Radio Interferometry

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

Outline

- Single Dish versus Interferometers
- Basic Interferometry
- What does an interferometer measure?
- Sensitivity
- Spectral Setup
- Calibration

Single Dish Radio Telescopes

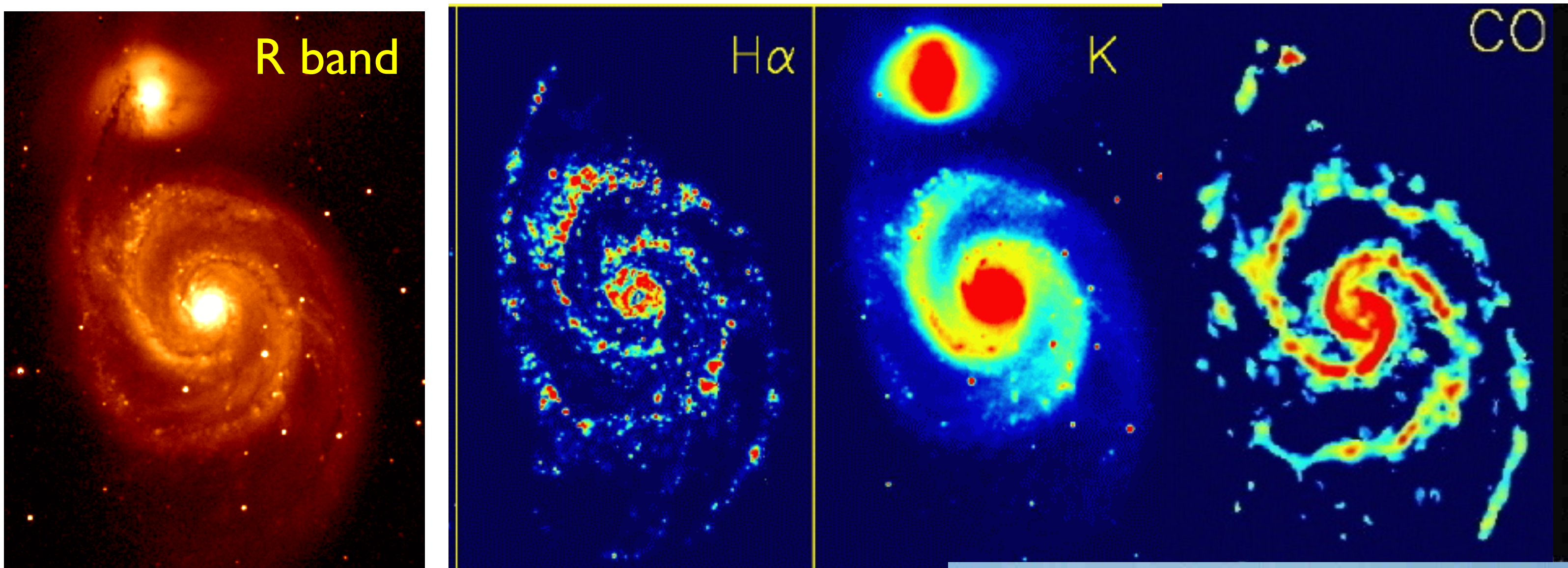
- A single dish measurement is important to get a measure of the total power / zero-spacing data!

- GBT + VLA
- ALMA TP + 12m array
- IRAM 30m + PdBI

- Analogous to Optical Telescopes in nearly every way
  - Imaging usually done with bolometers (CCD / cameras)
  - PSF = Beam much coarser than at optical / IR wavelengths
  - Field of view set by instrument at the focal plane – large areas of the sky can be mosaicked
  - Spectroscopy – higher velocity resolution than at optical or IR wavelengths.
  - Very large bandwidth instruments now coming on line

NRAO

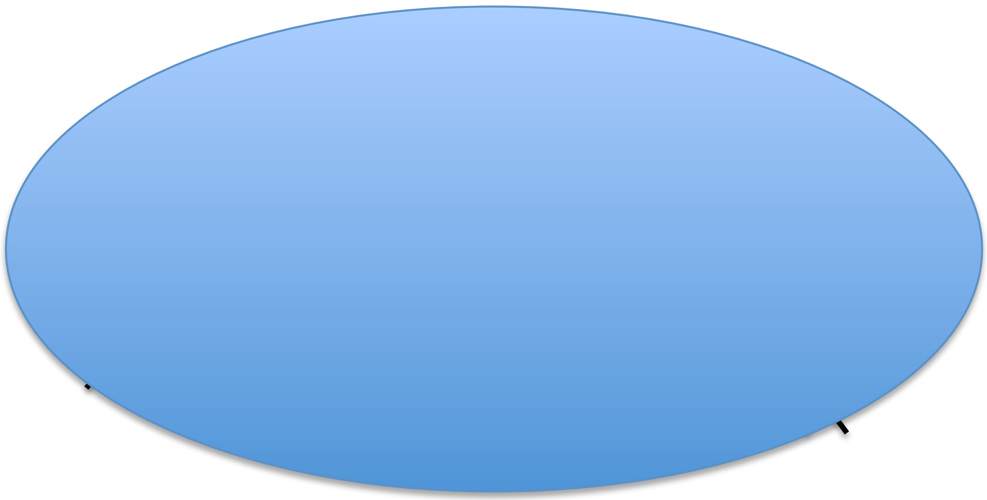
Resolution, resolution, resolution…



- $\Theta = \Lambda / D$
- Even for a 100m dish, $\Theta \sim 6''$
- Interferometry is critical!

An Interferometer

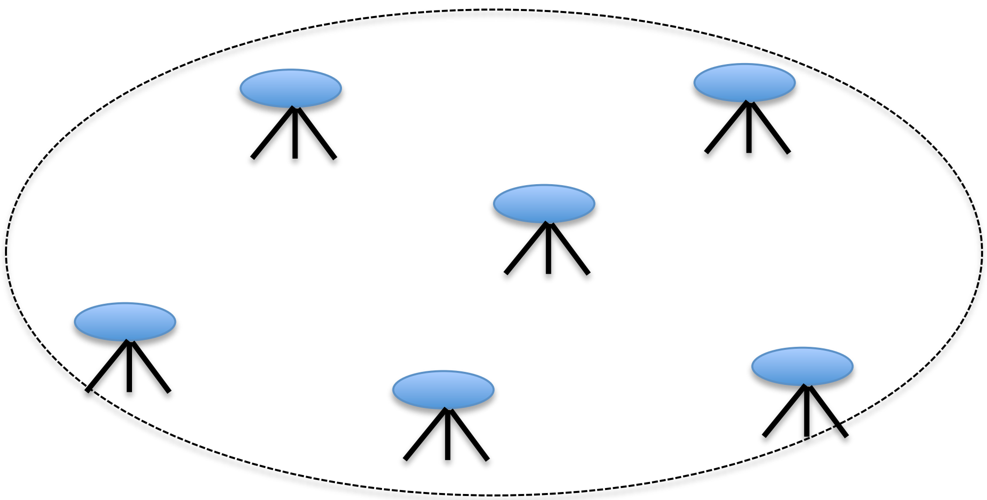
- Need a very large telescope to get arcsecond / sub-arcsecond resolution
  - Technically difficult and costly to construct + hard to point



- Break the large dish into many smaller dishes!

An Interferometer

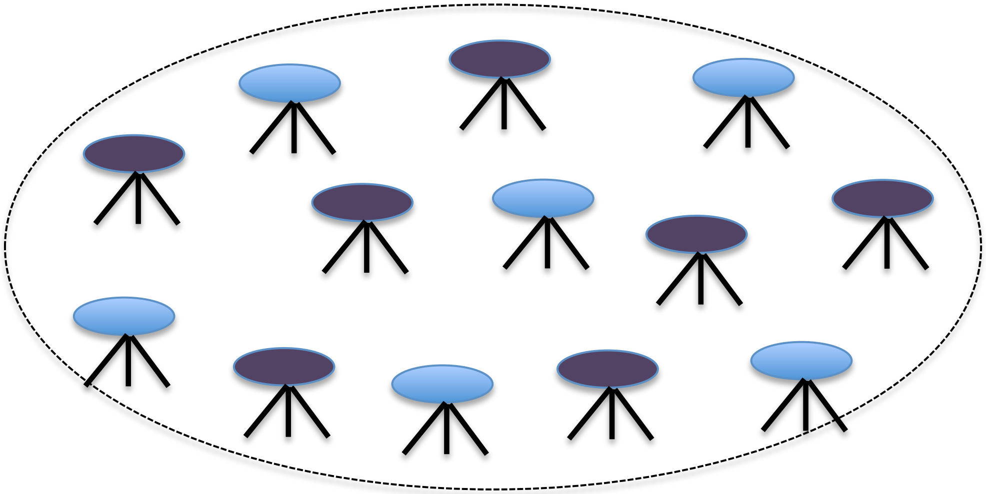
- One problem: Our telescope has holes in it!
  - Less light collecting power
  - Unfilled aperture → sensitive to only certain spatial scales!



An Interferometer

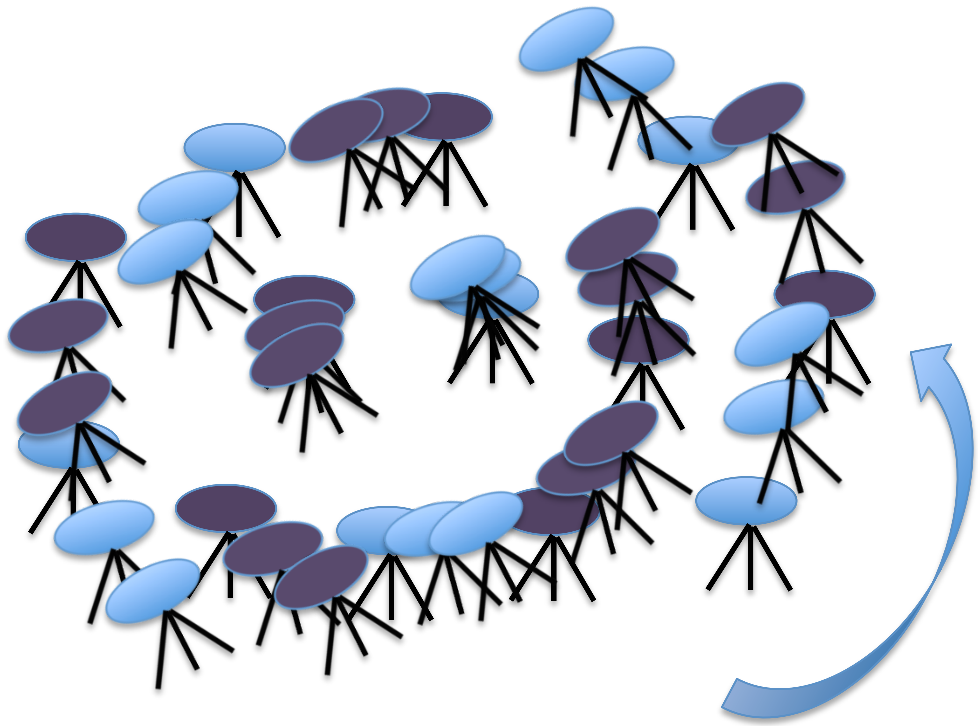
- How can we fill the aperture?

1. Add Antennas!



An Interferometer

- How can we fill the aperture?

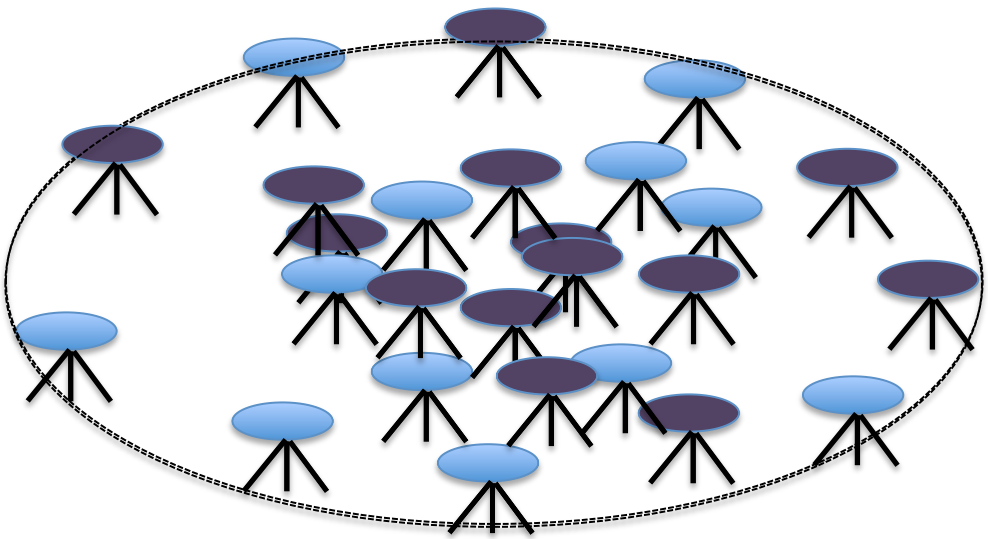


Use the rotation of the earth!

An Interferometer

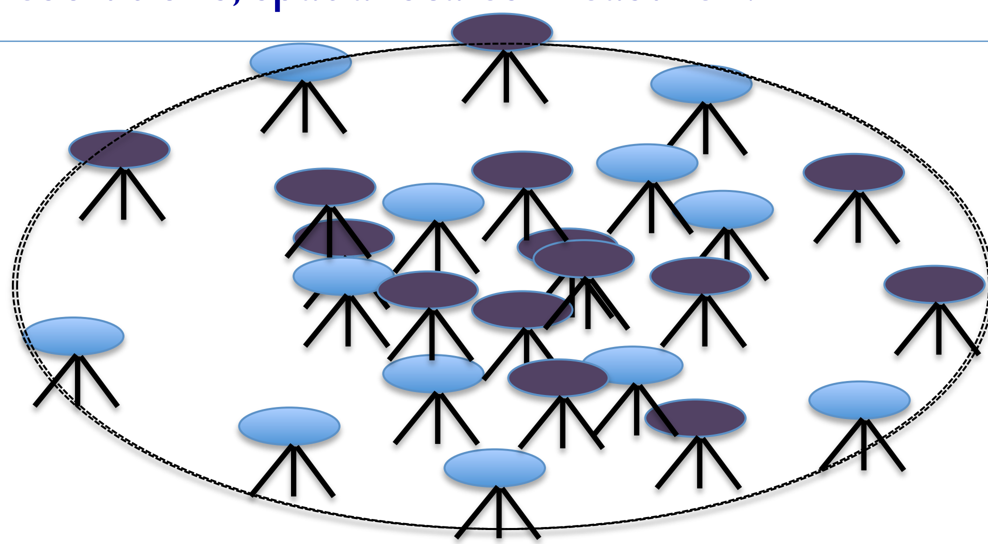
- How can we fill the aperture?

1. Move antennas in & out



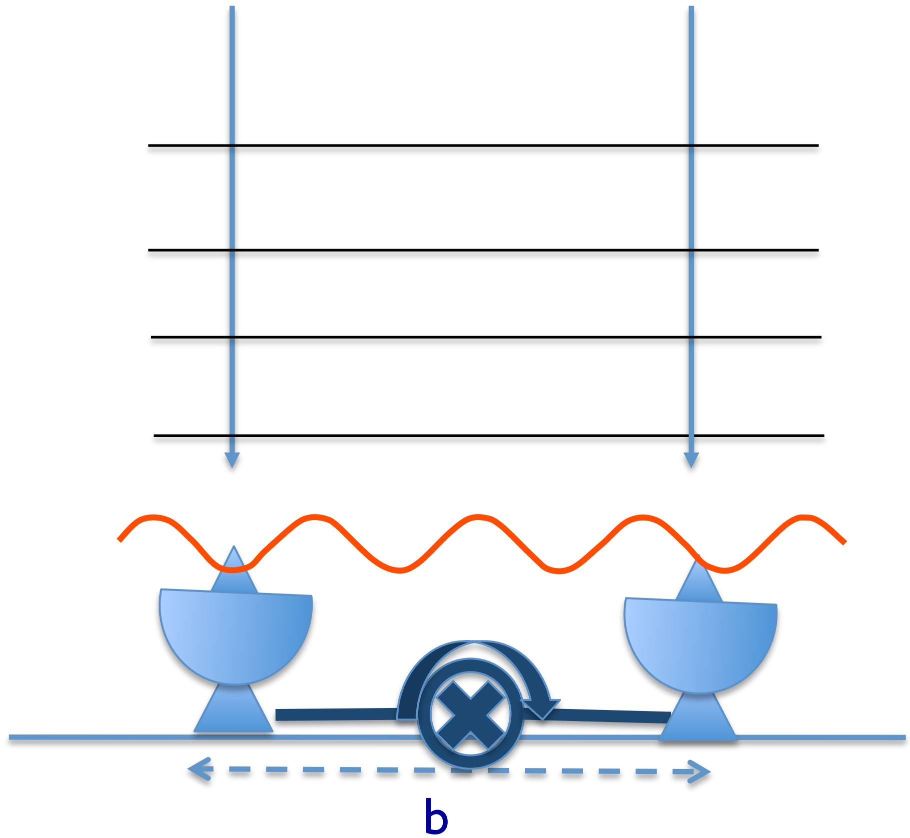
An Interferometer

- We simulate a large telescope and get better and better imaging by
  1. Adding antennas (usually fixed once construction is completed)
     - More baselines, more collecting area = higher sensitivity!
  2. Using earth's rotation for synthesis imaging
     - Different spatial scales due to projected baselines
  3. Moving telescopes into different configurations
     - Different resolutions, spatial scales measured!

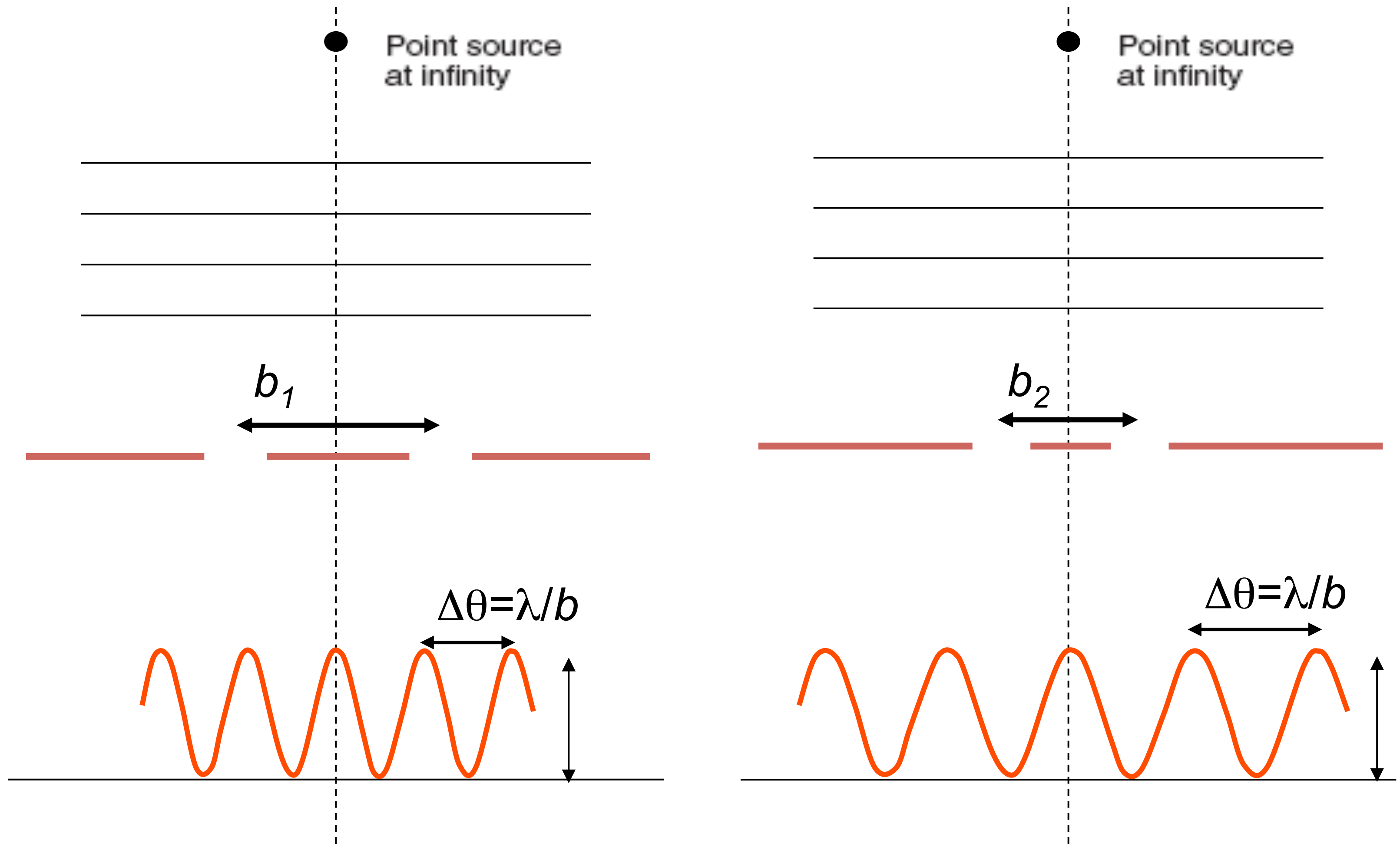


What Does an Interferometer Measure?

- An Interferometer measures the **interference pattern** produced by two apertures, which is related to the source brightness.

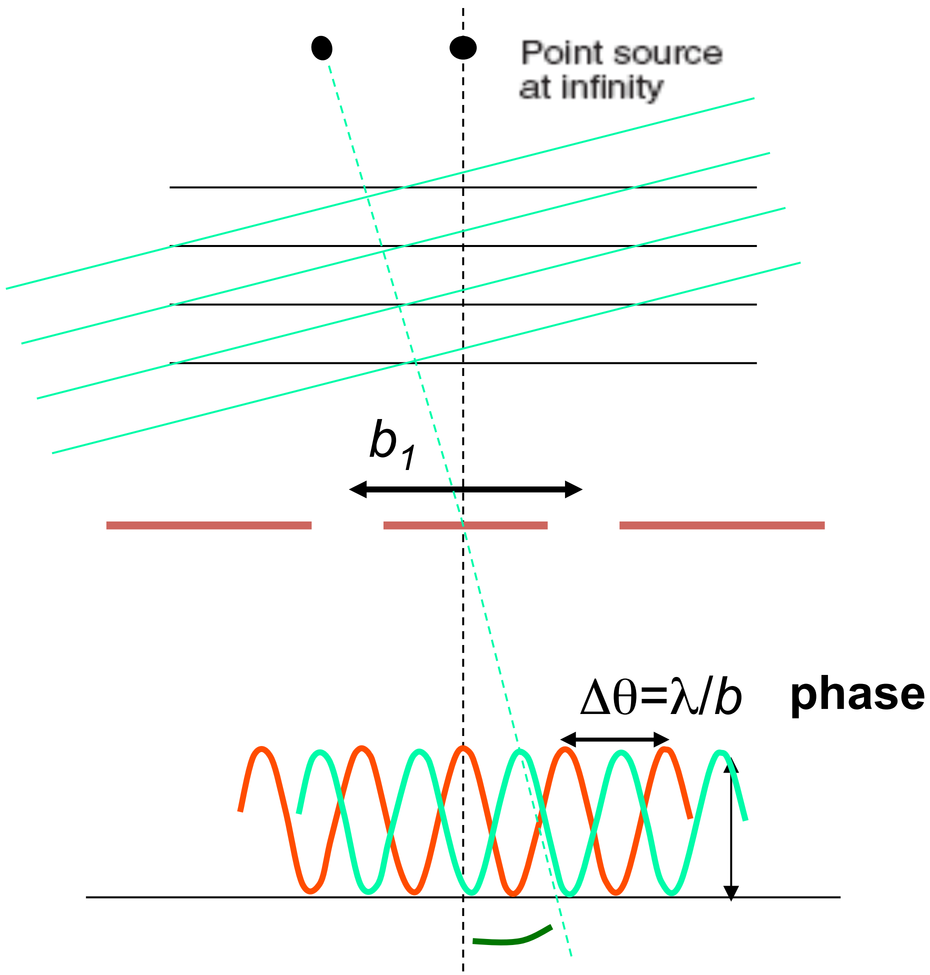


What Does an Interferometer Measure?

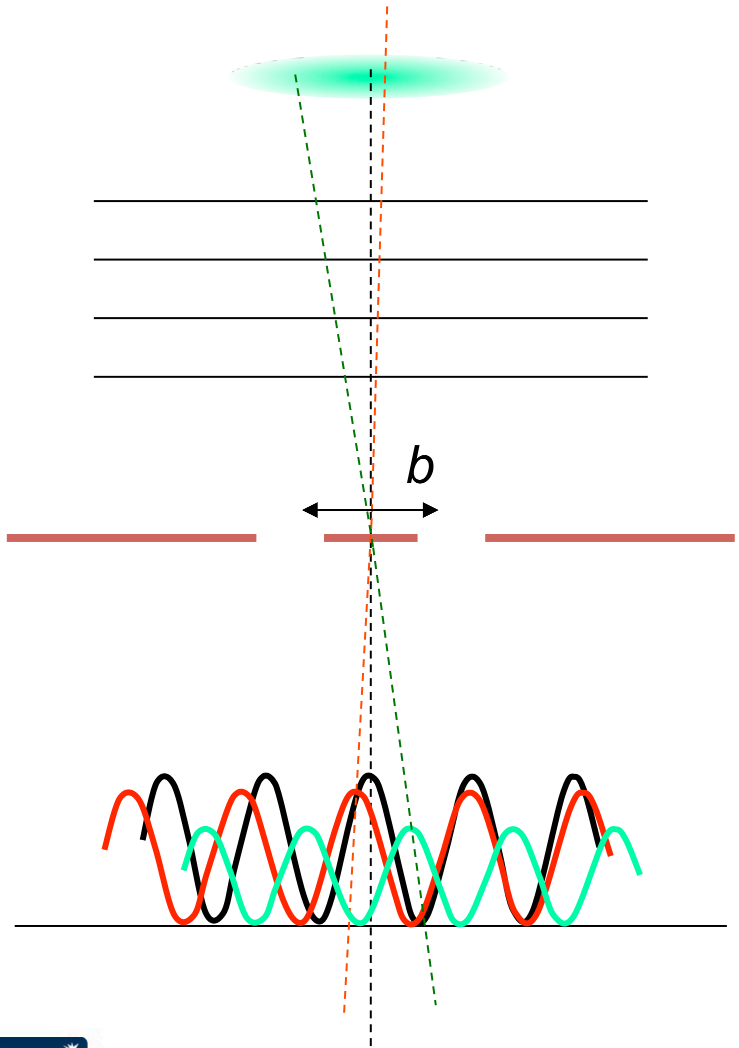


(based on CalTech CDE talk by A. Isella)

What Does an Interferometer Measure?



What Does an Interferometer Measure?



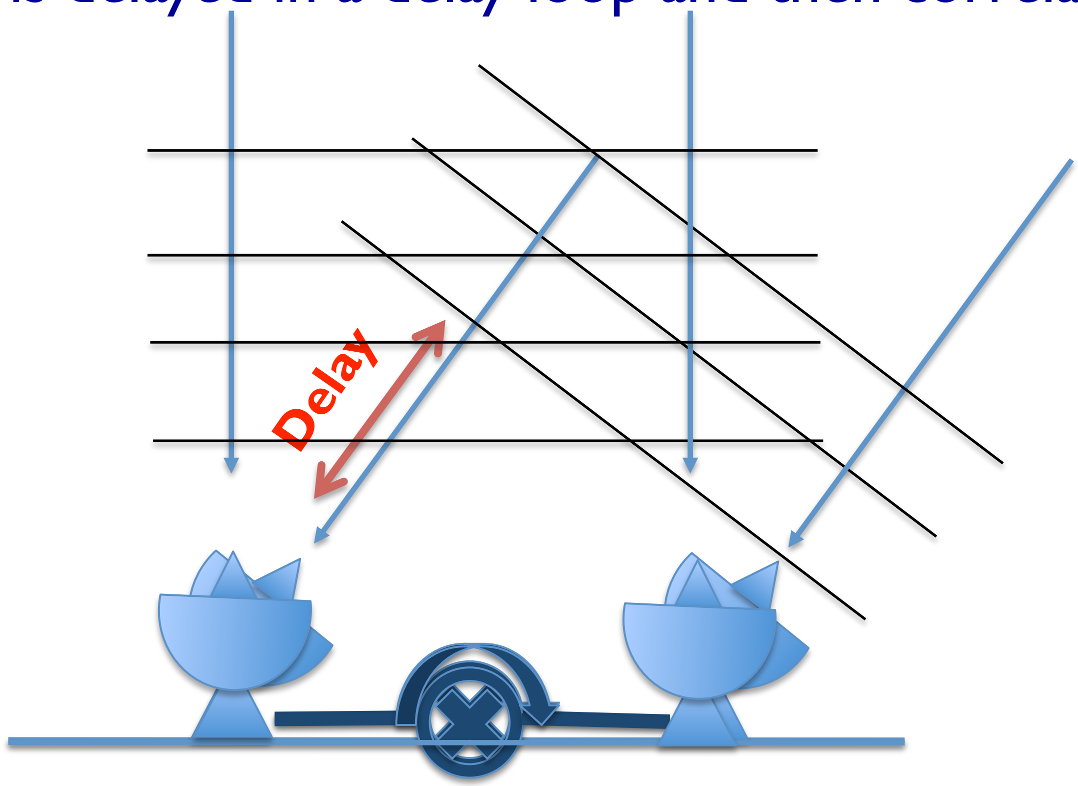
- **Amplitude** tells "how much" of a certain spatial frequency component

- **Phase** tells "where" this component is located

Visibility

Separation of slits / projected baseline

- Projected baseline changes as a source moves across the sky.
- Wavefront is delayed in a delay loop and then correlated

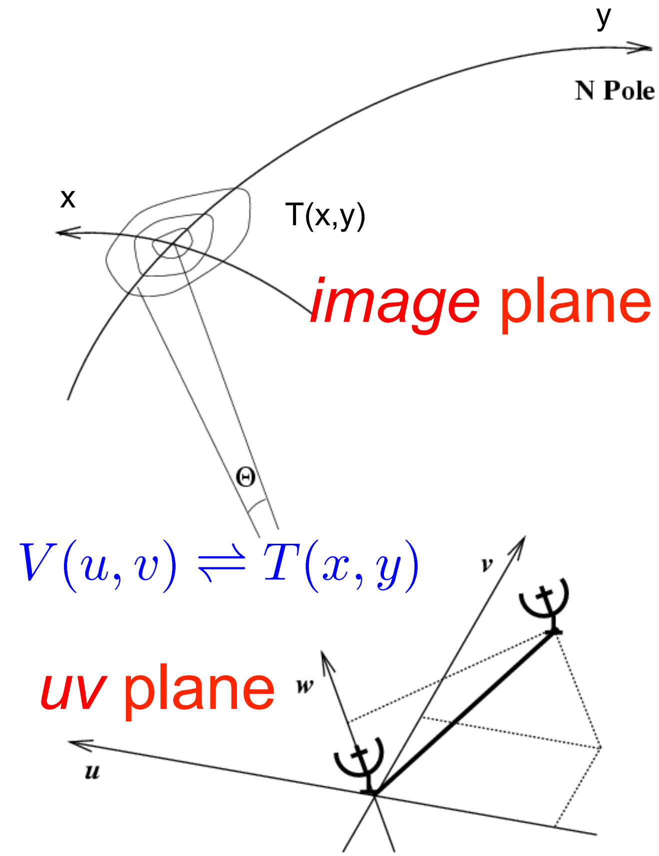


Visibility and Sky Brightness

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)

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

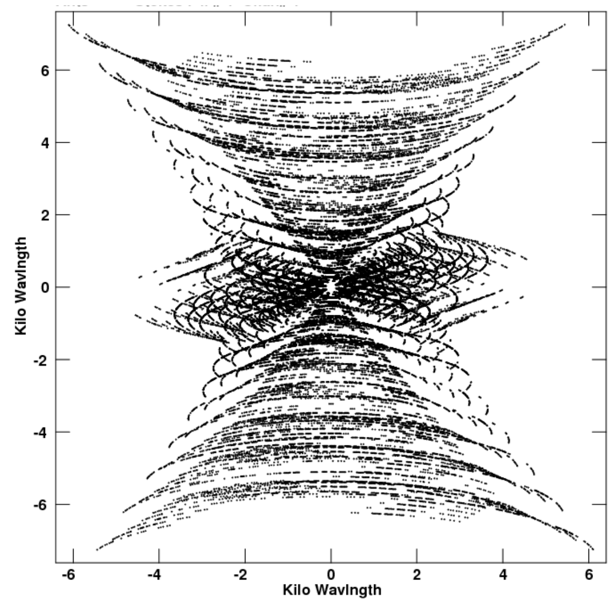
$$T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} du dv$$



- 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 ref position in E-W and N-S directions

Image Quality

- ALMA and JVLA are extremely sensitive but sensitivity may not be the only thing you need for your science!
- Image quality depends on *UV* coverage + density
- Image Fidelity is best when UV coverage is well matched to the source brightness distribution
- Note that poor UV coverage → reduced DYNAMIC RANGE and lower sensitivity

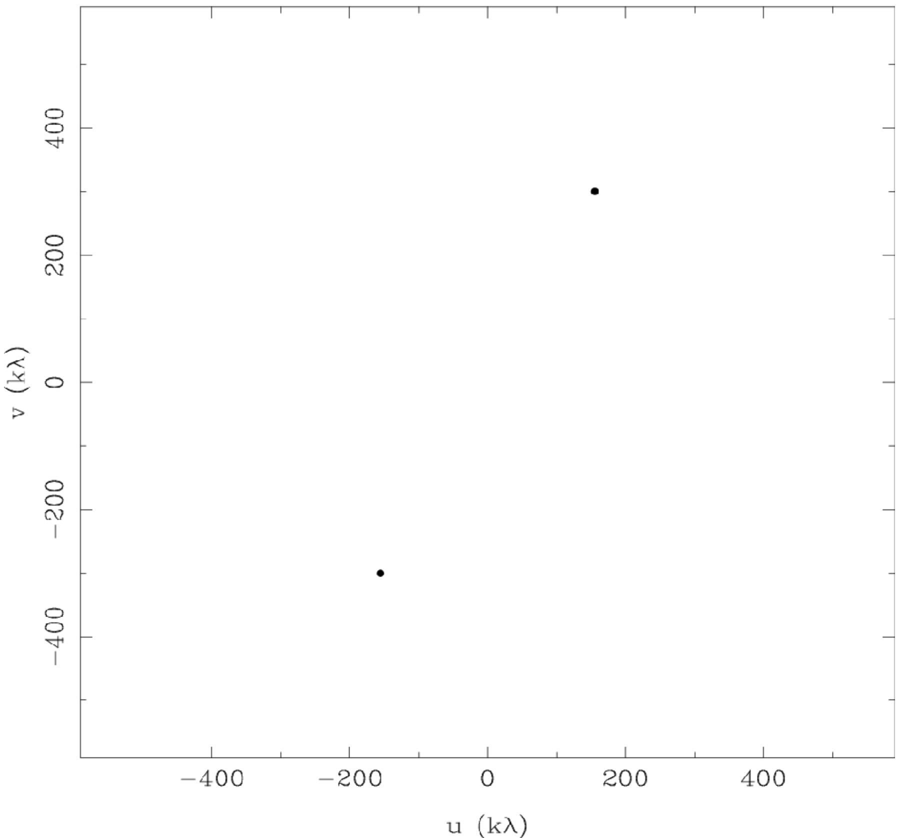


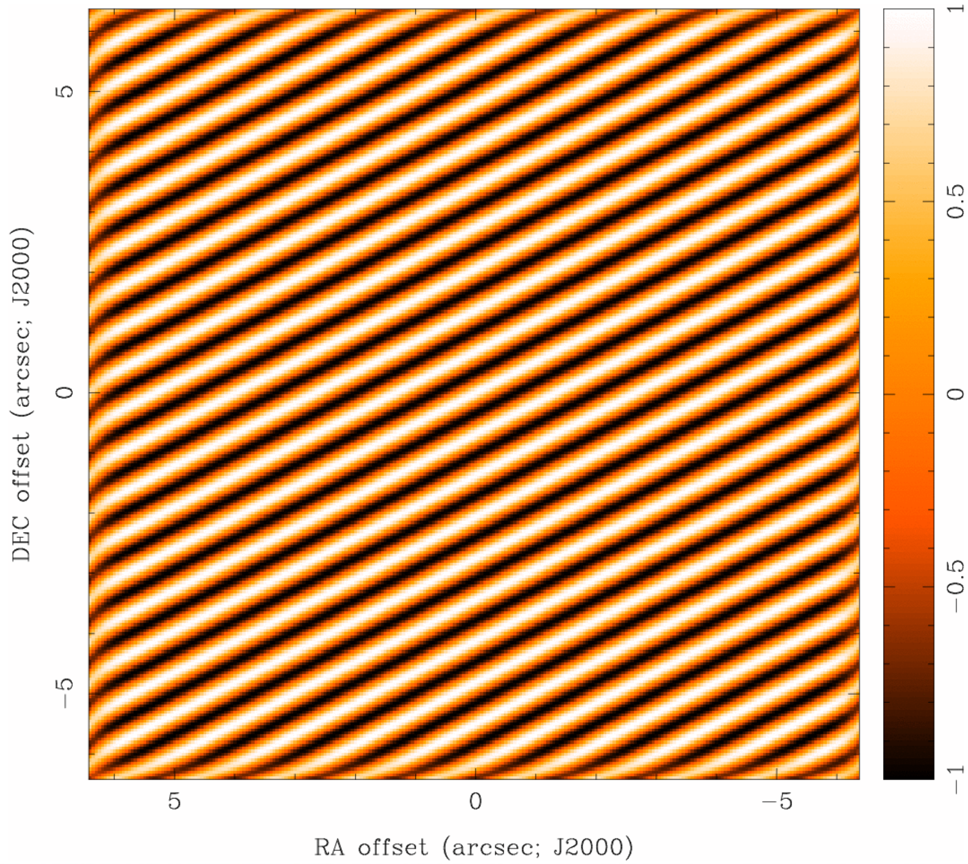
For ALMA you do not ask for time only sensitivity so must check box requesting extra time for UV coverage if needed + justify in proposal.

Beam Shape and Antennas

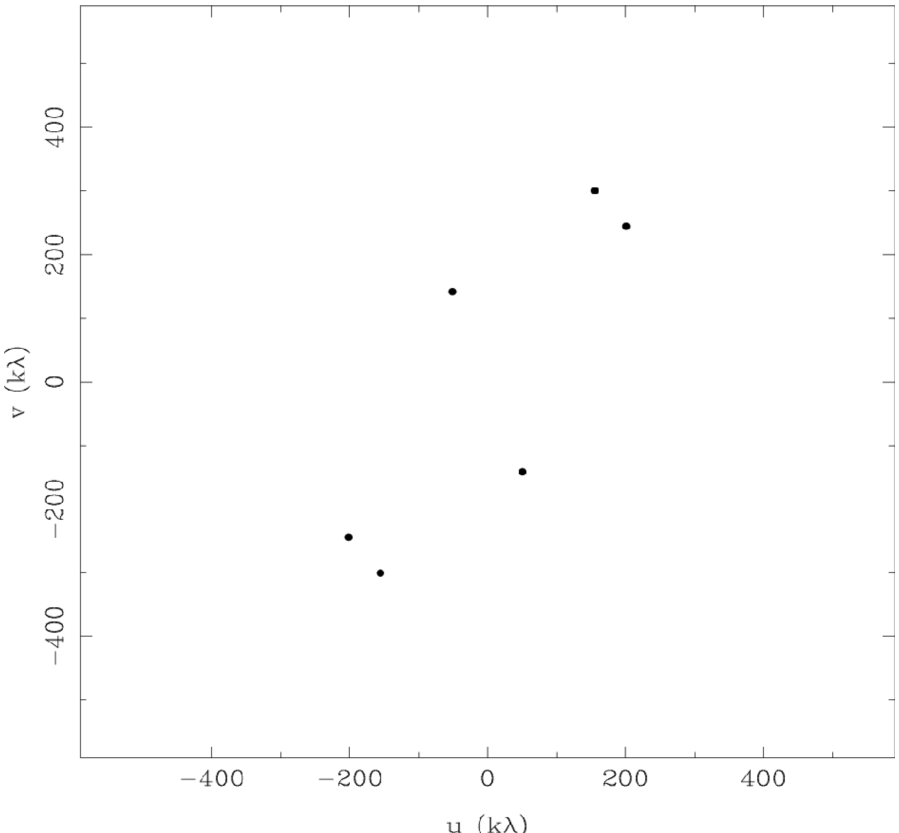
(Image sequence taken from Summer School lecture by D.Wilner)

2 Antennas

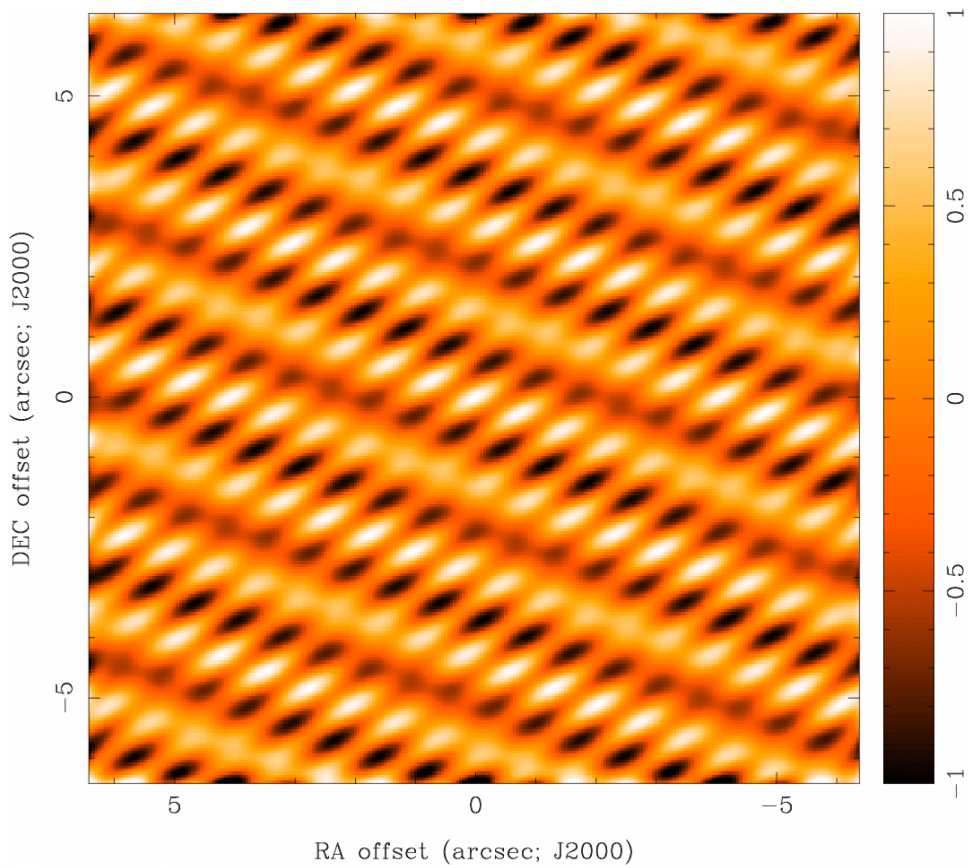




3 Antennas

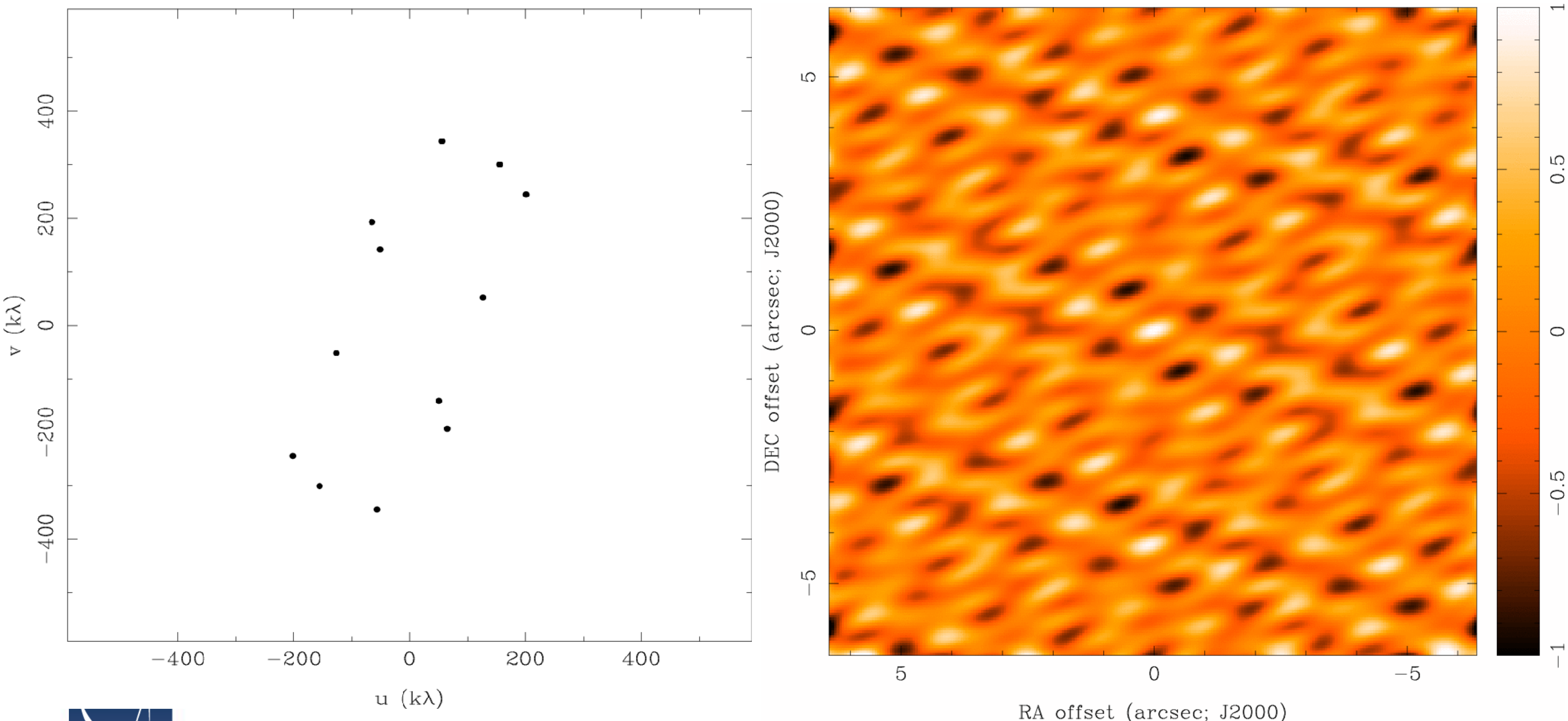


400
200
0
−200
−400
v (kλ)
−400
−200
0
200
400
u (kλ)



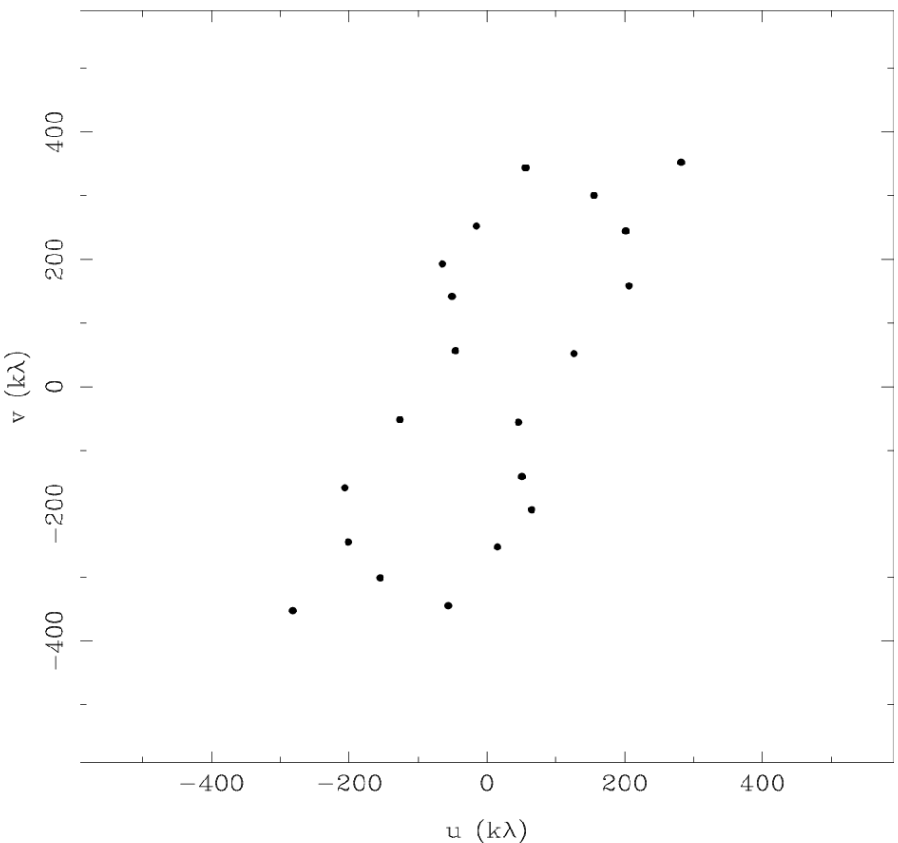
5
0
−5
DEC offset (arcsec; J2000)
5
0
−5
RA offset (arcsec; J2000)
1
0.5
0
−0.5
−1

4 Antennas

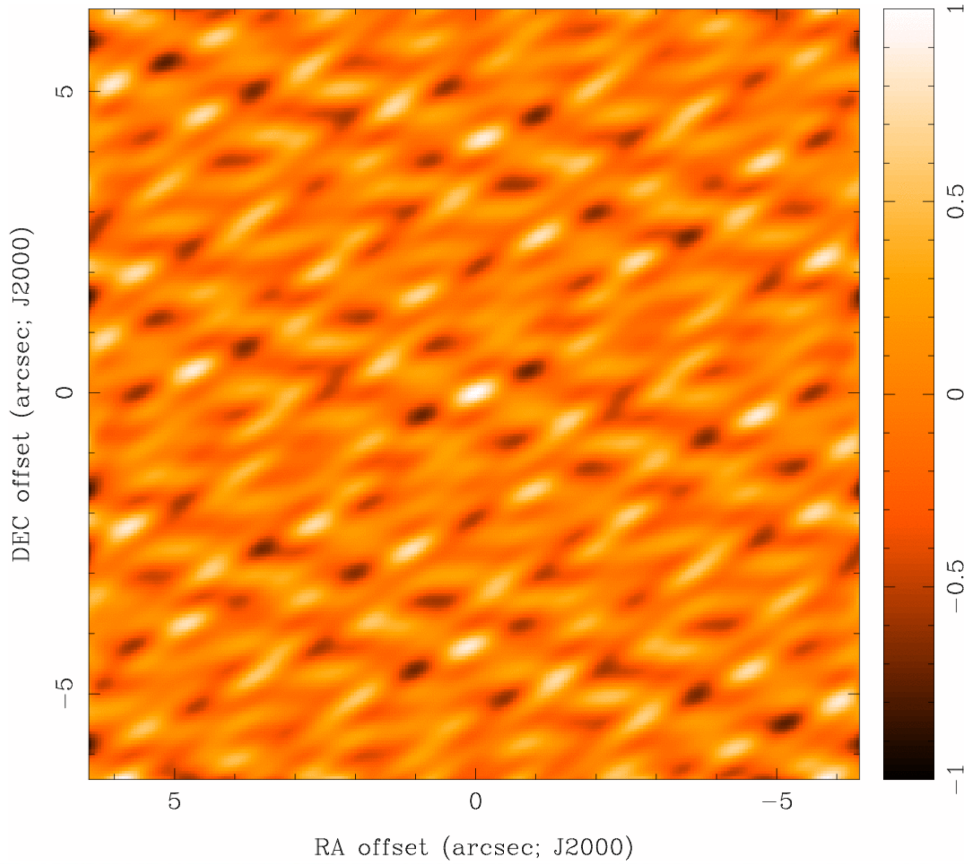


v (kλ)
400
200
0
−200
−400
−400
−200
0
200
400
u (kλ)
DEC offset (arcsec; J2000)
5
0
−5
5
0
−5
RA offset (arcsec; J2000)
1
0.5
0
−0.5
−1

5 Antennas

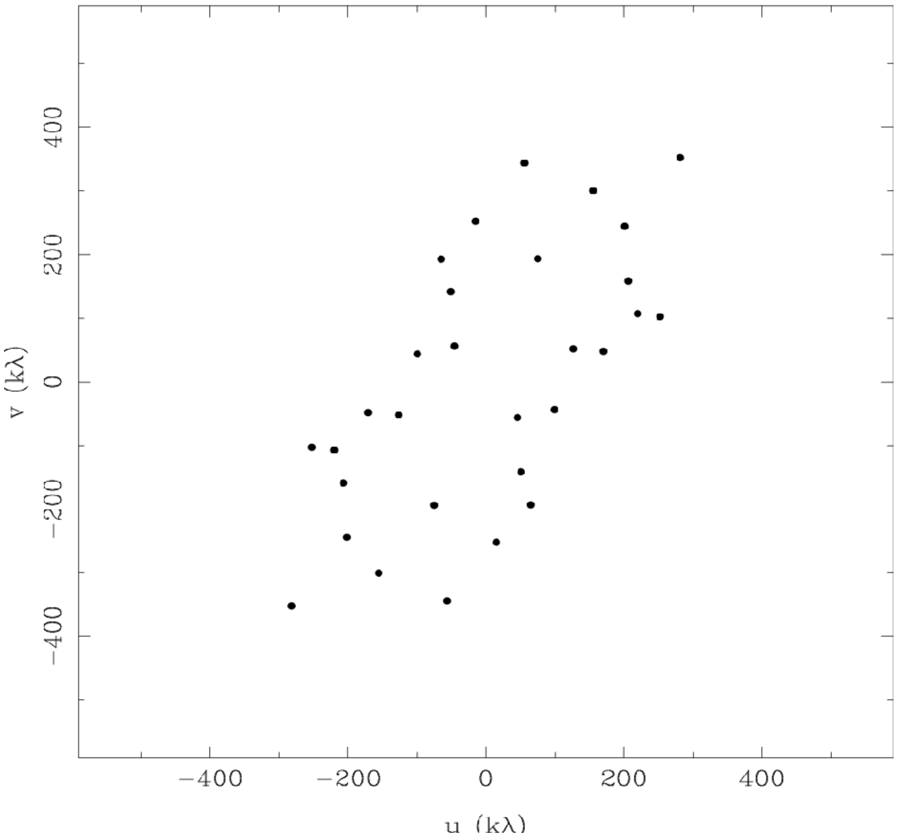


400
200
0
−200
−400
v (kλ)
−400
−200
0
200
400
u (kλ)

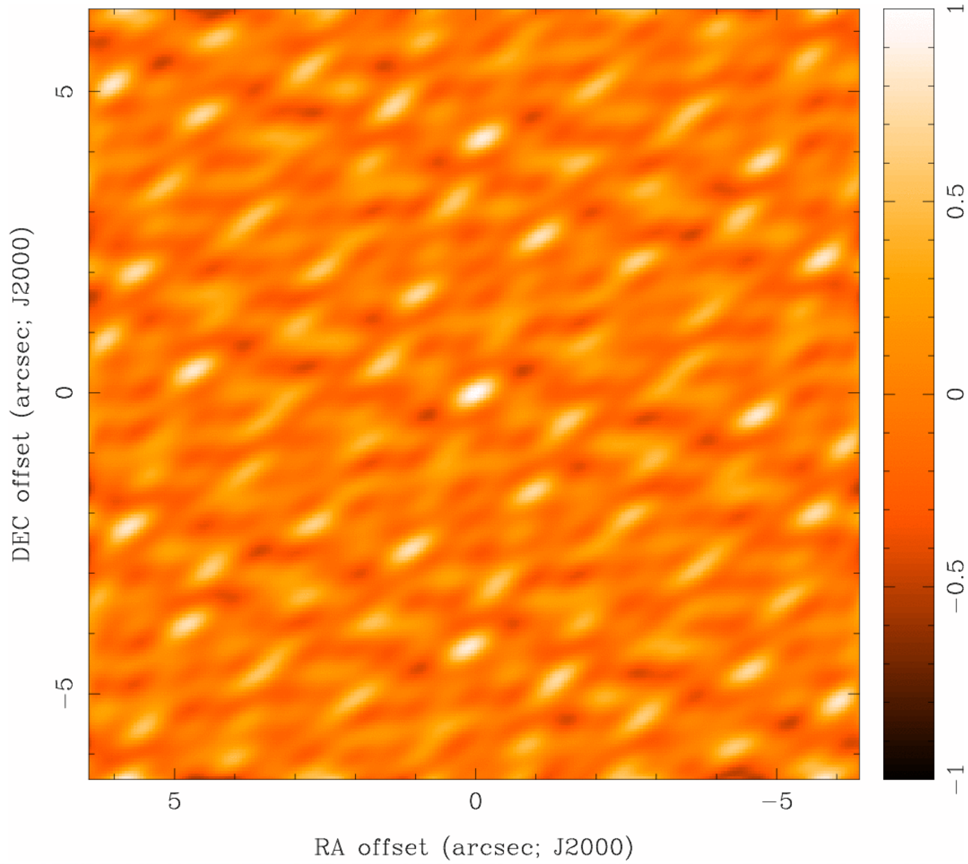


5
0
−5
DEC offset (arcsec; J2000)
5
0
−5
RA offset (arcsec; J2000)
1
0.5
0
−0.5
−1

6 Antennas

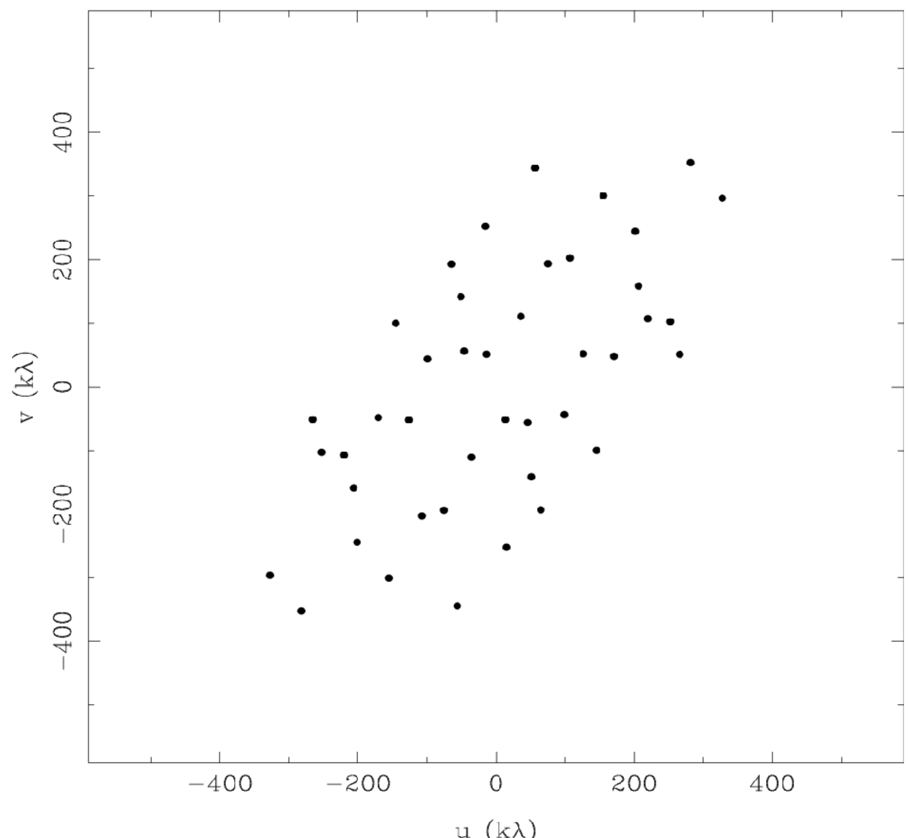


v (kλ)
400
200
0
−200
−400
−400
−200
0
200
400
u (kλ)

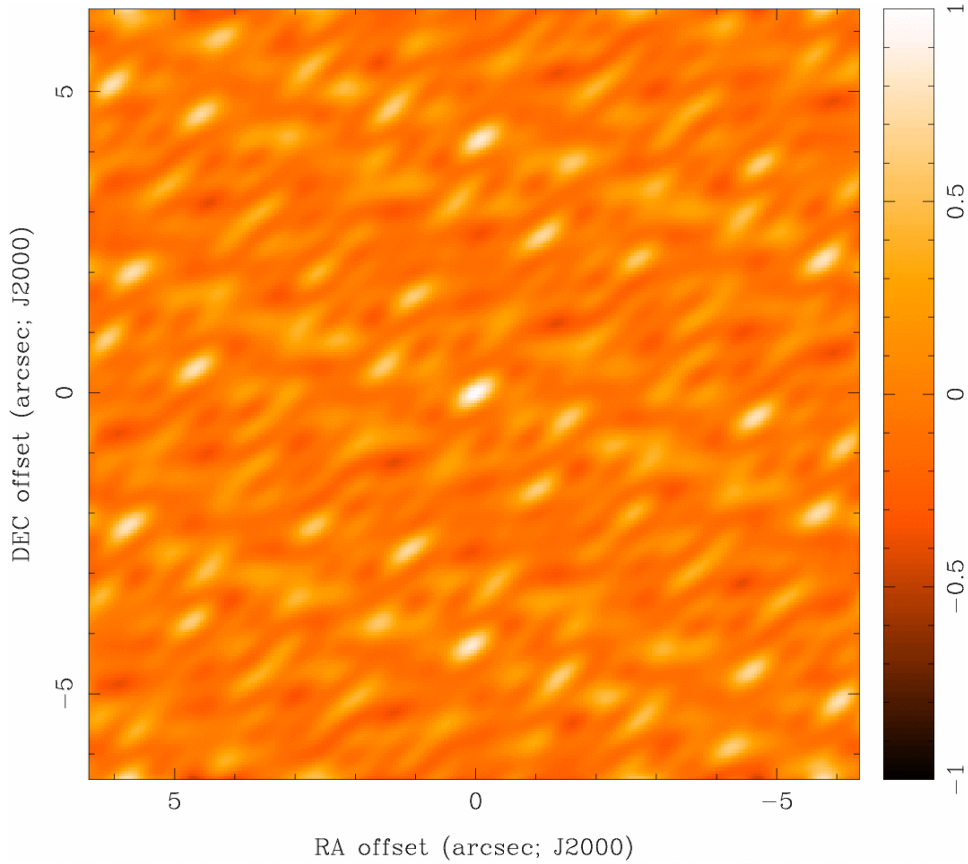


DEC offset (arcsec; J2000)
5
0
−5
5
0
−5
RA offset (arcsec; J2000)
1
0.5
0
−0.5
−1

7 Antennas

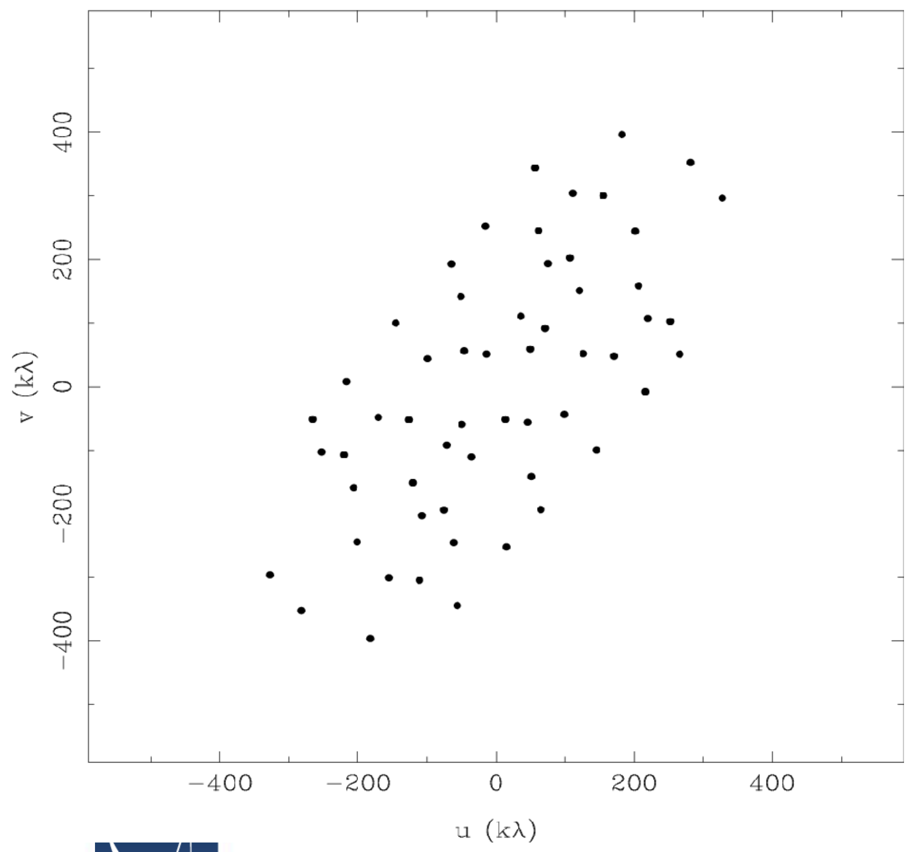


v (kλ)
u (kλ)
400
200
0
−200
−400

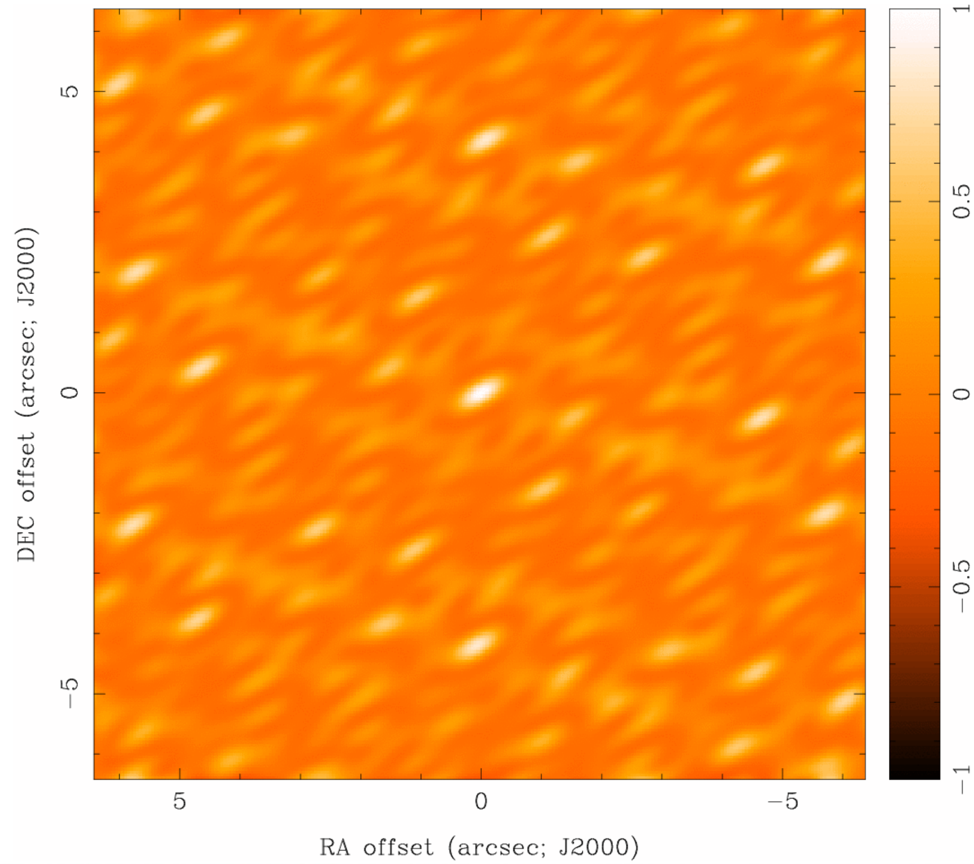


DEC offset (arcsec; J2000)
RA offset (arcsec; J2000)
5
0
−5
1
0.5
0
−0.5
−1

8 Antennas

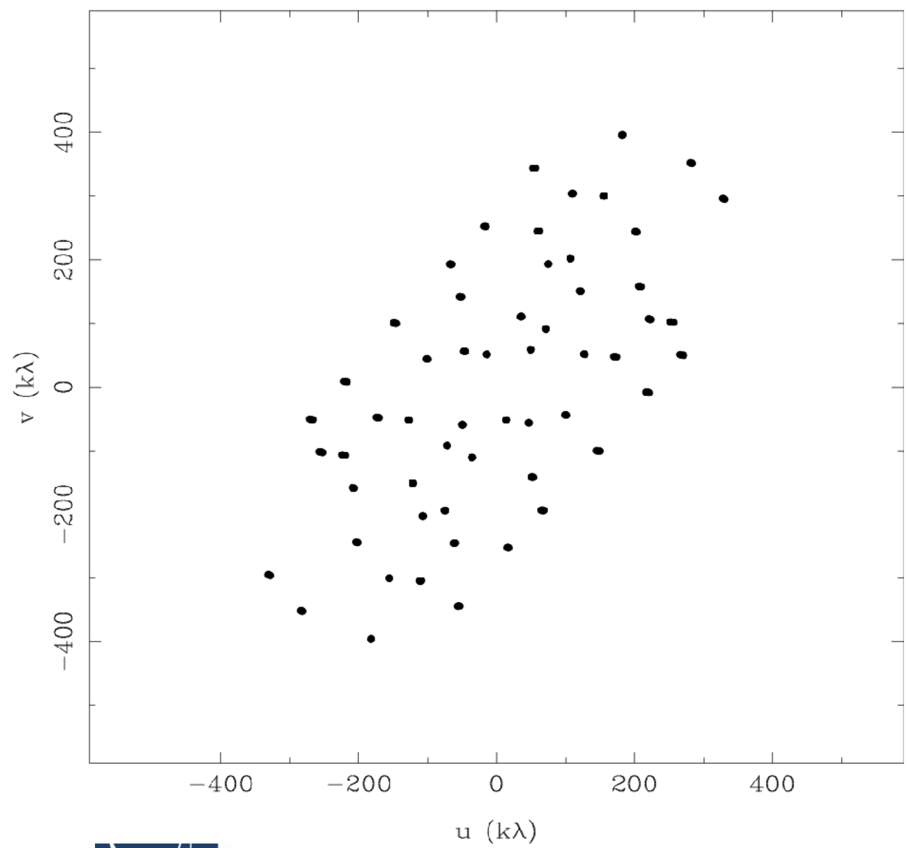


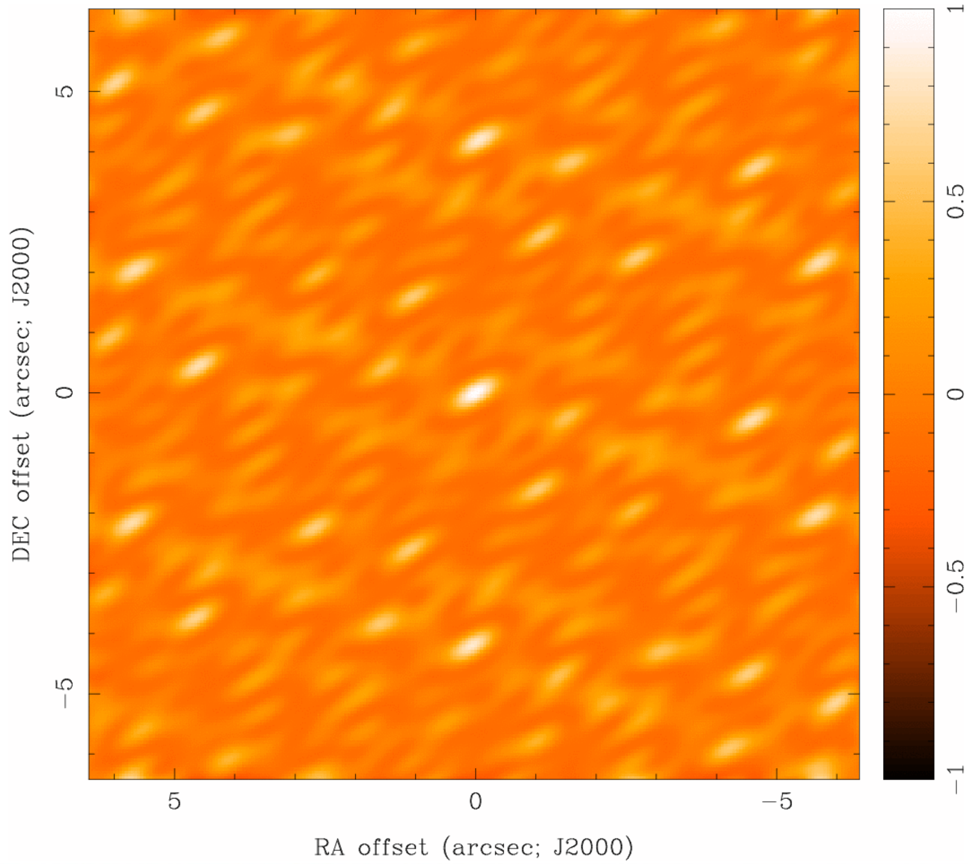
v (kλ)
400
200
0
−200
−400
−400
−200
0
200
400
u (kλ)



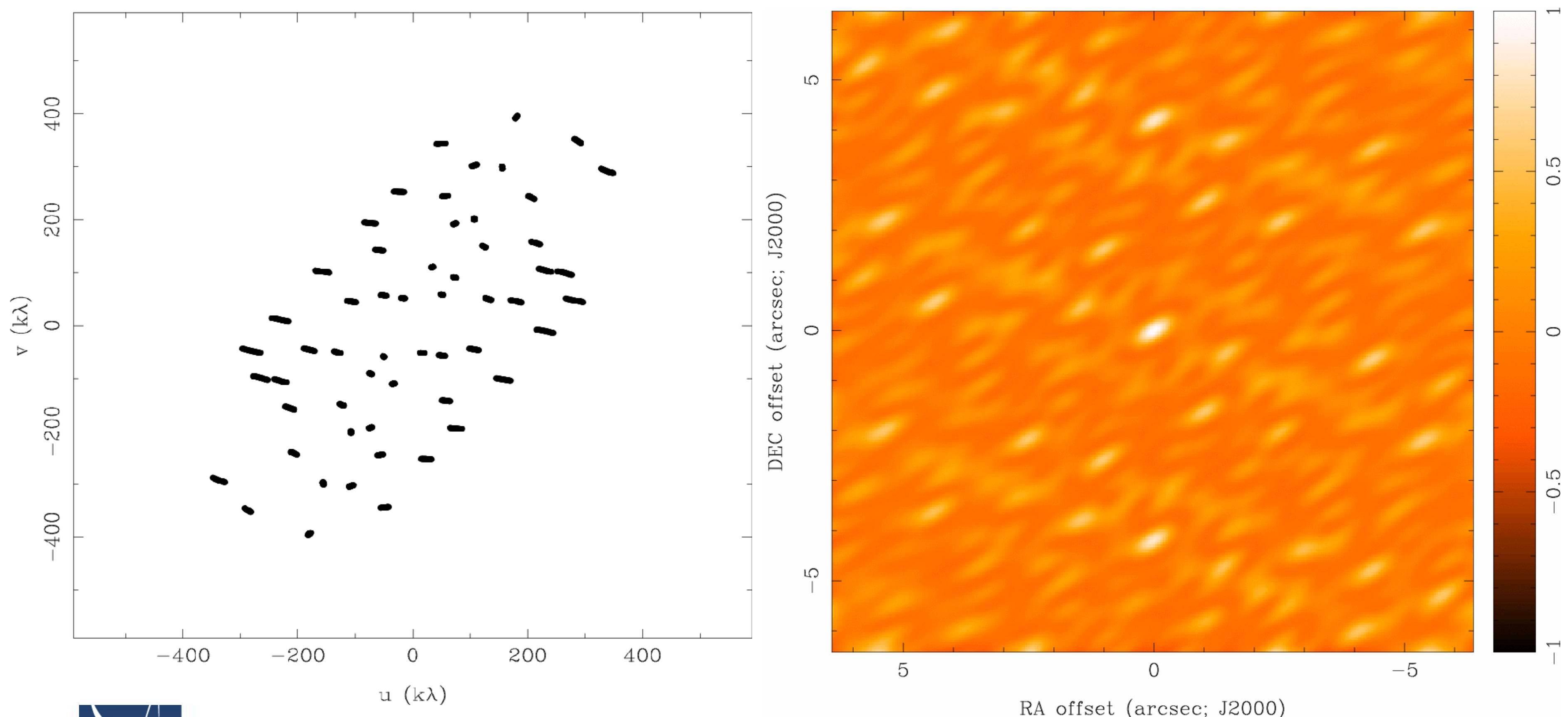
DEC offset (arcsec; J2000)
5
0
−5
5
0
−5
RA offset (arcsec; J2000)
1
0.5
0
−0.5
−1

8 Antennas x 6 Samples

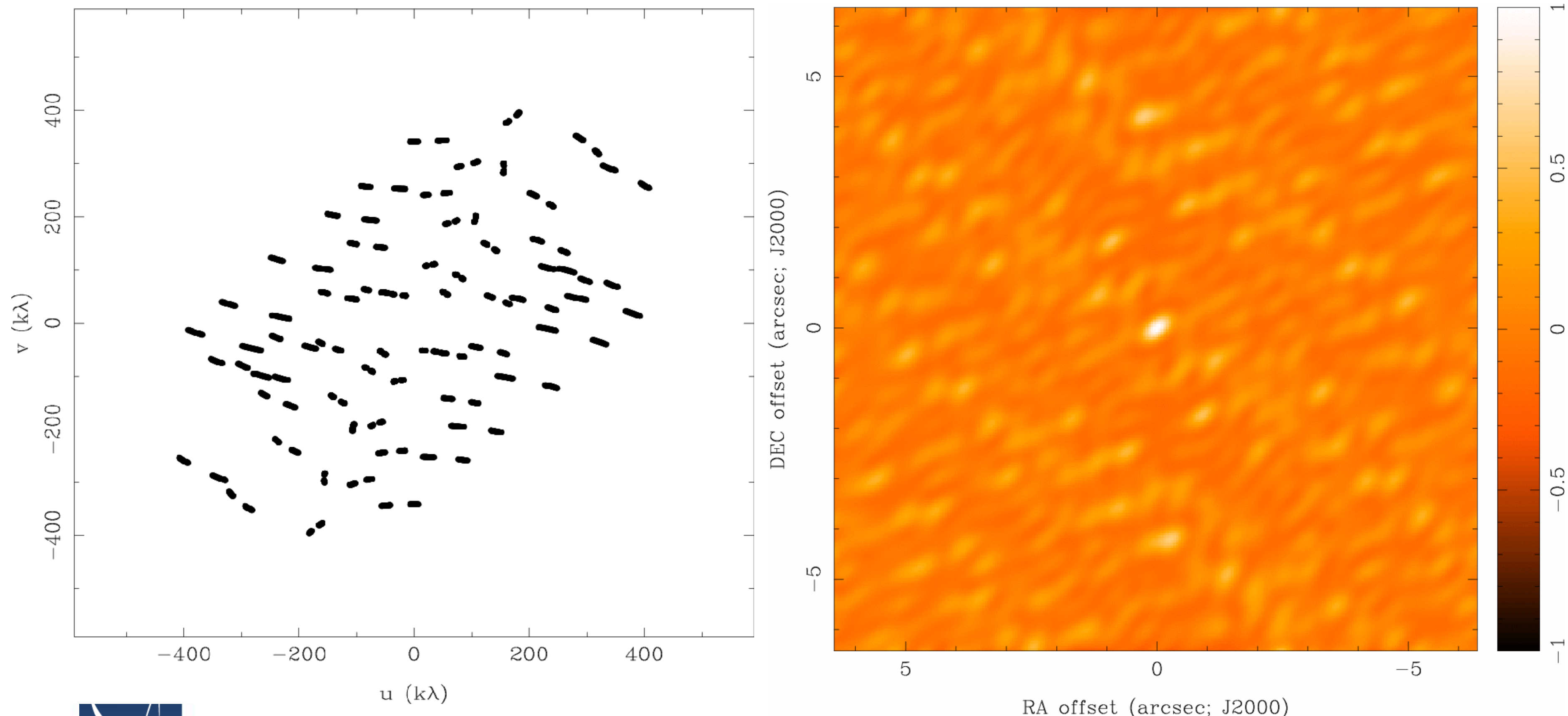




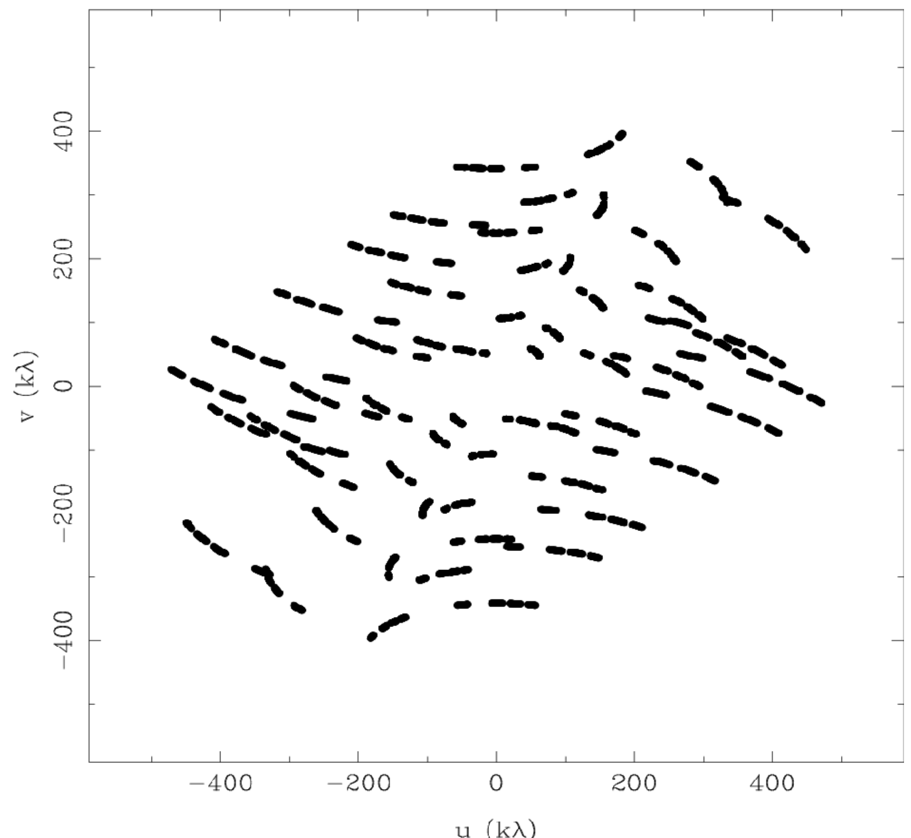
8 Antennas x 30 Samples

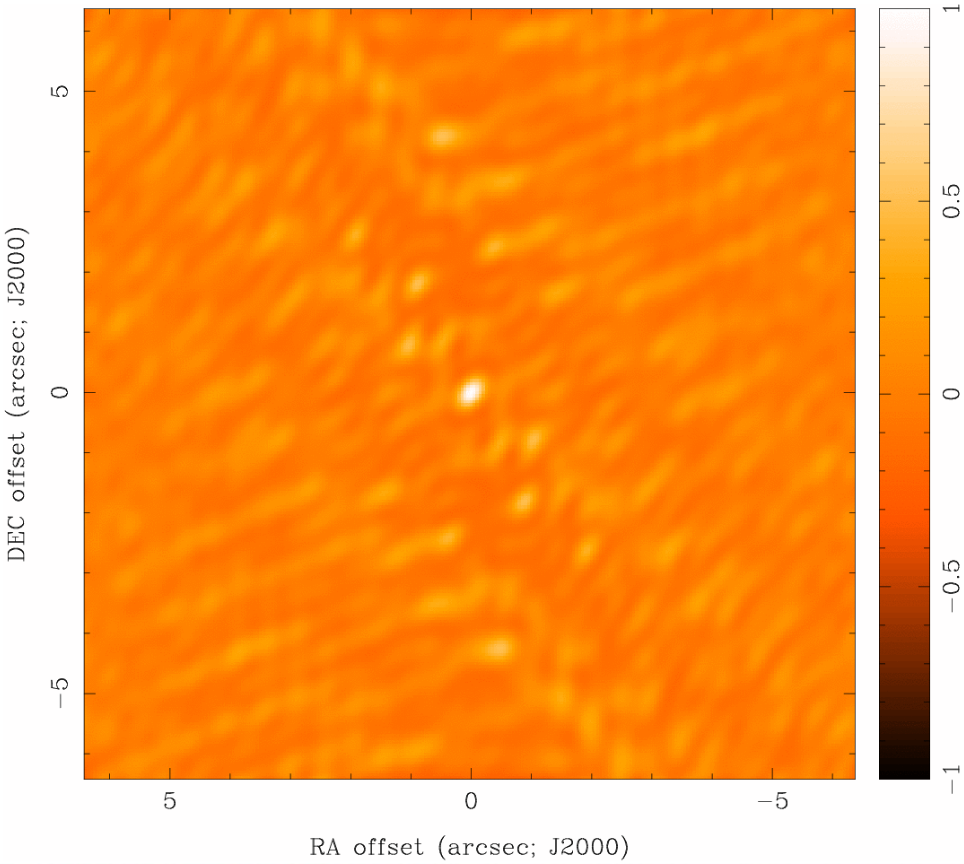


8 Antennas x 60 Samples

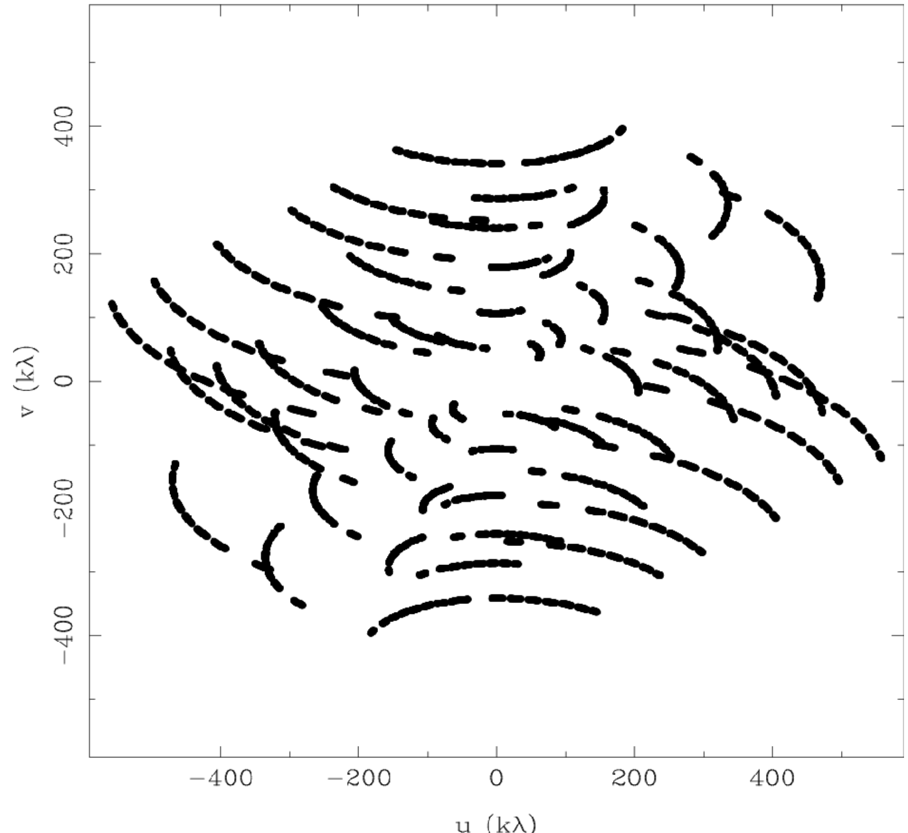


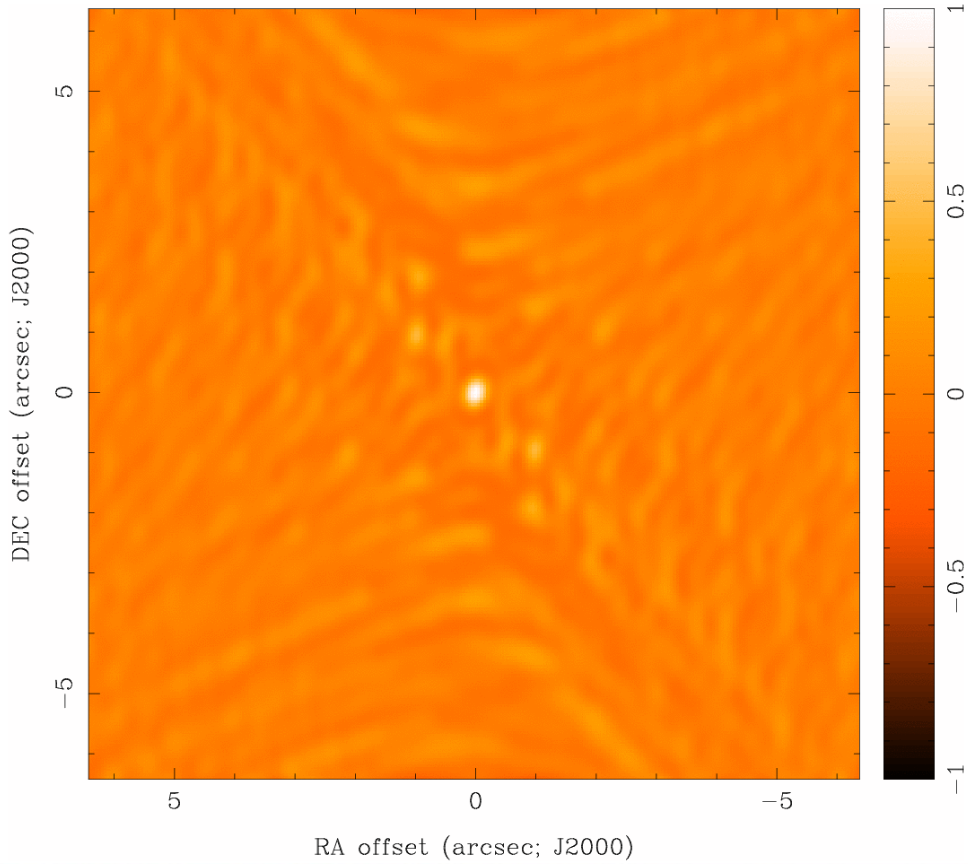
8 Antennas x 120 Samples



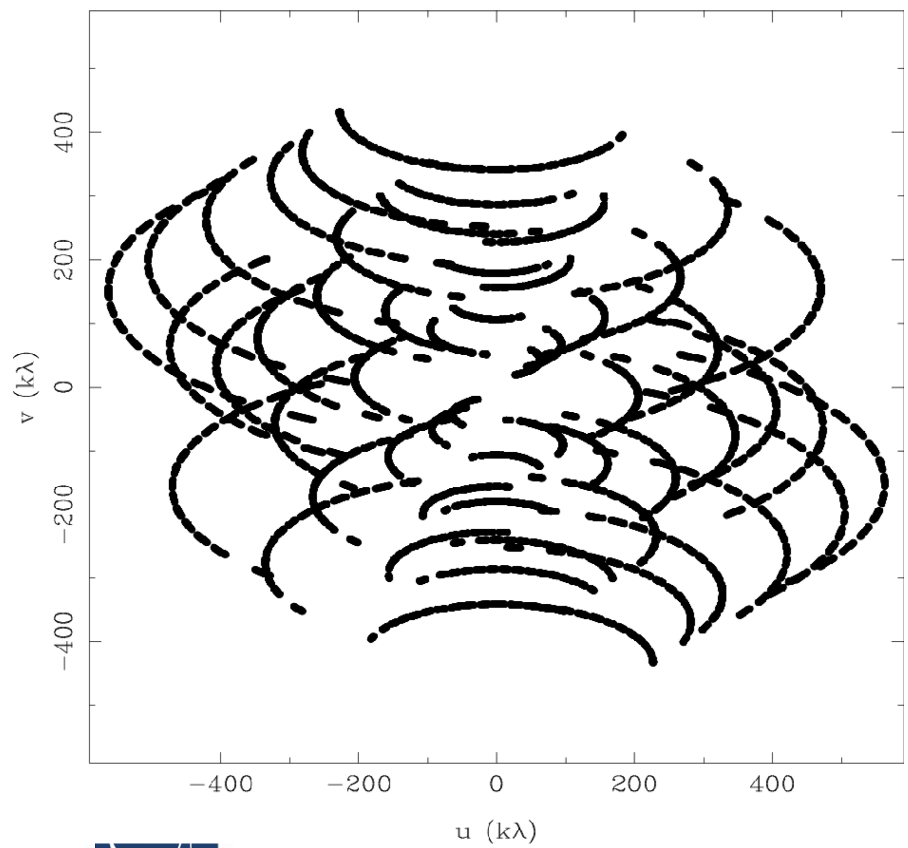


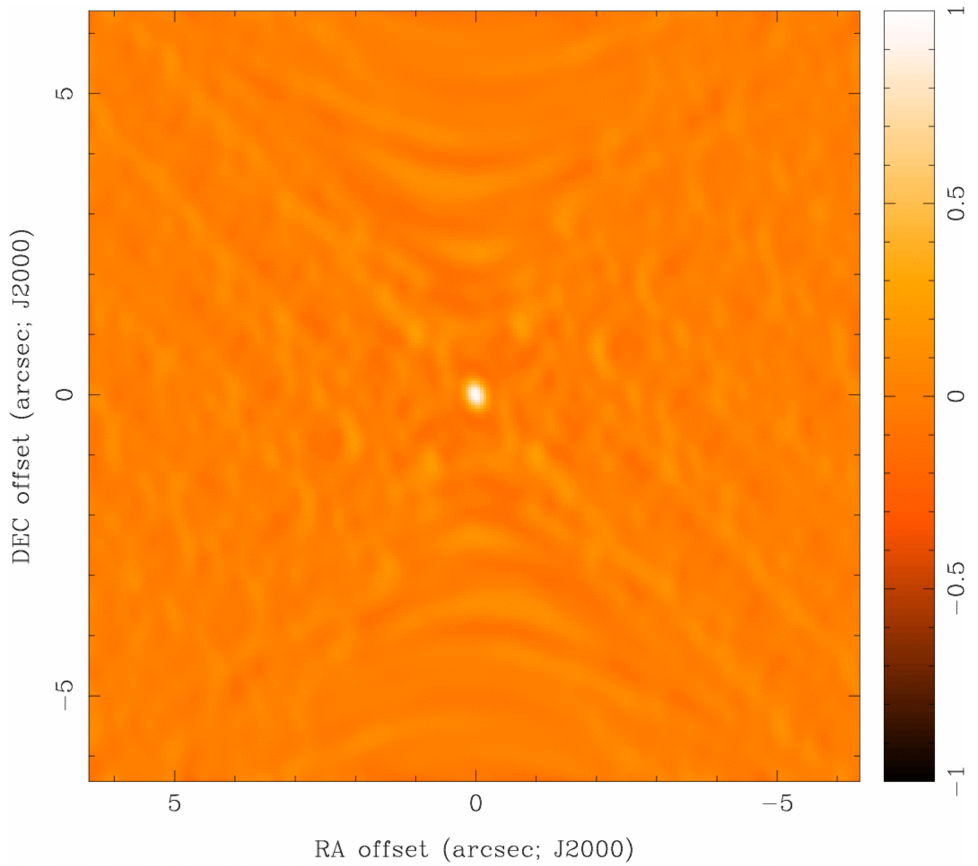
8 Antennas x 240 Samples



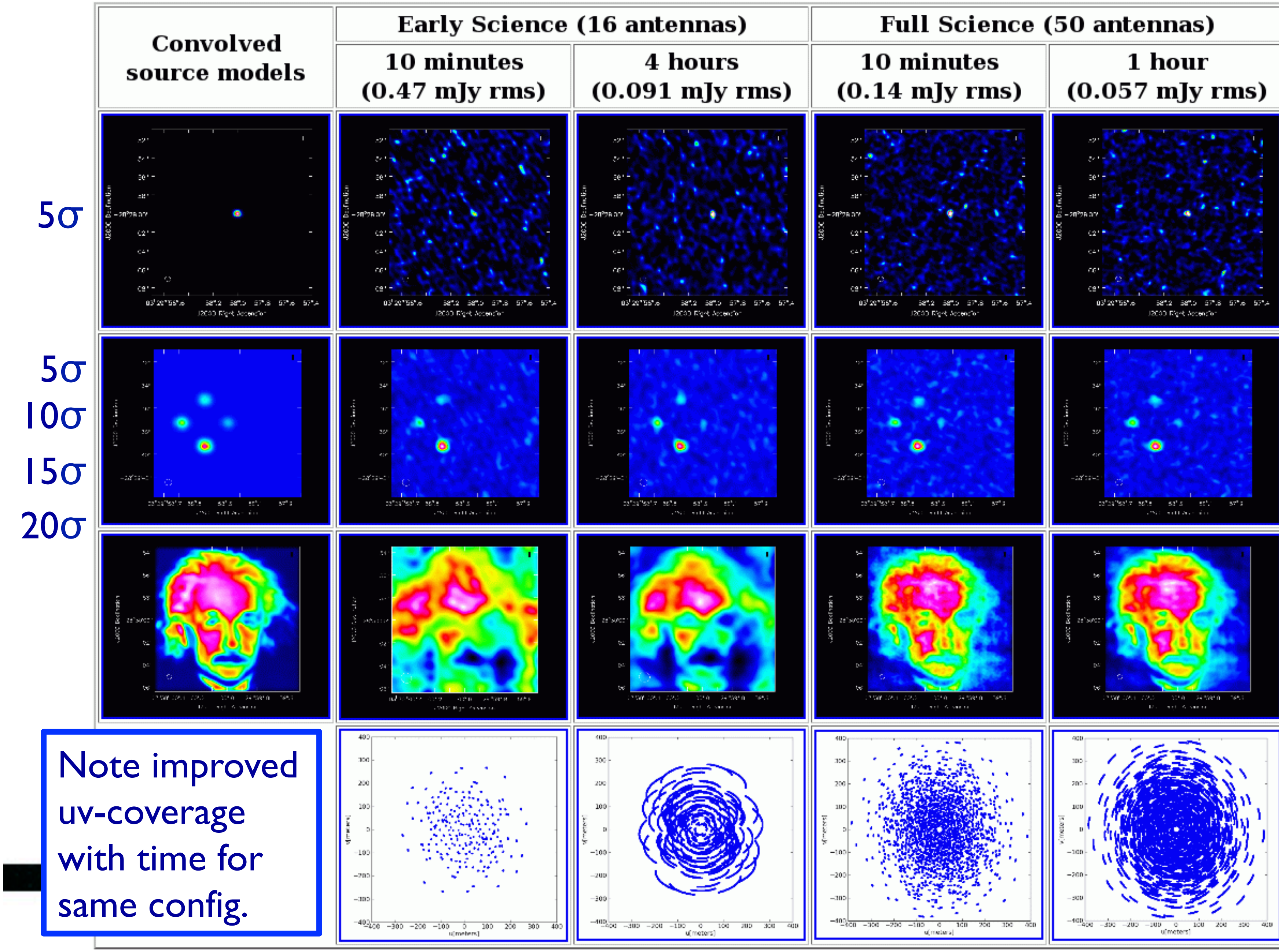


8 Antennas x 480 Samples





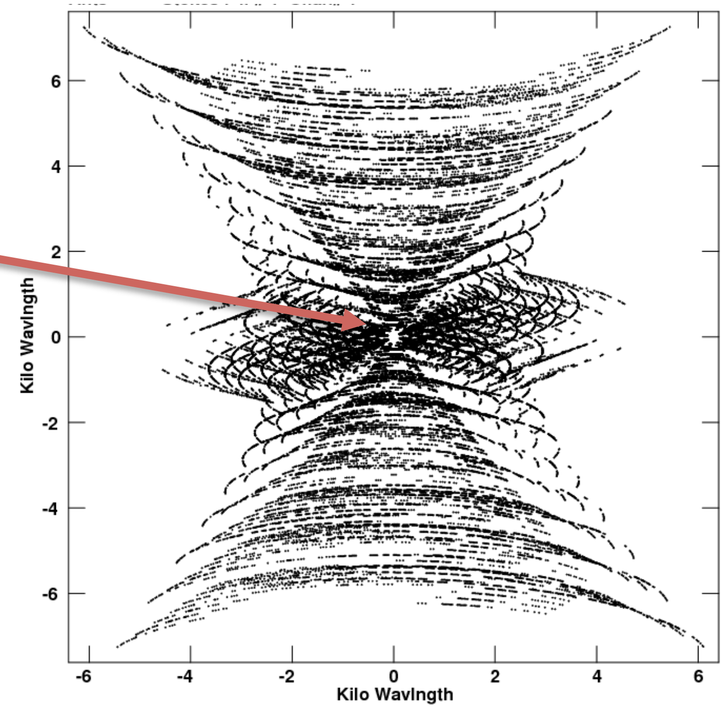
Effects of UV Coverage on Albert!



Note improved uv-coverage with time for same config.

The Problem with Interferometry!

Even in the most compact configuration there is always a CENTRAL HOLE in our uv-coverage



Shortest baseline → sets a maximum angular scale (MAS) that you can recover in the sky with your interferometer!

- **Smooth** structures larger than MAS begin to be resolved out.
- All flux on scales larger than λ/B_{min} (~2 x MAS) completely resolved out.

Maximum Angular Scale

Table A 2. Maximum Recoverable Scale[1] and Coarsest and Finest Angular Resolutions[1] for the Cycle 2 12-m Array configurations

Frequency (GHz)	Maximum Recoverable Scale[2,3,4] with no ACA (arcsec)	Coarsest allowed angular resolution[2,3,5] (arcsec)	Finest achievable angular resolution[2,3,6] (arcsec)
100	25	7.5	0.41
150	17	5.0	0.27
230	11	3.3	0.18
345	7.2	2.2	0.12
460	5.4	1.6	0.12
650	3.8	1.2	0.09

- **Smooth** structures larger than MAS begin to be resolved out.
- **All flux on scales larger than λ/B_{min} (~2 x MAS) completely resolved out.**

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

Maximum Angular Scale

Table A 3. Maximum Recoverable Scales for ACA 7-m observations

Frequency (GHz)	Maximum Recoverable Scale[1,2,3] with 7-m Array (arcsec)
100	42
150	28
230	18
345	12
460	9.1
650	6.4

- **Smooth** structures larger than MAS begin to be resolved out.
- **All flux on scales larger than λ/B_{min} (~2 x MAS) completely resolved out.**

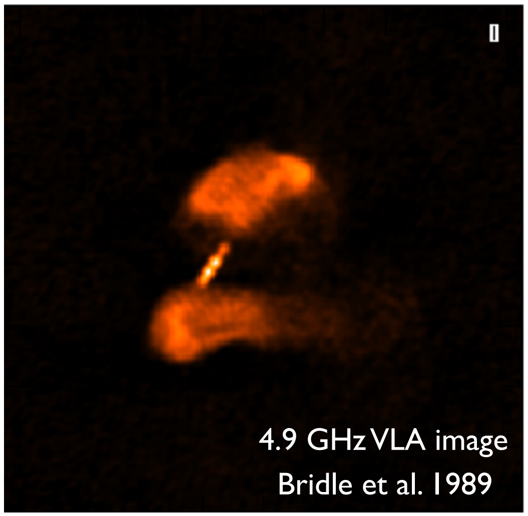
→ Need additional observations with a single-dish or a more compact array with smaller antennas

NRAO

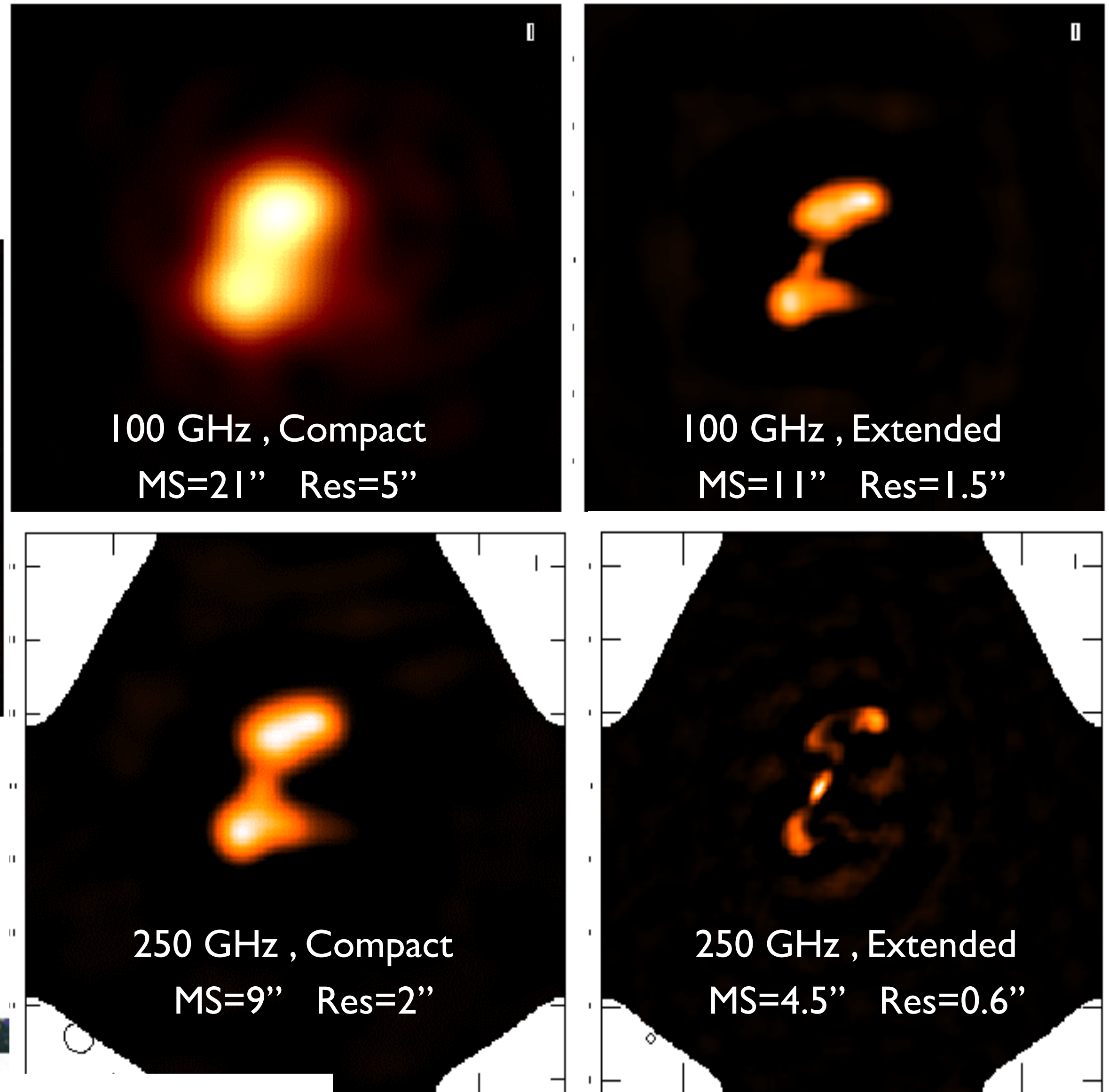
Effects of baselines & frequency on Imaging

Input Model:

3C288



Simulated Images (Dec=-30d, 6hr obs)

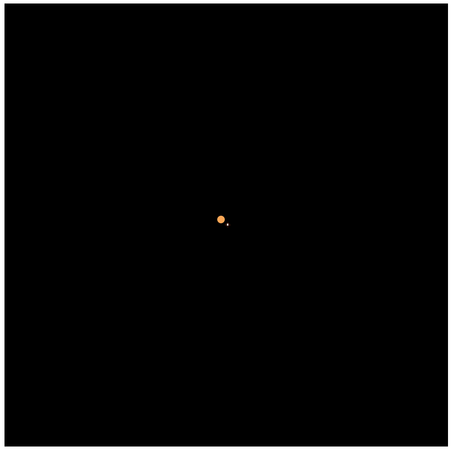


From ALMA Technical Handbook

Quick Reminder on 2D Fourier Transforms

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

δ Function



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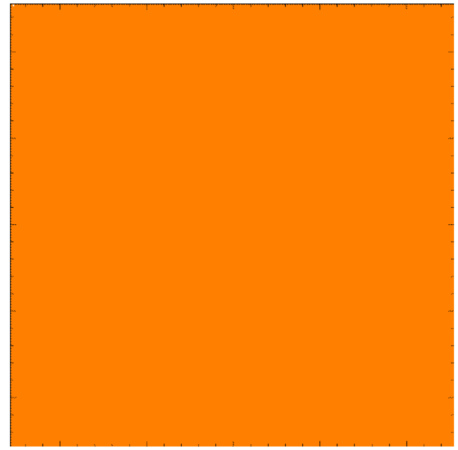
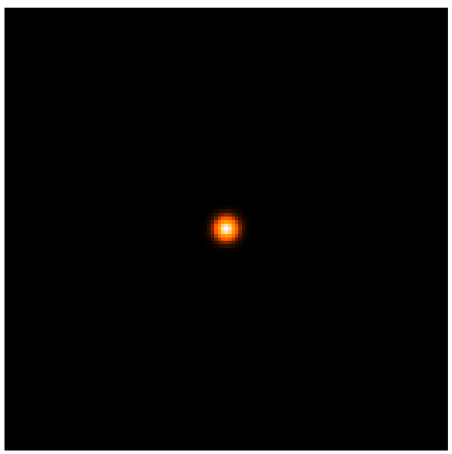
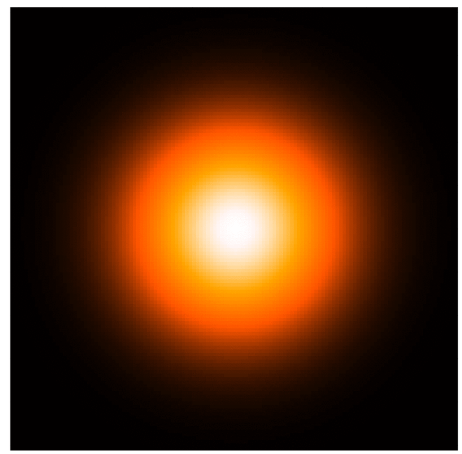


Constant

Gaussian



⇌



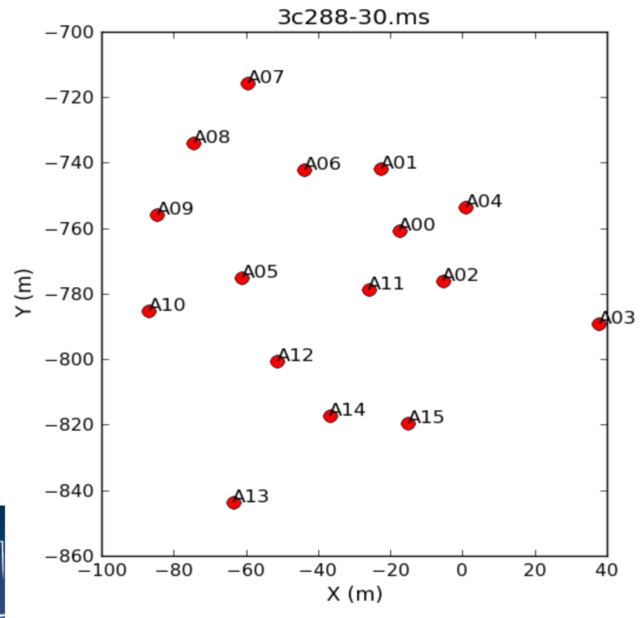
Gaussian

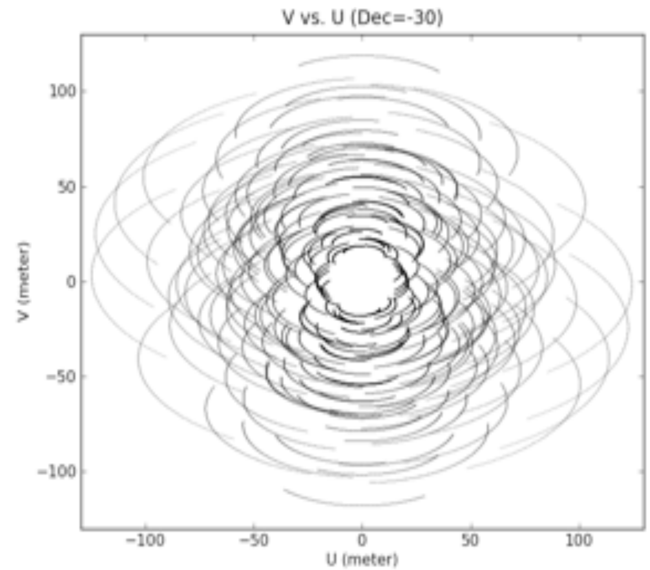
narrow features transform to wide features (and vice-versa)

(from Summer School lecture by D. Wilner)

Aperture Synthesis Imaging

- The Fourier transform of the array baseline configuration, projected onto the sky ("earth rotation aperture synthesis"), defines the spatial frequencies that the array is sensitive to
- Limited range of baseline lengths = Image with limited spatial frequencies
  – Spatial scales larger than the smallest baseline cannot be imaged
- More baselines, a wider range of baselines, and/or longer observations provide better imaging performance (higher image "fidelity")





Sampled Spatial Scales

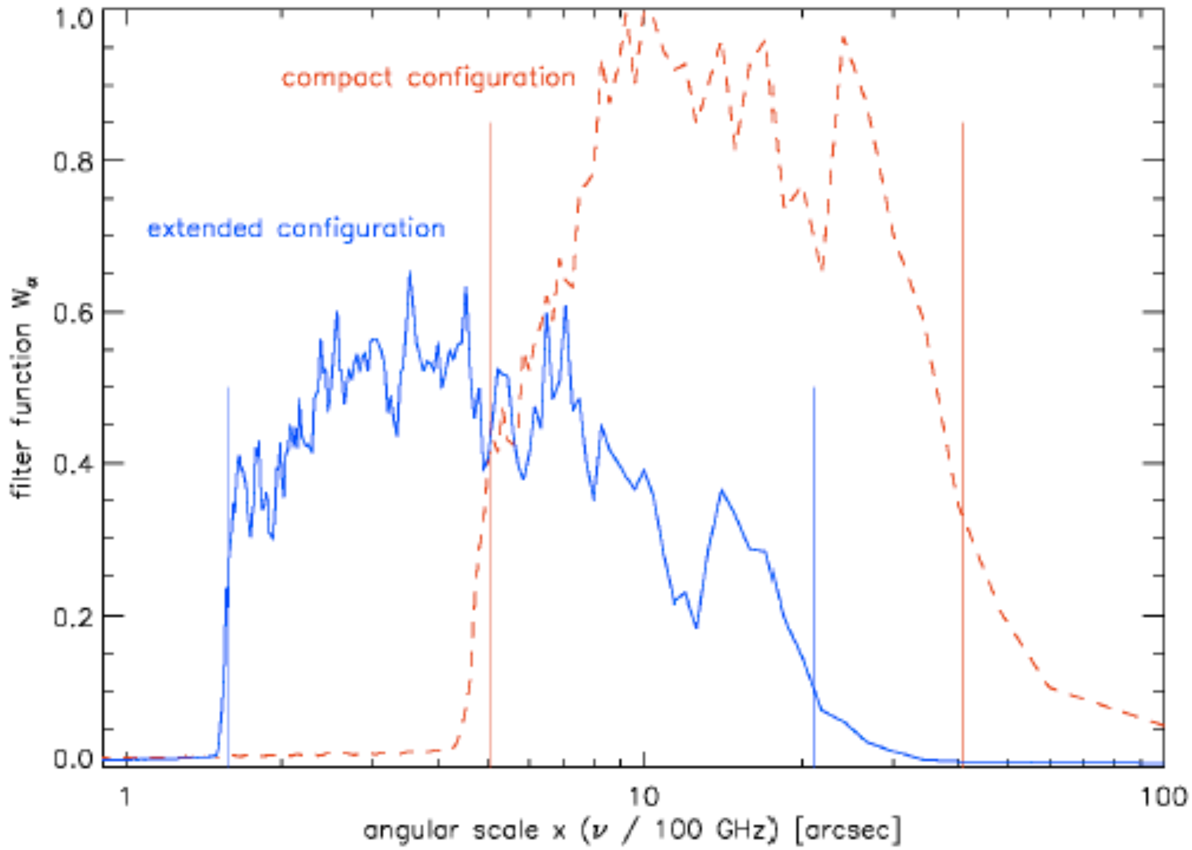
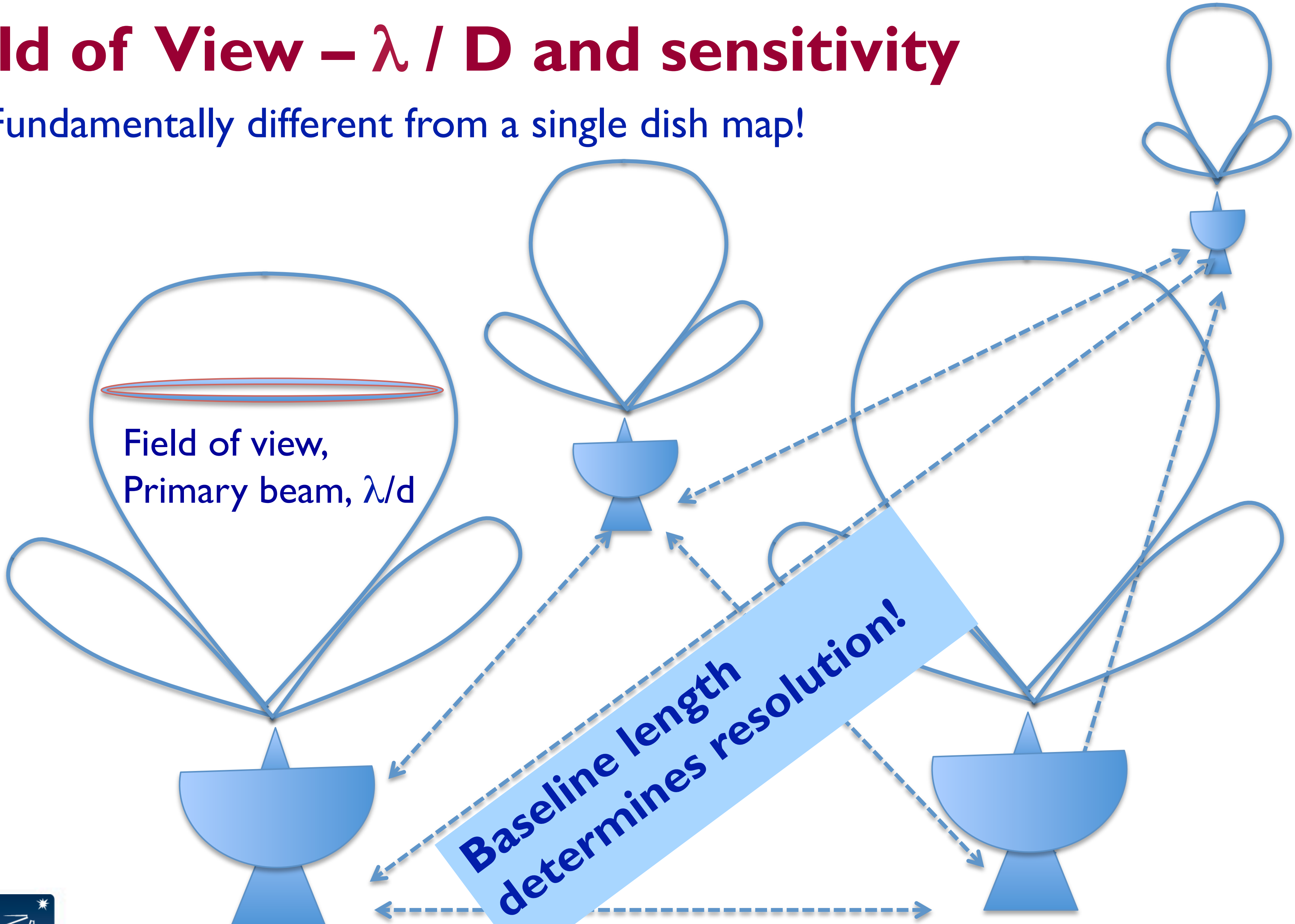


Figure 39. (top) Angular resolutions (FWHM of the synthezised beam at declination DEC = -40 deg) for the early science configurations. (bottom) Array sensitivity as function of angular scale for the Compact and Extended Cycle 0 configurations; normalized to 1 for the peak of the Compact Configuration. The angular scales decrease linearly with observing frequency as indicated on the axis label. The UV sampling results from a 6 hour observation of a source at DEC = -35 deg. The vertical lines are the equivalent angular scales on the minimum and maximum baselines per configuration.

Field of View – λ / D and sensitivity

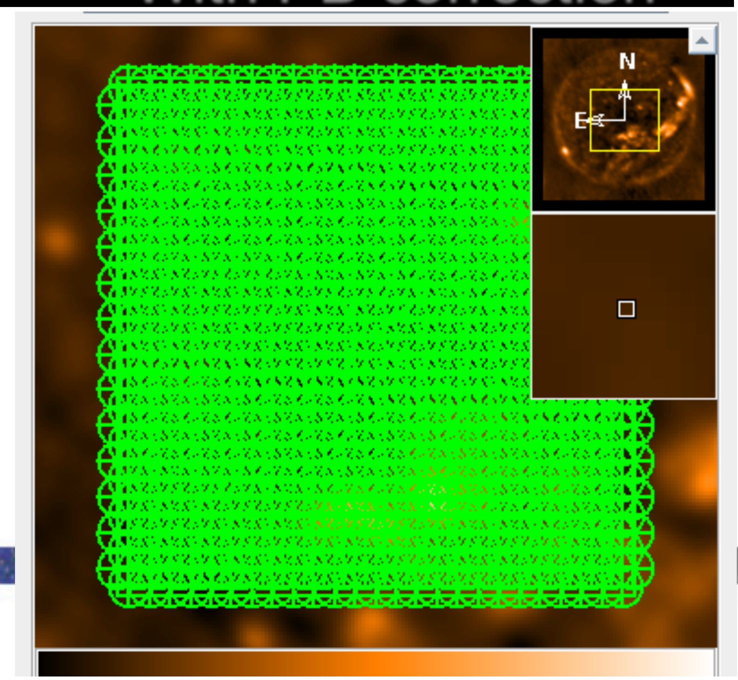
- Fundamentally different from a single dish map!



Field of View – λ / D and sensitivity

- Fundamentally different from a single dish map!

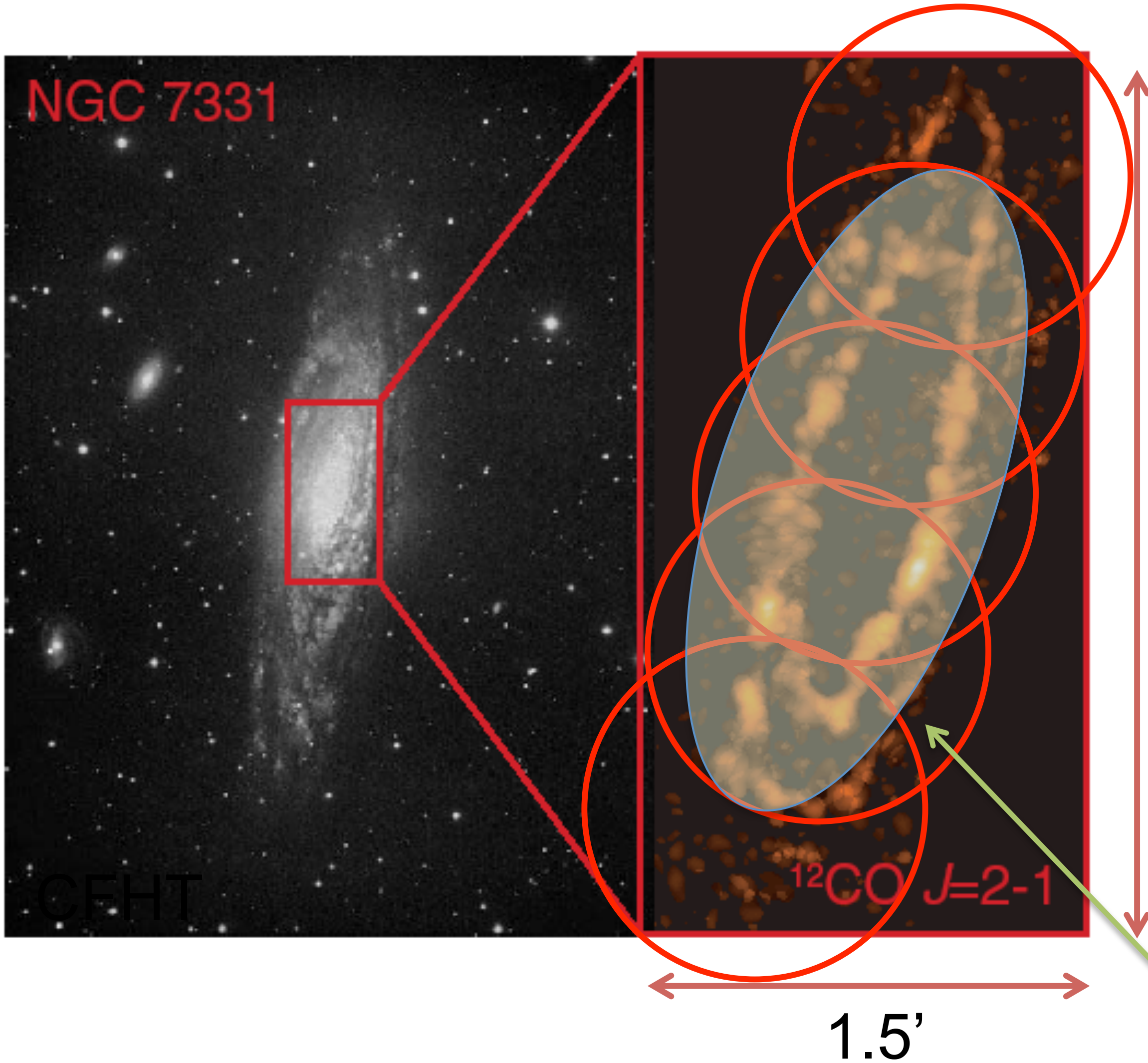
(SENSITIVITY VARIES w/ DISTANCE FROM CENTER OF THE BEAM!!)



- Whole Sun ~7000 12-m 100-GHz mosaic pointings

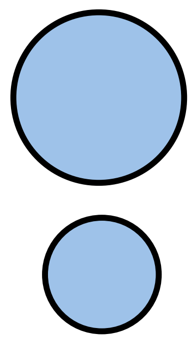
NRAO

Large Fields Require Mosaicking



Example: SMA 1.3 mm observations: 5 pointings

- Primary beam ~1’
- Resolution ~3”



Uniform Sensitivity Area

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

Calculate Integration Time | Calculate Sensitivity

NRAO

Introduction to Sensitivity Calculation

- Calculate sensitivity based on an integration time
  - And vice versa
  - Standard equations used
  - Interferometers (ALMA and ACA) and Single Dish
- Used for
  - Planning purposes
  - Estimating time required for your project
- Accessible via
  - The ALMA Observing Tool (OT)
  - ALMA Science Portal (www.almascience.org)

Courtesy A. Biggs, ESO

Interferometric Sensitivity equation

Antenna Efficiency
(includes rms surface accuracy
and area of telescope)

System temperature
(measures receiver performance
and effect of atmosphere)

$$\sigma = \frac{\rho T_{\mathrm{sys}}}{\eta_{\mathrm{c}} \sqrt{N(N-1)\, \Delta \nu \, t_{\mathrm{int}}}}$$

Correlator efficiency (0.88)

Time on source

Number of baselines

Effective Bandwidth
(includes number of polarizations)

Courtesy A. Biggs, ESO

Interferometric equation

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(includes rms surface accuracy
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Courtesy A. Biggs, ESO

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(includes number of polarizations)

Courtesy A. Biggs, ESO

Interferometric equation

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System temperature
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$$\sigma = \frac{\rho T_{\rm sys}}{\eta_{\rm c}\sqrt{N(N-1)\,\Delta\nu\, t_{\rm int}}}$$

Correlator efficiency (0.88)

Time on source

Number of baselines

Effective Bandwidth
(includes number of polarizations)

Courtesy A. Biggs, ESO

Sensitivity and ALMA

High & Dry site, near quantum limit Rx

Efficient antennas < 20μm surface rms

$$\sigma = \frac{\rho T_{\mathrm{sys}}}{\eta_{\mathrm{c}} \sqrt{N(N-1)\,\Delta\nu\, t_{\mathrm{int}}}}$$

Efficient correlator, 50 antennas, wide bandwidth

Courtesy A. Biggs, ESO

System Temperature

- System noise (power) is expressed as an equivalent noise temperature:

$$P_\nu = kT \qquad \text{(Nyquist formula)}$$

- Contributions to T_{sys} come from
  - The receivers themselves
  - The sky (atmosphere + CMB)
  - Ground spillover

Courtesy A. Biggs, ESO

Receiver temperatures

ALMA Band	T_{rx} (K)	Origin	Cycle 0?
1	17	Specification	
2	30	Specification	
3	45 (37)	Actual (spec)	☑
4	51	Specification	
5	65	Specification	
6	55 (83)	Actual (spec)	☑
7	75 (147)	Actual (spec)	☑
8	196	Specification	
9	110 (175)	Actual (spec)	☑
10	230	Specification	

"Actual" numbers are conservative, representative figures for the entire band

Courtesy A. Biggs, ESO

Sky temperature

- Atmosphere is very annoying
  - Attenuates source signal
  - Emits proportionally to the attenuated signal

$$T_{\mathrm{sky}} \approx 273\,\mathrm{K}\,(1 - e^{-\tau A})$$

τ = opacity
A = airmass

- Attenuation varies strongly with frequency
  - Generally increases with frequency
  - Depends on weather conditions (amount of water vapour)
  - Also depends on source elevation (airmass)
- ASC uses rigorous atmospheric models (ATM code)

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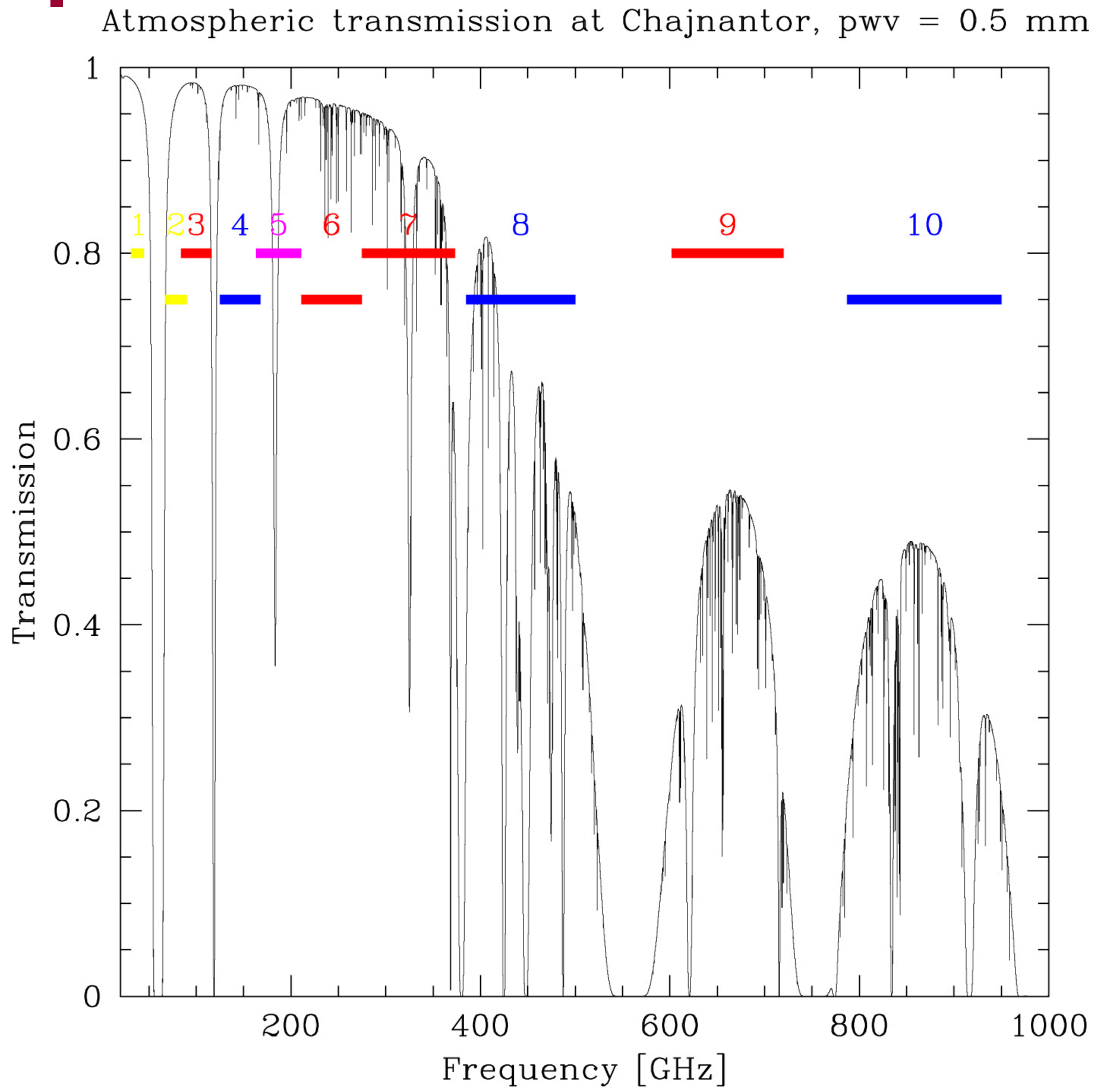
Courtesy A. Biggs, ESO

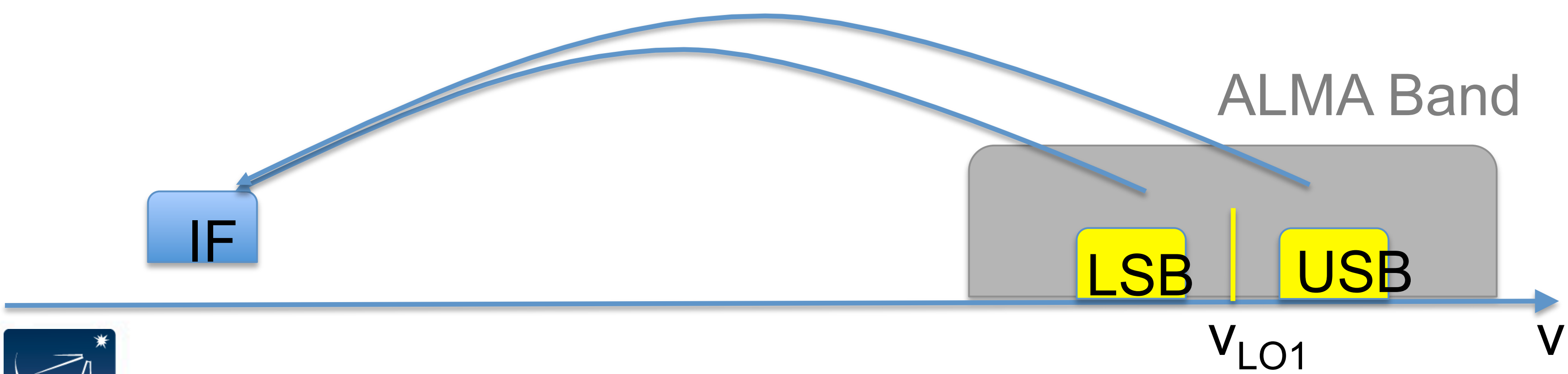
Atmospheric Transmission



Courtesy A. Biggs, ESO

Effect of Sidebands

- Radio astronomy receivers have two sidebands
  - Atmosphere contributes noise in both
- ALMA receivers treat the sidebands differently
  - Bands 3-8 separate the signal and noise in the receiver
  - Bands 9 and 10 do not
- Noise in bands 9 and 10 is effectively doubled
  - This factor recently added to ASC!



Courtesy A. Biggs, ESO

System Temperature

Contribution from "other" sideband (NEW! Zero apart from bands 9 and 10 - g=1)

Receiver temperature

Sky temperature (proportional to absorption by atmosphere)

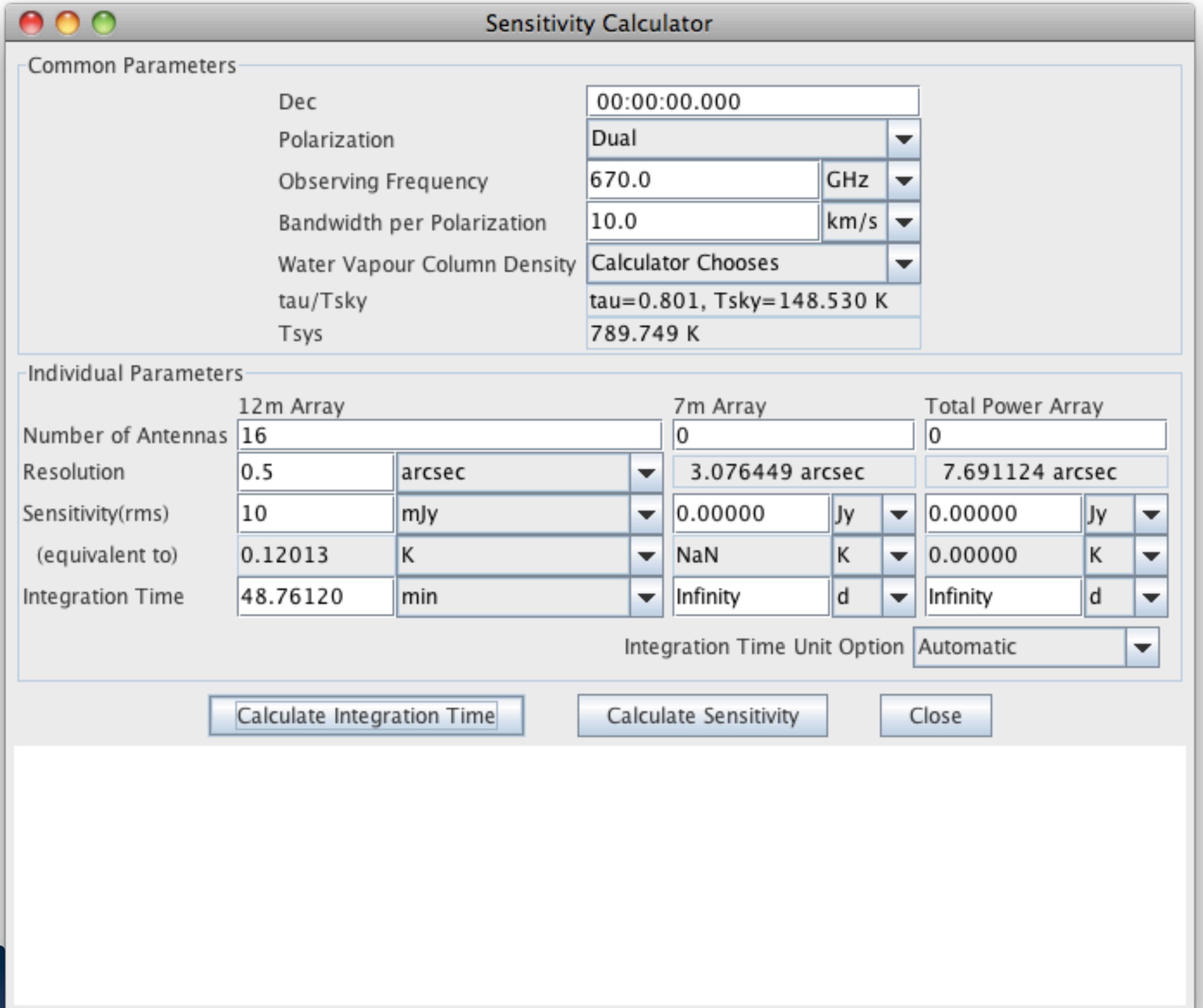
$$T_{\mathrm{sys}} = \frac{1+g}{\eta_{\mathrm{eff}} e^{-\tau AM}} \left[T_{\mathrm{rx}} + \eta_{\mathrm{eff}} T_{\mathrm{sky}} + (1-\eta_{\mathrm{eff}}) T_{\mathrm{amb}} \right]$$

Atmospheric transmission

Ground temperature ("spillover")

Courtesy A. Biggs, ESO

ALMA Sensitivity Calculator



Courtesy A. Biggs, ESO

ALMA Sensitivity Calculator Inputs

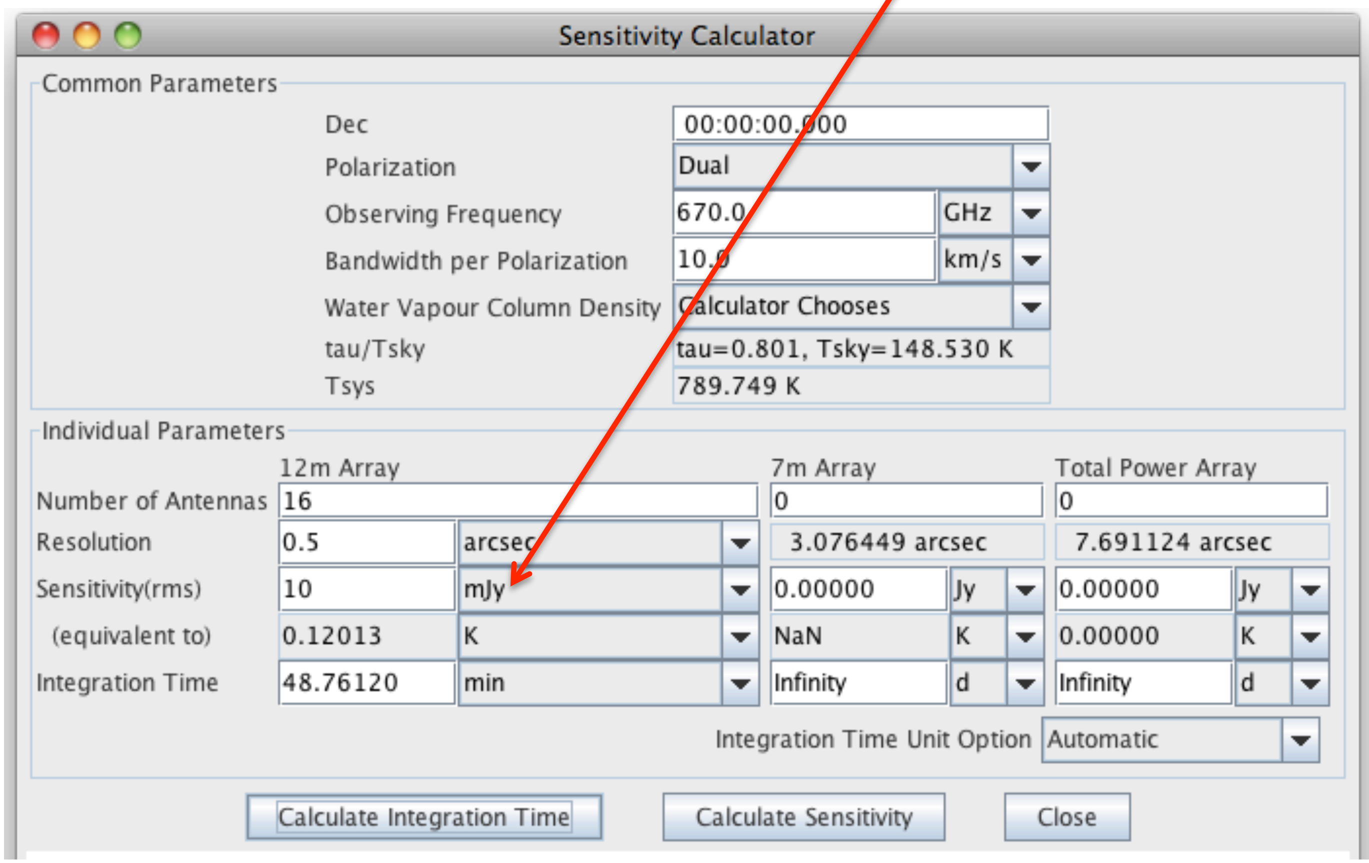
https://almascience.nrao.edu/call-for-proposals/sensitivity-calculator

- Source Declination (airmass - assume source at transit)
- Frequency (rx temperature, atmospheric attenuation)
- Bandwidth per polarization
  - In frequency or velocity units
- Water vapour
  - ASC will choose sensible defaults based on frequency
- Number of antennas
  - Defaults to Early Science values
- Angular resolution
  - Required for sensitivities in surface brightness units (K)

ALMA Sensitivity Calculator

IMPORTANT:

mJy PER BEAM!

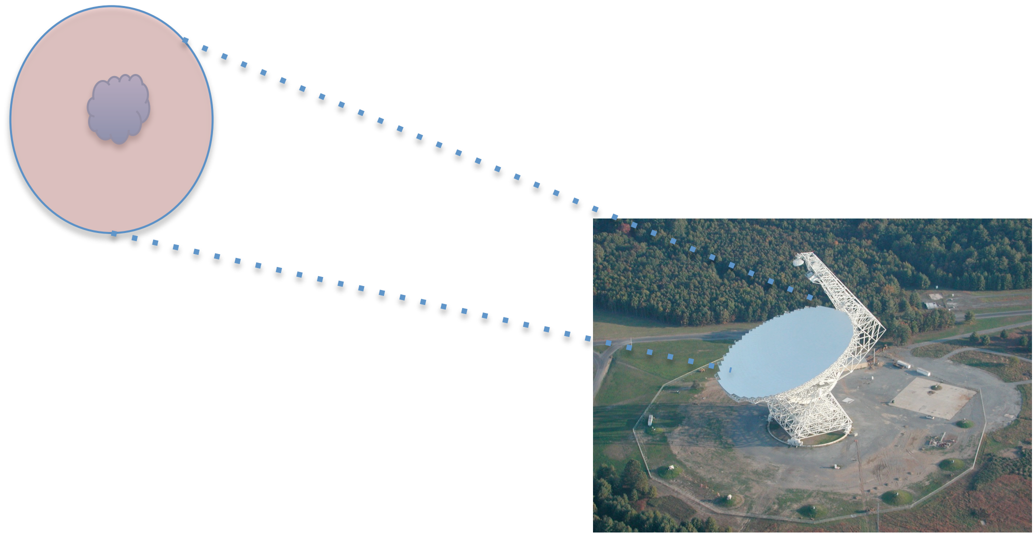


Courtesy A. Biggs, ESO

Point Source vs. Extended Source

1. Suppose you have an unresolved source measured to have a flux of 10 Jy observed with GBT (6”)

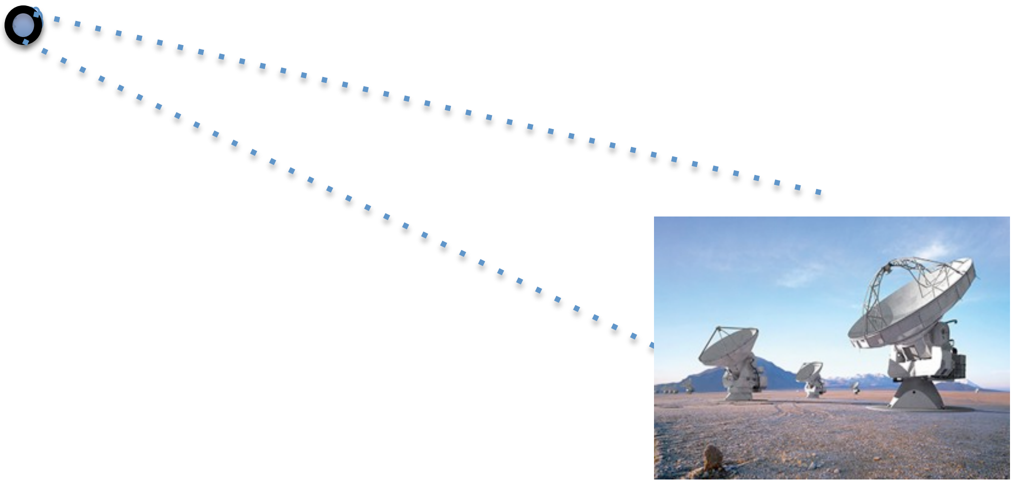
2. You seek to observe it at a resolution of 1” – what sensitivity should you request for a S/N ~10?



Point Source vs. Extended Source

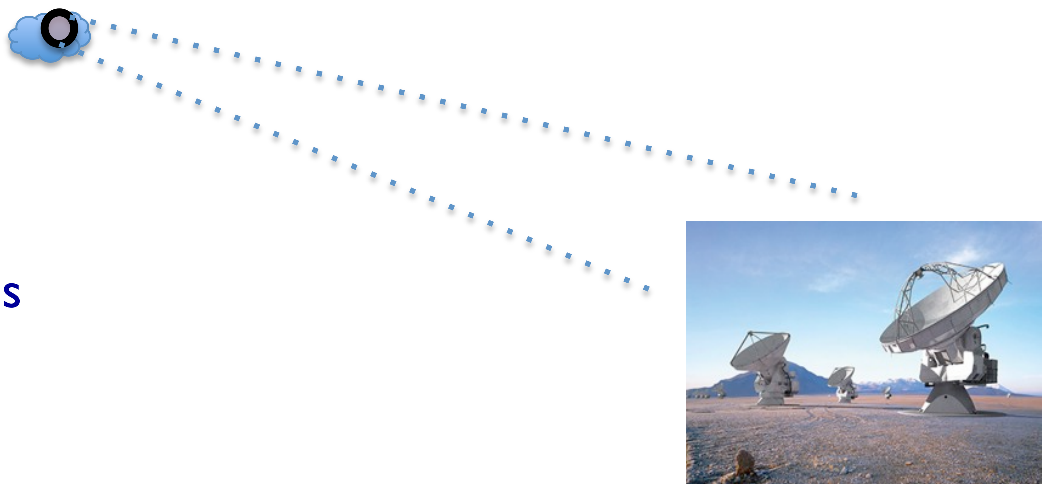
1. If the source is smaller than 1" then signal is still expected to be 10 Jy in the beam

2. To get a S/N ~10 you would request a sensitivity of 1 Jy (per beam ← implicit)



Point Source vs. Extended Source

1. If the source is resolved at 1"
   then expected signal is NO
   LONGER 10 Jy



2. You must make an educated guess at its surface brightness and request the appropriate mJy (/ beam) ← implicit!

3. Some folks measure the average surface brightness and use that to estimate the expected signal.

Sensitivity and Brightness Temperature

- Brightness temperature is a unit used more commonly in Galactic observations and it takes into account the beam size

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 formulae 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

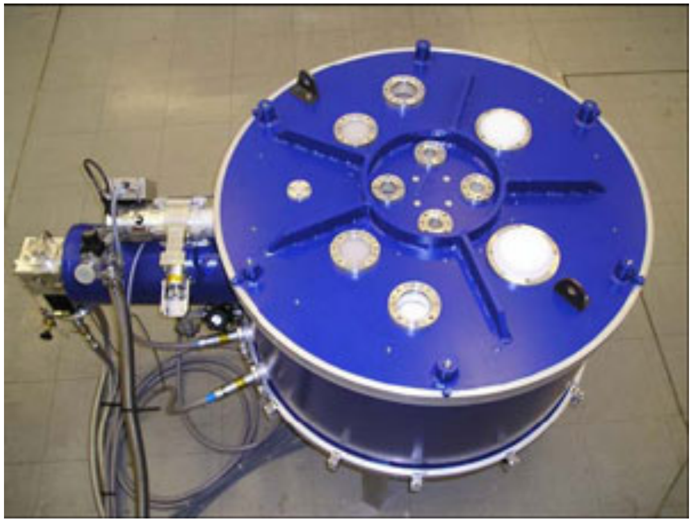
→ **It is harder to detect extended line emission at high angular resolution !**

ALMA 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

3mm **1.3** **0.87** **0.7** **0.45**

- 5 of 8 bands are available for Cycle 1, all with dual linear polarization feeds



- Only 3 receiver bands can be "ready" at one time Required lead time to stabilize a new band is about 20 minutes.

- With a variety of configurations matched resolution may be possible between different bands which may be useful, for example to measure the SEDs of resolved sources.

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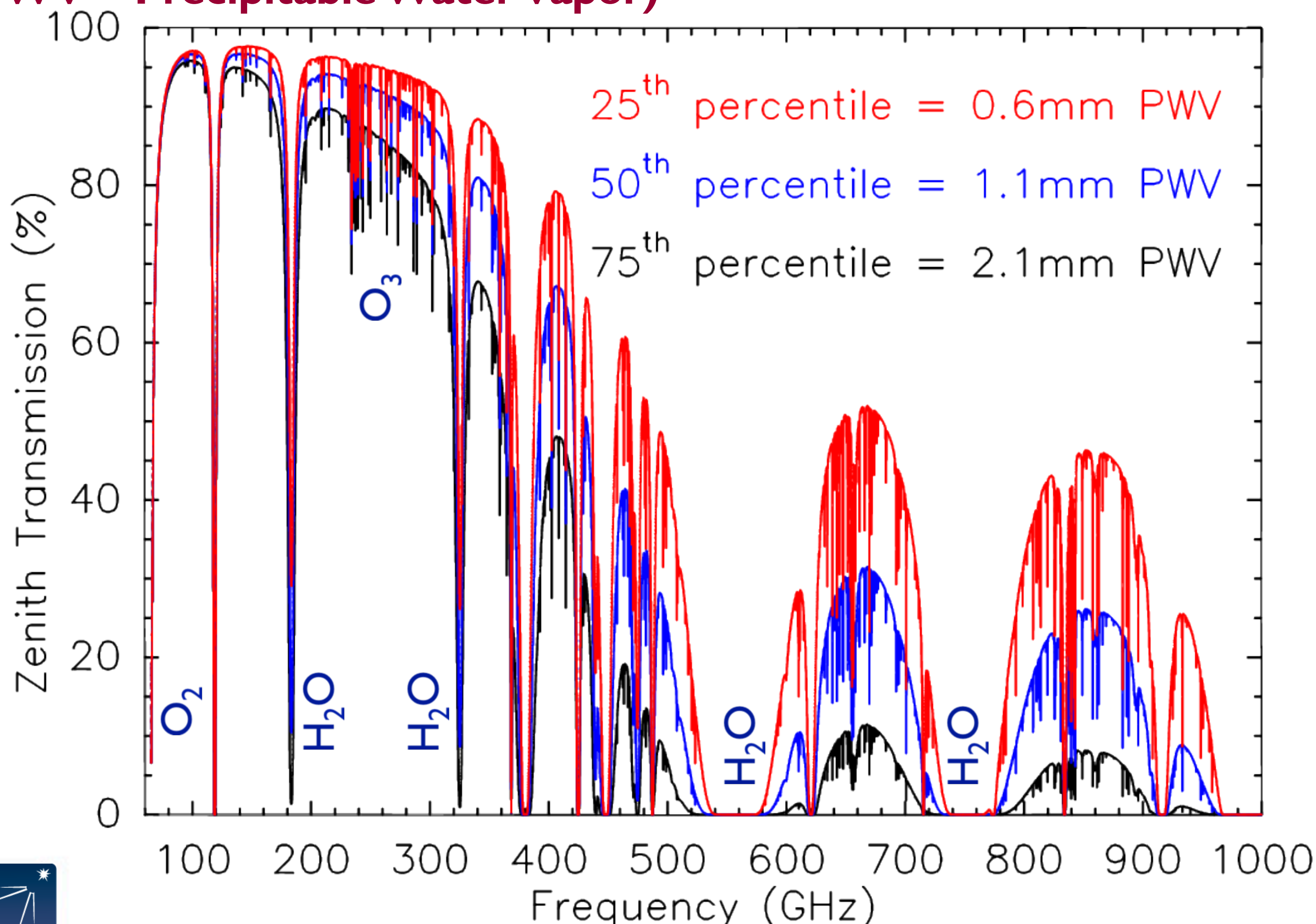
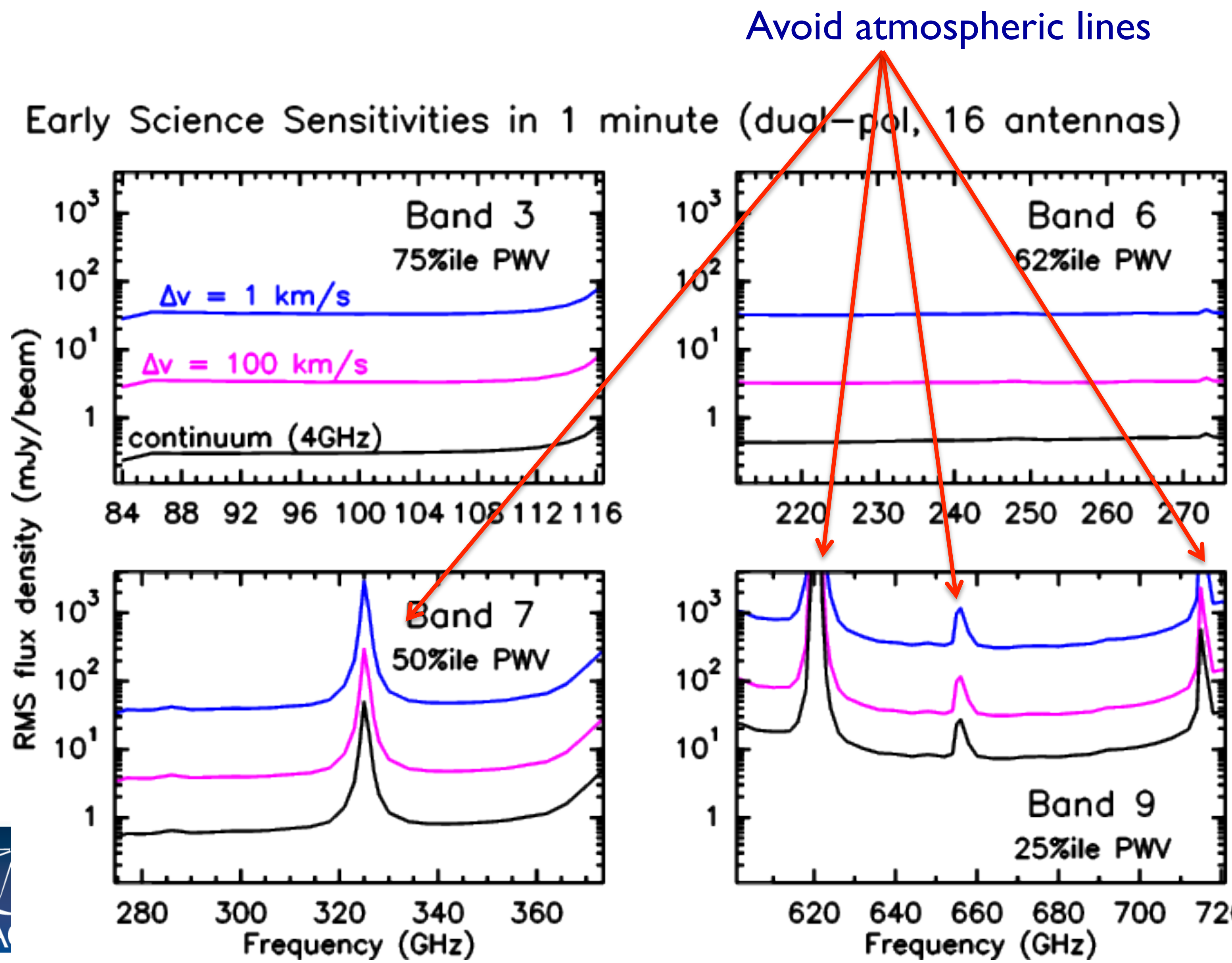
ALMA Atmospheric Opacity

(PWV = Precipitable Water Vapor)



Choice of Frequency – ALMA example



Signal to noise estimate & Technical Justification

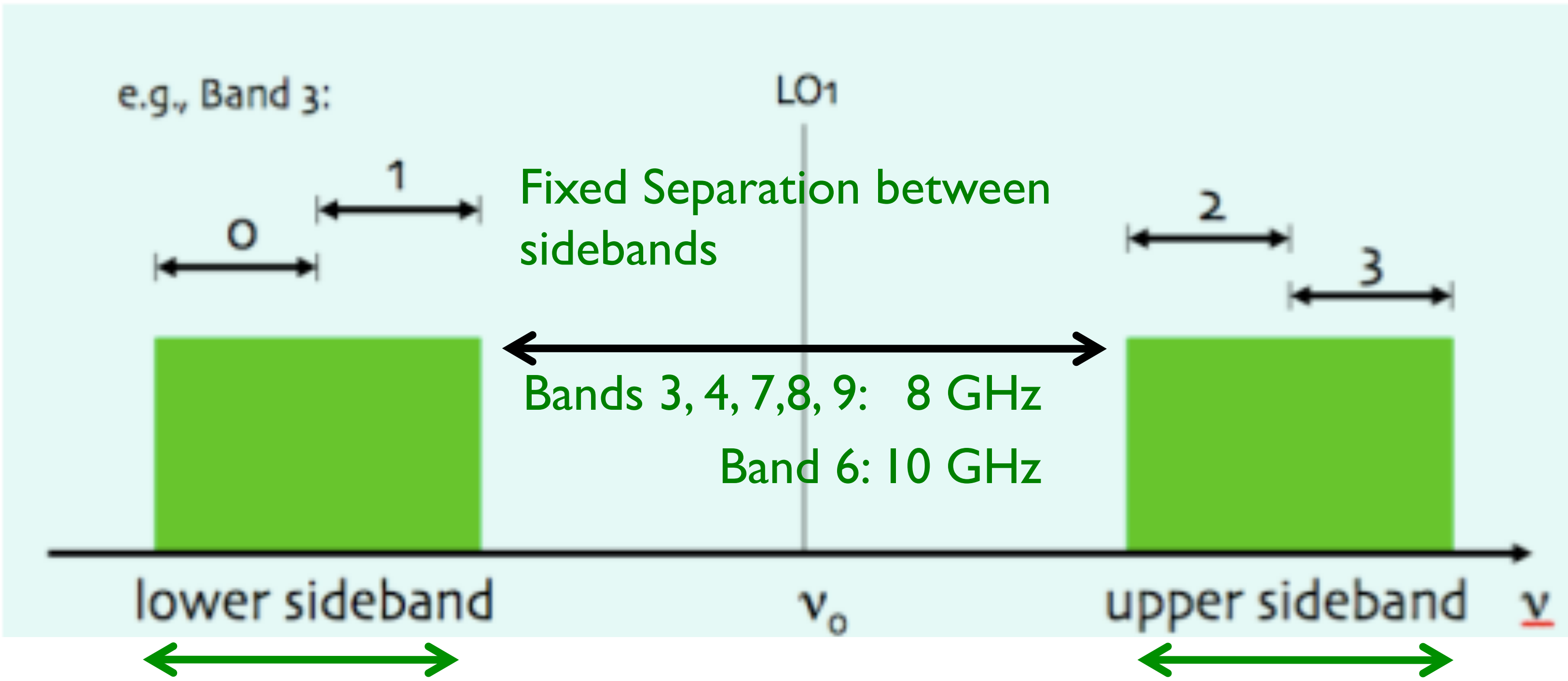
- The noise estimate is typically in mJy per beam

Outline

- Interferometry Basics
- Angular Scales and UV coverage
- Sensitivity
- Spectral Setup
- Calibration

Spectral Setup – I

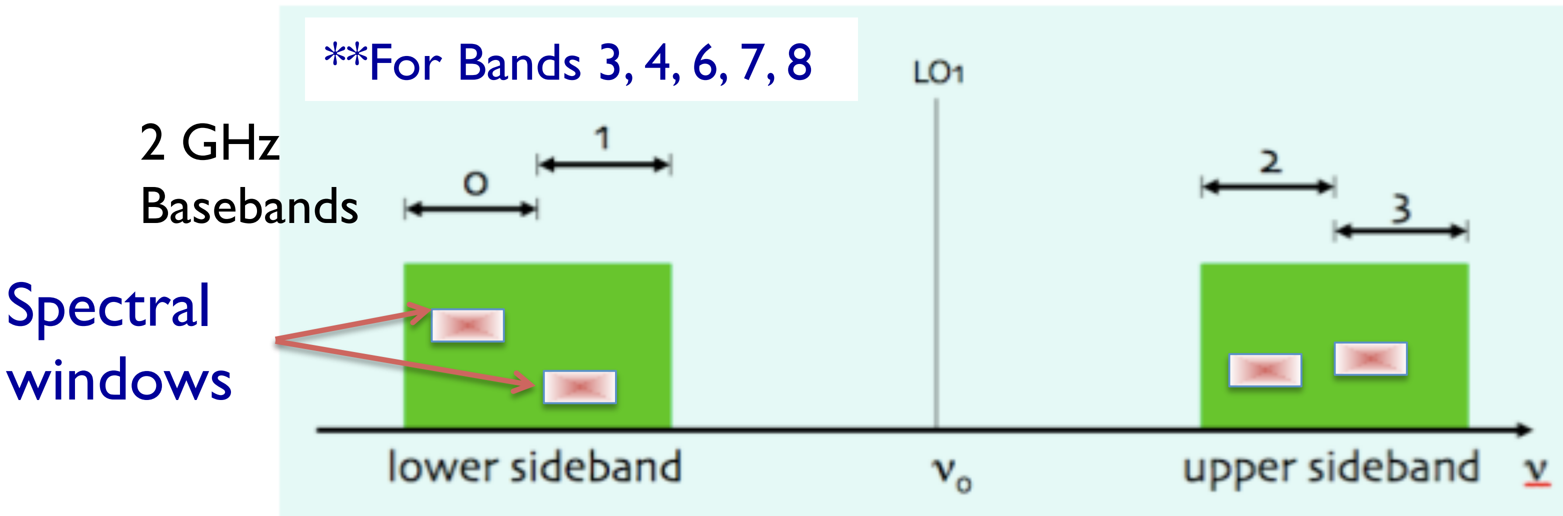
- Receivers are sensitive to two separate ranges of sky frequency: **sidebands**



Bands 3,4, 7, 8: 4.0 GHz
Band 6: 5.0 GHz
Band 9: 8.0 GHz

Sideband width varies by receiver band

Spectral Setup – II



- In order to collect data, you need to set up a spectral window within one (or more) basebands.
- In Cycle 2, four spectral windows are available, per baseband – each must have same spectral resolution but can have different smoothing
- 0,1,2 and 4 spectral windows can be placed in a sideband (but not 3) !

Correlator Modes and Resolution

Polarization	# Channels per baseband	Bandwidth per baseband (MHz)	Channel Spacing (MHz)
		(MHz = km/s @300 GHz)	
Dual	3840	1875	0.488
		938	0.244
		469	0.122
		234	0.061
		117	0.0305
		58.6	0.0153
Single	7680	58.6	0.0076
Dual	128	2000	15.6
Single	256	2000	7.8

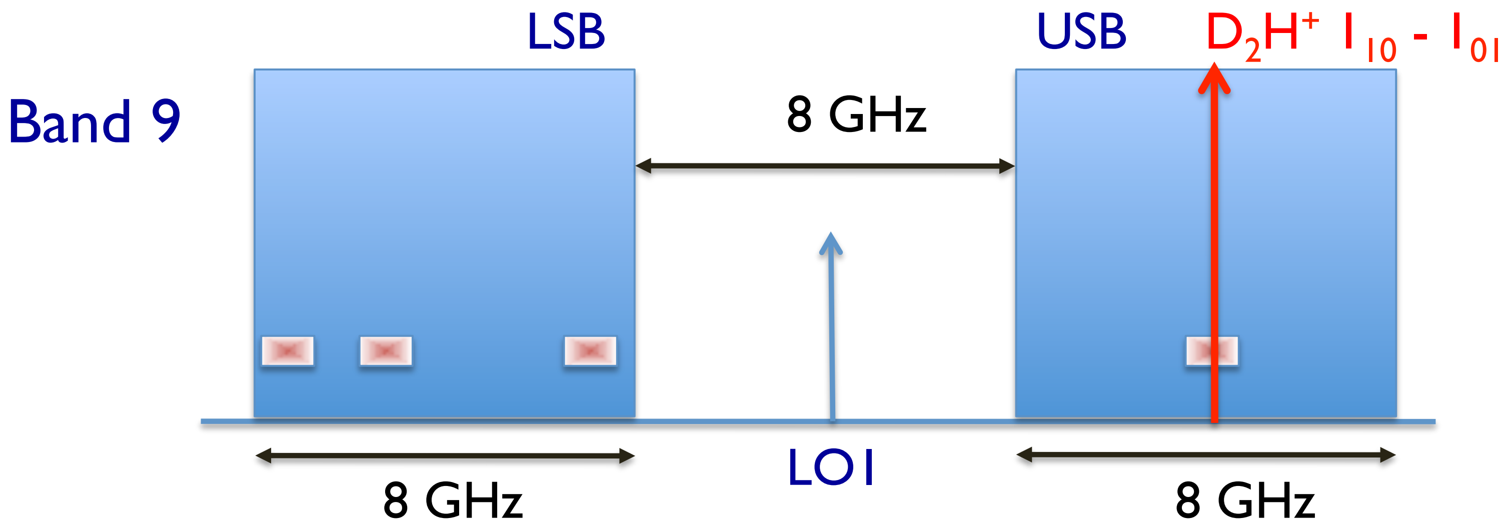
Typical purposes:

- Spectral scans (1875–938 MHz)
- Targeted imaging of moderately narrow lines: cold clouds / protoplanetary disks (469 MHz – Single 58.6 MHz)
- "Continuum" or broad lines (2000 MHz)

- Numbers are per baseband (you can use up to 4 basebands)
- **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

Example: Spectral Lines in Band 9



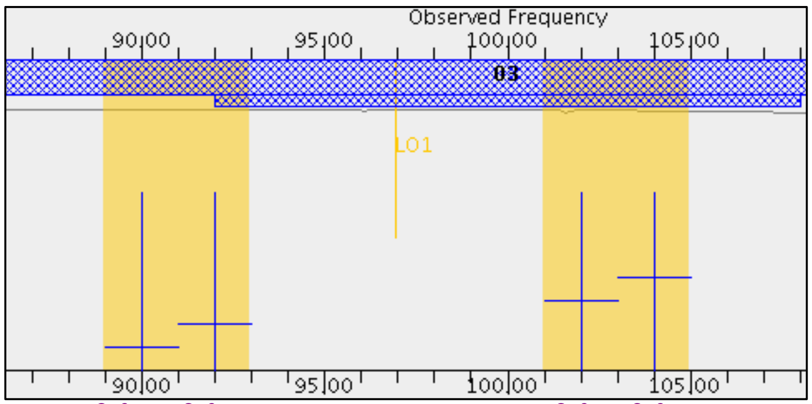
- Bands 3, 6, 7 receivers are sideband separating receivers (like PdBI)
- Band 9 receiver is DSB (like SMA and CARMA) but in Cycle 0, only one sideband per spectral window can be correlated
- for Band 9, there is full flexibility in that **each baseband can be connected to either one or the other sideband**
    - e.g. observe D_2H^+ at 691.66 GHz with one spectral window
    - can place 3 additional windows in USB or LSB

Correlator Setup
line vs. continuum

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

Band 3 (or 7)

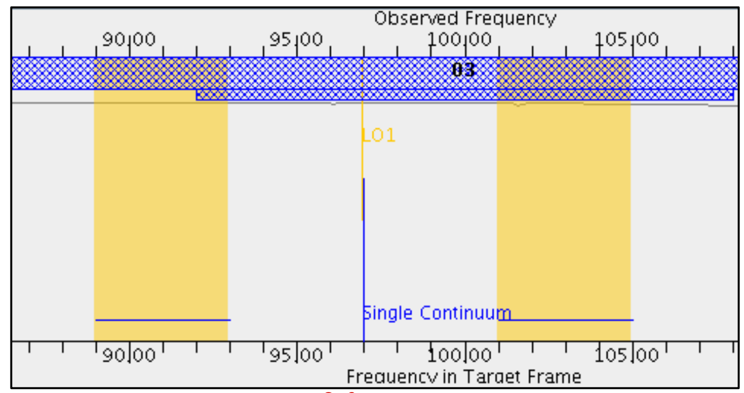
Spectral line mode:



ν_1 ν_2 ν_3 ν_4

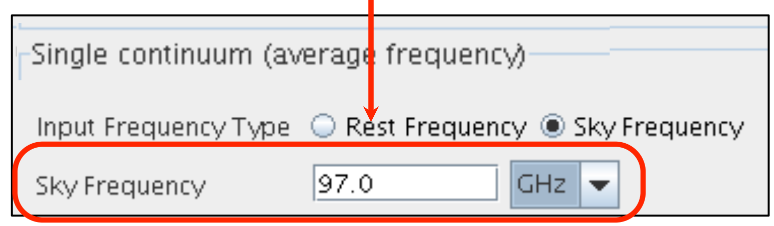
Center Freq Sky	...	Bandwidth, Channel Spacing
90.00000 GHz		1875.000 MHz(6246 km/s), 488.281 kHz...
92.00000 GHz		1875.000 MHz(6110 km/s), 488.281 kHz...
102.00000 GHz		1875.000 MHz(5511 km/s), 488.281 kHz...
104.00000 GHz		1875.000 MHz(5405 km/s), 488.281 kHz...

Continuum mode:



ν_{SKY}

2000 MHz bandwidth, 15.625 MHz resolution



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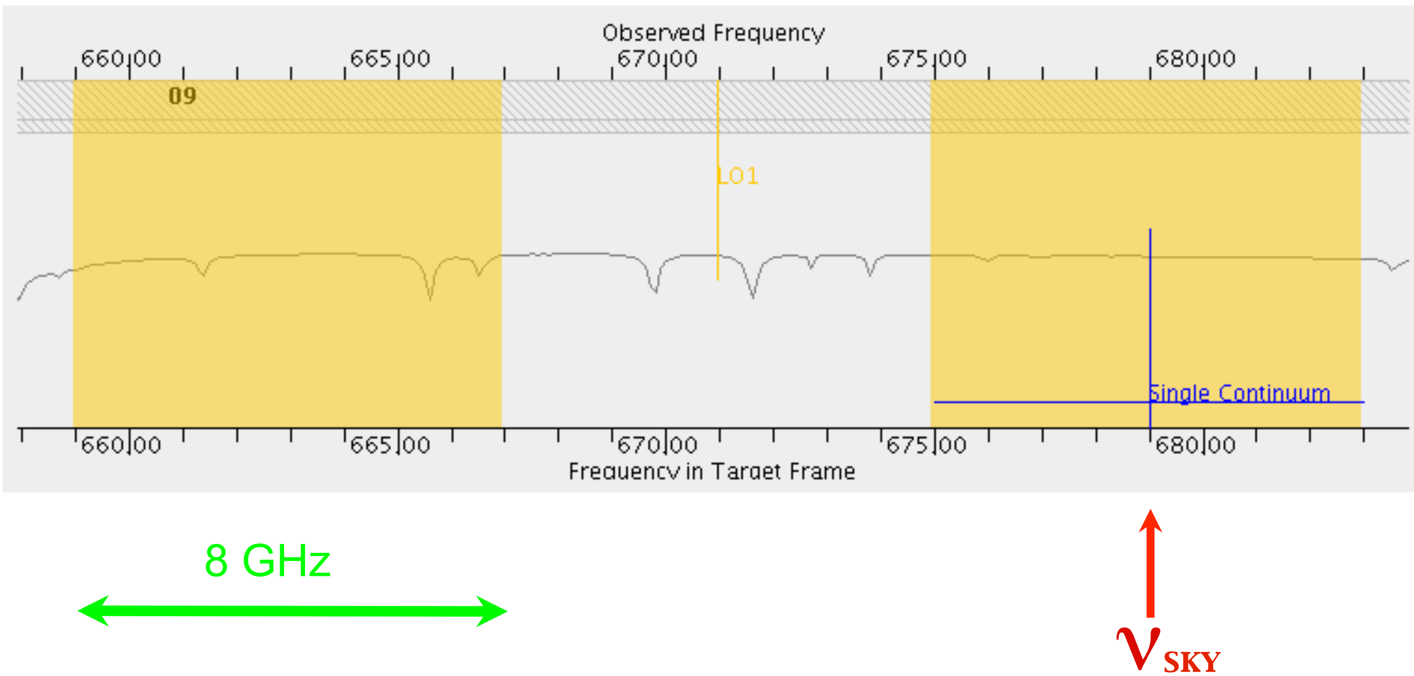
Correlator Setup

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

Continuum placement in Band 9



Another option: put 4 GHz at top end of USB and 4 GHz at bottom end of LSB, and thereby get a spectral index across 20 GHz -- it would be 11% different flux for nu^4

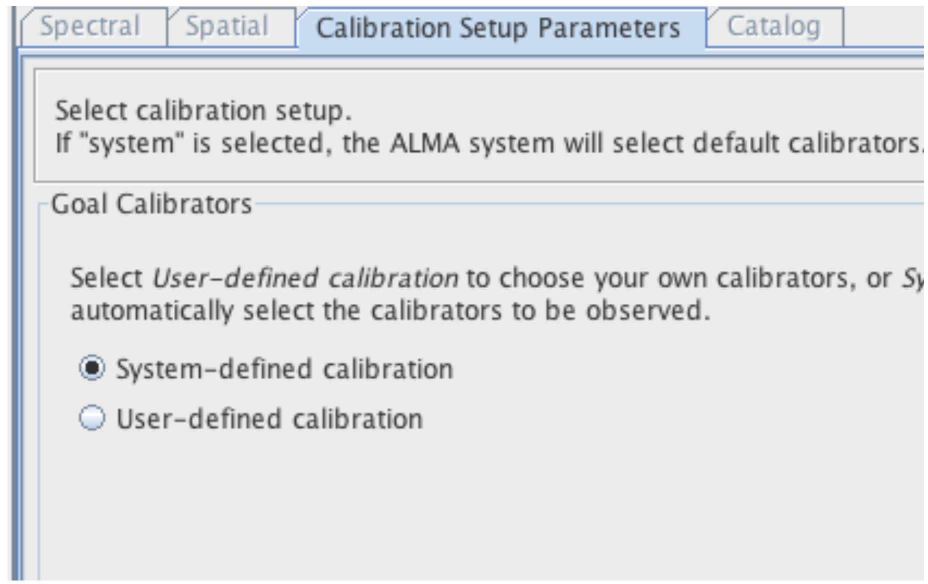
Outline

- Interferometry Basics
- Angular Scales and UV coverage
- Sensitivity
- Spectral Setup
- Calibration

Calibration

- Calibration is the effort to measure and remove the time-dependent and frequency-dependent atmospheric and instrumental variations.

- Following are the steps needed to fully calibrate interferometric data (You DON'T have to worry about these)



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

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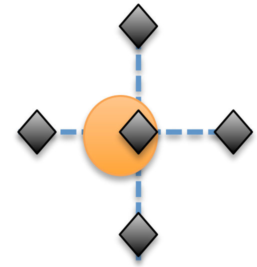
Pointing

- 5 point cross to point up.
- Depends on azimuth and elev
- Done whenever we go to a different part of the sky (more than 15 degrees away)

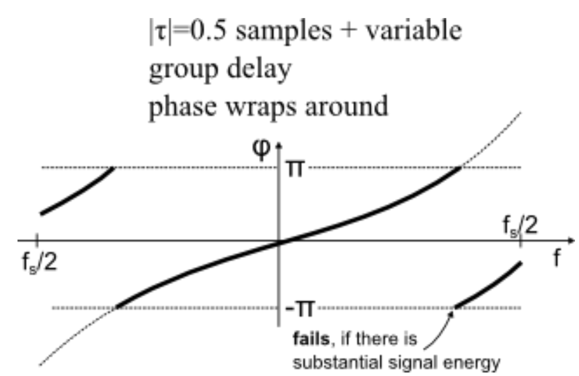


Focus

- Usually measured once per day
- Position of subreflector in x,y and Z
- Temperature dependent
- Band to band offsets used for high frequencies.

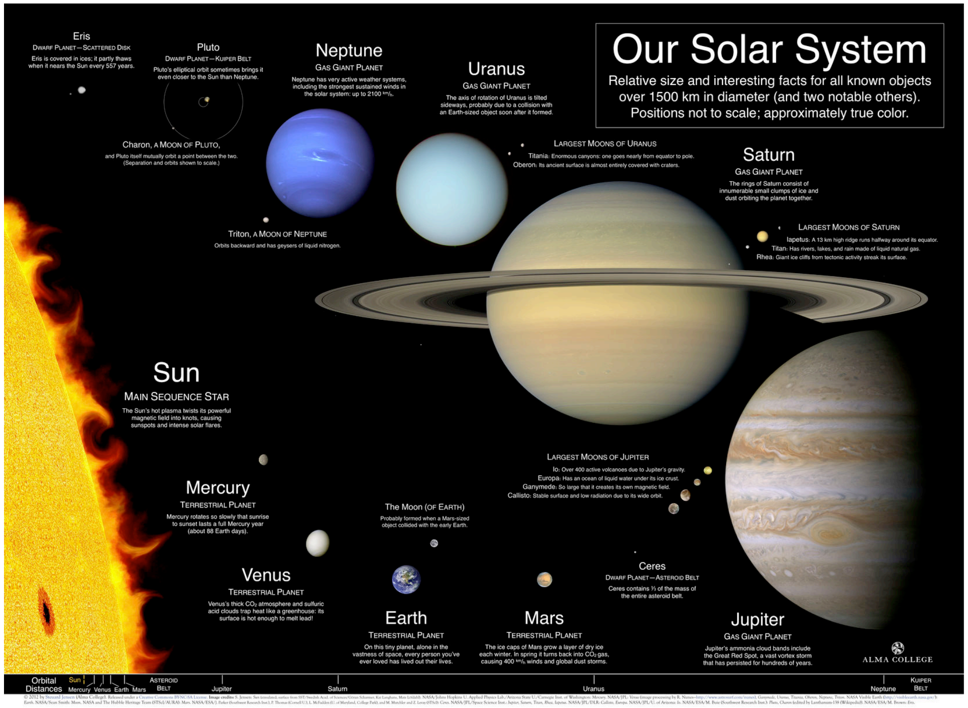
Delays

- Error in precise path length translates to a slow phase wraps as a function of wavelength.
- Usually corrected by observatory before observations



Absolute Flux Calibration

- Analogous to observations of standard stars in the optical!
- Done once in a SB
- Uses known targets, preferably **unresolved** (on at least six to ten baselines)
- Mercury, Ceres, Uranus, Ganymede etc.
- Secondary set involves bright quasars (can fluctuate by ~x2)

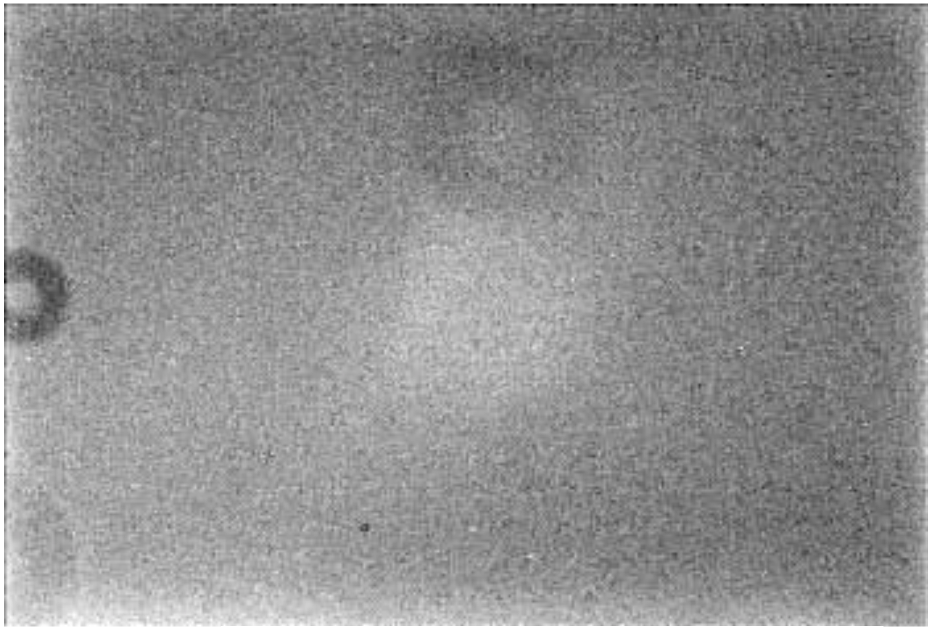


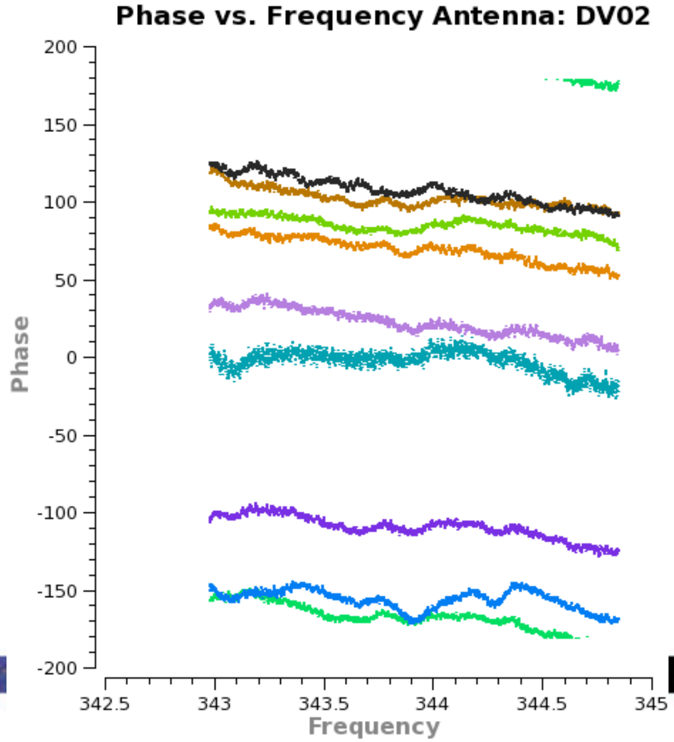
- **MAIN PURPOSE – get the flux of the gain calibrator!**

Bandpass or Passband Caibration

- Analogous to observations of a flat field + darks + bias in the optical!
- Primarily correcting for imperfections in the correlator / spectral windows
- Done once in a SB
- Uses very bright point sources (quasars) to measure the channel to channel variation in amplitude and phase

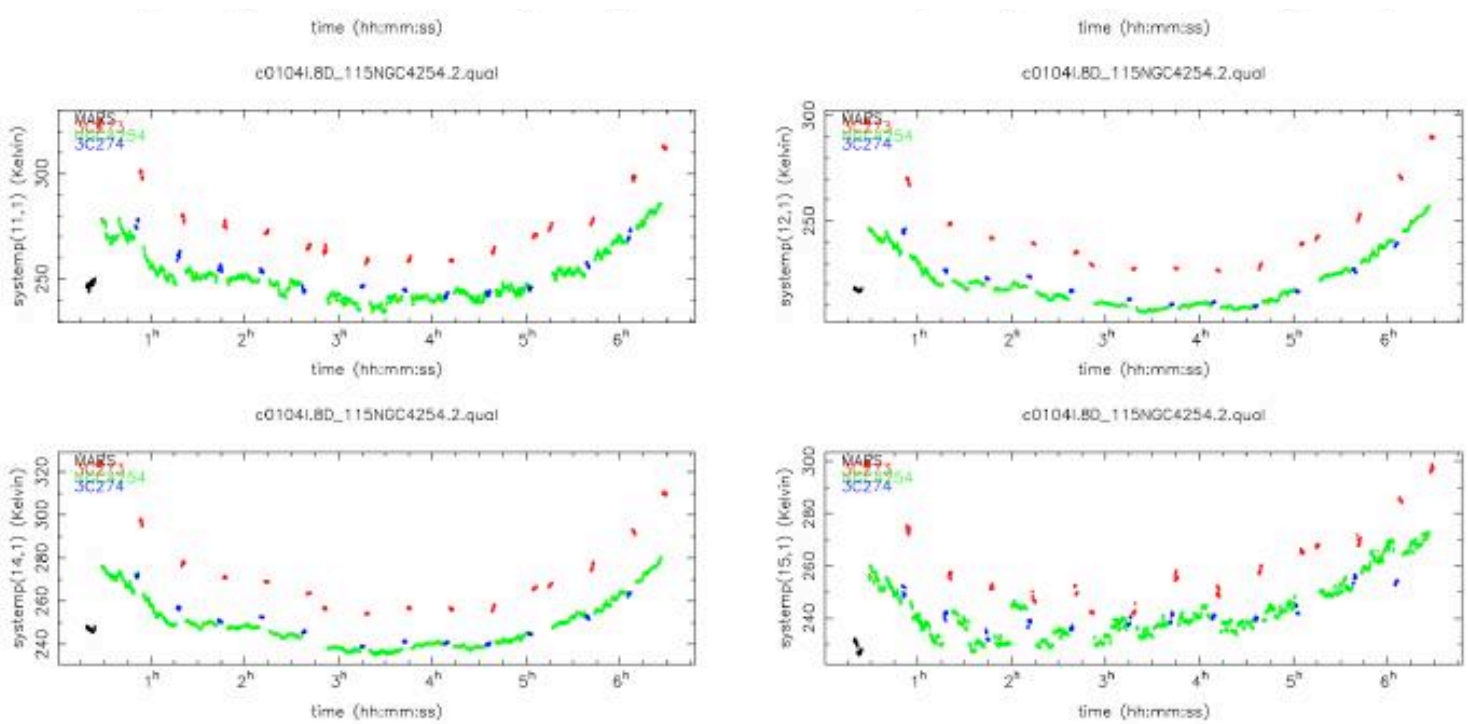
- **MAIN PURPOSE – get flat spectra!**





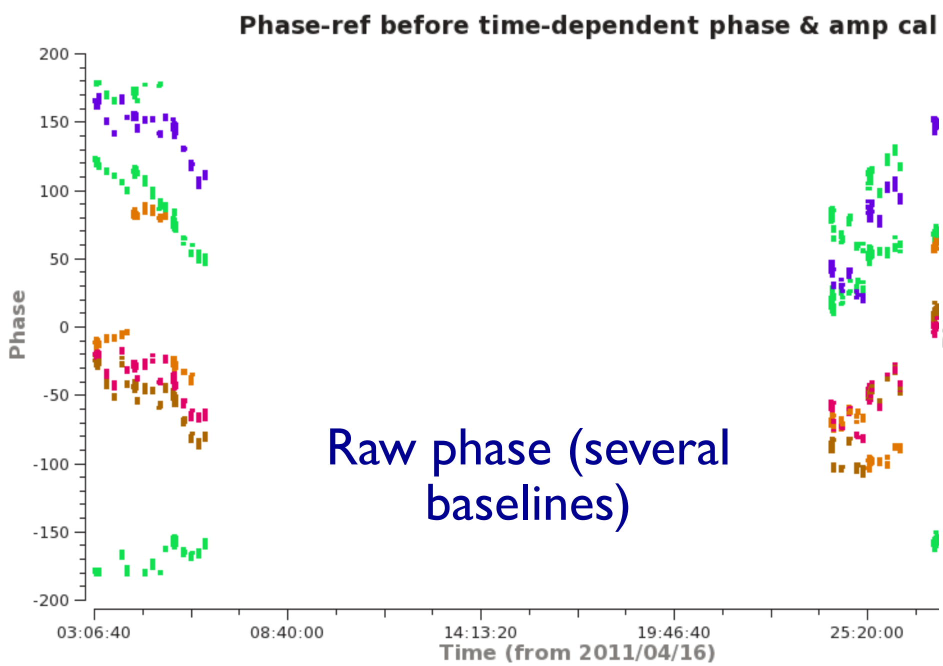
System Temperature Calibration

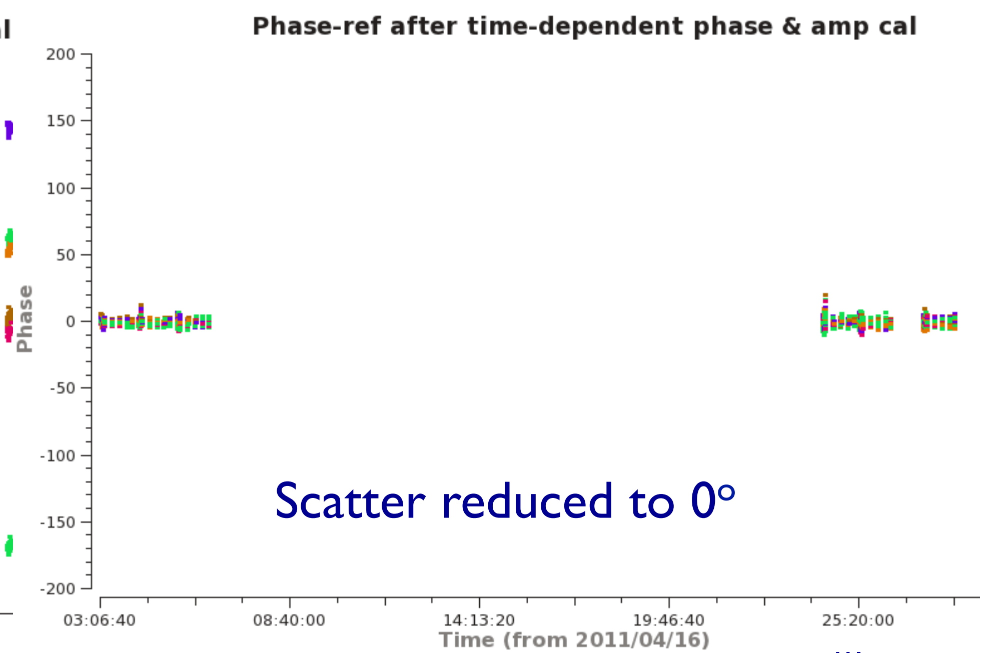
- Analogous to corrections of opacity or airmass
- Done every few minutes throughout an execution block
- Alternating measurements of a hot load, cold load and sky to measure water column above each telescope
- Elevation, precipitable water vapor and frequency + receiver noise affect Tsys



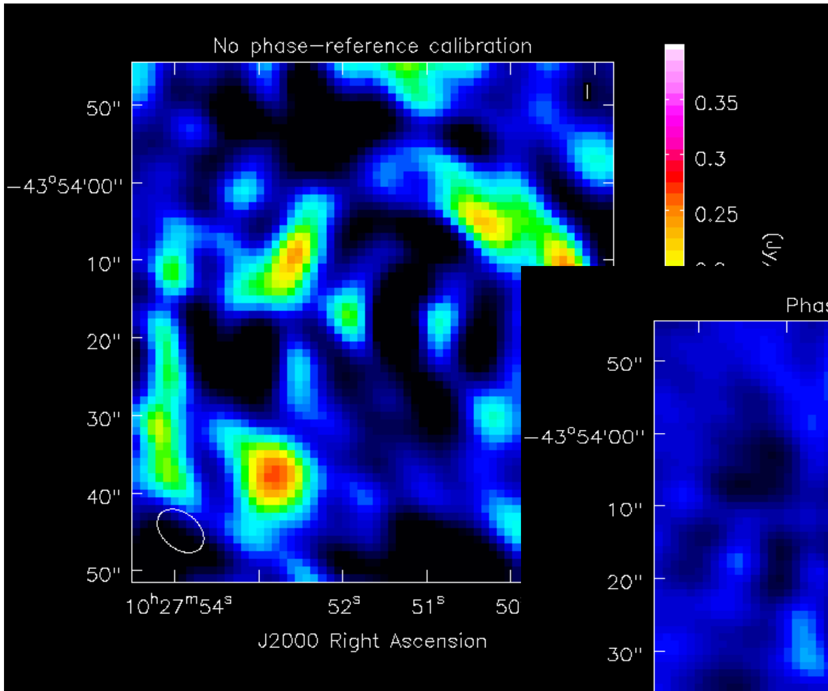
Phase & Amplitude Gain Calibration

- Analogous to Standard Star – Object- Standard Star – Object sequence
- Done every few minutes throughout an execution block
- Nearby (within 10 degrees) and bright quasar used to give phase and amplitude variations as a function of time
- Removes long term atmospheric + instrumental gain variations (assumes quasar is a point source and thus should always give constant amplitude and zero phase)

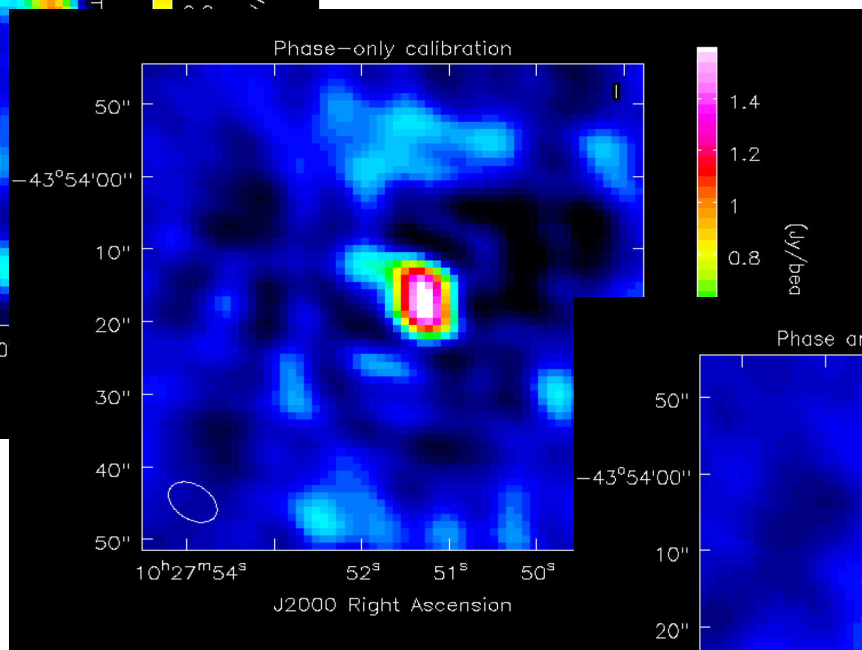




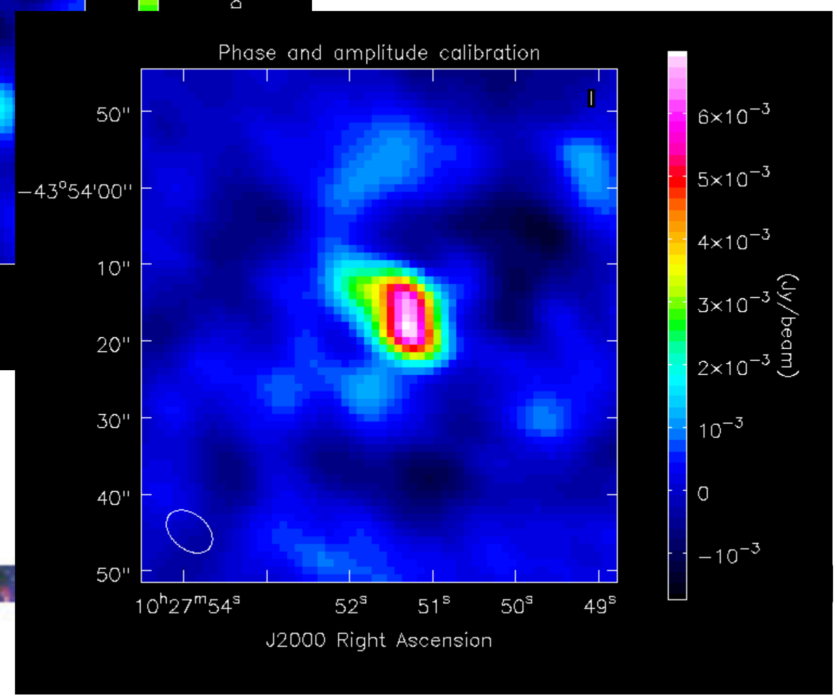
Effects on imaging



No astrophysical calibration:
no source seen



Phase-only solutions:
source seen, S/N ~ 15
but no flux scale



Amplitude and phase solutions: source seen with a S/N ~22

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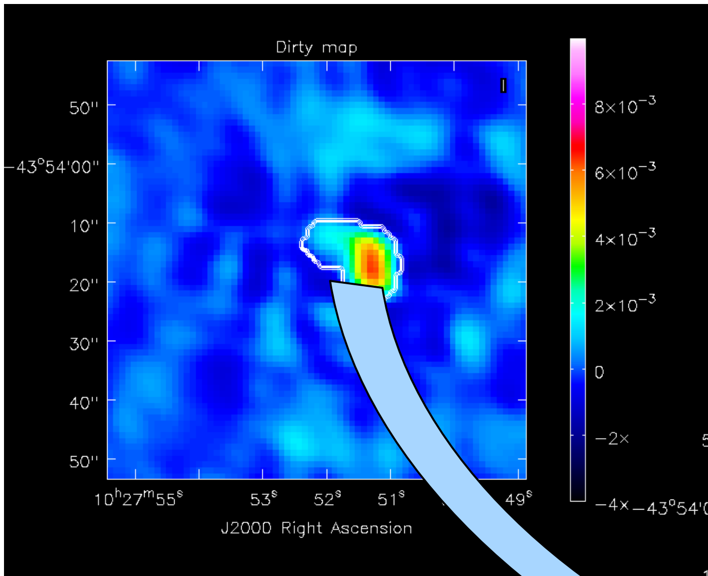
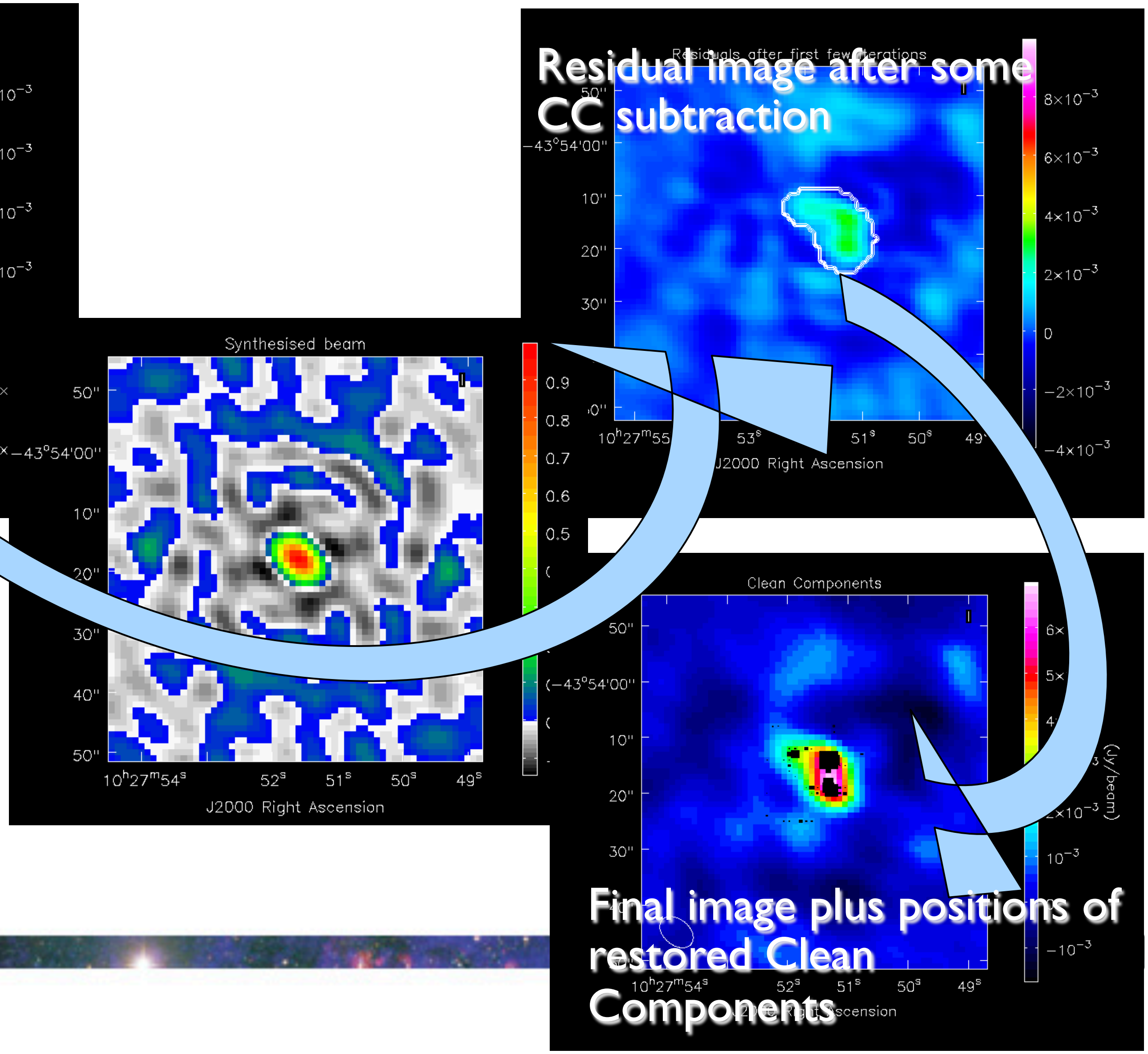
Fourier transform and Clean





FT calibrated visibilities to get a dirty Map

Define a Clean region

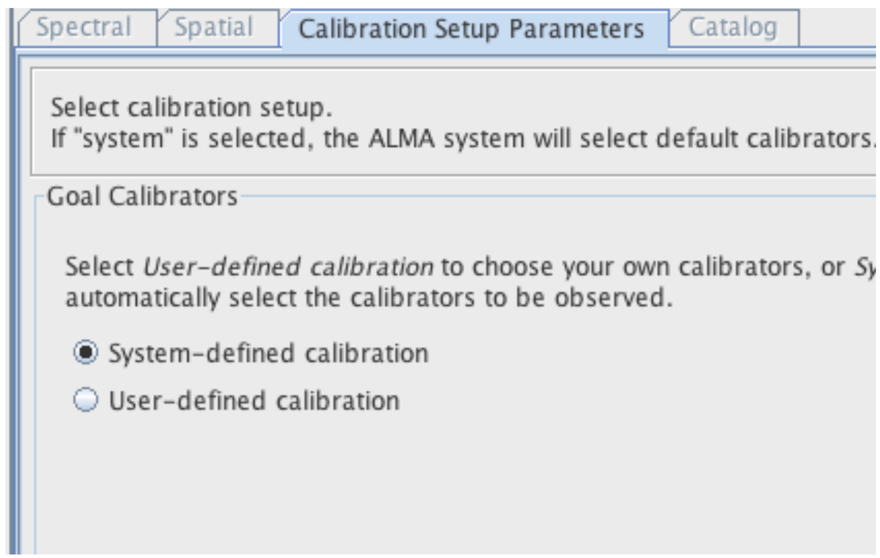
Deconvolve iteratively

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):

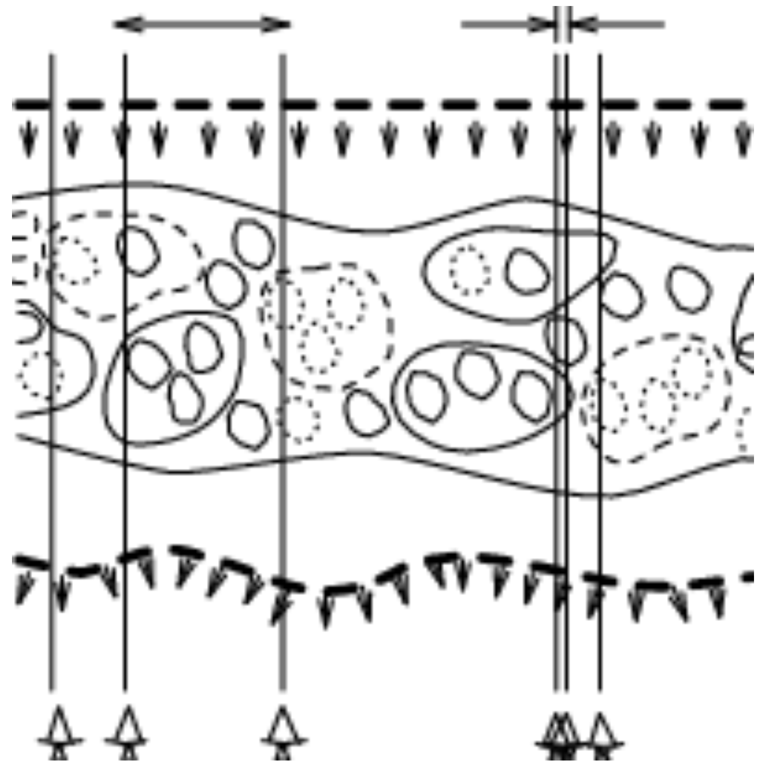
  1. Pointing, focus, and delay calibration
  2. Phase and amplitude gain calibration
  3. Absolute flux calibration
  4. Bandpass calibration
  5. System Temperature calibration
  6. Water-vapor radiometry correction



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

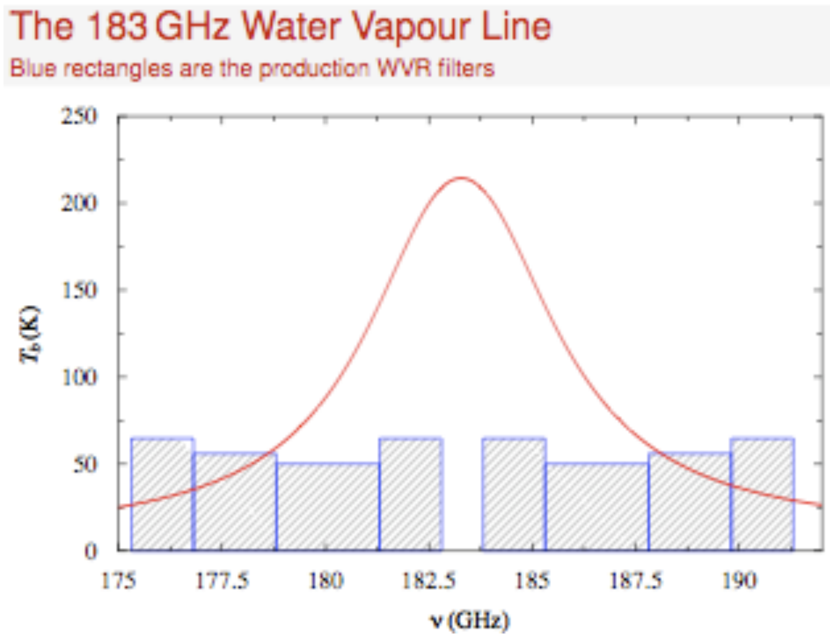
You can observe in apparently excellent submm weather (in terms of transparency) and still have terrible "seeing" i.e. phase stability.



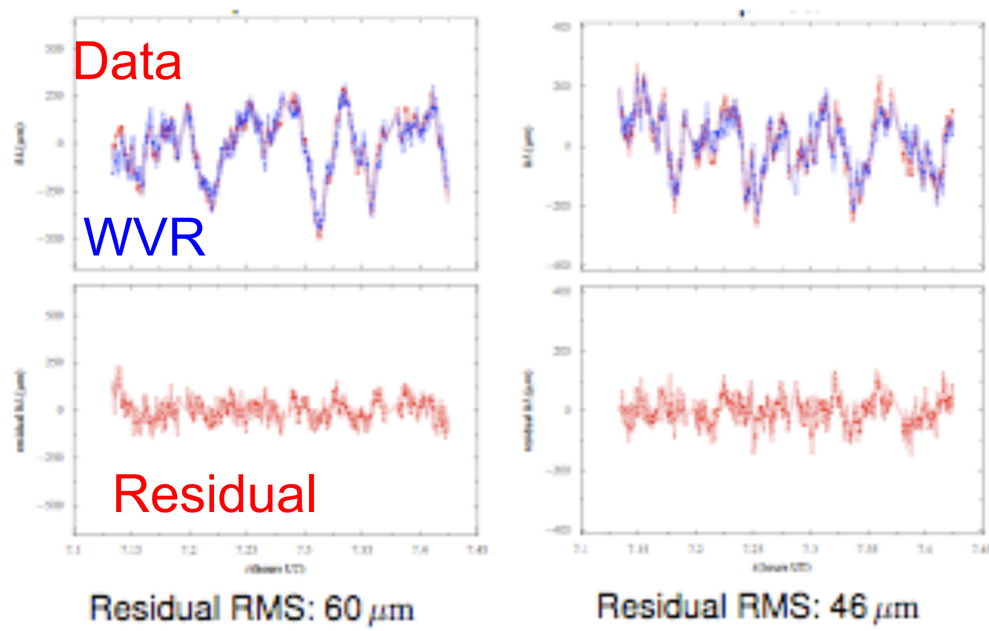
Patches of air with different water vapor content (and hence index of refraction) affect the incoming wave front differently.

ALMA WVR System (Adaptive optics!)

Installed on every antenna



Two different baselines Jan 4, 2010

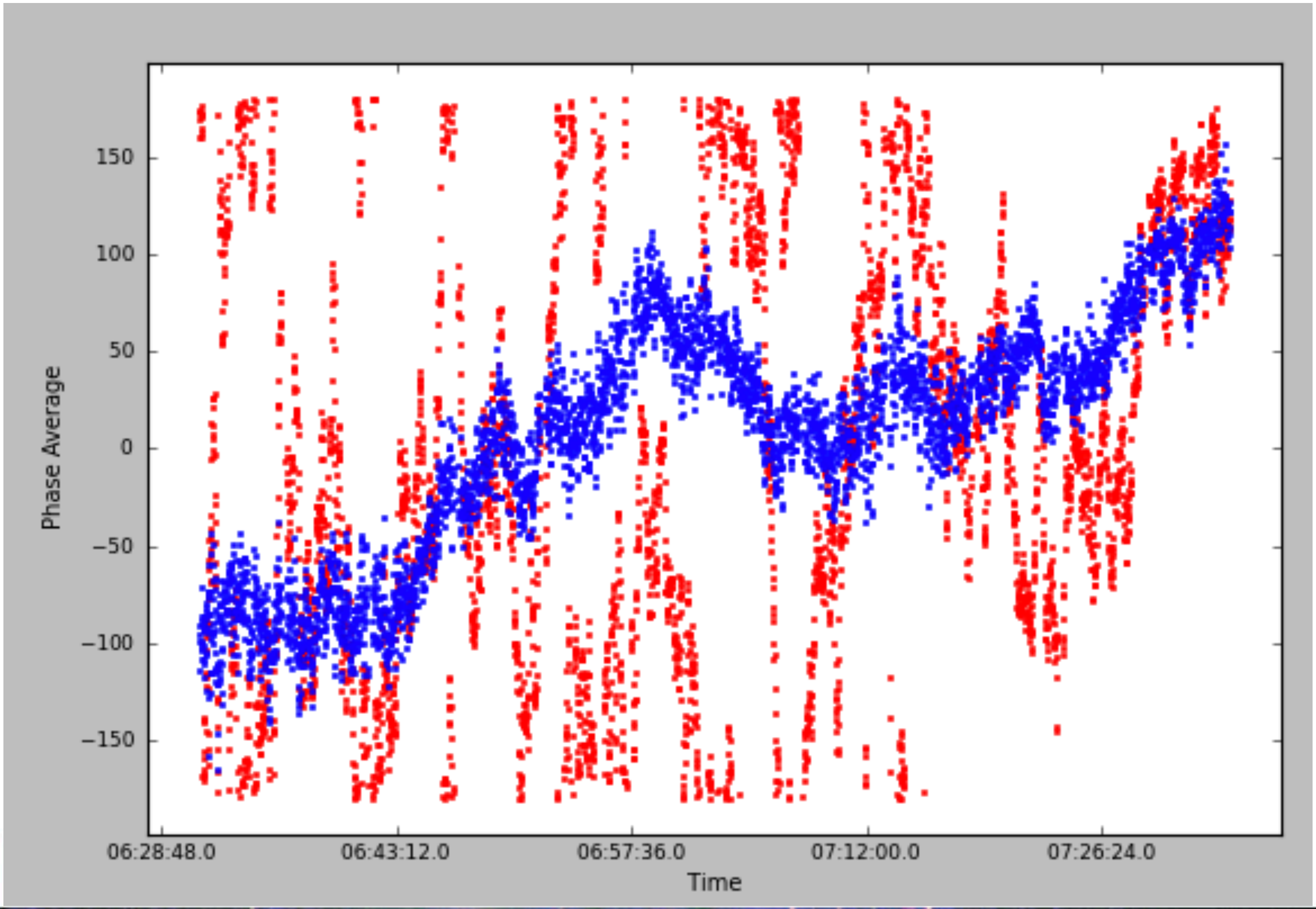


4 "channels" flanking the peak of the 183 GHz water line

- Data taken every second, and are written to the ASDM (science data file)
- Convert models to phase noise at observing frequency
- Removes the atmosphere on short time scale (successful but remains to be fully tested at high frequencies and long baselines).

ALMA WVR System

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



Phase correction methods

- 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:

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

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