

ALMA: MM Observing Considerations

Focus on Early Science (cycle 0)



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Atacama Large Millimeter/submillimeter Array

Expanded Very Large Array

Robert C. Byrd Green Bank Telescope

Very Long Baseline Array



- **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

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

Northern sources: Maximum length of observation (hours)

Dec	Elev > 10°	Elev > 15°	Elev > 20°	Elev > 30°
+55	2.7	-	-	-
+50	5.9	2.5	-	-
+40	7.0	5.8	4.3	-
+30	8.3	7.3	6.3	3.9
+20	9.2	8.4	7.5	5.7

Note: This table does not account for shadowing, which further complicates low elevation observations.

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

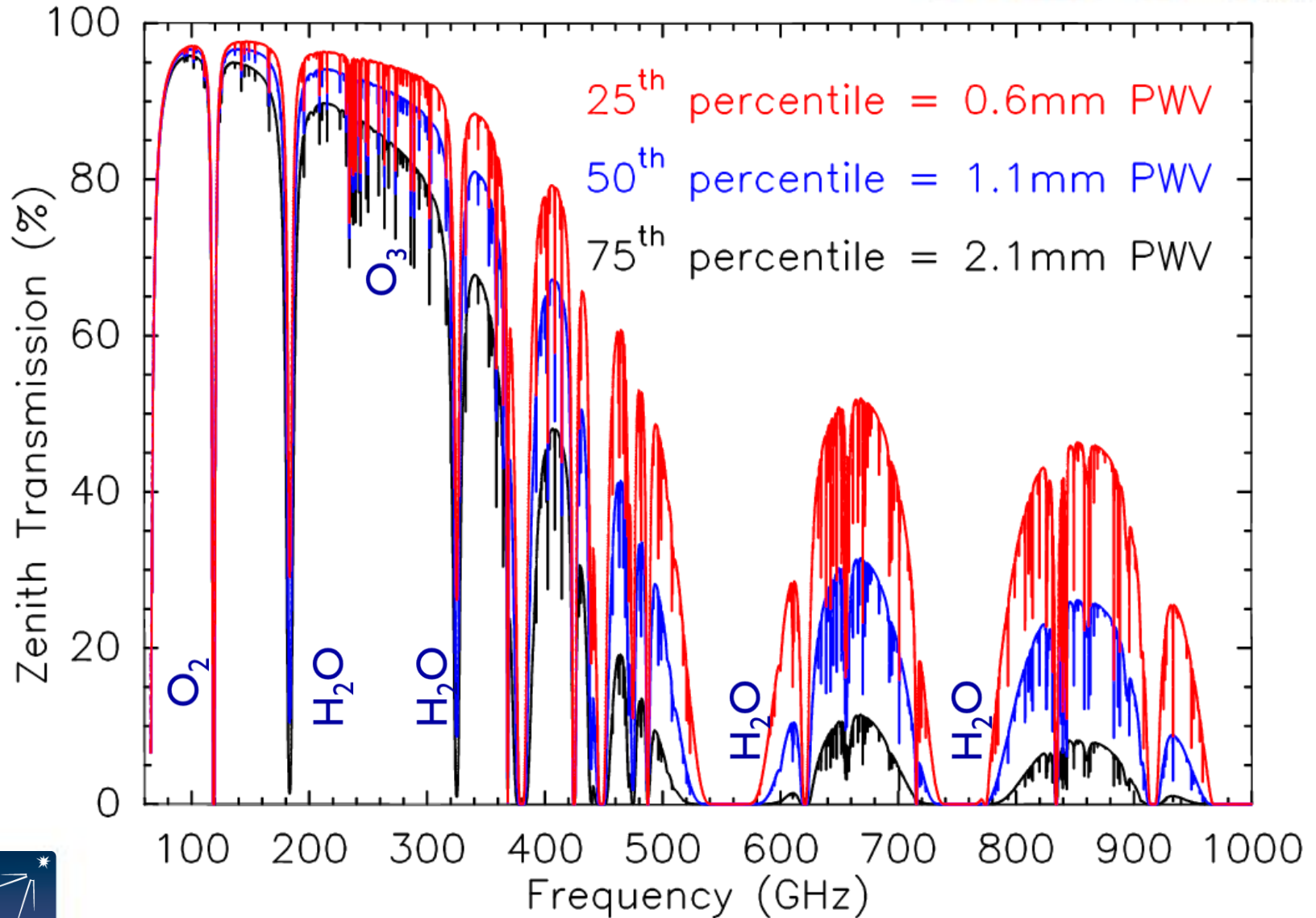
0.45 mm

- 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 $\sim 125\text{m}$ and $\sim 400\text{m}$, 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)



Sensitivity calculator

<http://www.eso.org/sci/facilities/alma/observing/tools/etc>

Common Parameters

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

n_p = # polarizations

N = # antennas

$\Delta\nu$ = channel width

Δt = total time

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
Sensitivity(rms)	0.04802	Jy	Infinity	Jy	Infinity
(equivalent to)	1.22370	K	Infinity	K	Infinity
Integration Time	1.00000	min	0.00000	s	0.00000
Integration Time Unit Option					Automatic

Calculate Integration Time

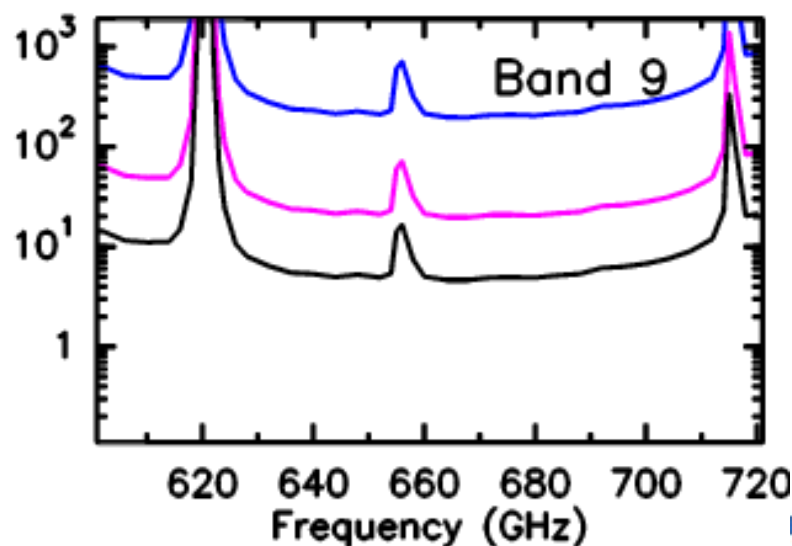
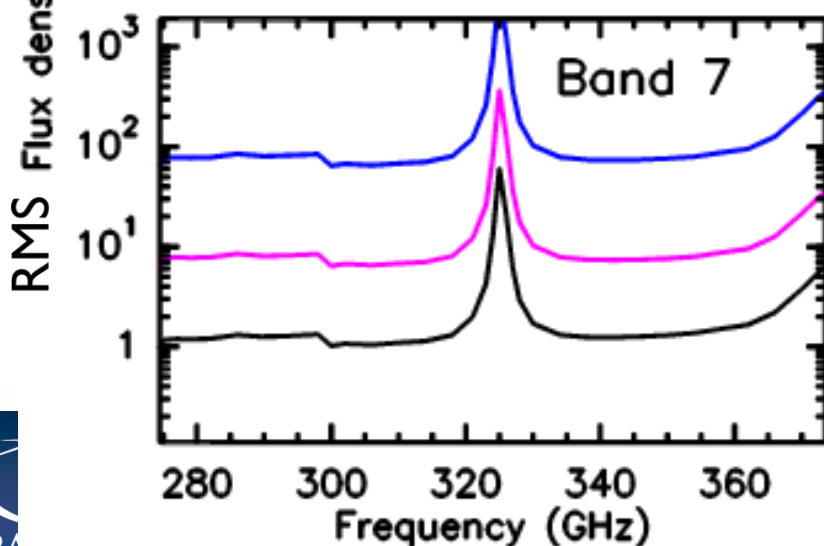
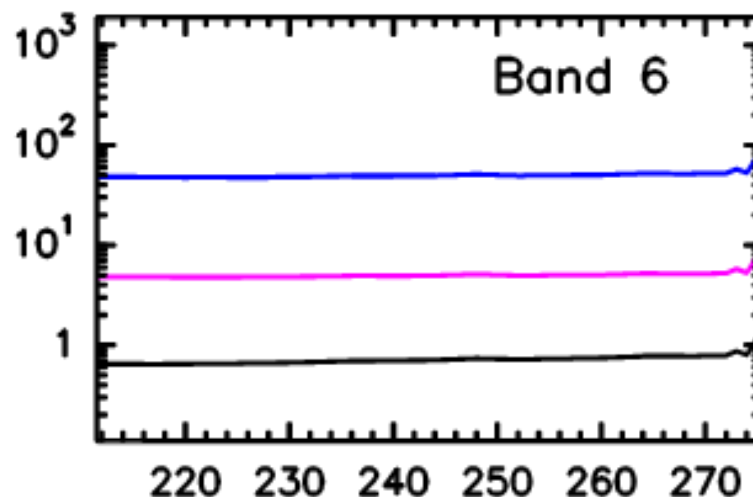
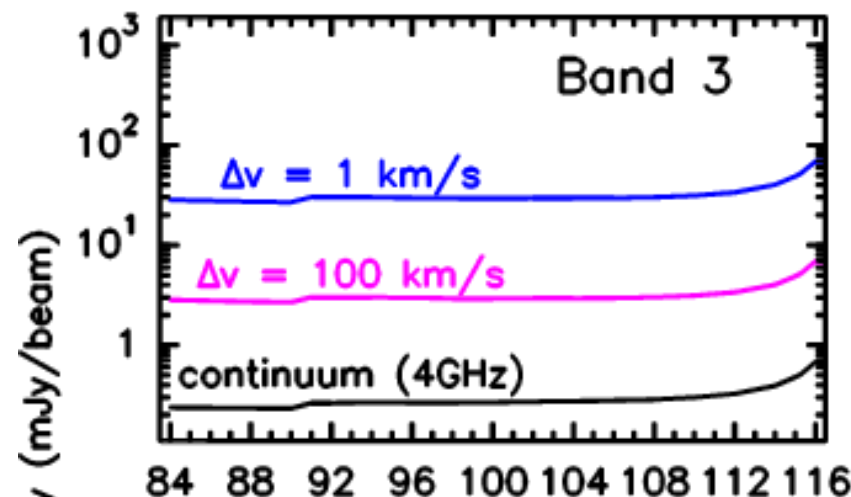
Calculate Sensitivity

Choosing your bands - I

(constructed from sensitivity calculator)



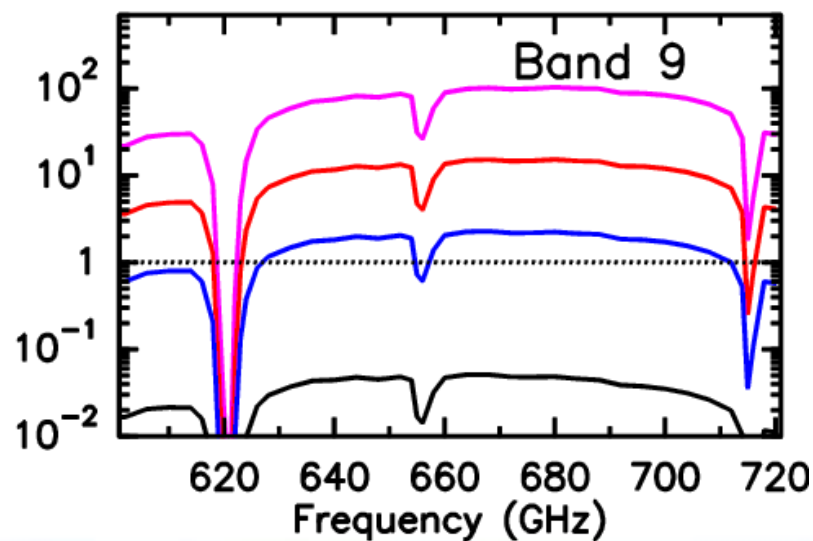
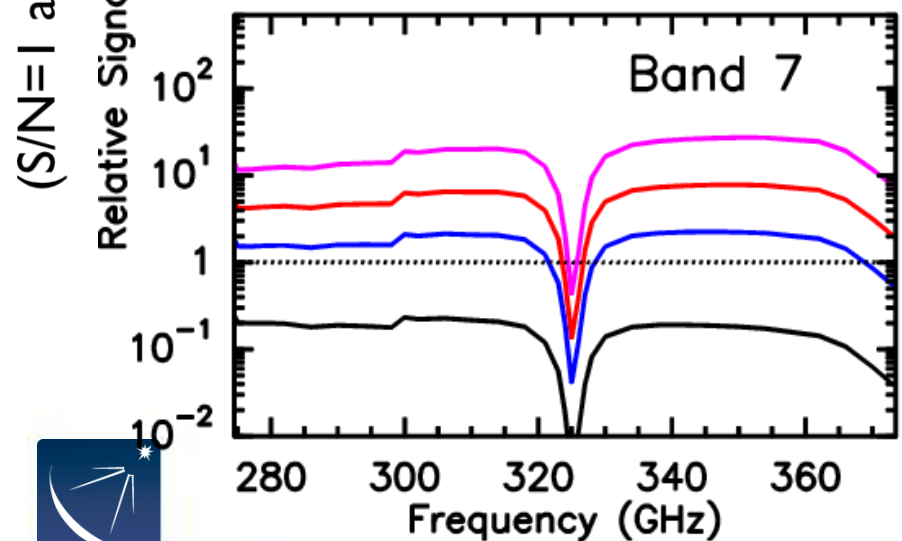
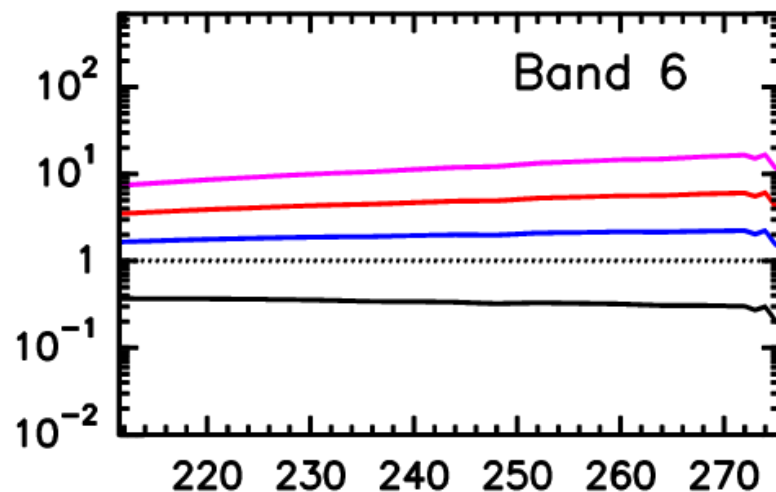
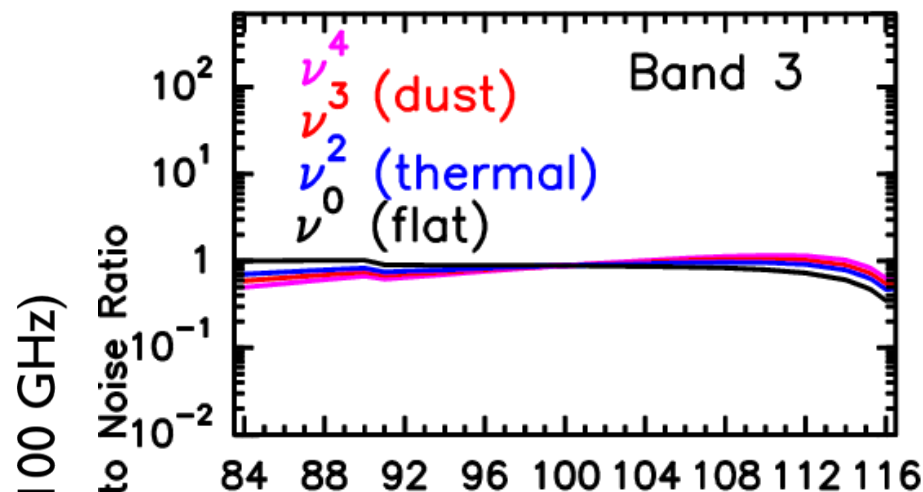
Early Science Sensitivities in 1 minute (dual-pol, 16 antennas)



NOTE: For 8 GHz continuum bandwidth divide by $\sqrt{2}$

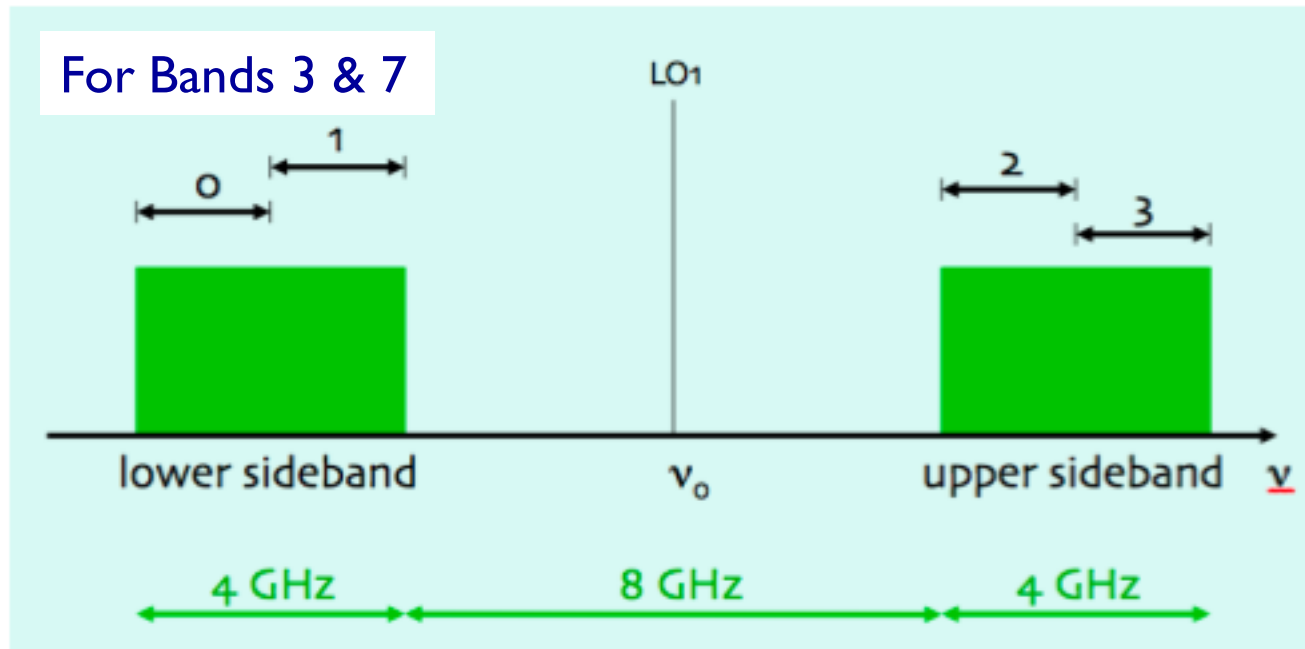
Choosing your bands - II

Relative Signal to Noise ratio for different spectral indices



Correlator Modes, Spectral Resolution, Spectral Coverage - I

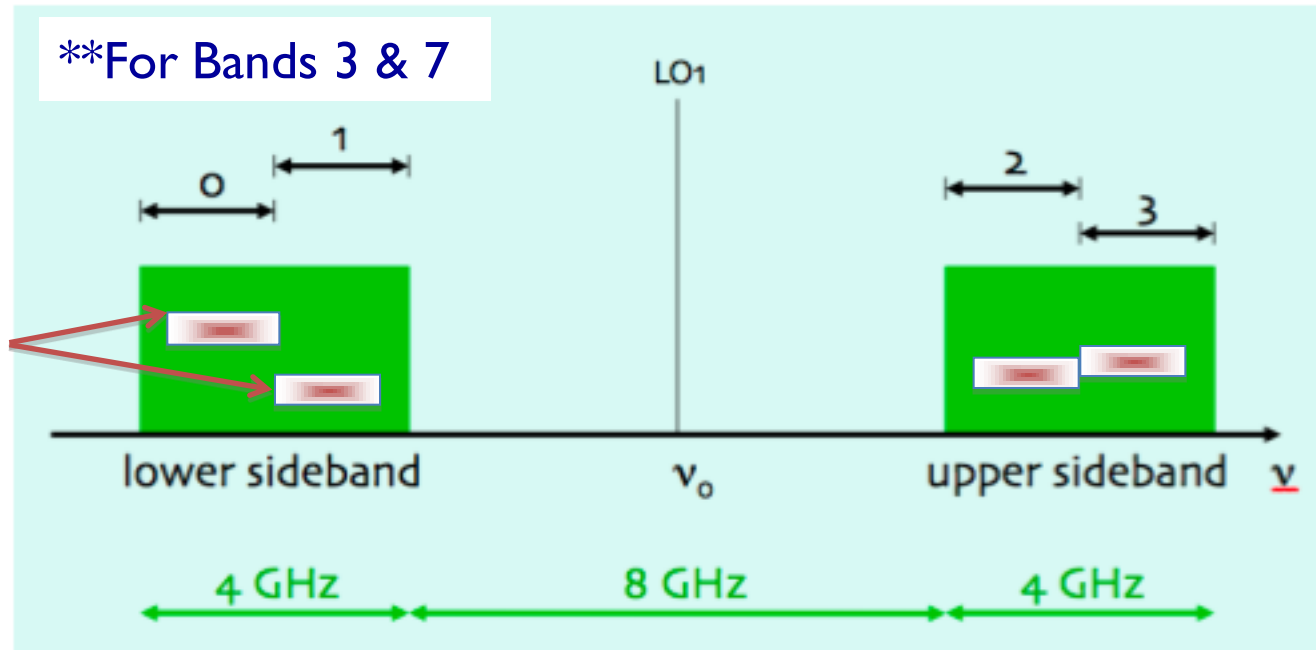
- Receivers are sensitive to two separate ranges of sky frequency: **sidebands**
- Each antenna has 4 digitizers which can each sample 2 GHz of bandwidth
- These 2 GHz chunks are termed **basebands**, and can be distributed among the sidebands (in ES: either all four in one, or two in both as shown below)



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, Spectral Resolution, Spectral Coverage - II



Typical purposes:

Spectral scans

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

“Continuum” or broad lines

Corr-elator Mode	Polari-zation	Bandwidth per baseband (MHz)	Number of channels per baseband	Channel Spacing (MHz)	Velocity width at 1mm (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

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



Spectral Lines in the ALMA bands



<http://www.splatalogue.net>

(large subset also available in OT)

The screenshot shows the splatalogue.net website interface. The browser address bar displays <http://www.splatalogue.net/>. The page features a navigation menu on the left with links such as "Splatalogue Home", "What's New (Updates & Announcements)", "Motivation", "Notes on Observing Frequencies", "Notes on Quantum Numbers", "Applications (SLAP Interface)", "NRAO Homepage", and "NAASC ALMA Science Homepage". The main content area is divided into two sections: "Search Parameters" and "Search Results".

Search Parameters:

- Select Species:** A list of species is shown, ordered by mass. The selected species is "00102 Ps - Positronium". Other species include "All", "00101 H-atom - Atomic Hydrogen", "00103 H α - Hydrogen Recombination Line", "00104 H β - Hydrogen Recombination Line", "00105 H γ - Hydrogen Recombination Line", "00106 H δ - Hydrogen Recombination Line", "00107 H ϵ - Hydrogen Recombination Line", "00108 H ζ - Hydrogen Recombination Line", and "00201 D-atom - Atomic Deuterium". A "Mass calculator..." button is also present.
- Data Versions:** A dropdown menu shows "Version 2 (1/1/2010)".
- Specify Ranges:** Fields for "Specify a Frequency Range" (From to) and "Specify an Energy Range" (From to) are provided. Radio buttons allow selection of units: MHz or GHz for frequency, and E_L (cm^{-1}) or E_U (cm^{-1}) for energy. Additional radio buttons are present for E_L (K) and E_U (K).
- Line Intensity Lower Limits:** A dropdown menu is visible.

Search Results:

The "Search Results" section contains the following text:

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 Toiyama 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 Drizin, 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)

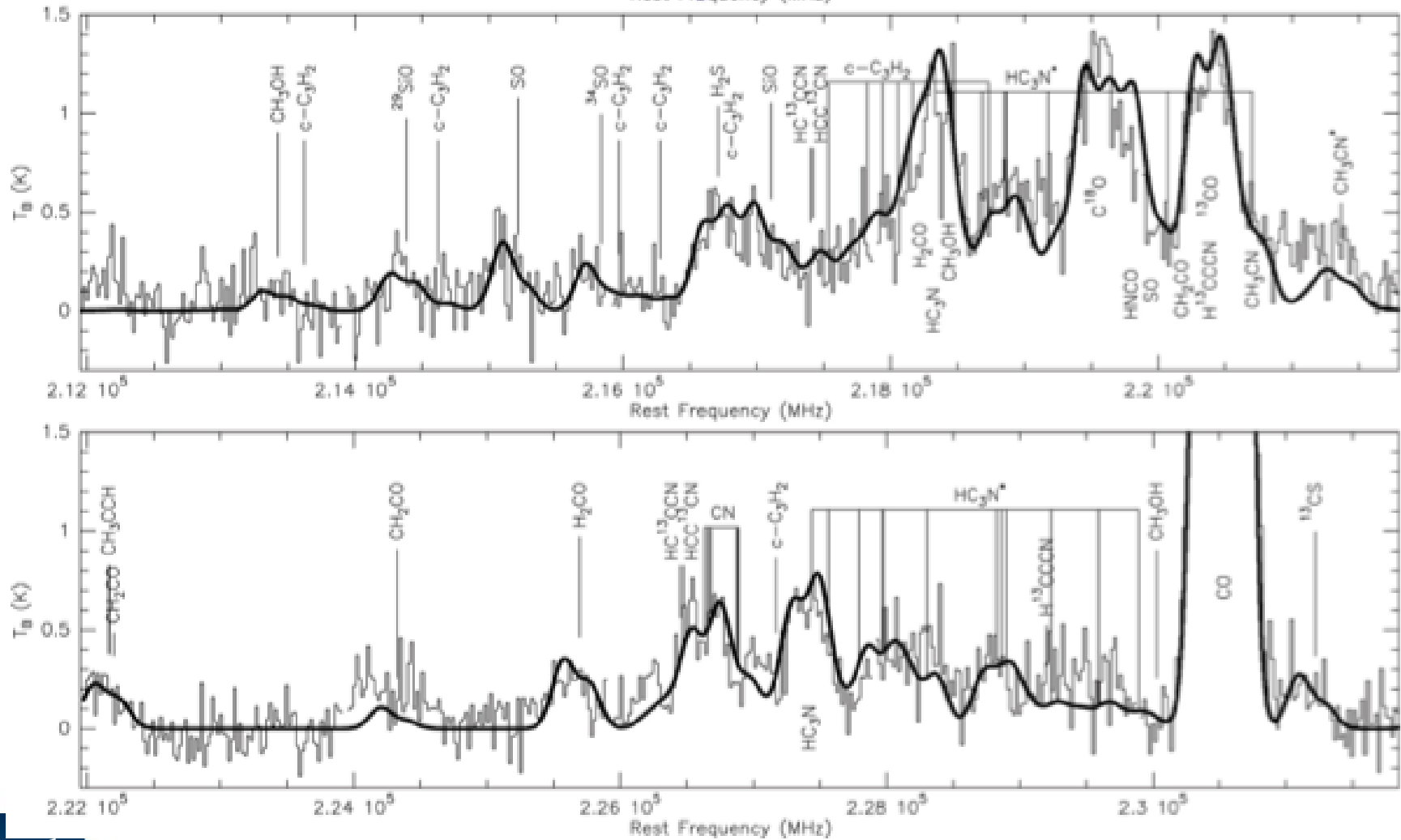


Image Quality

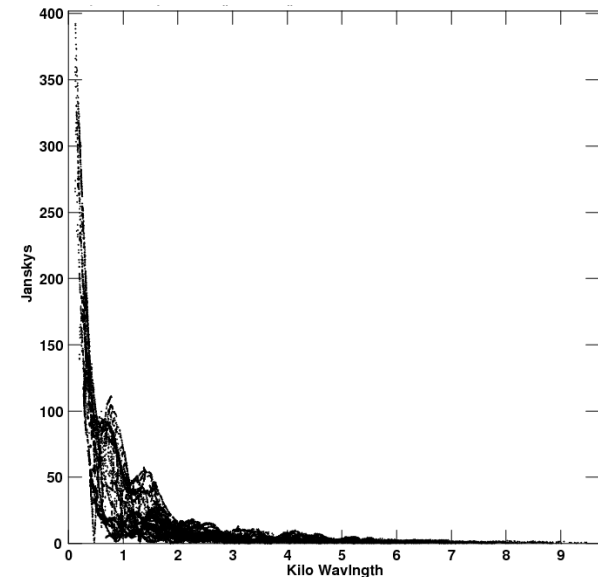
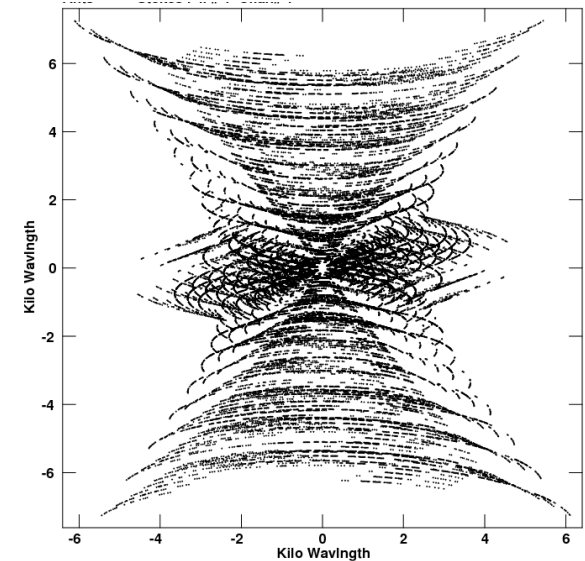
Sensitivity is not enough! Image quality also depends on:

- ❖ *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

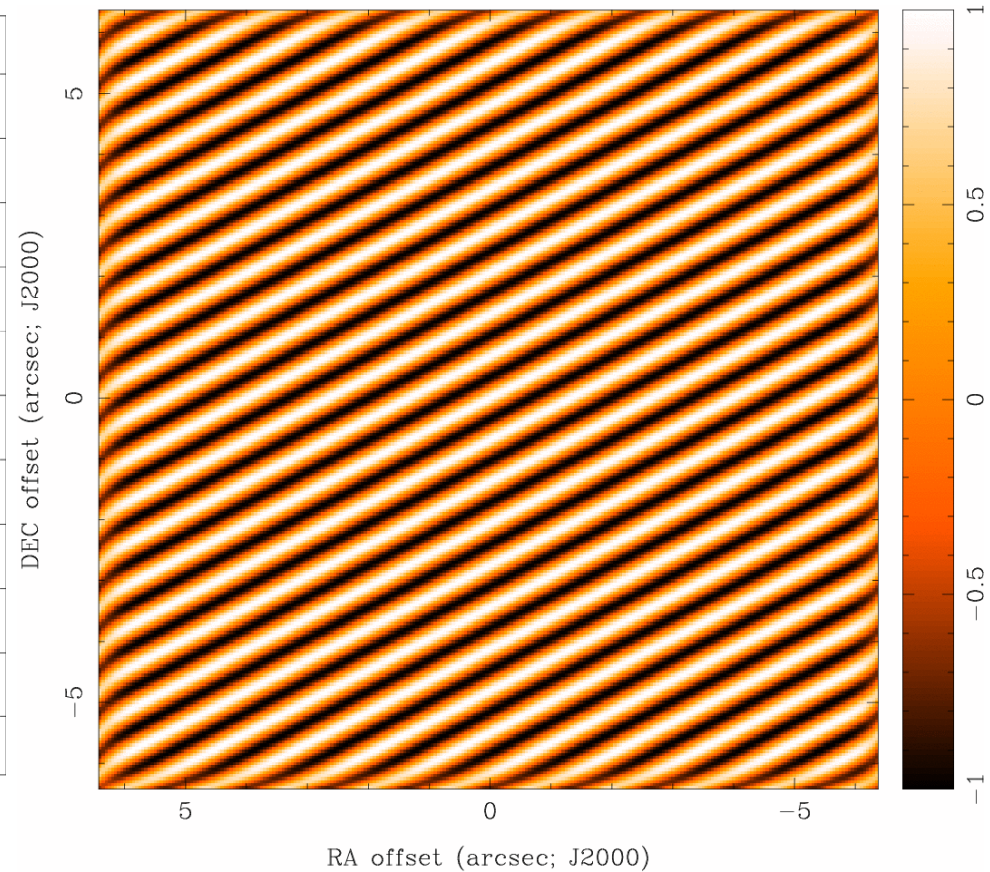
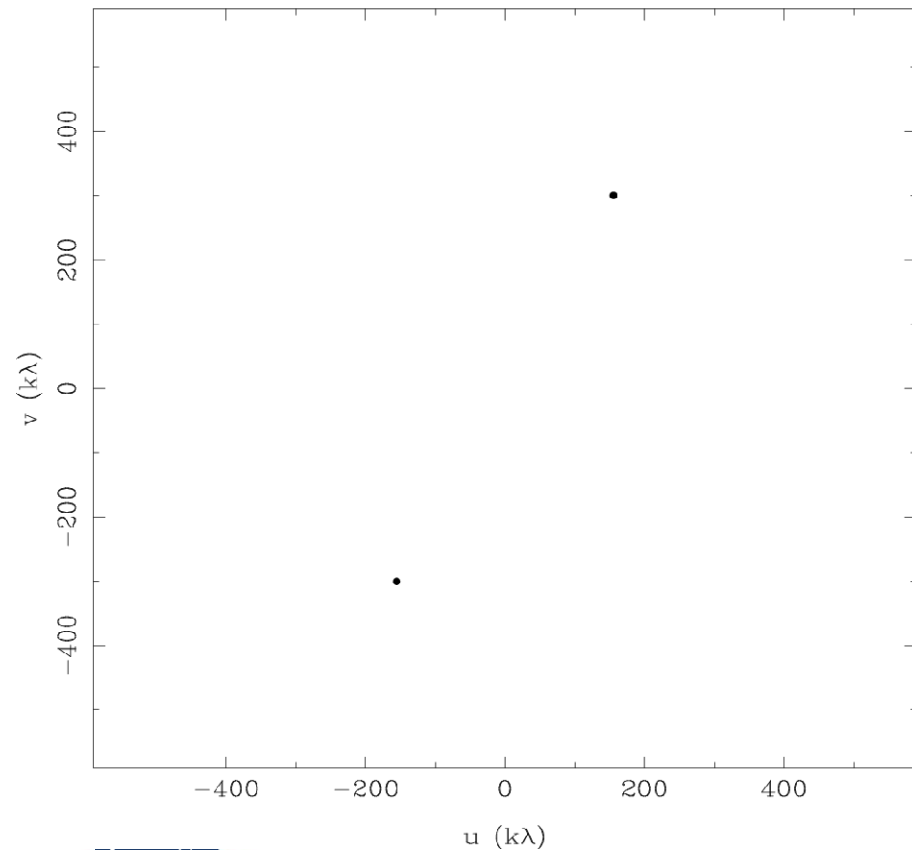
➔ Technical justification



Dirty Beam Shape and N Antennas

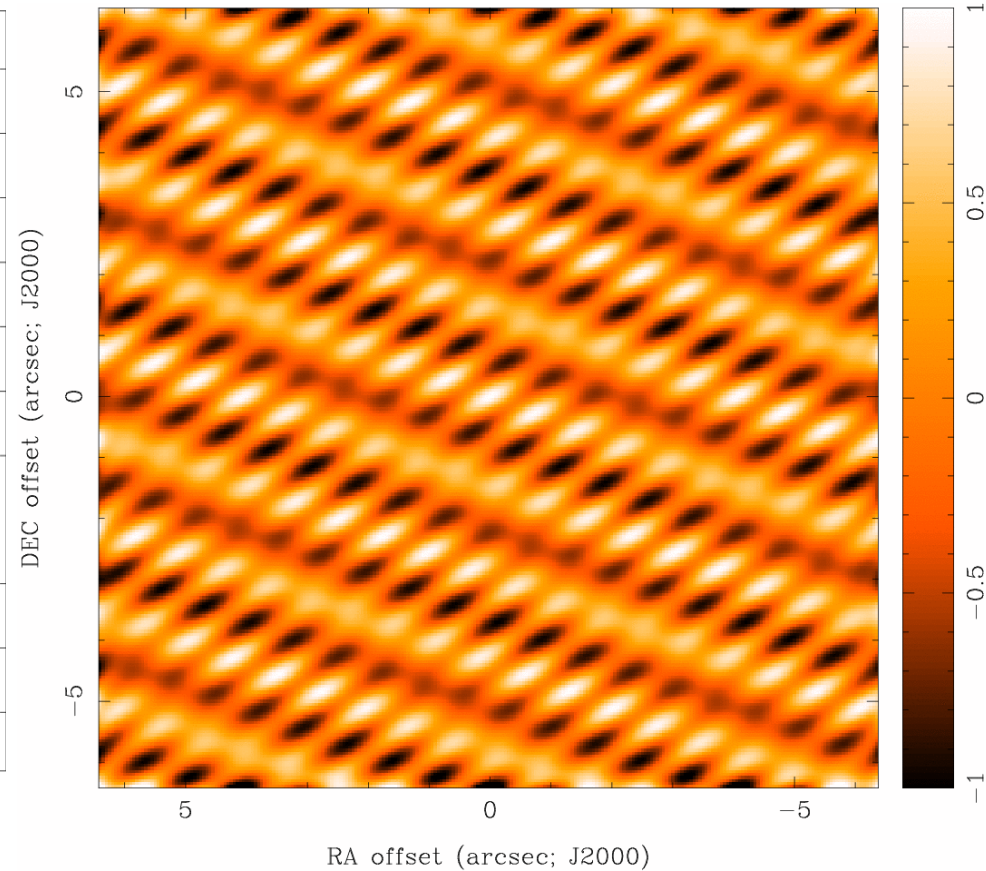
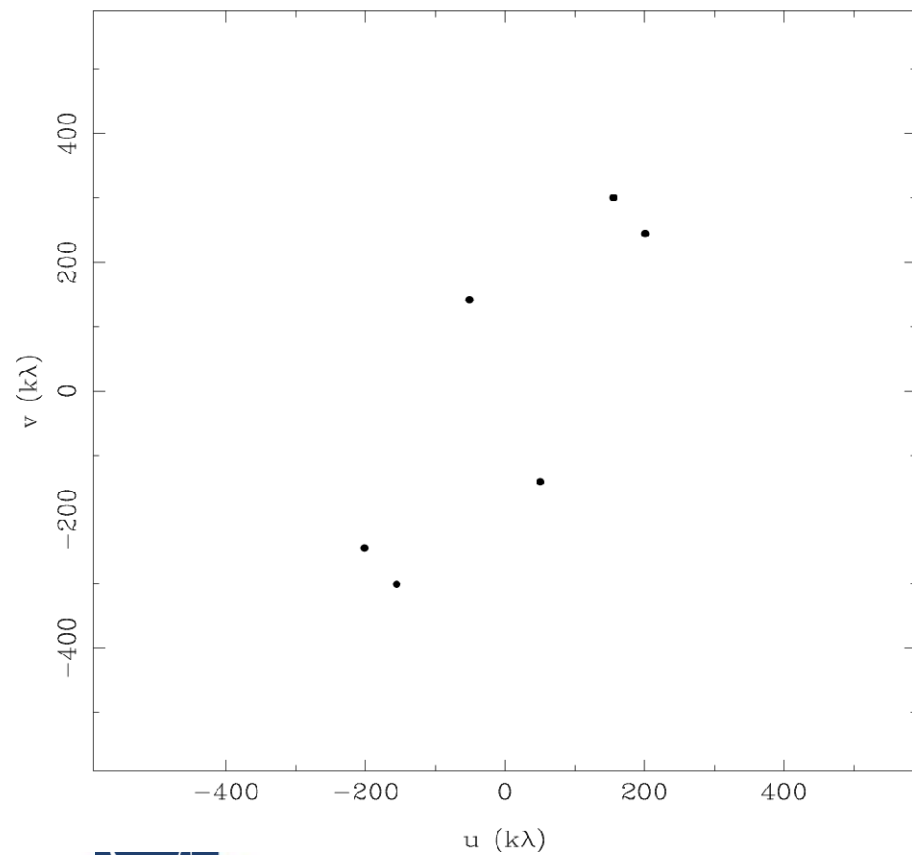
(Image sequence taken
from Summer School
lecture by D. Wilner)

2 Antennas



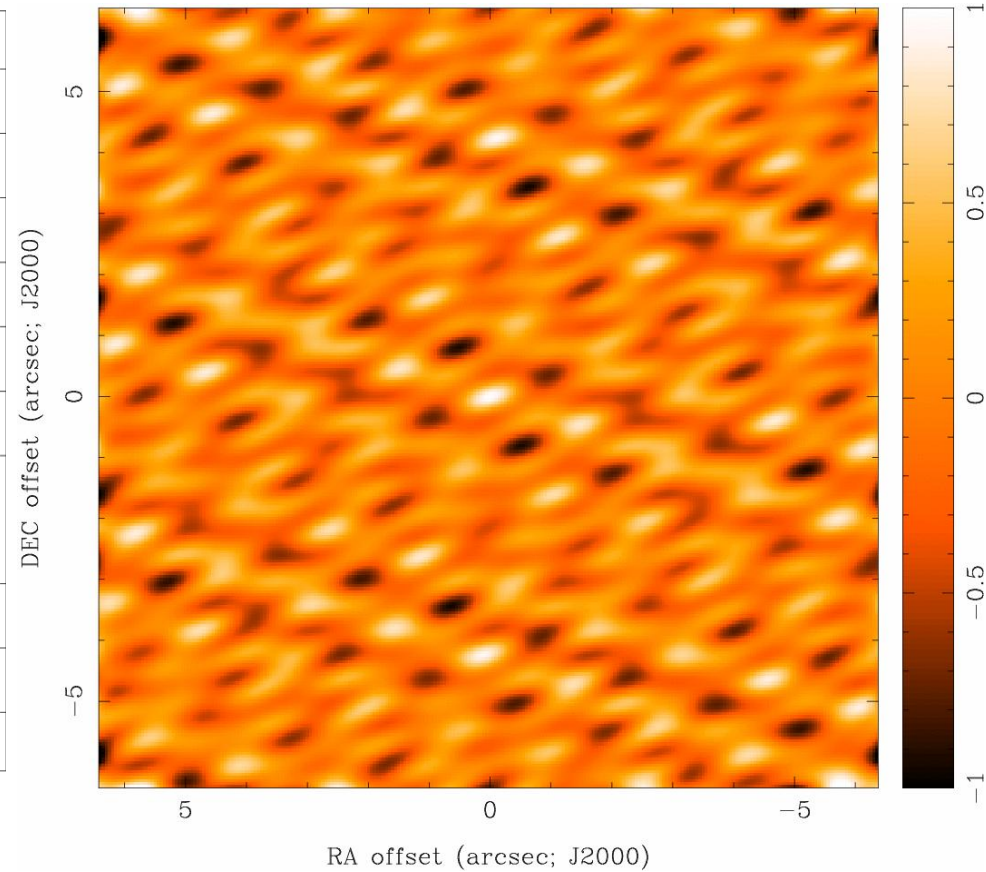
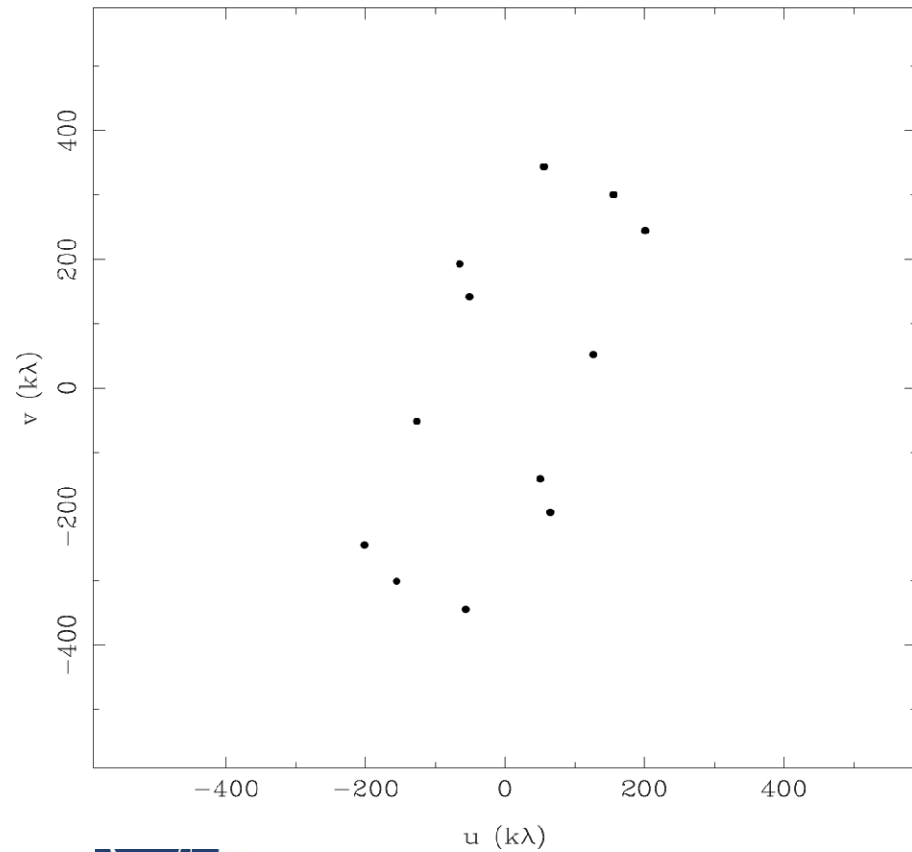
Dirty Beam Shape and N Antennas

3 Antennas



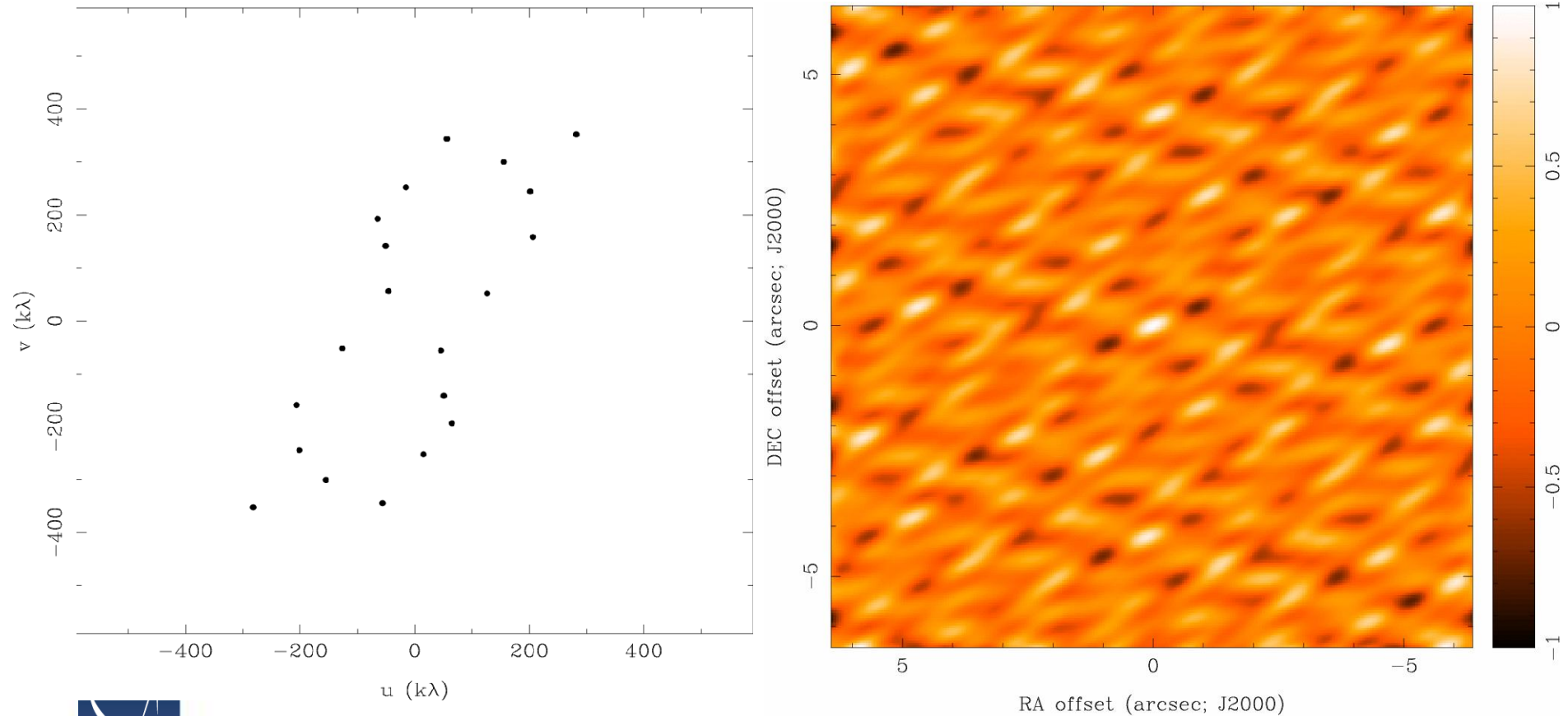
Dirty Beam Shape and N Antennas

4 Antennas



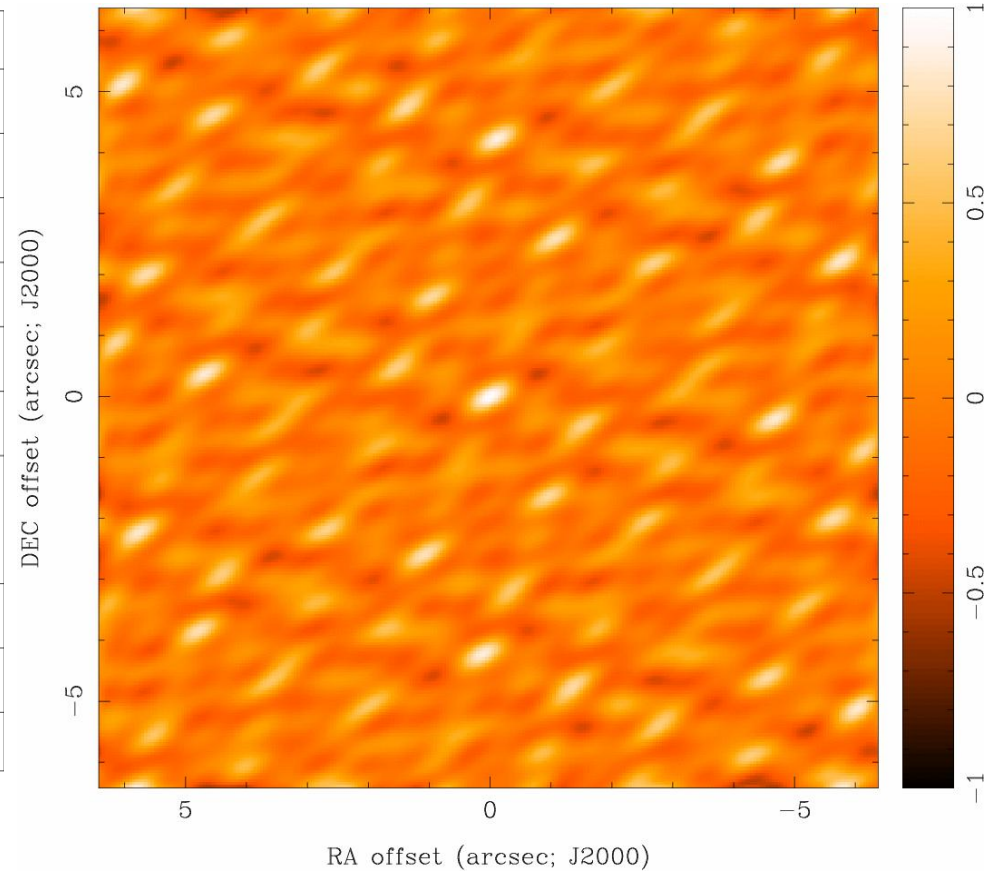
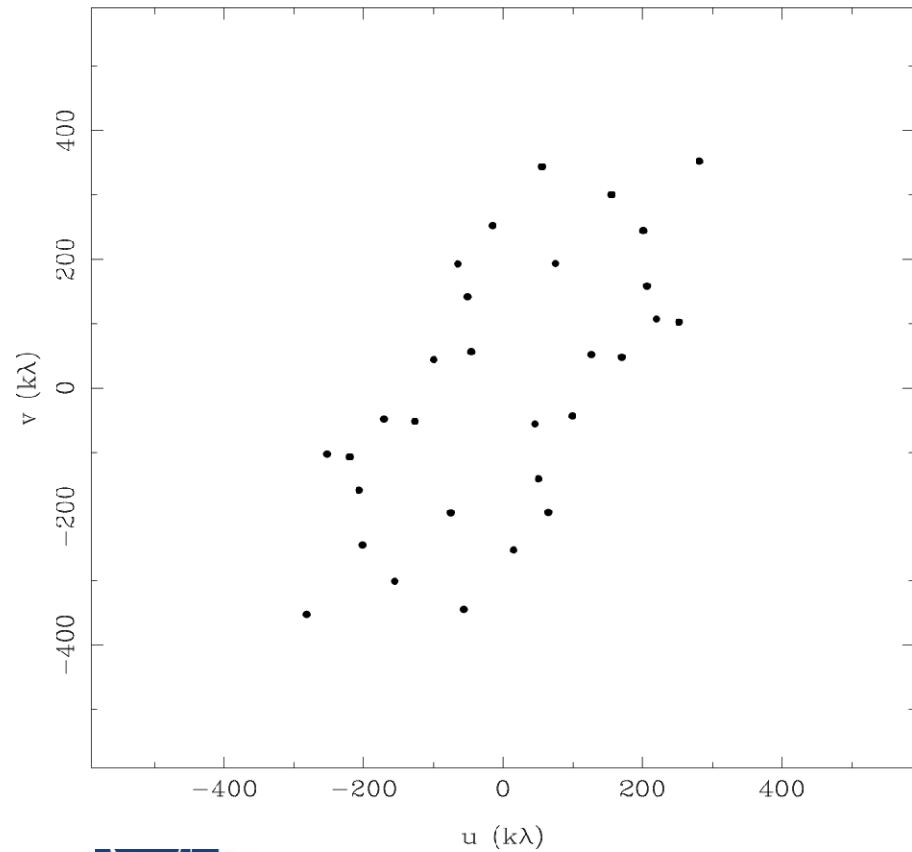
Dirty Beam Shape and N Antennas

5 Antennas



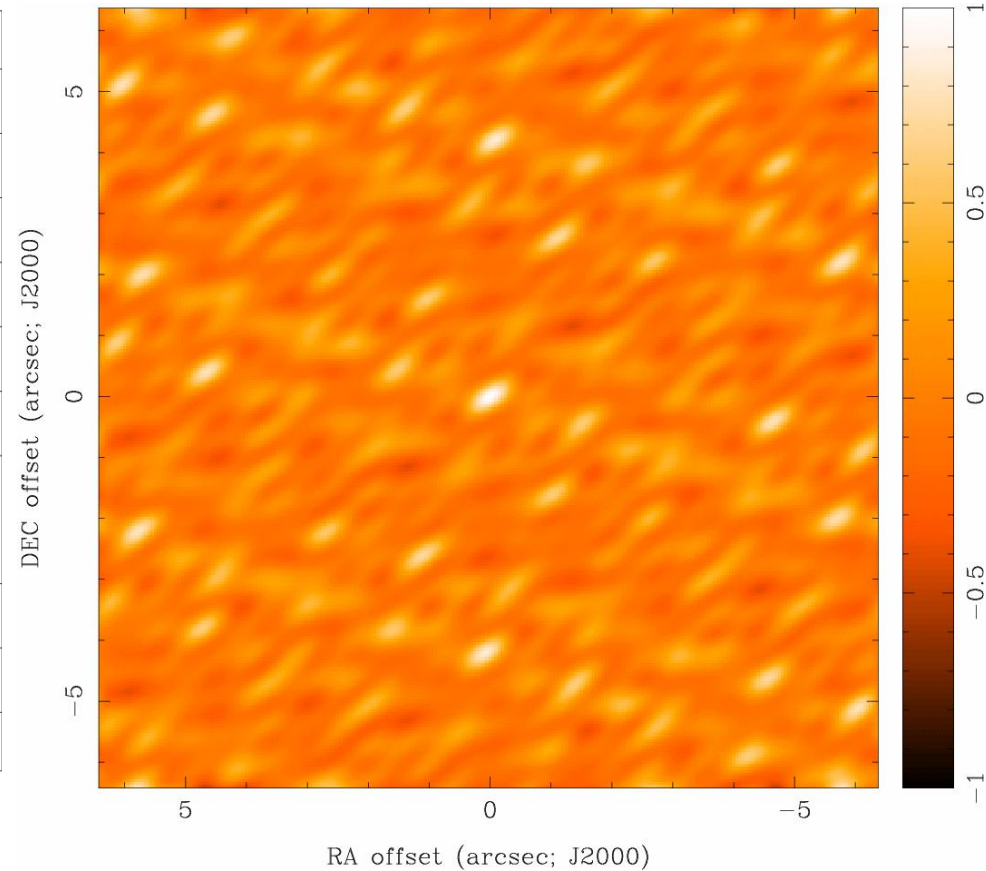
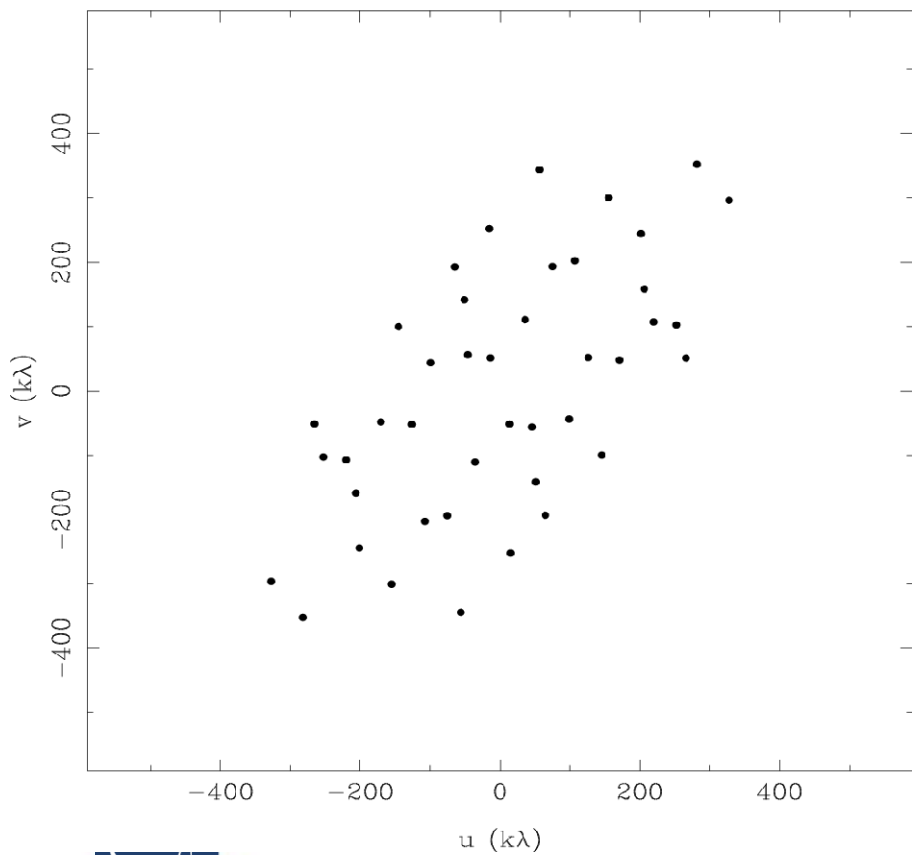
Dirty Beam Shape and N Antennas

6 Antennas



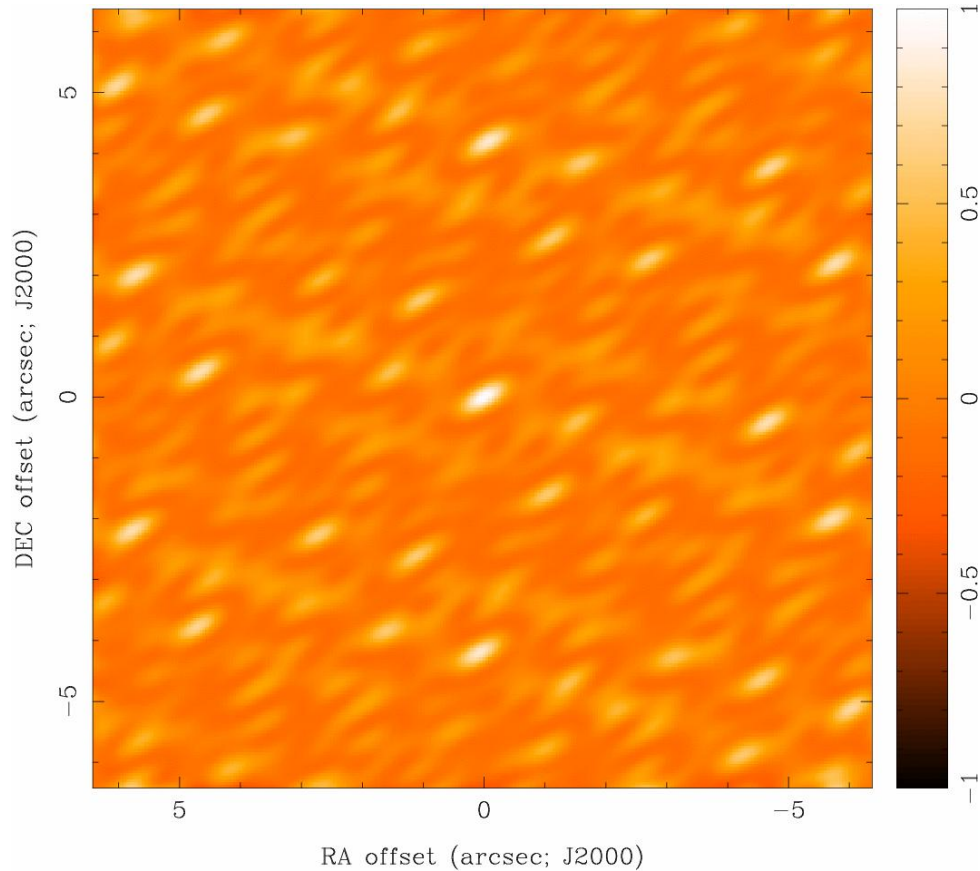
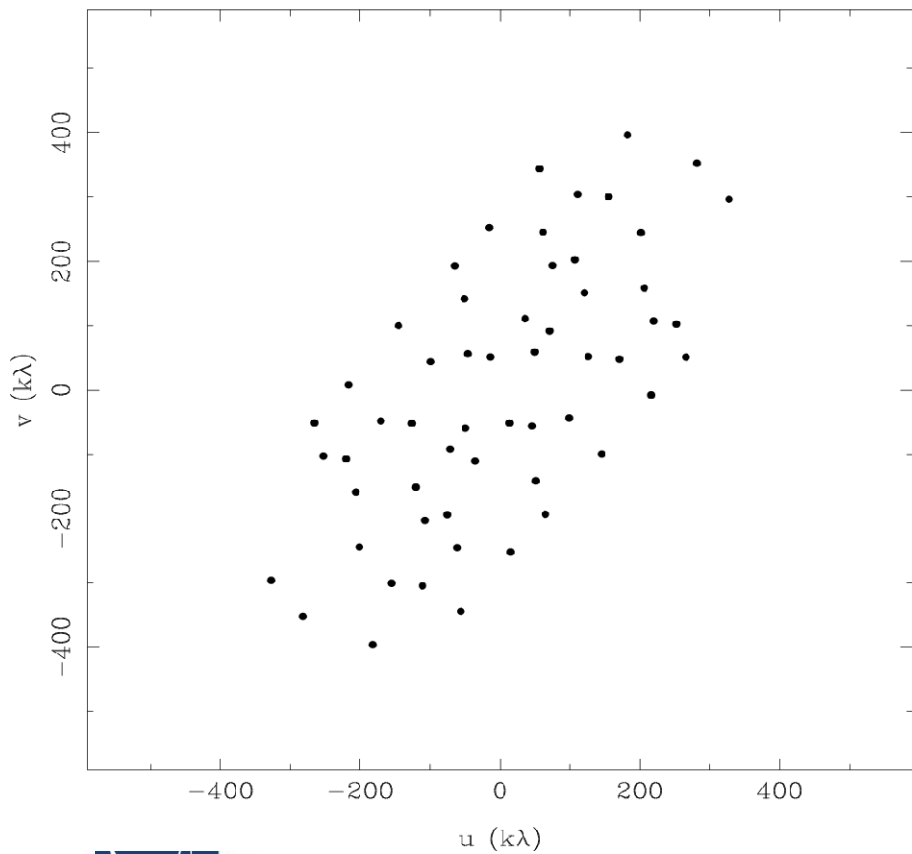
Dirty Beam Shape and N Antennas

7 Antennas



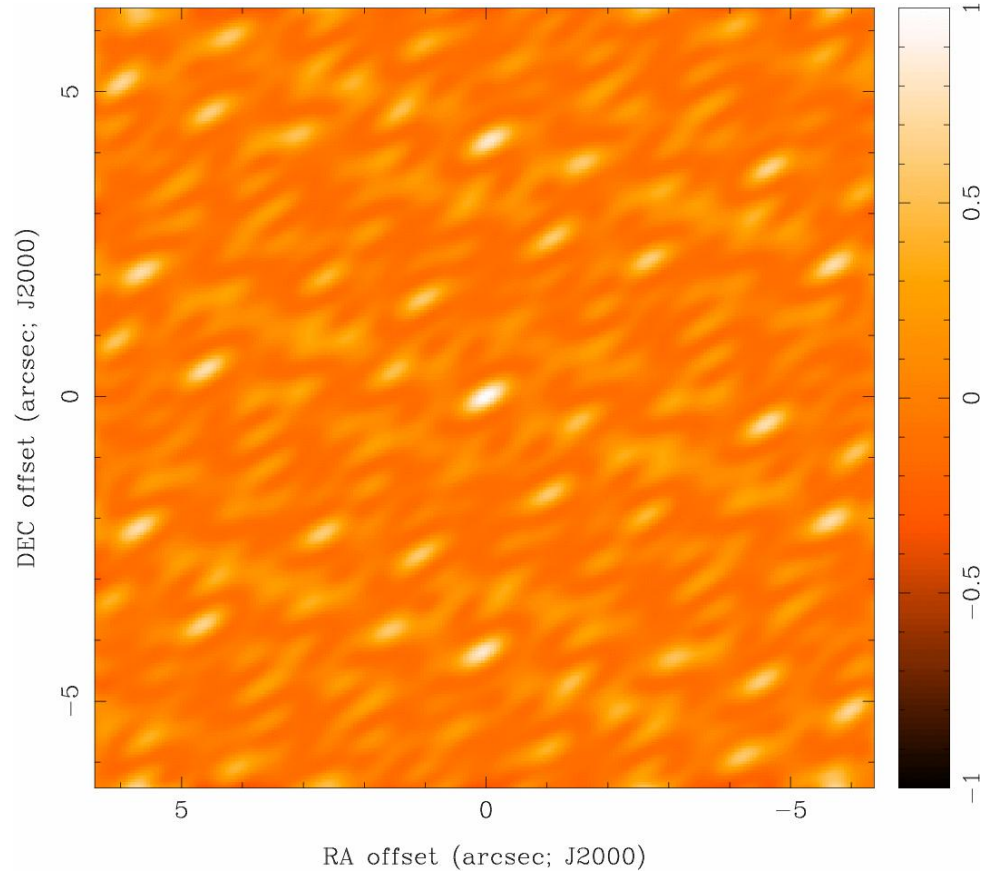
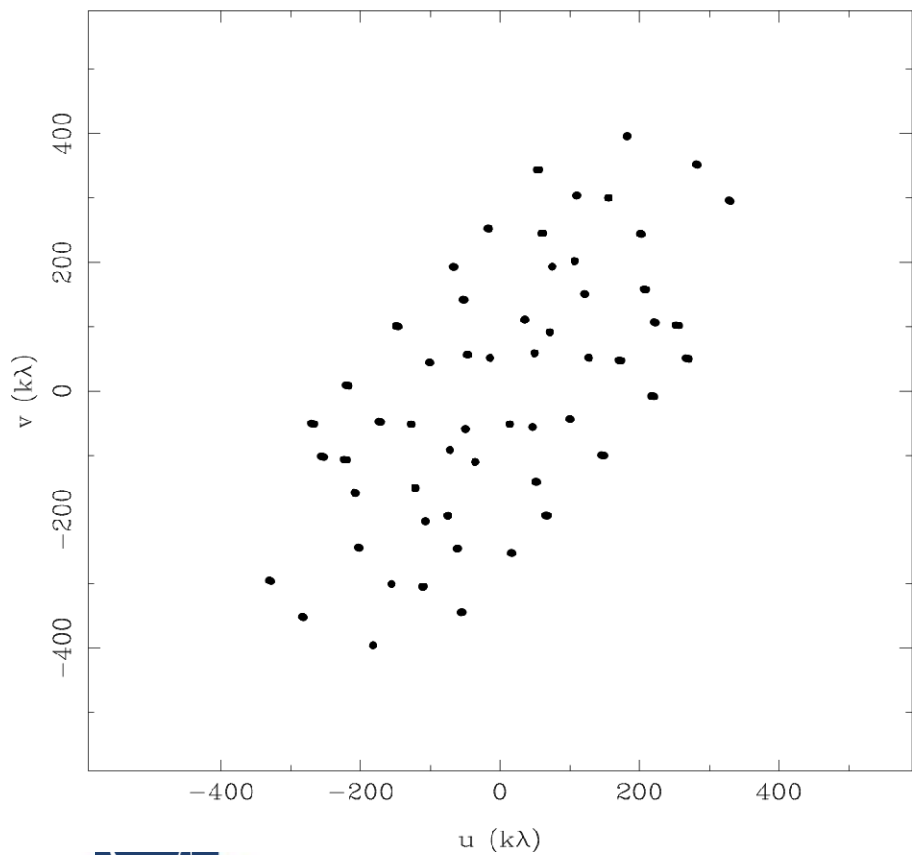
Dirty Beam Shape and N Antennas

8 Antennas



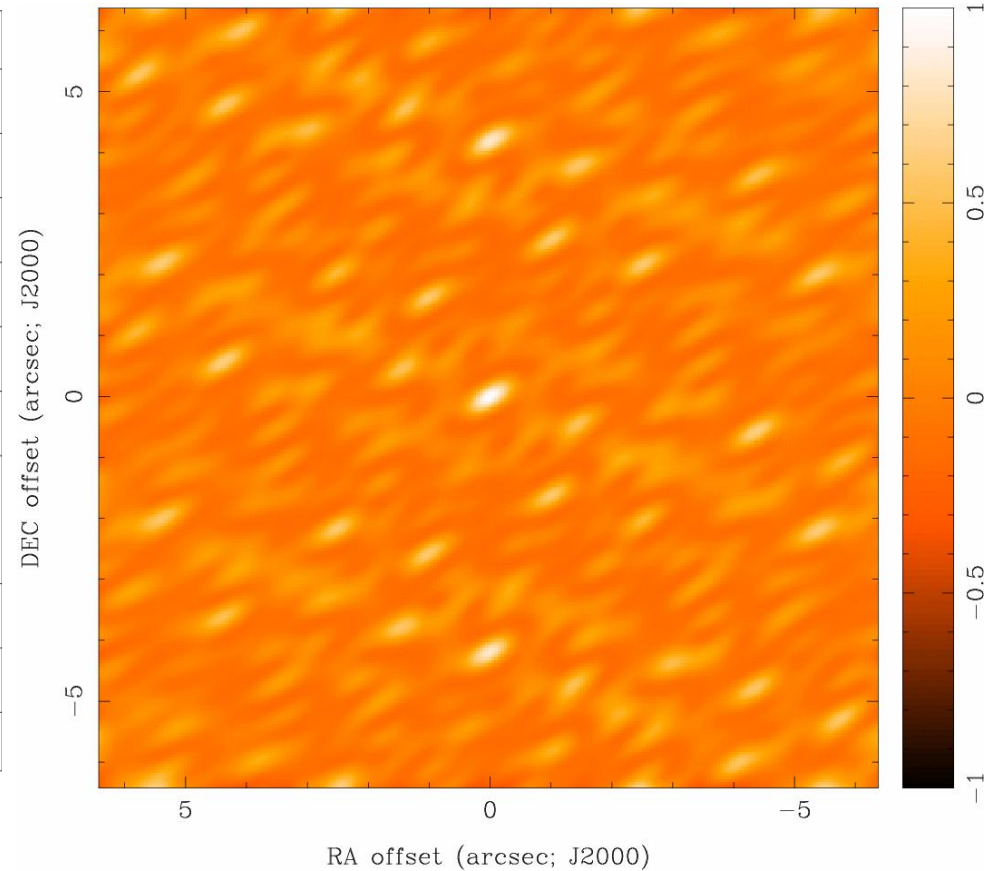
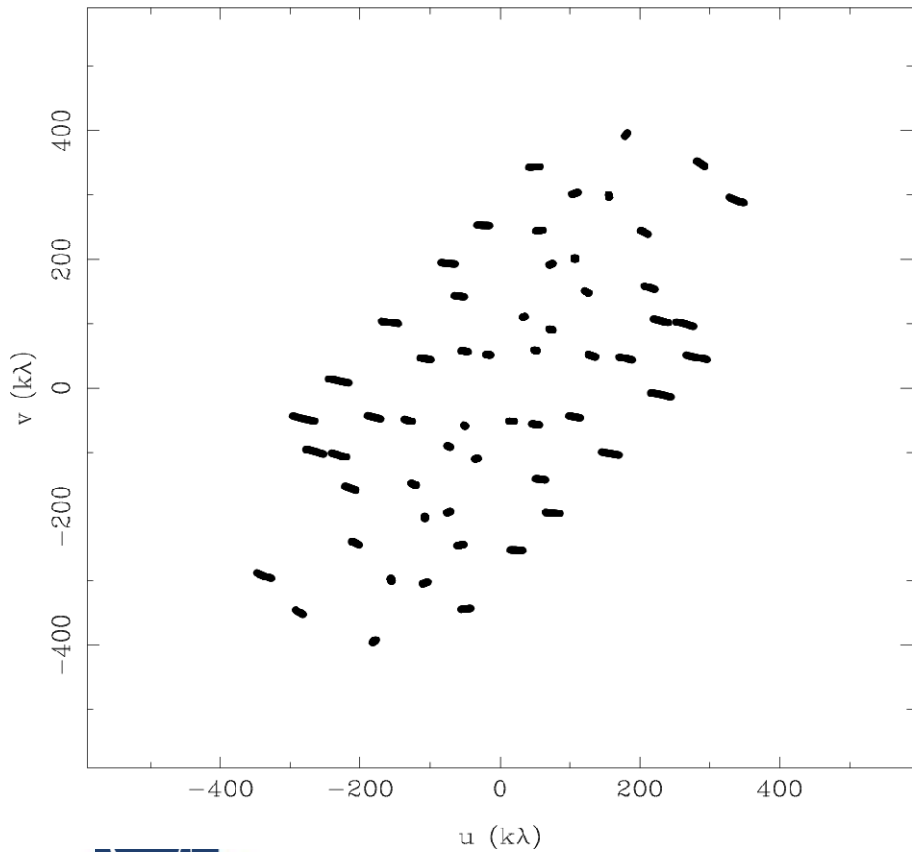
Dirty Beam Shape and N Antennas

8 Antennas x 6 Samples



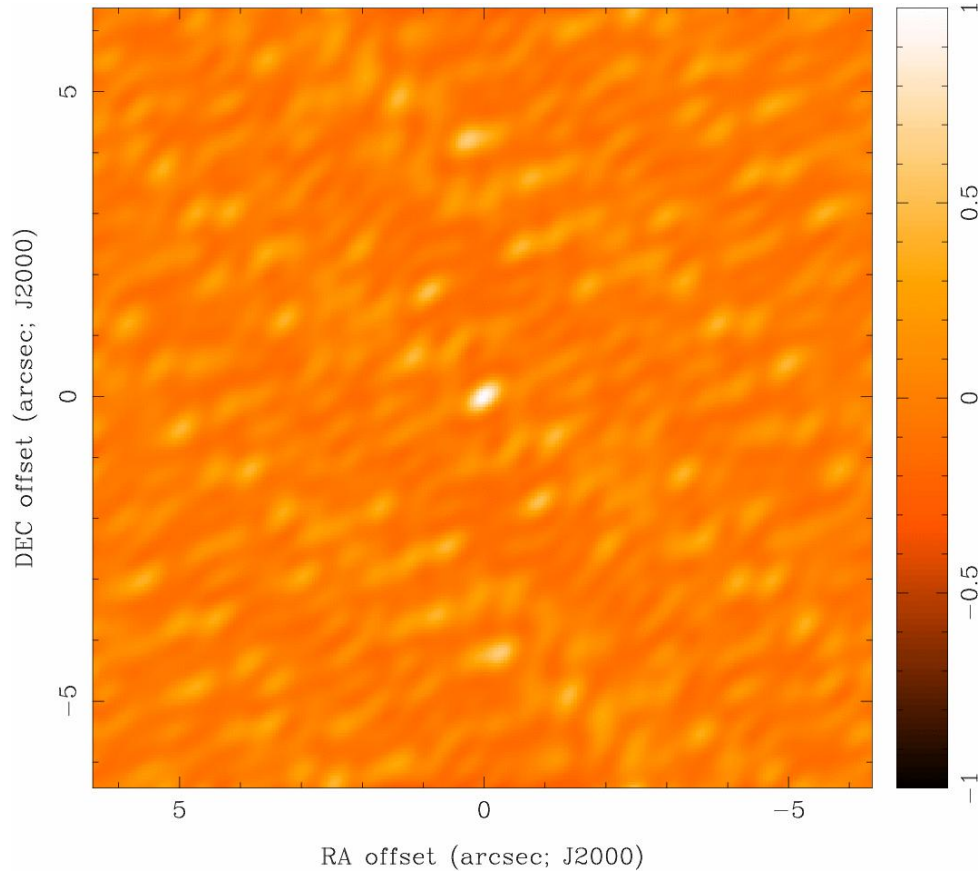
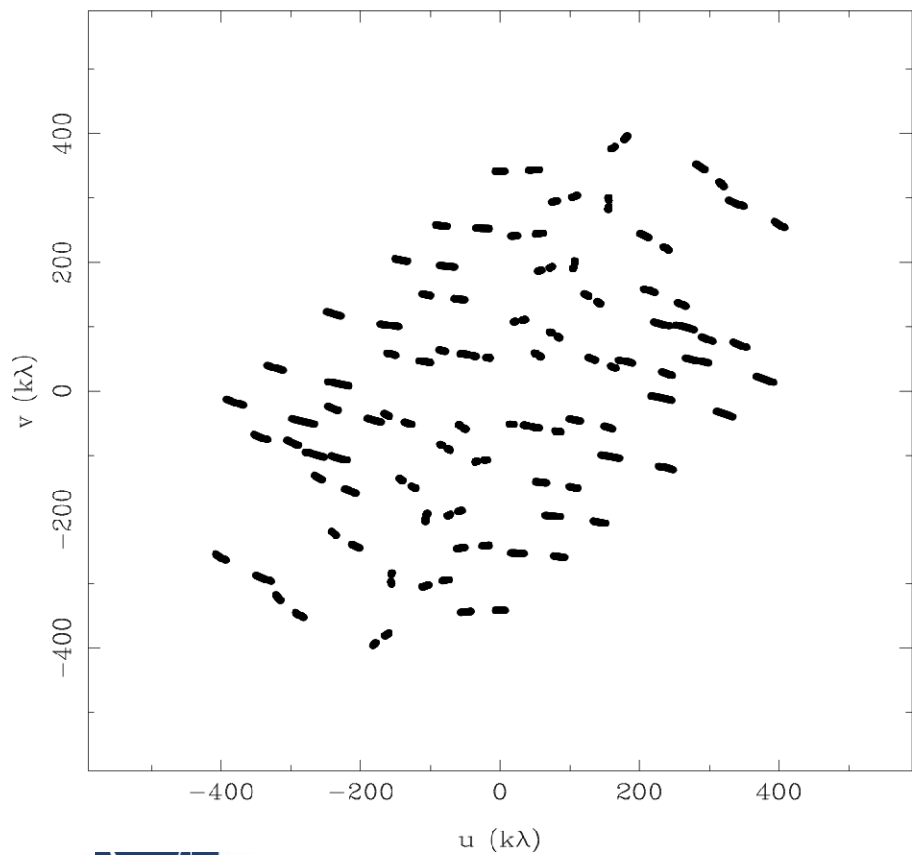
Dirty Beam Shape and N Antennas

8 Antennas x 30 Samples



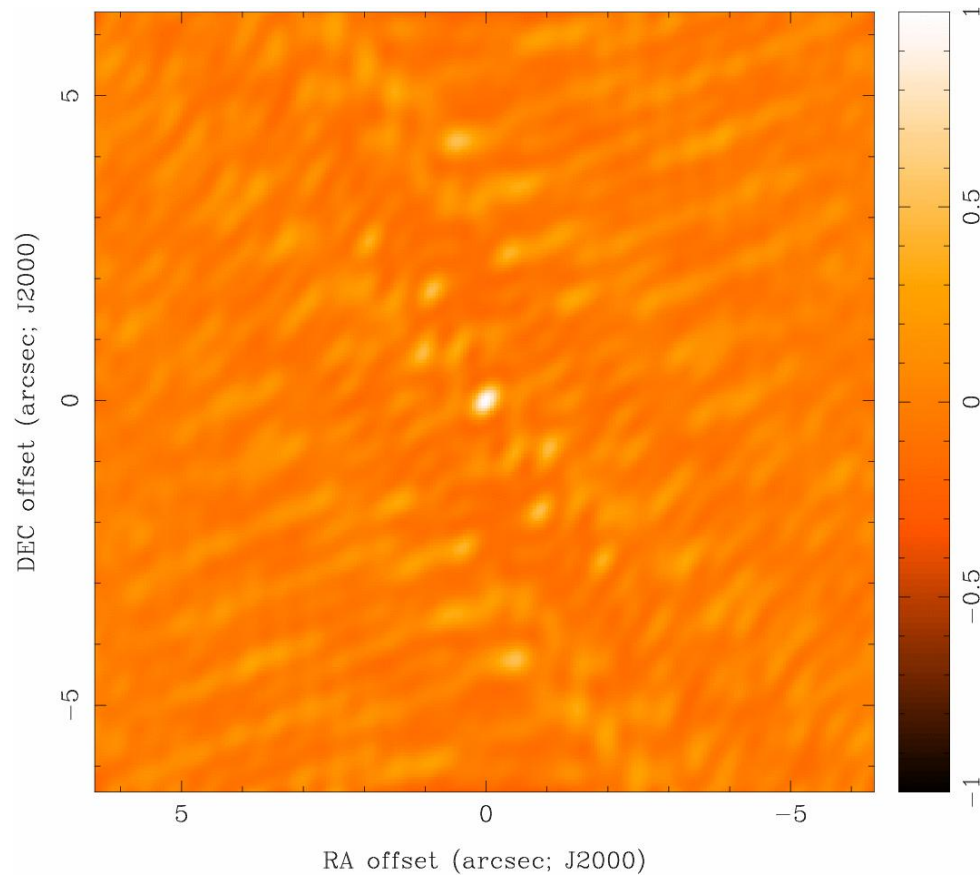
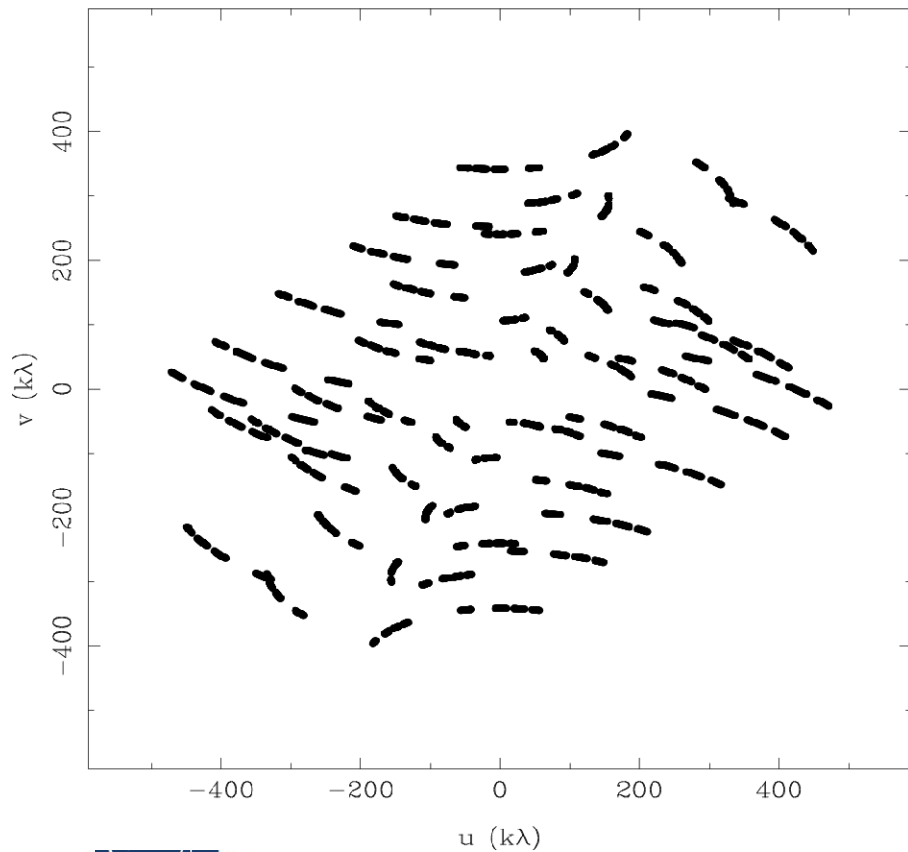
Dirty Beam Shape and N Antennas

8 Antennas x 60 Samples



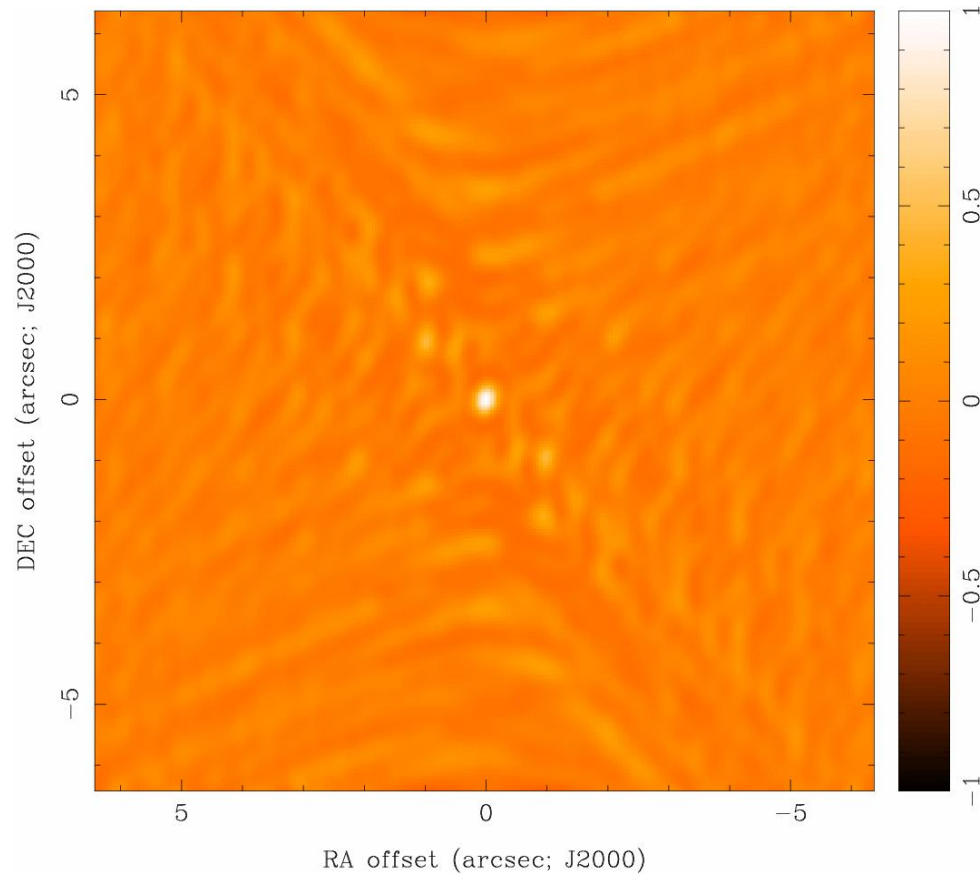
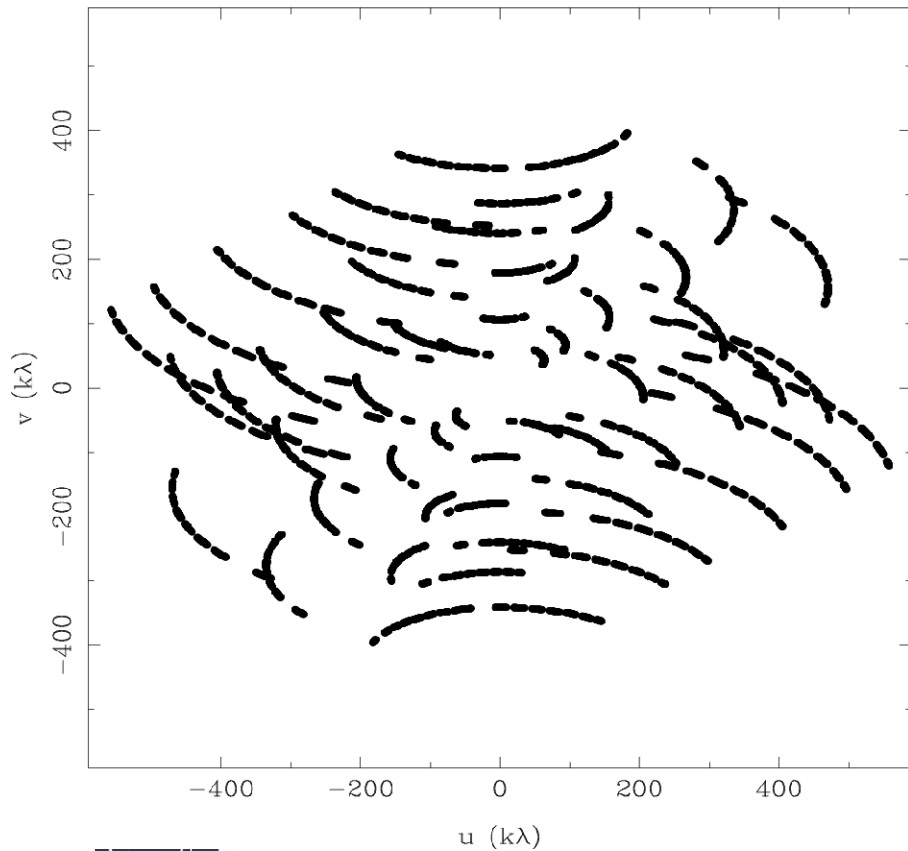
Dirty Beam Shape and N Antennas

8 Antennas x 120 Samples



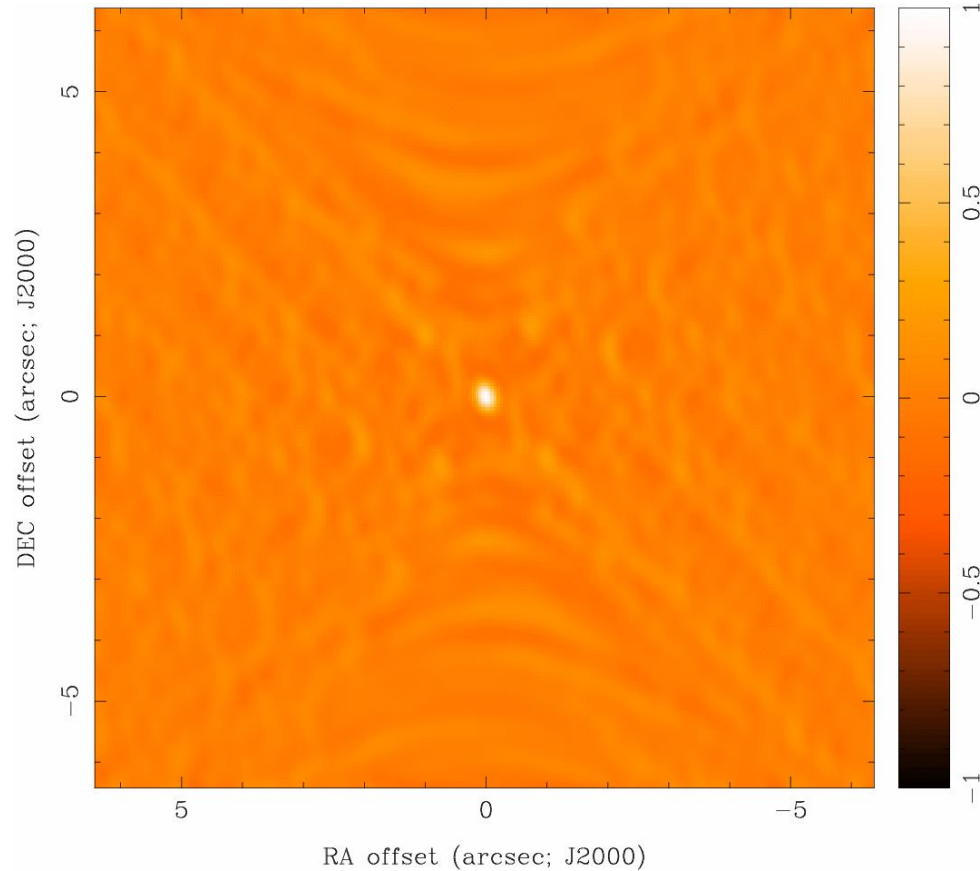
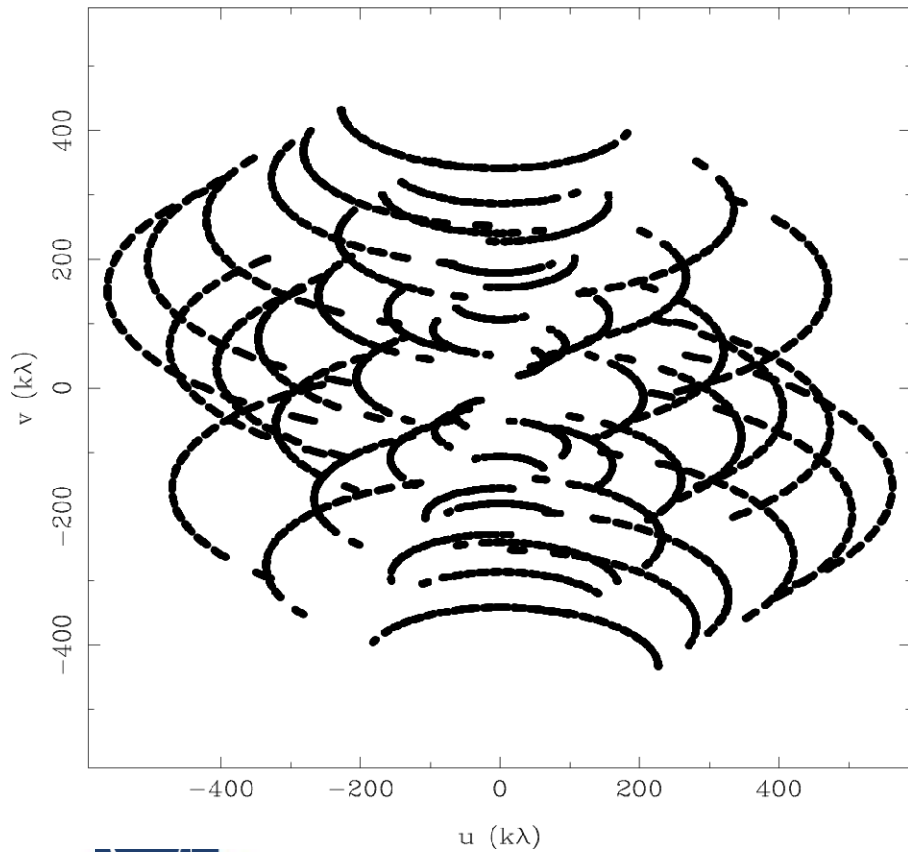
Dirty Beam Shape and N Antennas

8 Antennas x 240 Samples



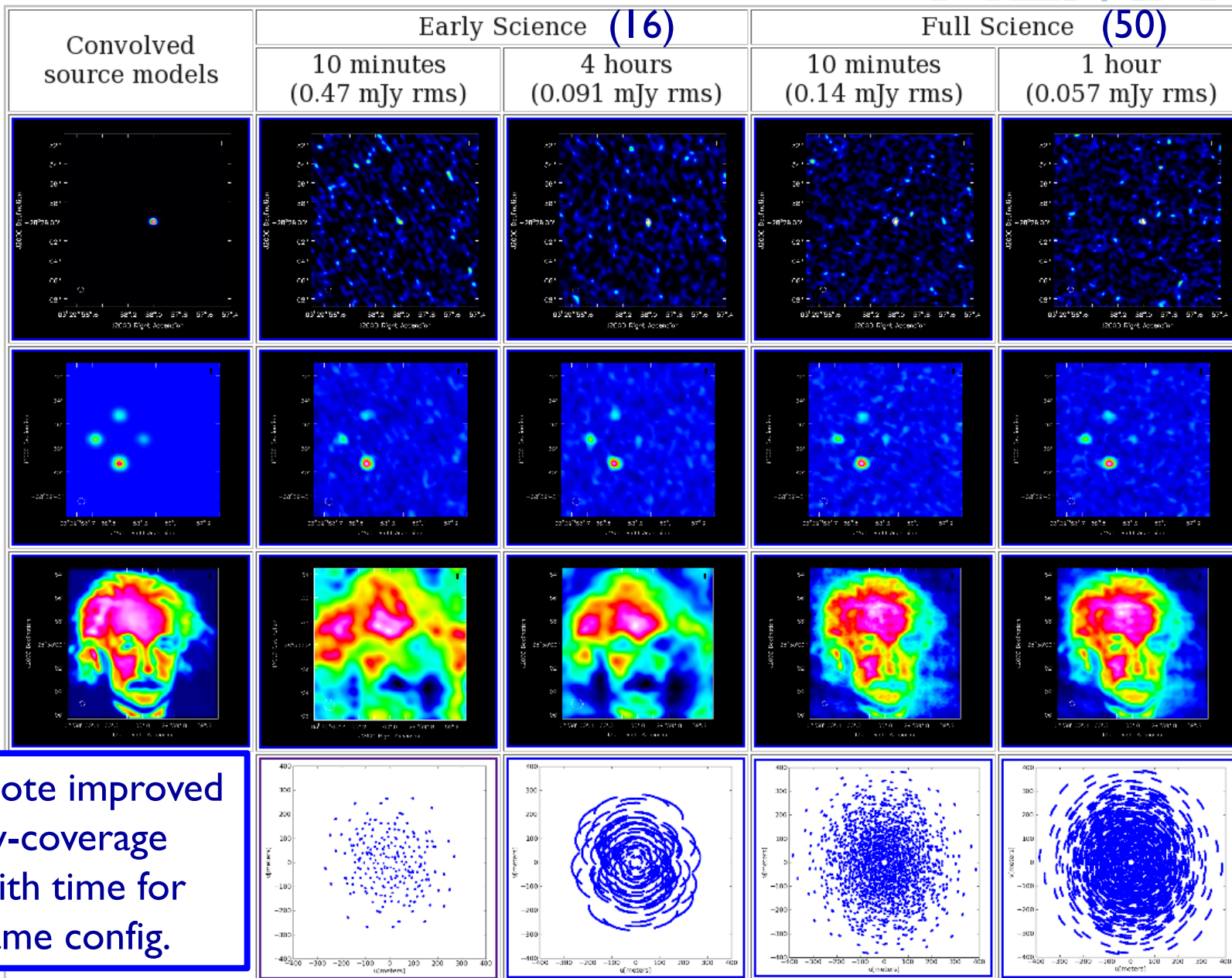
Dirty Beam Shape and N Antennas

8 Antennas x 480 Samples



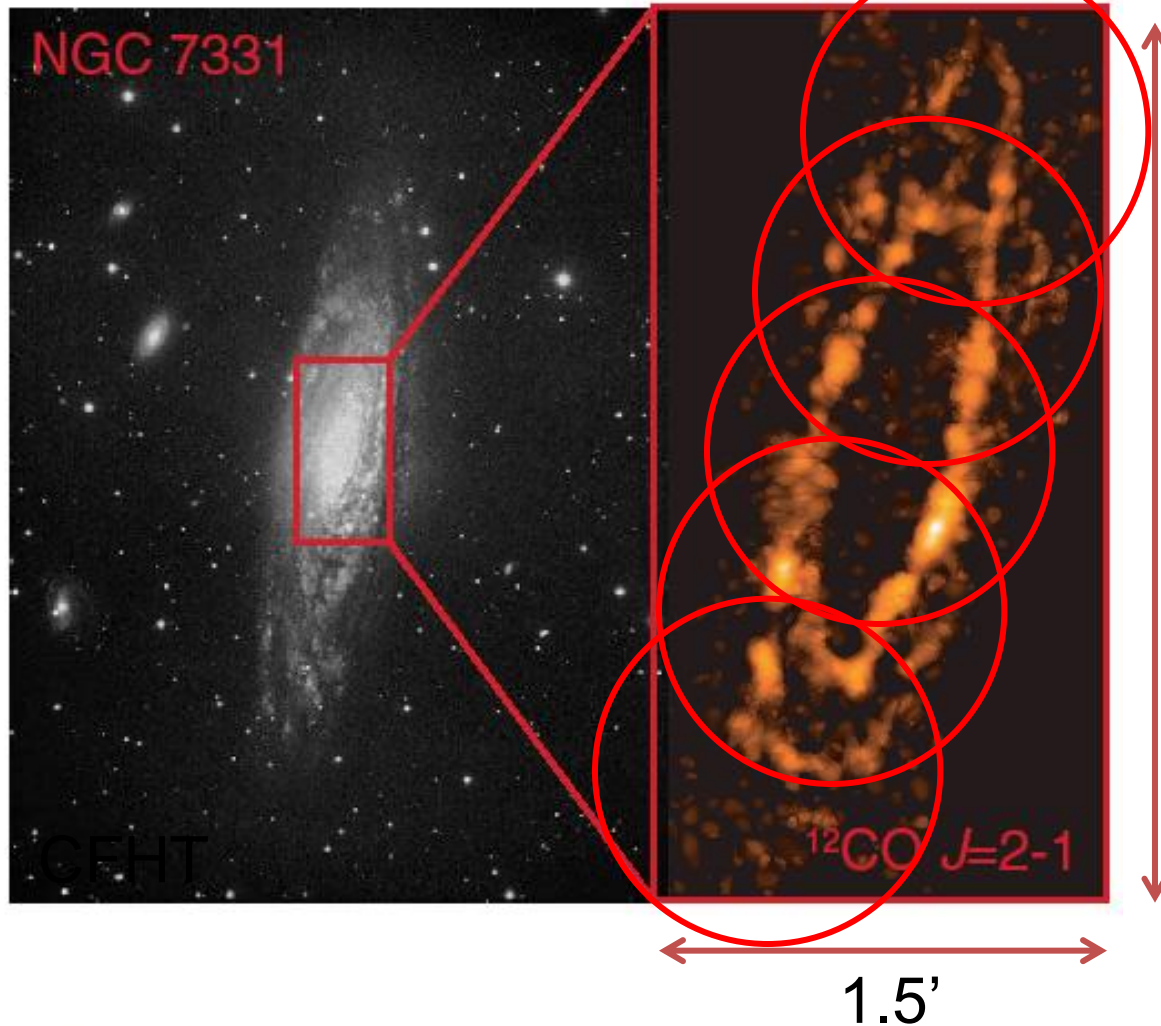
Effects of UV Coverage

ALMA



Note improved uv-coverage with time for same config.

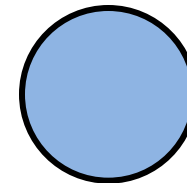
Source Size: Single Field or Mosaic



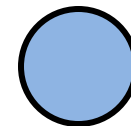
Example: SMA 1.3 mm observations: 5 pointings

- Primary beam $\sim 1'$
- Resolution $\sim 3''$

3.0'



ALMA 1.3mm
PB



ALMA 0.85mm
PB

In ES, the number of pointings will be limited

Band	Frequency (GHz)	Primary beam (")	Approximate Largest Angular Scale in compact configuration (")
3	84-116	72 - 52	37
6	211-275	29 - 22	18
7	275-373	22 - 16	12
9	602-720	10 – 8.5	6

- **Smooth** structures larger than LAS are completely resolved out
- Begin to lose total recovered flux for objects on the order of half LAS
- The LAS of the 400m configuration will likely be smaller than the 125m configuration

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

$$S_\nu = \frac{2\nu^2 kT}{c^2} \Omega_s.$$

An alternate formulae that is often useful is

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

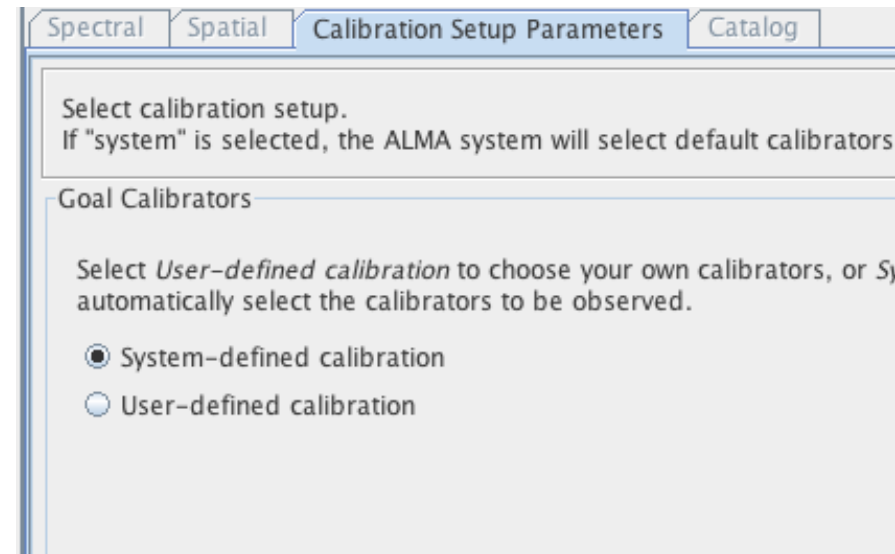
Example: 1 minute integration at 230 GHz with 1 km/sec channels:

Configuration	Beamsize	Flux density Sensitivity	Brightness sensitivity
125 m	3''	48 mJy/beam	0.14 K
400 m	1''	48 mJy/beam	1.2 K

Observatory Default Calibration

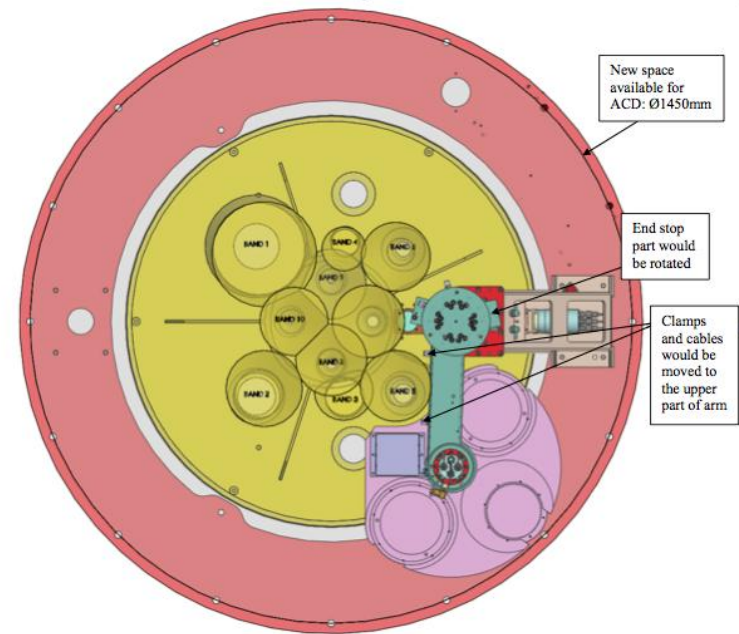
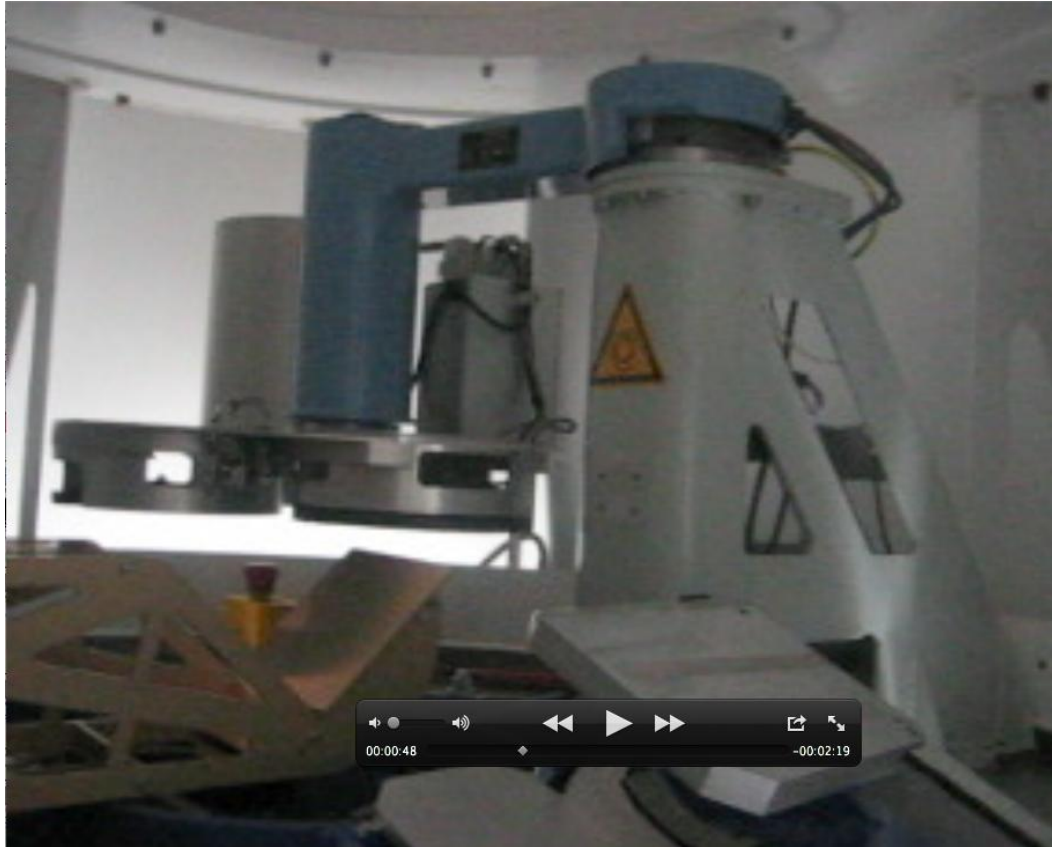


- Need to measure and remove the (time-dependent and frequency-dependent) atmospheric and instrumental variations.
- Set calibration to **system-defined calibration** unless you have very specific requirements for calibration (which then must be explained in the Technical Justification). Defaults include (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



ALMA Calibration Device

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



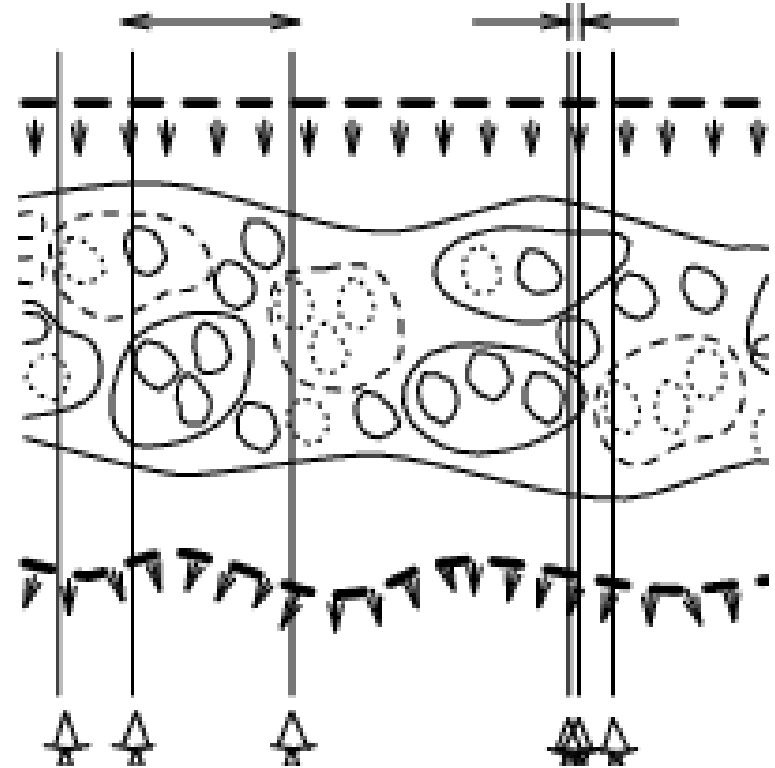
$$T_{\text{sys}} \approx T_{\text{atm}}(e^{\tau} - 1) + T_{\text{rx}}e^{\tau}$$

$$\tau = \tau_0 \sec(\epsilon)$$

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 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.

- **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, 2pol, 8GHz, 1 minute	0.64 mJy/beam	0.10
1 baseline, 2pol, 8GHz, 1 minute	15 mJy	2.5
1 baseline, 1pol, 2 GHz	60 mJy	10 mJy
3-sigma	180 mJy	30 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)

- **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 = WVR

- **Water Vapor Radiometry (WVR) concept:** measure the rapid fluctuations in $T_{\text{B}}^{\text{atm}}$ 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:

$$\otimes \phi_e \approx 12.6\pi \otimes w / \lambda$$

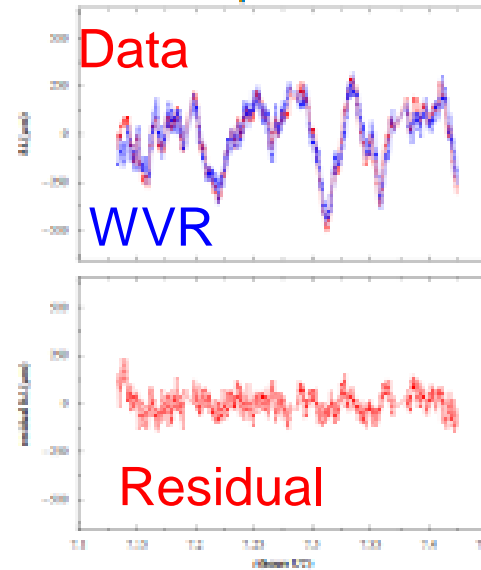
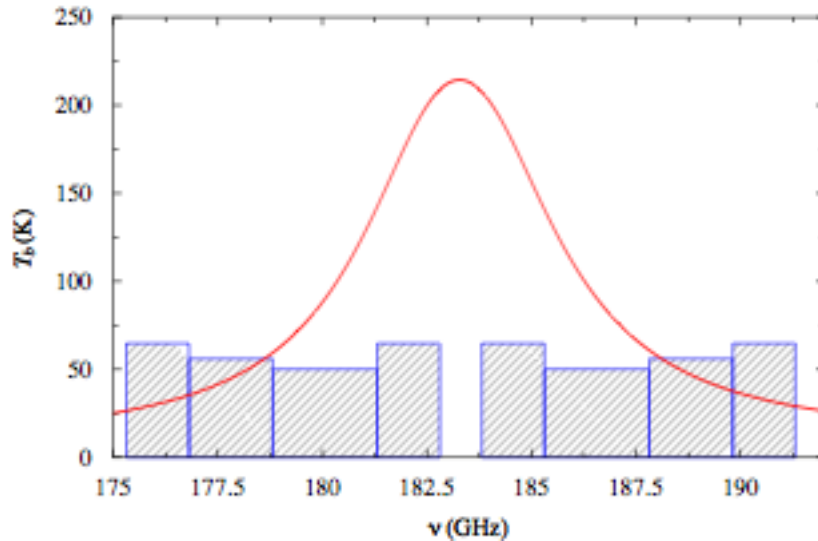
Tests of ALMA WVR Correction



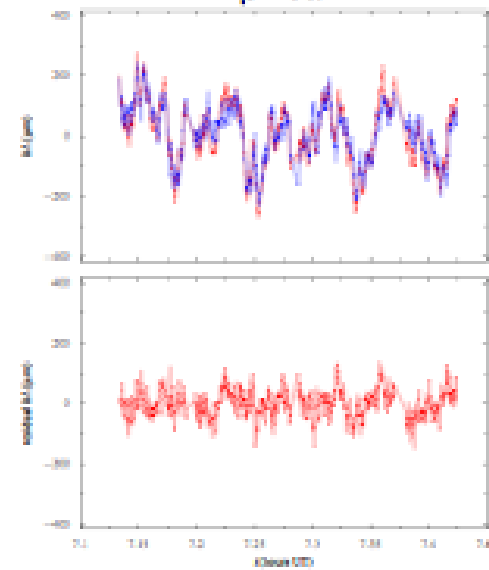
Two different baselines Jan 4, 2010

The 183 GHz Water Vapour Line

Blue rectangles are the production WVR filters



Residual RMS: 60 μm



Residual RMS: 46 μm

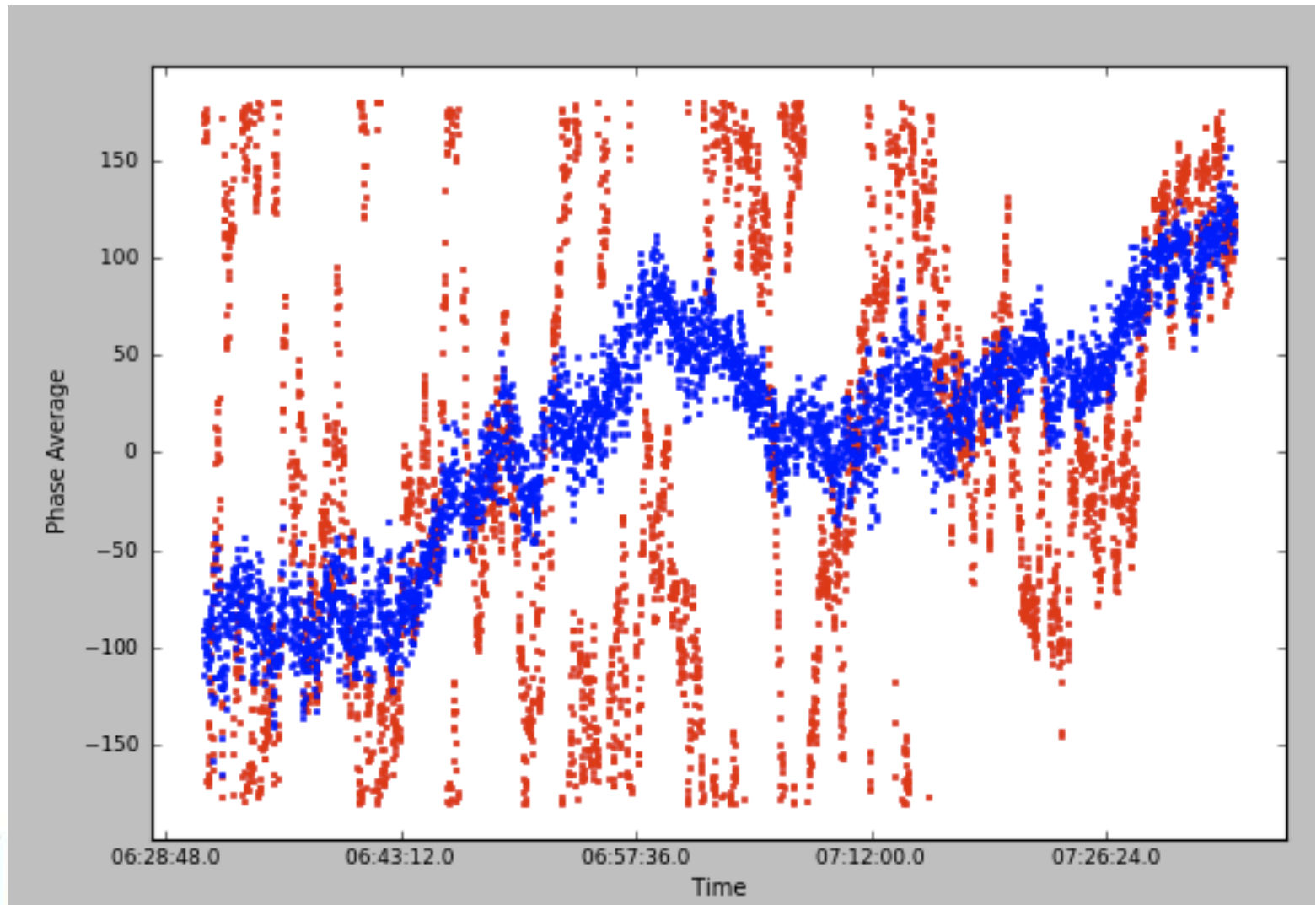
There are 4 “channels” flanking the peak of the 183 GHz water line

- 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 Correction



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



- **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 $T_{\text{B}}^{\text{atm}}$ with a radiometer, then use these to derive changes in water vapor column (w) and convert these into phase corrections using:
$$\otimes \phi_e \approx 12.6\pi \otimes w / \lambda$$
- **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:** for bright sources. Need S/N per baseline of a few on short times scales (typically a few seconds).

- >3x better sensitivity with 50 x 12m antennas in main array
 - Fantastic “snapshot” uv-coverage (1225 baselines)
 - Imaging fidelity ~10x better!
- Higher angular resolution: baselines ~15km, matched beams possible in all bands
- Better imaging of resolved objects and mosaics
 - TPA: 4 x 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



www.almaobservatory.org

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