MM Interferometry and ALMA

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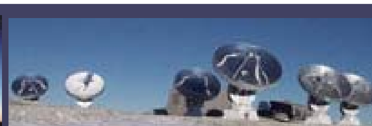
Claire Chandler & Todd Hunter

- Why a special lecture on mm interferometry?
  - High frequency interferometry suffers from unique problems
  - We are poised on the brink of a mm/summ revolution with the advent of new telescopes

Tenth Synthesis Imaging Summer School, University of New Mexico, June 13-20, 2006

Outline


- Summary of existing and future mm/sub-mm arrays
- Unique science at mm & sub-mm wavelengths
- Problems unique to mm/sub-mm observations
  - Atmospheric opacity
  - Absolute gain calibration
  - Tracking atmospheric phase fluctuations
  - Antenna and instrument constraints
- Summary
- Practical aspects of observing at high frequency with the VLA


Summary of existing and future mm/sub-mm arrays

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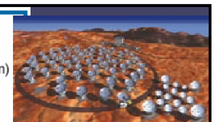
Telescope	altitude (feet)	diam. (m)	No. dishes	A (m²)	ν_{max} (GHz)
NMA	2,000	10	6	470	250
CARMA[1]	7,300	3.5/6/10	23	800	250
IRAM PdB	8,000	15	6	1060	250
JCMT-CSO	14,000	10/15	2	260	650
SMA	14,000	6	8	230	650
ALMA[2]	16,400	12	50	5700	950

[1] BIMA+OVRO+SZA 3.5 m Array at higher site = CARMA first call for proposals soon

[2] First call for early science proposals expected in Q2 2009, planned for full operation by 2012

Capabilities of ALMA



Specifications

		Large Array	Compact Array
Array	Number of Antennas	up to 64	12 (7 m) + 4 (12 m)
	Total Collecting Area	up to 7240 m²	460 + 450 m²
	Angular Resolution	0.02" (λ /1 mm)(10 km/baseline)	5.7" (λ /1 mm)
	Continuous Zoom	150 - 18500 m	
Antennas	Diameter	12 m	7 m, 12 m
	Surface Precision	<25 μm	<20 μm, <25 μm
	Offset Pointing	<0.6"	<0.6"
Correlator	Baselines	2016	120
	Bandwidth	16 GHz per baseline	16 GHz per baseline
	Spectral Channels	4096	4096

Band Number	Frequency Range (GHz)	Wavelength (mm)	Instantaneous Bandwidth (GHz)
1	31.3 - 45.0	6.7 - 9.6	1 × 8
2	67 - 90	3.3 - 4.5	1 × 8
3	84 - 116	2.6 - 3.6	2 × 4
4	125 - 163	1.8 - 2.4	2 × 4
5	163 - 211	1.4 - 1.8	2 × 4
6	211 - 275	1.1 - 1.4	1 × 8
7	275 - 373	0.8 - 1.1	2 × 4
8	385 - 500	0.6 - 0.8	2 × 8
9	602 - 720	0.4 - 0.5	2 × 8
10	787 - 950	0.3 - 0.4	2 × 8

First Light

ALMA Sensitivity Goals for Receivers Available at First Light (Large Array)

For an integration time of 60 seconds, the RMS flux density and brightness temperature sensitivity will be:

Frequency (GHz)	Continuum ΔS (mJy)	Spectral Line ΔS (mJy) 1 km s^{-1}	B_{max} = 0.2 km ΔT_{cont} (K)	B_{max} = 0.2 km ΔT_{line} (K)	B_{max} = 15 km ΔT_{cont} (K)	B_{max} = 15 km ΔT_{line} (K)
110	0.037	5.5	0.0005	0.070	2.7	390
140	0.040	5.8	0.0005	0.075	2.9	420
230	0.061	6.2	0.0008	0.080	4.4	450
345	0.150	13.0	0.0019	0.160	11	900
409	0.260	20.0	0.0034	0.260	19	1500
675	0.800	48.0	0.0010	0.610	57	3400

Progress in ALMA construction

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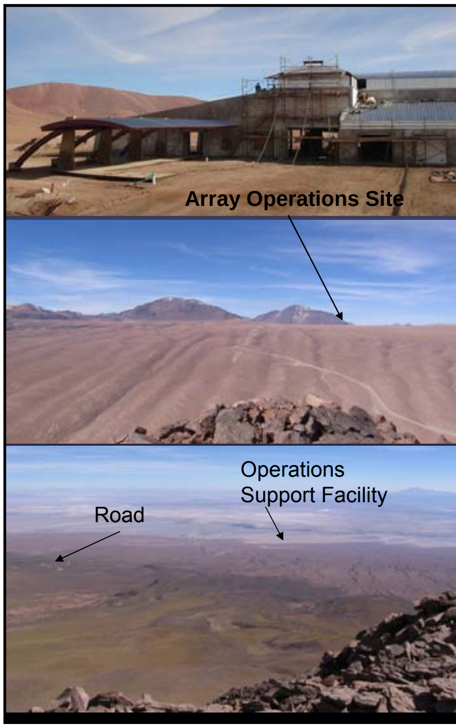

The Tri-Partner ALMA Project

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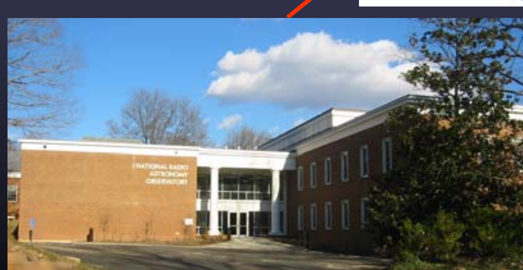

One-stop shopping for NA astronomers

- Proposals
- Observing scripts
- Data archive and reduction

NAASC: North America ALMA Science Center, Charlottesville, VA

Why do we care about mm/submm?

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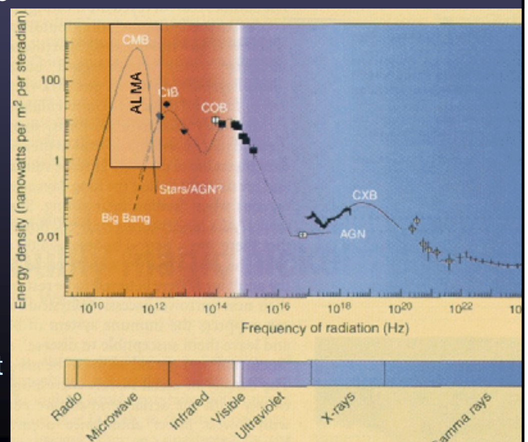
- mm/submm photons are the most abundant photons in the spectrum of most spiral galaxies – 40% of the Milky Way Galaxy
- After the 3K cosmic background radiation, mm/submm photons carry most of the energy in the Universe
- Unique science can be done at mm/sub-mm wavelengths because of the sensitivity to thermal emission from dust and lines
- Probe of cool gas and dust in:
  - Proto-planetary disks
  - Star formation in our Galaxy
  - Star formation at high-redshift



Science at mm/submm wavelengths: dust emission

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In the Rayleigh-Jeans regime, $h\nu \ll kT$,

$$S_\nu = \frac{2kT\nu^2\tau_\nu\Omega}{c^2} \quad \mathrm{Wm^{-2}\,Hz^{-1}}$$

and dust opacity, $\tau_\nu \propto \nu^2$

so for optically-thin emission, flux density

$$S_\nu \propto \nu^4$$

$\Rightarrow$ emission is brighter at higher frequencies

Dusty Disks in our Galaxy: Physics of Planet Formation

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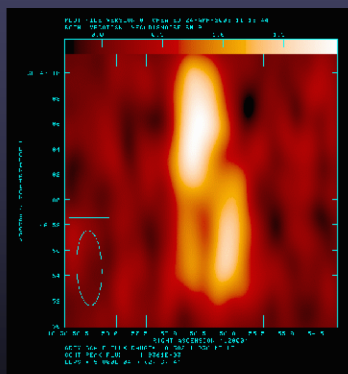
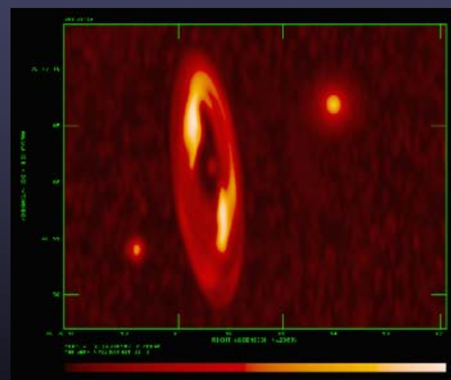
Vega debris disk simulation: PdBI & ALMA



Simulated PdBI image



Simulated ALMA image

Science at mm/sub-mm wavelengths: molecular line emission

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- Most of the dense ISM is H_2, but H_2 has no permanent dipole moment $\Rightarrow$ use trace molecules

Table 28–1. Low Order Rotational Transitions of Simple Heavy Molecules

Molecule	J(1-0) GHz	J(2-1) GHz	J(3-2) GHz	n_{crit}[J(1-0)] cm^{-3}
CO	115.271	230.538	345.795	10^2 - 10^3
CS	48.991	97.981	146.969	10^3 - 10^4
HCN	88.631	177.260	265.886	10^5
HCO^+	89.188	178.375	267.557	10^5
SiO	43.122	86.243	130.268	10^3 - 10^4

Plus: many more complex molecules (e.g. N_2H^+, CH_3OH, CH_3CN, etc)

- Probe kinematics, density, temperature
- Abundances, interstellar chemistry, etc…
- For an optically-thin line $S_\nu \propto \nu^4$; $T_B \propto \nu^2$ (cf. dust)

SMA 850 μm of Massive Star Formation in Cepheus A-East

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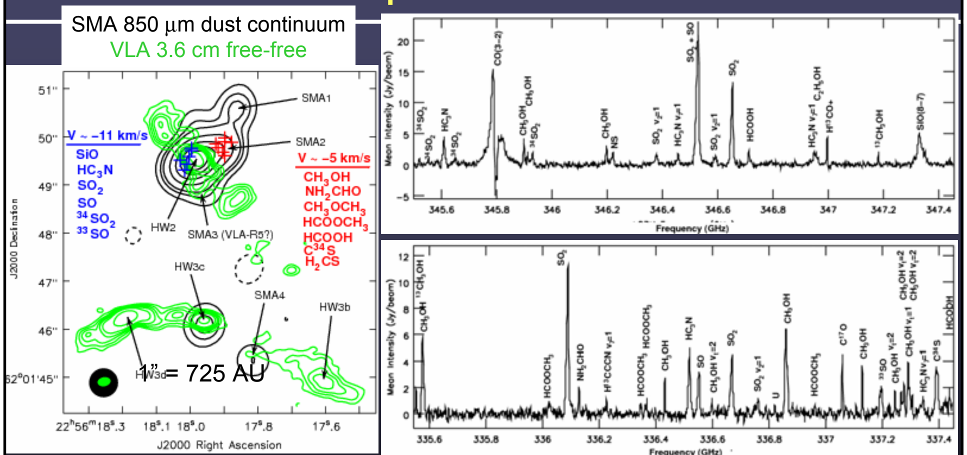

Massive stars forming regions are at large distances ⇨ need high resolution

Clusters of forming protostars and copious hot core line emission

Chemical differentiation gives insight to physical processes

ALMA will routinely achieve resolutions of better than 0.1”

Brogan et al., in prep.

List of Currently Known Interstellar Molecules (DEMIRM)

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H_2	HD	H_3+	H_2D+				
CH	CH^+	C_2	CH_2	C_2H	*C_3		
CH_3	C_2H_2	C_3H(lin)	c-C_3H	*CH_4	C_4		
c-C_3H_2	H_2CCC(lin)		C_4H	*C_5	*C_2H_4	C_5H	
H_2C_4(lin)	*HC_4H	CH_3C_2H	C_6H	*HC_6H	H_2C_6		
*C_7H	CH_3C_4H	C_8H	*C_6H_6				
OH	CO	CO+	H_2O	HCO	HCO+		
HOC+	C_2O	CO_2	H_3O+	HOCO+	H_2CO		
C_3O	CH_2CO	HCOOH	H_2COH+	CH_3OH	CH_2CHO		
CH_2CHOH	CH_2CHCHO		HC_2CHO	C_5O	CH_3CHO	c-C_2H_4O	
CH_3OCHO	CH_2OHCHO		CH_3COOH	CH_3OCH_3	CH_3CH_2OH	CH_3CH_2CHO	
$(CH_3)_2CO$	$HOCH_2CH_2OH$		$C_2H_5OCH_3$	$(CH_2OH)_2CO$			
NH	CN	N_2	NH_2	HCN	HNC		
N_2H^+	NH_3	$HCNH^+$	H_2CN	HCCN	C_3N		
CH_2CN	CH_2NH	HC_2CN	HC_2NC	NH_2CN	C_3NH		
CH_3CN	CH_3NC	HC_3NH^+	*HC_4N	C_5N	CH_3NH_2		
CH_2CHCN	HC_5N	CH_3C_3N	CH_3CH_2CN	HC_7N	CH_3C_5N?	HC_9N	$HC_{11}N$
NO	HNO	N2O	HNCO	NH2CHO			
SH	CS	SO	SO+	NS	SiH		
*SiC	SiN	SiO	SiS	HCl	*NaCl		
*AlCl	*KCl	HF	*AlF	*CP	PN		
H_2S	C_2S	SO_2	OCS	HCS+	c-SiC_2		
*SiCN	*SiNC	*NaCN	*MgCN	*MgNC	*AlNC		
H_2CS	HNCS	C_3S	c-SiC_3	*SiH_4	*SiC_4		
CH_3SH	C_5S	FeO					

Galaxy Feeding

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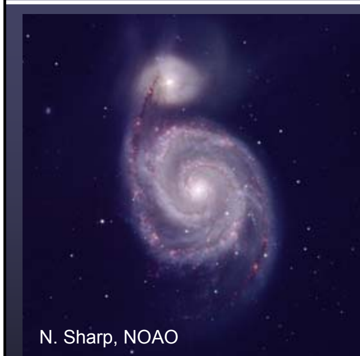
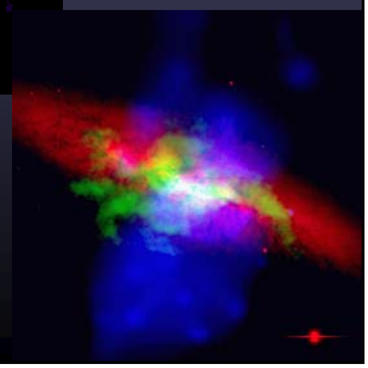


CO(1-0) BIMA-SONG

ALMA science goal: Ability to trace chemical composition of galaxies to redshift of 3 in less than 24 hours

M82 starburst
Red: optical emission
Blue: x-ray emission
Green: OVRO $^{12}CO(J=1-0)$
(Walter, Weiss, Scoville 2003)



Unique mm/submm access to highest z

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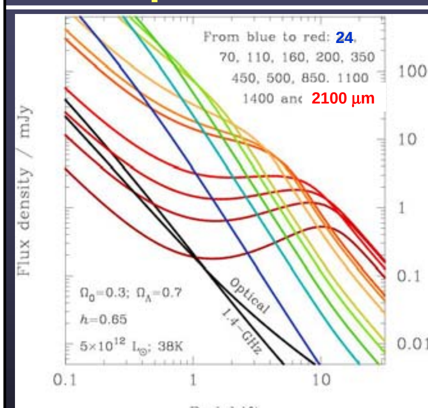
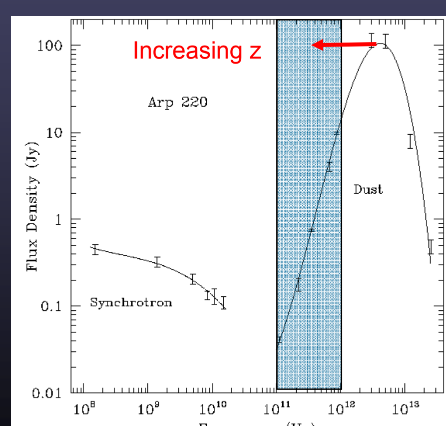


- Redshifting the steep submm SED counteracts inverse square law dimming



- Detect high-z galaxies as easily as those at z~0.5
- 2mJy at 1mm ~5×10^{12} L_o
  - Current depth of submm surveys
  - ALMA has no effective limit to depth

Andrew Blain

Problems unique to the mm/sub-mm

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- Atmospheric opacity significant λ<1cm: raises T_{sys} and attenuates source
  - Opacity varies with frequency and altitude
  - Gain calibration must correct for opacity variations
- Atmospheric phase fluctuations
  - Cause of the fluctuations: variable H_2O
  - Calibration schemes must compensate for induced loss of visibility amplitude (coherence) and spatial resolution (seeing)
- Antennas
  - Pointing accuracy measured as a fraction of the primary beam is more difficult to achieve: PB ~ 1.22 λ/D
  - Need more stringent requirements than at cm wavelengths for: surface accuracy & baseline determination

Problems, continued…

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- Instrument stability
  - Must increase linearly with frequency (delay lines, oscillators, etc…)
- Millimeter/sub-mm receivers
  - SIS mixers needed to achieve low noise characteristics
  - Cryogenics cool receivers to a few K
  - IF bandwidth
- Correlators
  - Need high speed (high bandwidth) for spectral lines:
    $\Delta V = 300$ km s^{-1} → 1.4 MHz @ 1.4 GHz, 230 MHz @ 230 GHz
  - Broad bandwidth also needed for sensitivity to thermal continuum and phase calibration
- Limitations of existing and future arrays
  - Small FoV ⇨ mosaicing: FWHM of 10 m antenna @ 230 GHz is ~ 30''
  - Limited *uv*-coverage, small number of elements (improved with CARMA, remedied with ALMA)

Atmospheric opacity

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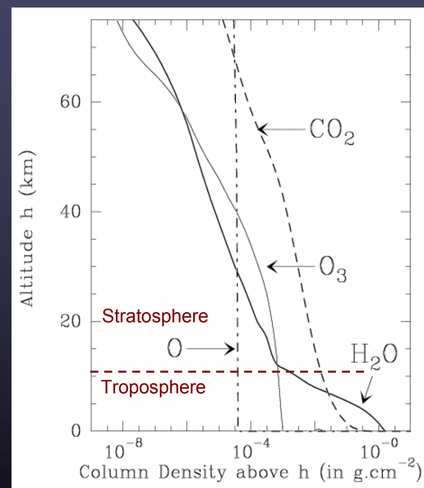
- Due to the troposphere (lowest layer of atmosphere): h < 10 km
- Temperature decreases with altitude: clouds & convection can be significant
- Dry Constituents of the troposphere: N_2, O_2, Ar, CO_2, Ne, He, Kr, CH_4, H_2
- H_2O: abundance is highly variable but is < 1% in mass, mostly in the form of water vapor



Troposphere opacity increases with frequency:

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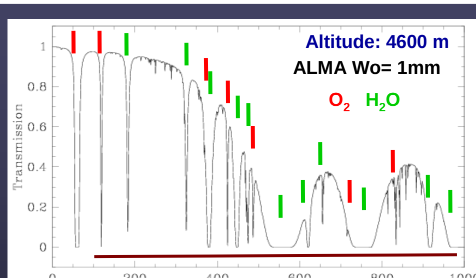

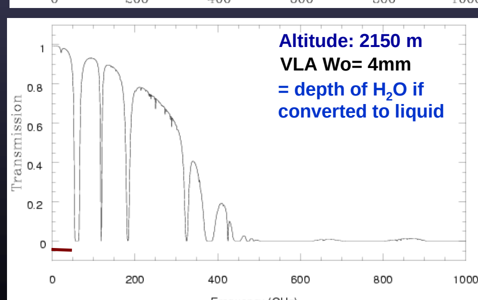

Models of atmospheric transmission from 0 to 1000 GHz for the ALMA site in Chile, and for the VLA site in New Mexico

$\Rightarrow$ Atmosphere transmission not a problem for λ > cm (most VLA bands)

Optical depth of the atmosphere at the VLA site

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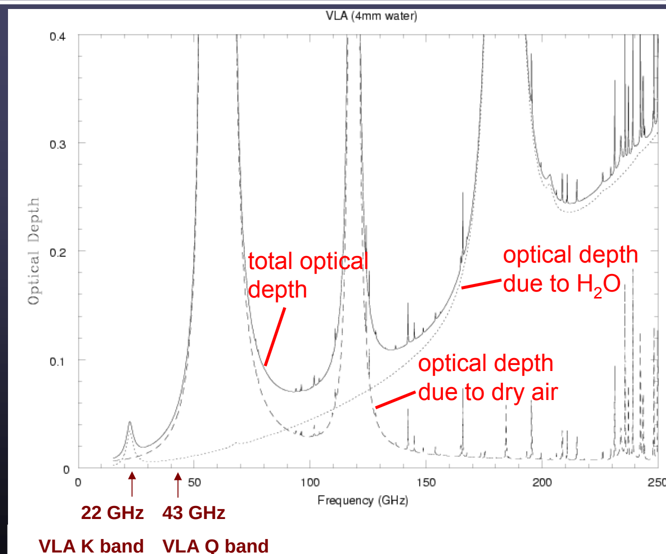

Sensitivity: Receiver noise temperature

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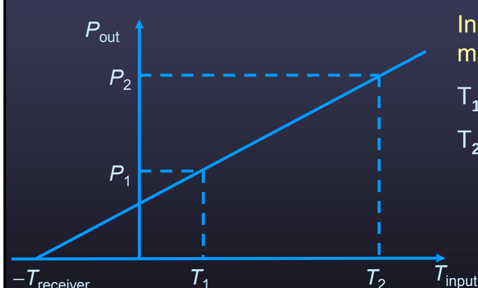
- Good receiver systems have a linear response: y = m(x + constant)

  output power: $P_{out} = m \times (T_{input} + T_{receiver})$

  Unknown slope — Calibrated 'load' — Receiver temperature



In order to measure $T_{receiver}$, you need to make measurements of two calibrated 'loads':

T_1 = 77 K liquid nitrogen load

$T_2 = T_{load}$ room temperature load

$$T_{receiver} = \frac{(T_2 - T_1)}{(P_2 - P_1)} P_1 - T_1$$

Let $y = P_2/P_1$

$$\frac{(T_2 - yT_1)}{(y - 1)}$$

Sensitivity: System noise temperature

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In addition to receiver noise, at millimeter wavelengths the atmosphere has a significant brightness temperature:

$$T_B^{atm} = T_{atm} \times (1 - e^{-\tau})$$

(where T_{atm} = temperature of the atmosphere, ~ 300 K)

T_B^{atm} represents additional noise at the input of the receiver:

atmosphere receiver

The "system noise temperature" is a measure of the overall sensitivity:

$$T_{noise} = T_{atm}(1-e^{-\tau}) + T_{rec}$$

Emission from atmosphere — Receiver temperature

Consider the signal to noise ratio for a source outside the atmosphere:

$$S / N = (T_{source}\, e^{-\tau}) / T_{noise} = T_{source} / (T_{noise}\, e^{\tau})$$

$$\boxed{T_{sys} = T_{noise}\, e^{\tau} = T_{atm}(e^{\tau}-1) + T_{rec}e^{\tau}}$$

The system sensitivity drops rapidly (exponentially) as opacity increases

Practical measurement of T_{sys}

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- So how do we measure T_{sys} without constantly measuring $T_{receiver}$ and the opacity? $T_{sys} = T_{atm}(e^{\tau}-1) + T_{rec}e^{\tau}$
- At mm λ, T_{sys} is usually obtained with the absorbing-disc method (Penzias & Burrus 1973) in which an ambient temperature load (T_{load}) is occasionally placed in front of the receiver.

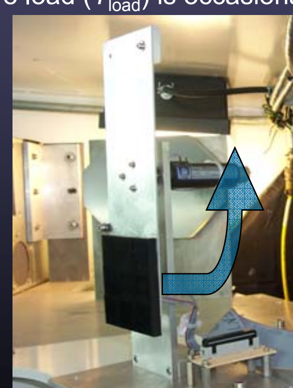
• We want to know the overall sensitivity, not how much is due to the receiver vs. how much is due to the sky. Therefore, we can use:

$$T_{sys} = T_{load} * T_{noise} / (T_{cal} - T_{noise})$$

$T_{cal} = T_{load} + T_{rec}$
$T_{noise} = T_B^{atm} + T_{rec}$

These are really the measured power but is ∝ temperature in the R-J limit

• As long as T_{atm} is similar to T_{load}, this method automatically compensates for rapid changes in mean atmospheric absorption



SMA calibration load swings in and out of beam

Atmospheric opacity, continued

Typical optical depth for 345 GHz observing at the SMA:

at zenith τ_{225} = 0.08 = 1.5 mm PWV, at elevation = $30^o \Rightarrow \tau_{225}$ = 0.16

Conversion from 225 GHz to 345 GHz ⇨ $\tau_{345} \sim 0.05 + 2.25\ \tau_{225} \sim 0.41$

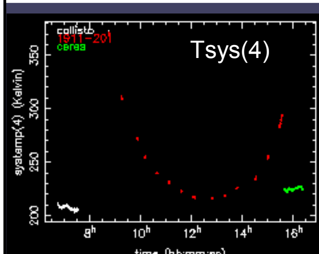
$T_{sys}(DSB) = T_{sys}\, e^{\tau} = e^{\tau}(T_{atm}(1-e^{-\tau}) + T_{rec}) = 1.5(101 + 100) \sim 300$ K

assuming T_{atm} = 300 K

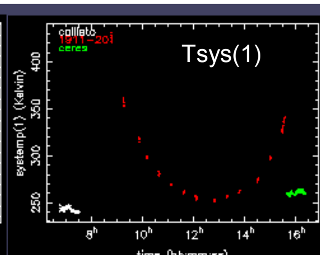
For single sideband, $T_{sys}(SSB) = 2\ T_{sys}\ (DSB) \sim 600\ K$

⇨ Atmosphere adds considerably to T_{sys} and since the opacity can change rapidly, T_{sys} must be measured often

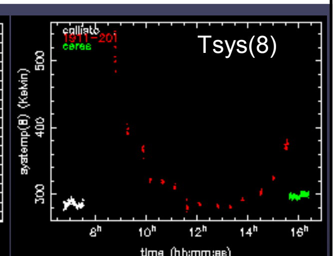
Example SMA 345 GHz Tsys Measurements



Good



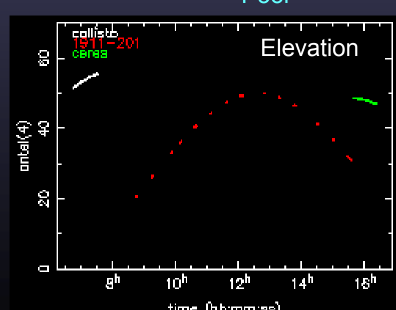
Medium



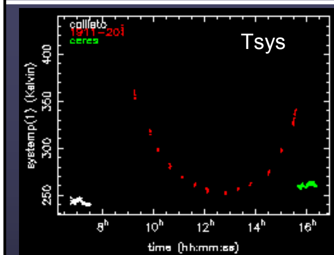
Poor

For calibration and imaging,

visibility "sensitivity" weight is $\propto 1/[T_{sys}(i) * T_{sys}(j)]$



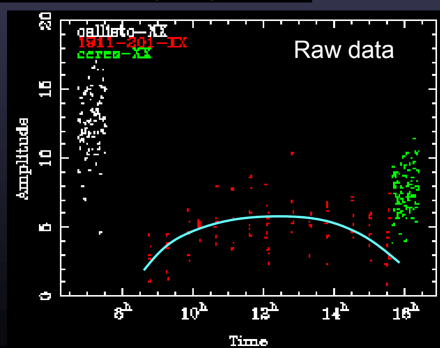
Correcting for T_{sys} and conversion to a Jy Scale

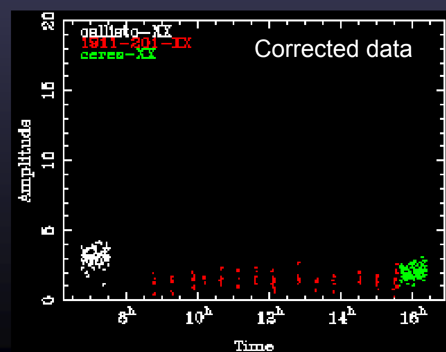


$S = S_o * [T_{sys}(1) * T_{sys}(2)]^{0.5} * 130$ Jy/K $* 5 \times 10^{-6}$ Jy

SMA gain for 6m dish and 75% efficiency

Correlator unit conversion factor





Absolute gain calibration

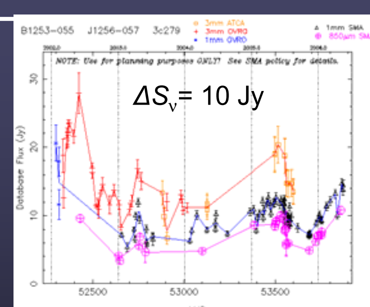
- No non-variable quasars in the mm/sub-mm for setting the absolute flux scale; instead, have to use:

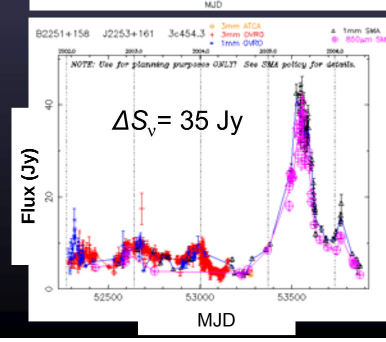
Planets and moons: roughly black bodies of known size and temperature, e.g.,

Uranus @ 230 GHz: $S_\nu \sim 37$ Jy, $\theta \sim 4''$

Callisto @ 230 GHz: $S_\nu \sim 7.2$ Jy, $\theta \sim 1.4''$

- S_ν is derived from models, can be uncertain by ~ 10%
- If the planet is resolved, you need to use visibility model for each baseline
- If larger than primary beam it shouldn't be used (can be used for bandpass)





Mean Effect of Atmosphere on Phase

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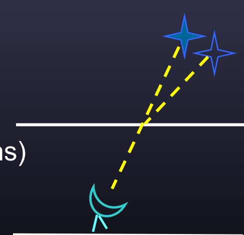
• Since the refractive index of the atmosphere ≠1, an electromagnetic wave propagating through it will experience a phase change (i.e. Snell's law)

• The phase change is related to the refractive index of the air, *n*, and the distance traveled, *D*, by

$$\phi_e = (2\pi/\lambda) \times n \times D$$

For water vapor $n \propto \frac{w}{D T_{atm}}$ *w*=precipitable water vapor (PWV) column

so $\phi_e \approx \frac{12.6\pi}{\lambda} \times w$ for T_{atm} = 270 K



This refraction causes:

- Pointing off-sets, $\Delta\theta \approx 2.5 \times 10^{-4} \times \tan(i)$ (radians)
  @ elevation 45° typical offset~1'

- Delay (time of arrival) off-sets

⇨ These "mean" errors are generally removed by the online system

Atmospheric phase fluctuations

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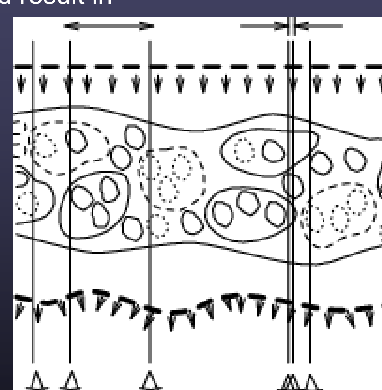
• Variations in the amount of precipitable water vapor cause phase fluctuations, which are worse at shorter wavelengths, and result in
  – Low coherence (loss of sensitivity)
  – Radio "seeing", typically 1-3″ at 1 mm
  – Anomalous pointing offsets
  – Anomalous delay offsets

Simplifying assumption:

The timescale for changes in the water vapor distribution is long compared to time for wind to carry features over the array

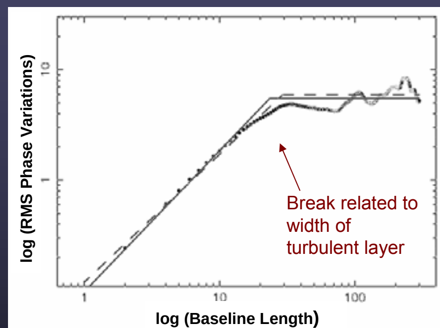
V_w~10 m/s



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

Atmospheric phase fluctuations, continued…

Phase noise as function of baseline length



"Root phase structure function" (Butler & Desai 1999)

rms phase of fluctuations given by Kolmogorov turbulence theory

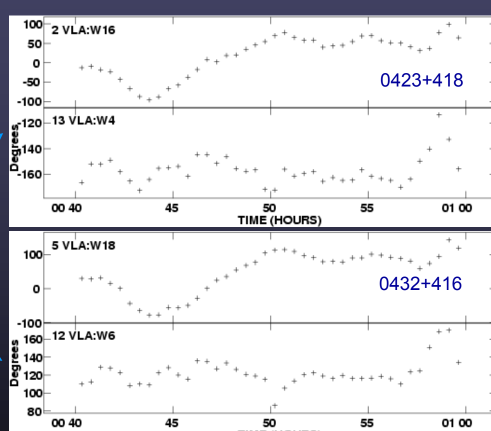
$\rightarrow \phi_{rms} = K b^{\alpha} / \lambda$ [deg],

Where b = baseline length (km); α ranges from 1/3 to 5/6; λ = wavelength (mm); and K = constant (~100 for ALMA, 300 for VLA)

The position of the break and the maximum noise are weather and wavelength dependent

Atmospheric phase fluctuations, continued…

22 GHz VLA observations of 2 sources observed simultaneously (paired array)



Antennas 13 & 12 are adjacent, phases track each other closely

Antennas 2 & 5 are adjacent, phases track each other closely

Self-cal applied using a reference antenna within 200 m of W4 and W6, but 1000 m from W16 and W18:

⇨ Long baselines have large amplitude, short baselines smaller amplitude

⇨ Nearby antennas show correlated fluctuations, distant ones do not

VLA observations of the calibrator 2007+404
at 22 GHz with a resolution of 0.1″ (Max baseline 30 km):

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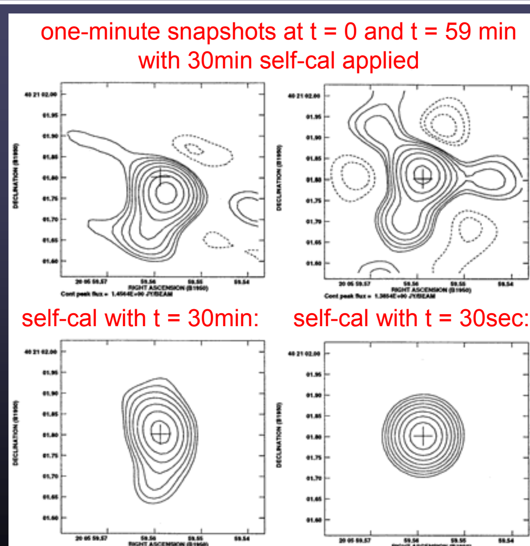
Position offsets due to large scale structures that are correlated ⇨ phase gradient across array



Sidelobe pattern shows signature of antenna based phase errors ⇨ small scale variations that are not correlated

Reduction in peak flux (decorrelation) and smearing due to phase fluctuations over 60 min

Phase fluctuations with timescale ~ 30 s

⇨ Uncorrelated phase variations degrades and decorrelates image;
Correlated phase offsets = position shift

Phase fluctuations: loss of coherence

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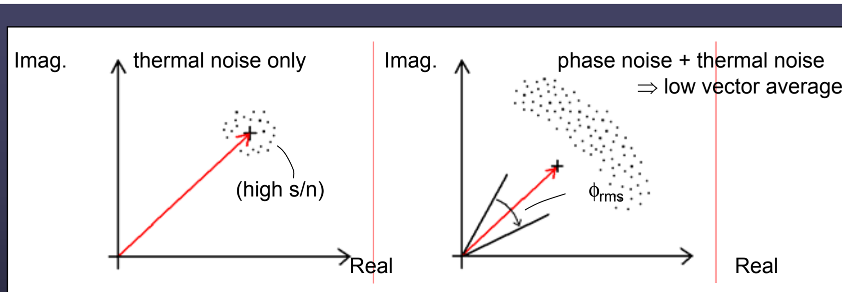

Coherence = (vector average/true visibility amplitude) = $\langle V \rangle / V_0$

Where, $V = V_0 e^{i\phi}$

The effect of phase noise, ϕ_{rms}, on the measured visibility amplitude in a given averaging time:

$$\langle V \rangle = V_0 \times \langle e^{i\phi} \rangle = V_0 \times e^{-\phi^2_{rms}/2} \text{ (Gaussian phase fluctuations)}$$

Example: if ϕ_{rms} = 1 radian (~60 deg), coherence = $\frac{\langle V \rangle}{V_0}$ = 0.60

Phase fluctuations: radio "seeing"

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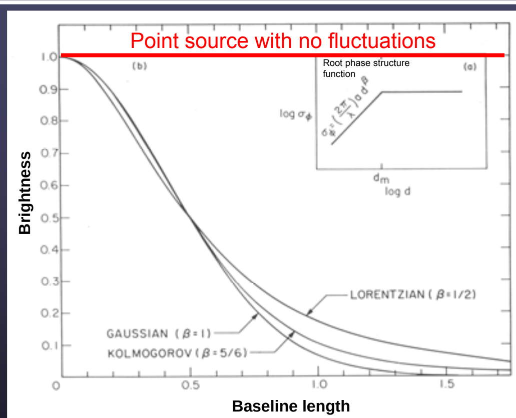

Phase variations lead to decorrelation that worsens as a function of baseline length

Point-source response function for various power-law models of the rms phase fluctuations (Thompson, Moran, & Swenson 1986)

$\langle V \rangle / V_0 = \exp(-\phi^2_{rms}/2) = \exp(-[K' b^{\alpha} / \lambda]^2/2)$ [Kolmogorov with K'=K *pi/180]

- Measured visibility decreases with baseline length, *b,* (until break in root phase structure function)
- Source appears resolved, convolved with "seeing" function

⇨ Diffraction limited seeing is precluded for baselines longer than 1 km at ALMA site!

⇒ Phase fluctuations severe at mm/submm wavelengths, correction methods are needed

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- Self-calibration: OK for bright sources that can be detected in a few seconds.
- Fast switching: used at the VLA for high frequencies and will be used at CARMA and ALMA. Choose fast switching cycle time, t_{cyc}, short enough to reduce ϕ_{rms} to an acceptable level. Calibrate in the normal way.
- Paired array calibration: divide array into two separate arrays, one for observing the source, and another for observing a nearby calibrator.
  - Will not remove fluctuations caused by electronic phase noise
  - Only works for arrays with large numbers of antennas (e.g., VLA, ALMA)

Phase correction methods (continued):

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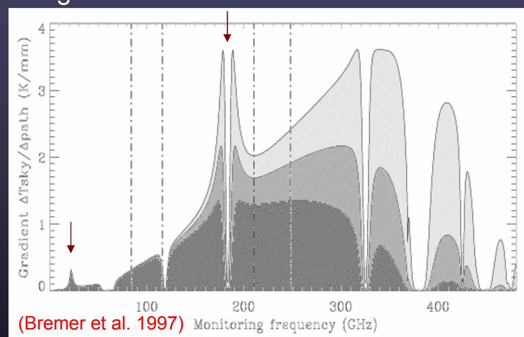
- Radiometry: measure fluctuations in T_B^{atm} with a radiometer, use these to derive changes in water vapor column (w) and convert this into a phase correction using

$$\phi_e \approx \frac{12.6\pi \times w}{\lambda}$$



Monitor: 22 GHz H_2O line (CARMA, VLA)
183 GHz H_2O line (CSO-JCMT, SMA, ALMA)
total power (IRAM, BIMA)

Results from VLA 22 GHz Water Vapor Radiometry

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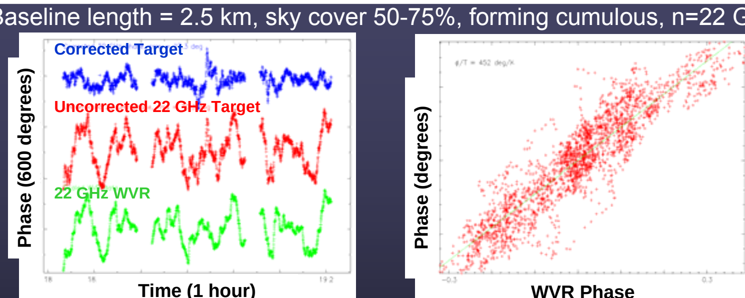
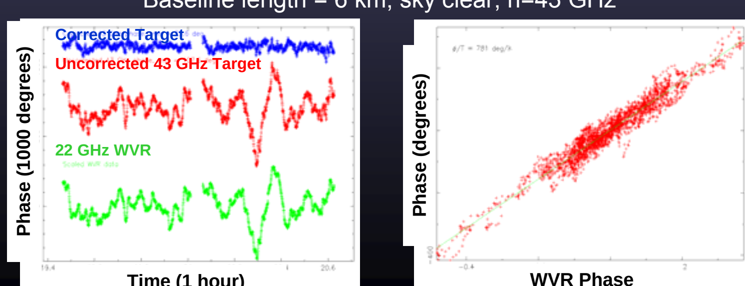
Baseline length = 2.5 km, sky cover 50-75%, forming cumulous, n=22 GHz



Baseline length = 6 km, sky clear, n=43 GHz



Examples of WVR phase correction:
22 GHz Water Line Monitor at OVRO, continued…

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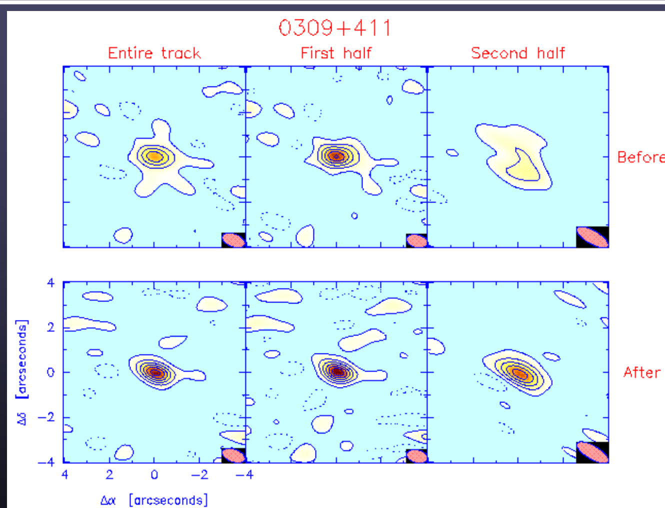

“Before” and “after” images from Woody, Carpenter, & Scoville 2000

Examples of WVR phase correction:
183 GHz Water Vapor Monitors at the CSO-JCMT and for ALMA

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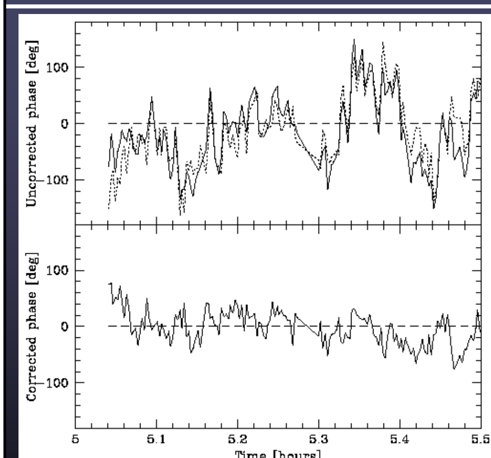

CSO-JCMT Phase fluctuations are reduced from 60° to 26° rms (Wiedner et al. 2001).

Pre-production ALMA Water Vapor Radiometer Operating in an SMA Antenna on Mauna Kea (January 19, 2006)

Antenna requirements

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- **Pointing:** for a 10 m antenna operating at 350 GHz the primary beam is ~ 20″

  a 3″ error $\Rightarrow$ Δ(Gain) at pointing center = 5%

  Δ(Gain) at half power point = 22%

  $\Rightarrow$ need pointing accurate to ~1″

- **Aperture efficiency, η:** Ruze formula gives

  $\eta = \exp(-[4\pi\sigma_{rms}/\lambda]^2)$

  $\Rightarrow$ for η = 80% at 350 GHz, need a surface accuracy, σ_{rms}, of 30μm

Antenna requirements, continued…

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•**Baseline determination:** phase errors due to errors in the positions of the telescopes are given by

$$\Delta\phi = \frac{2\pi}{\lambda} \times \Delta b \times \Delta\theta$$

$\Delta\theta$ = angular separation between source & calibrator

Δb = baseline error

Note: $\Delta\theta$ = angular separation between source and calibrator, can be > 20° in mm/sub-mm

$\Rightarrow$ to keep $\Delta\phi < \Delta\theta$ need $\Delta b < \lambda/2\pi$

e.g., for λ = 1.3 mm need Δb < 0.2 mm

Observing Practicalities

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Do:

- Use shortest possible integration times given strength of calibrators
- Point often
- Use closest calibrator possible
- Include several amplitude check sources
- Bandpass calibrate often on strong source
- *Always* correct bandpass before gain calibration (phase slopes across wide band)
- *Always* correct phases before amplitude (prevent decorrelation)

Summary

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- Atmospheric emission can dominate the system temperature
  - Calibration of T_{sys} is different from that at cm wavelengths
- Tropospheric water vapor causes significant phase fluctuations
  - Need to calibrate more often than at cm wavelengths
  - Phase correction techniques are under development at all mm/sub-mm observatories around the world
  - Observing strategies should include measurements to quantify the effect of the phase fluctuations
- Instrumentation is more difficult at mm/sub-mm wavelengths
  - Observing strategies must include pointing measurements to avoid loss of sensitivity
  - Need to calibrate instrumental effects on timescales of 10s of mins, or more often when the temperature is changing rapidly

Recent advances in overcoming these challenges is what is making the next generation of mm/submm arrays possible ⇨ the future is very bright

Practical aspects of observing at high frequencies with the VLA

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Note: details may be found at
http://www.aoc.nrao.edu/vla/html/highfreq/

- Observing strategy: depends on the strength of your source
  - Strong (≥ 0.1 Jy on the longest baseline for continuum observations, stronger for spectral line): can apply self-calibration, use short integration times; no need for fast switching
  - Weak: external phase calibrator needed, use short integration times and fast switching, especially in A & B configurations
  - If strong maser in bandpass: monitor the atmospheric phase fluctuations using the maser, and apply the derived phase corrections; use short integration times, calibrate the instrumental phase offsets between IFs every 30 mins or so

Practical aspects, continued…

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- Referenced pointing: pointing errors can be a significant fraction of a beam at 43 GHz
  - Point on a nearby source at 8 GHz every 45-60 mins, more often when the az/el is changing rapidly. Pointing sources should be compact with $F_{8GHz} \geq$ 0.5 Jy
- Calibrators at 22 and 43 GHz
  - Phase calibration: the spatial structure of water vapor in the troposphere requires that you find a phase calibrator < 3° from your source, if at all possible; for phase calibrators weaker than 0.5 Jy you will need a separate, stronger source to track amplitude variations
  - Absolute Flux calibrators: 3C48/3C138/3C147/3C286. All are extended, but there are good models available for 22 and 43 GHz

Practical aspects, continued…

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- If you have to use fast switching
  - Quantify the effects of atmospheric phase fluctuations (both temporal and spatial) on the resolution and sensitivity of your observations by including measurements of a nearby point source with the same fast-switching settings: cycle time, distance to calibrator, strength of calibrator (weak/strong)
  - If you do not include such a "check source" the temporal (but not spatial) effects can be estimated by imaging your phase calibrator using a long averaging time in the calibration
- During the data reduction
  - Apply phase-only gain corrections first, to avoid de-correlation of amplitudes by the atmospheric phase fluctuations

The Atmospheric Phase Interferometer at the VLA

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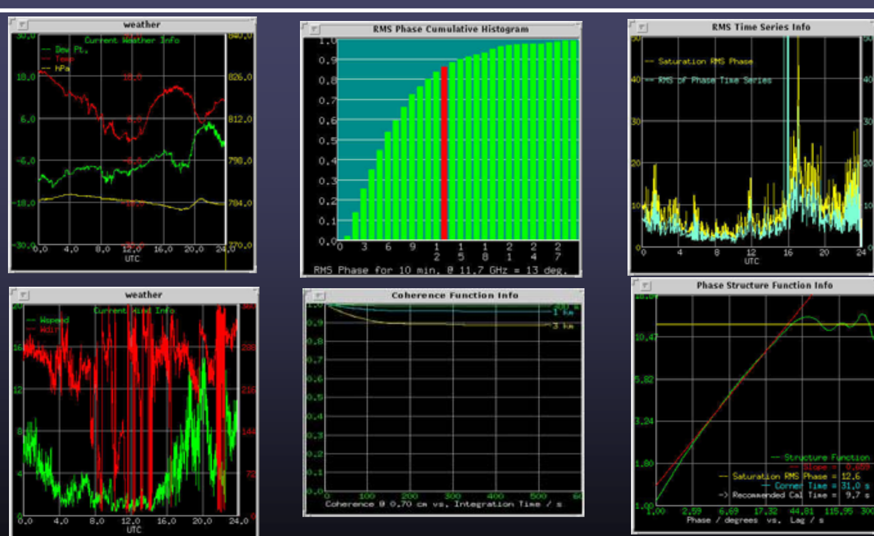

Accessible from http://www.vla.nrao.edu/astro/guides/api