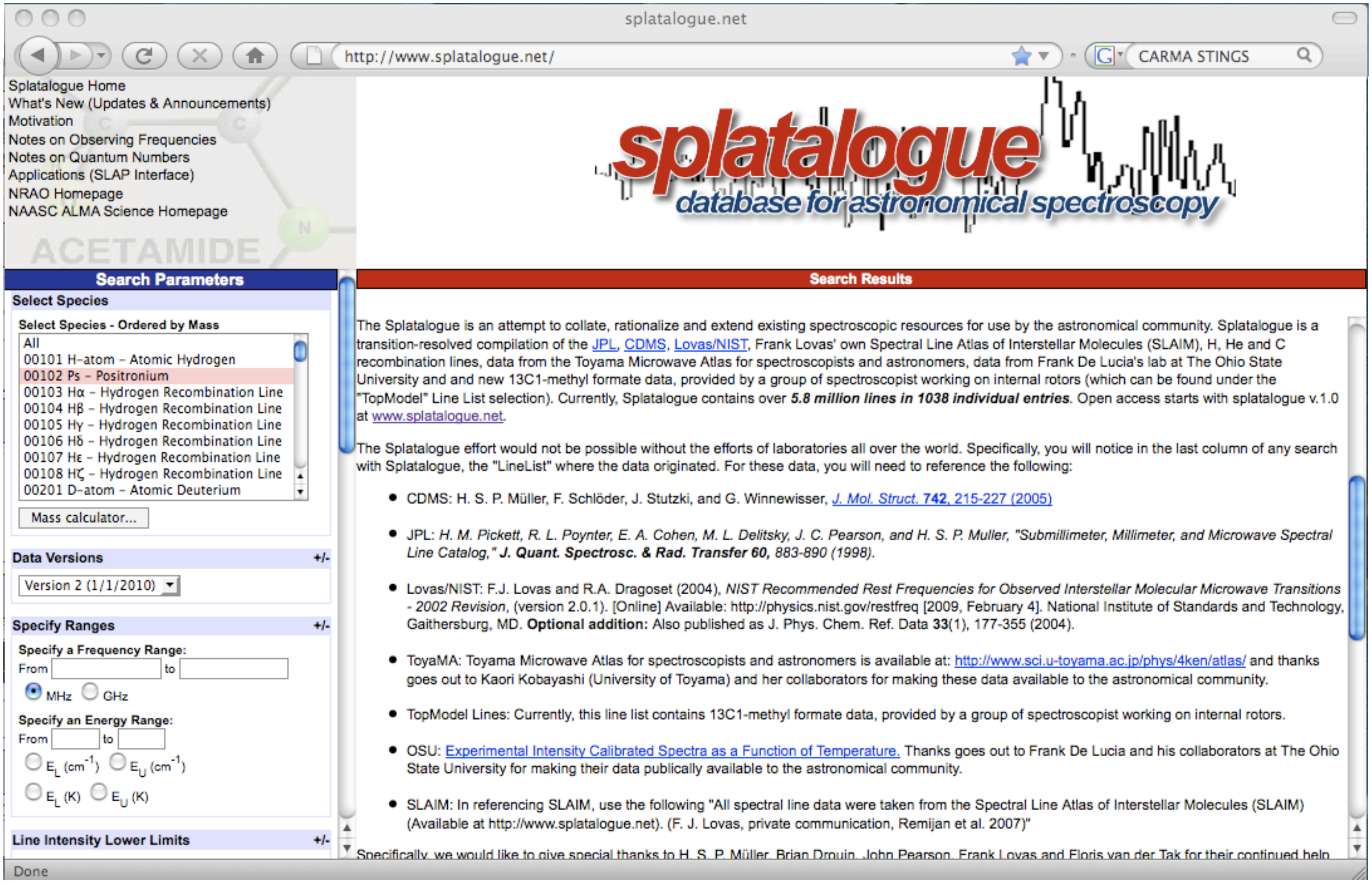
Choosing your bands - II

Relative Signal to Noise ratio for different spectral indices



Spectral Lines in the ALMA bands

http://www.splatalogue.net (large subset also available in OT)



The Splatalogue is an attempt to collate, rationalize and extend existing spectroscopic resources for use by the astronomical community. Splatalogue is a transition-resolved compilation of the JPL, CDMS, Lovas/NIST, Frank Lovas' own Spectral Line Atlas of Interstellar Molecules (SLAIM), H, He and C recombination lines, data from the Toyama Microwave Atlas for spectroscopists and astronomers, data from Frank De Lucia's lab at The Ohio State University and and new 13C1-methyl formate data, provided by a group of spectroscopist working on internal rotors (which can be found under the "TopModel" Line List selection). Currently, Splatalogue contains over ***5.8 million lines in 1038 individual entries***. Open access starts with splatalogue v.1.0 at www.splatalogue.net.

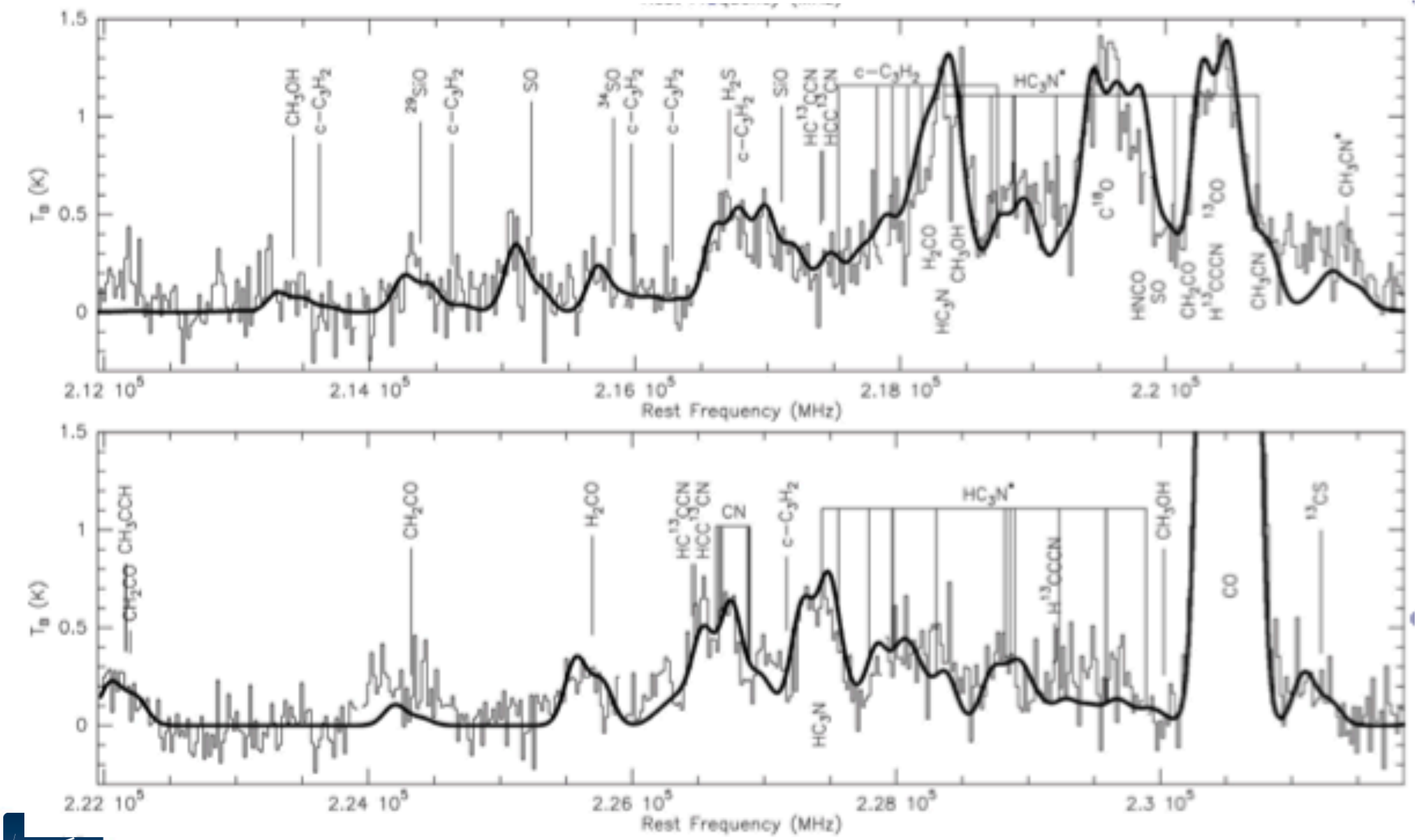
The Splatalogue effort would not be possible without the efforts of laboratories all over the world. Specifically, you will notice in the last column of any search with Splatalogue, the "LineList" where the data originated. For these data, you will need to reference the following:

- CDMS: H. S. P. Müller, F. Schlöder, J. Stutzki, and G. Winnewisser, *J. Mol. Struct.* **742**, 215-227 (2005)
- JPL: *H. M. Pickett, R. L. Poynter, E. A. Cohen, M. L. Delitsky, J. C. Pearson, and H. S. P. Muller, "Submillimeter, Millimeter, and Microwave Spectral Line Catalog,"* ***J. Quant. Spectrosc. & Rad. Transfer 60,*** *883-890 (1998).*
- Lovas/NIST: F.J. Lovas and R.A. Dragoset (2004), *NIST Recommended Rest Frequencies for Observed Interstellar Molecular Microwave Transitions - 2002 Revision*, (version 2.0.1). [Online] Available: http://physics.nist.gov/restfreq [2009, February 4]. National Institute of Standards and Technology, Gaithersburg, MD. **Optional addition:** Also published as J. Phys. Chem. Ref. Data **33**(1), 177-355 (2004).
- ToyaMA: Toyama Microwave Atlas for spectroscopists and astronomers is available at: http://www.sci.u-toyama.ac.jp/phys/4ken/atlas/ and thanks goes out to Kaori Kobayashi (University of Toyama) and her collaborators for making these data available to the astronomical community.
- TopModel Lines: Currently, this line list contains 13C1-methyl formate data, provided by a group of spectroscopist working on internal rotors.
- OSU: Experimental Intensity Calibrated Spectra as a Function of Temperature. Thanks goes out to Frank De Lucia and his collaborators at The Ohio State University for making their data publically available to the astronomical community.
- SLAIM: In referencing SLAIM, use the following "All spectral line data were taken from the Spectral Line Atlas of Interstellar Molecules (SLAIM) (Available at http://www.splatalogue.net). (F. J. Lovas, private communication, Remijan et al. 2007)"

Specifically, we would like to give special thanks to H. S. P. Müller, Brian Drouin, John Pearson, Frank Lovas and Floris van der Tak for their continued help

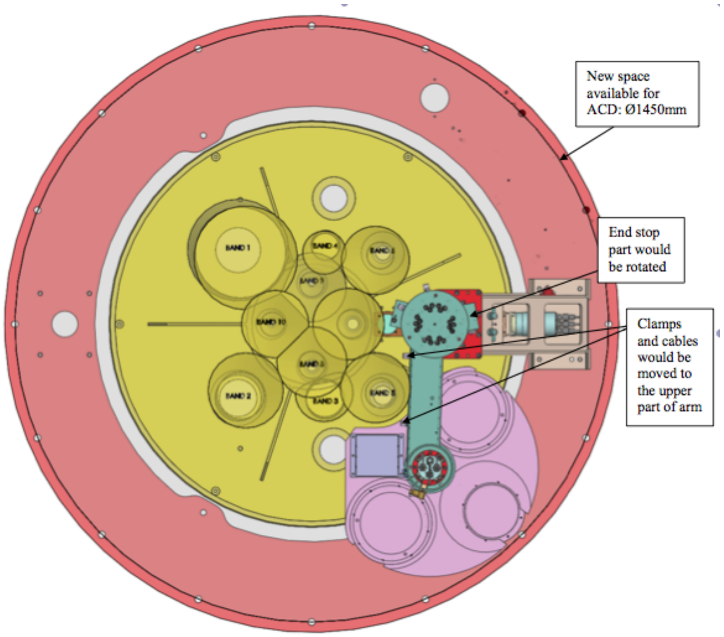
Spectral lines in the ALMA bands

SMA spectrum of Arp 220 (Band 6) (Martin et al. 2011)



ALMA Calibration Device

Two-temperature load system (100C & ambient) maneuvered by robotic arm (shown in a Melco antenna below)



New space available for ACD: Ø1450mm

End stop part would be rotated

Clamps and cables would be moved to the upper part of arm

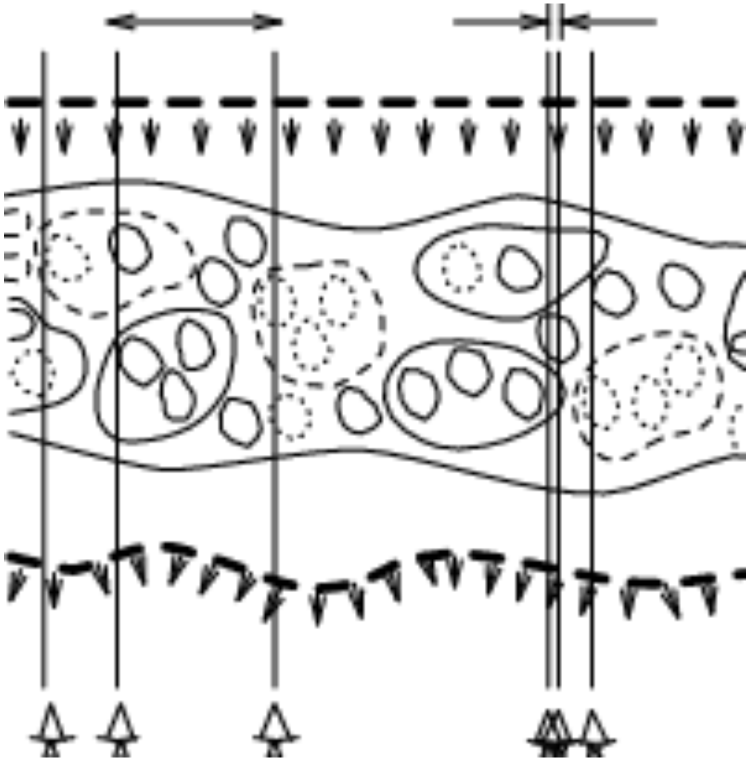
$$T_{sys} \approx T_{atm}(e^{\tau}-1) + T_{rx}e^{\tau}$$

$$\tau = \tau_o \sec(el)$$

Atmospheric phase fluctuations

- Variations in the amount of precipitable water vapor (PWV) cause phase fluctuations, which are worse at shorter wavelengths (higher frequencies), and result in:
  - Low coherence (loss of sensitivity)
  - Radio "seeing", typically 0.1-1″ at 1 mm
  - Anomalous pointing offsets
  - Anomalous delay offsets

You can observe in apparently excellent submm weather (in terms of transparency) and still have terrible "seeing" i.e. phase stability.



Patches of air with different water vapor content (and hence index of refraction) affect the incoming wave front differently.

Phase correction methods

ALMA

- **Fast switching:** used at the EVLA for high frequencies and will be used at ALMA. Choose cycle time, t_{cyc}, short enough to reduce ϕ_{rms} to an acceptable level. Calibrate in the normal way.

	Band 9 (690 GHz)	Band 7 (345 GHz)
50 antennas, 2 pol, 8 GHz, 1 minute, yields 1-sigma sensitivity:	1.94 mJy/beam	0.18 mJy/beam
Phase measurement on one baseline: with 1 pol, 2 GHz, 1 minute at 3-sigma requires source flux density:	F > 600 mJy	F > 54 mJy

- Traditional calibrators (quasars) are more scarce at high frequency
- But ALMA sensitivity is high, even on a per baseline basis
- Key will be calibrator surveys (probably starting with ATCA survey)

Phase correction methods

ALMA

- Fast switching: used at the EVLA for high frequencies and will be used at ALMA. Choose cycle time, t_{cyc}, short enough to reduce ϕ_{rms} to an acceptable level. Calibrate in the normal way.

However, the atmosphere often varies faster than the timescale of Fast Switching. The solution for ALMA is the WVR system.

- **Water Vapor Radiometry (WVR) concept**: measure the rapid fluctuations in T_B^{atm} with a radiometer at each antenna, then use these measurements to derive changes in water vapor column (w) and convert these into phase corrections using:

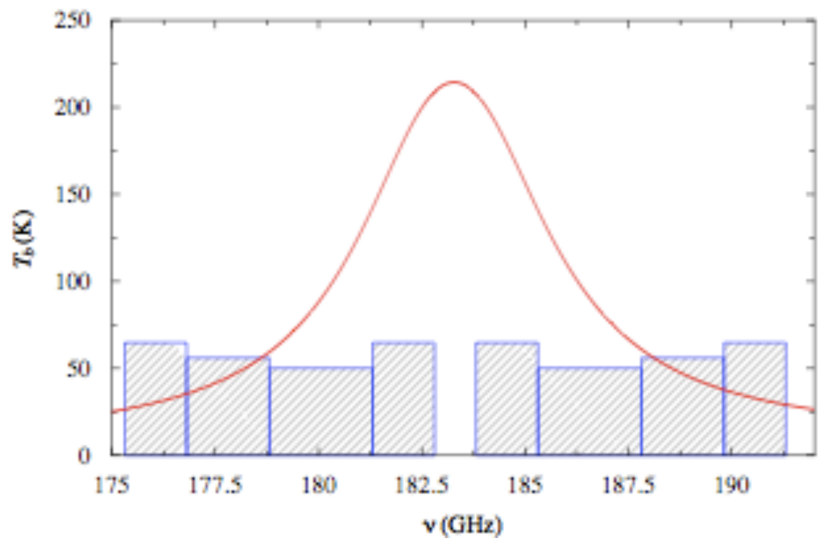
$$\Delta\phi_e \approx 12.6\,\pi\,\Delta w / \lambda$$

ALMA WVR System

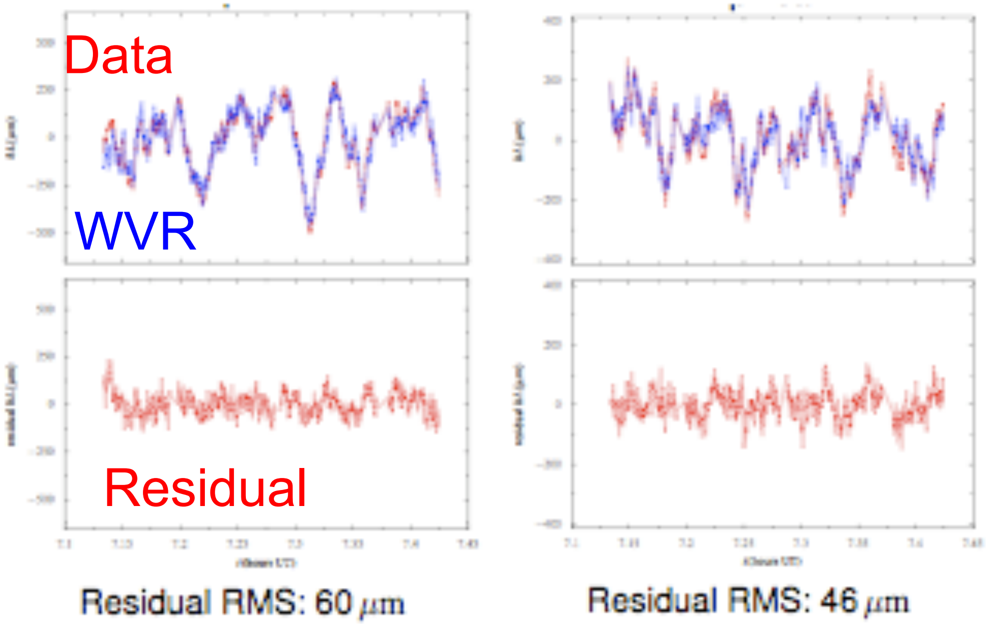
Installed on every antenna

The 183 GHz Water Vapour Line

Blue rectangles are the production WVR filters



Two different baselines Jan 4, 2010

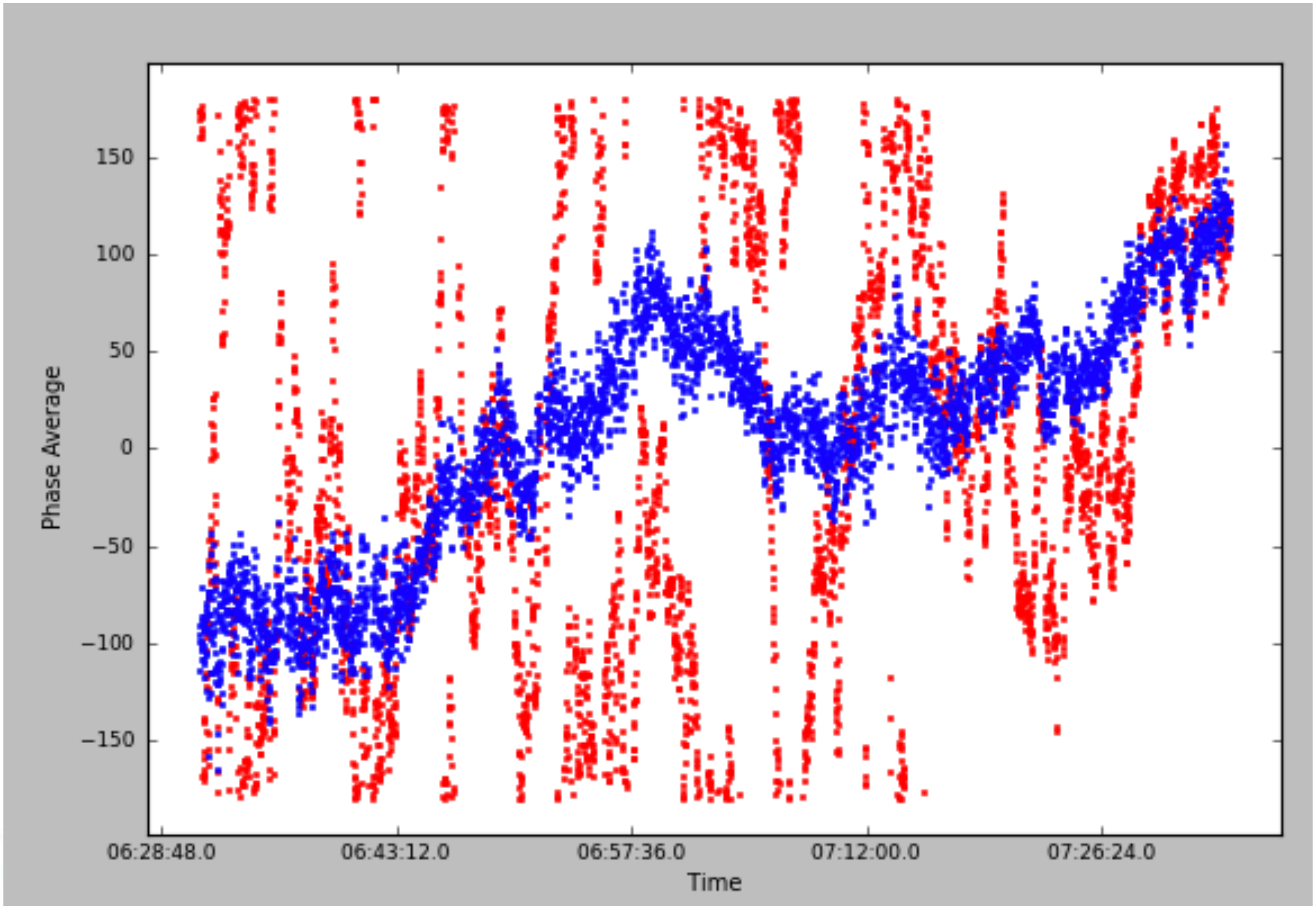


There are 4 "channels" flanking the peak of the 183 GHz water line

- Matching data from opposite sides are averaged
- Data taken every second, and are written to the ASDM (science data file)
- The four channels allow flexibility for avoiding saturation
- Next challenges are to perfect models for relating the WVR data to the correction for the data to reduce residual phase noise prior to performing the traditional calibration steps.

Tests of ALMA WVR System

600m baseline, Band 6, Mar 2011 (red=raw data, blue=corrected)



Phase correction methods

ALMA

- Fast switching: used at the EVLA for high frequencies and will be used at ALMA. Choose cycle time, t_{cyc}, short enough to reduce ϕ_{rms} to an acceptable level. Calibrate in the normal way.

- Water Vapor Radiometry: measure rapid fluctuations in T_B^{atm} with a radiometer, then use these to derive changes in water vapor column (w) and convert these into phase corrections using: $\Delta\phi_e \approx 12.6\pi\Delta w/\lambda$

- **Phase transfer:** alternate observations at low frequency (calibrator) and high frequency (science target), and transfer scaled phase solutions from low to high frequency. Can be tricky, requires well characterized system due to differing electronics at the frequencies of interest.

- **Self-calibration**: possible for bright sources. Need S/N per baseline of a few on short times scales (typically a few seconds).