Mm-Wave Interferometry

Claire Chandler

- Why a special lecture on mm interferometry?
  - –everything about interferometry is more difficult at high frequencies
  - –some of the problems are unique to the mm/submm, and affect the way observations are carried out

---

Why do we care about mm/submm?

- unique science can be done at mm/submm wavelengths, because of the sensitivity to thermal emission from dust and molecular lines
- e.g.: @ $\lambda = 1$ mm ($\nu = 300$ GHz) $h\nu/k \sim 14$ K
  - $\Rightarrow$probe of cool gas and dust in:
  - —molecular clouds
  - —dust in dense regions
  - —star formation in our Galaxy and in the high-redshift universe
  - —protoplanetary disks
  - —etc…

Science at mm/submm wavelengths: dust emission

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

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

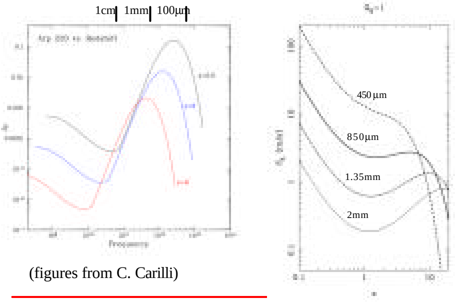
dust opacity $\propto \nu^2$

so for optically-thin emission, flux density

$$S_\nu \propto \nu^4; \qquad T_B \propto \nu^2$$

$\Rightarrow$ emission is brighter at higher frequencies

Star-forming galaxies in the early universe



(figures from C. Carilli)

Science at mm/submm wavelengths: molecular line emission

- most of the dense ISM is H_2, but H_2 has no permanent dipole moment $\Rightarrow$ use trace molecules
- lines from heavy molecules $\rightarrow$ mm
- lighter molecules (e.g. hydrides) $\rightarrow$ submm

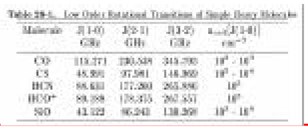


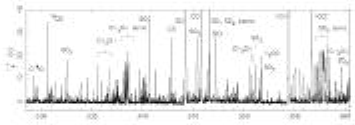
Table 29-1. Low Order Rotational Transitions of Simple Heavy Molecules

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	[illegible]
CS	48.991	97.981	146.969	[illegible]
HCN	88.631	177.261	265.886	[illegible]
HCO$^+$	89.189	178.375	267.557	[illegible]
SiO	43.423	86.243	130.269	[illegible]

+ many more complex molecules (CH_3CH_2CN, CH_2OHCHO, CH_3COOH, etc.)

- –probe kinematics, density, temperature
- –abundances, interstellar chemistry, etc…
- –for an optically-thin line in turns out that

$$S_\nu \propto \nu^4; \quad T_B \propto \nu^2 \quad \text{(cf. dust)}$$



Spectrum of molecular emission from Orion at 345 GHz

Problems unique to the mm/ submm

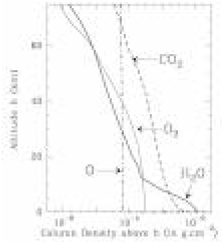
- atmospheric opacity: raises T_{sys}, attenuates source
  - opacity vs frequency and altitude, typical values
  - calibration techniques, rapid calibration
- atmospheric phase fluctuations
  - cause of the fluctuations: variable H_2O
  - current and planned calibration schemes
- antennas
  - pointing accuracy, surface accuracy
  - baseline determination
- instrument stability

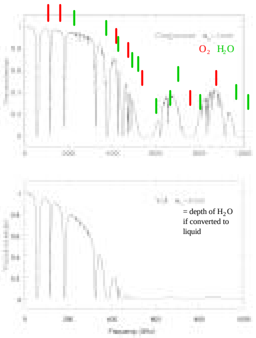
Problems, continued…

- millimeter/submm receivers (will not be discussed further)
  - SIS mixers, cryogenics
  - local oscillators
  - IF bandwidths
- correlators (will not be discussed further)
  - need high speed (high bandwidth) for spectral lines: $\Delta V = 300$ km s^{-1} $\equiv$ 1.4 MHz @ 1.4 GHz, 230 MHz @ 230 GHz
  - broad bandwidth also needed for sensitivity to thermal continuum and phase calibration, $\gtrsim$ GHz
- existing and future arrays
  - small field of view, need for mosaicing: FWHM of 10 m antenna @ 230 GHz is ~ 30″
  - limited *uv*-coverage, small number of elements

Atmospheric opacity

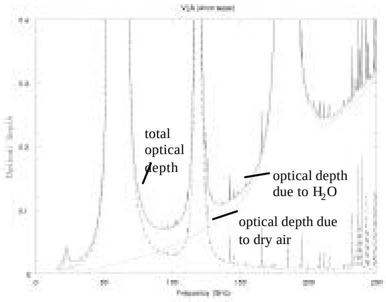
- due to the troposphere, h $\lesssim$ 7–10 km
- constituents of the troposphere = dry air (N_2, O_2, Ar, CO_2, Ne, He, Kr, CH_4, H_2, N_2O)
  - +H_2O: abundance is highly variable but is < 1% in mass, mostly in the form of water vapor
  - +particulates





Transmission of the atmosphere from 0 to 1000 GHz for the ALMA site in Chile, and for the VLA site in New Mexico

$\Rightarrow$ atmosphere little problem for $\lambda >$ cm (most VLA bands)



Optical depth of the atmosphere at the VLA site

Effect of atmospheric noise on T_{sys}

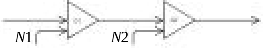
- consider a simple cascaded amplifier system, with one component:

input $S_{in}+N1$ output = $G\times(S_{in}+N1)$

gain G

output noise relative to S_{in}, $N_{out} = G\,N1/G = N1$

- now consider two components:



input S_{in} $N1$ $N2$ output = $G2[G1(S_{in}+N1)+N2]$

…divide by $G1G2$ to find noise relative to S_{in}, then

$$N_{in}^{eff} = N1 + \frac{N2}{G1}$$

…and in general, $N_{in}^{eff} = N1 + \frac{N2}{G1} + \frac{N3}{G1G2} + \ldots$

Atmospheric opacity, continued…

Now consider the troposphere as the first element of a cascaded amplifier system:

- – $G_{atm} = e^{-\tau}$
- – $T_B^{atm} = T_{atm} \times (1 - e^{-\tau})$, where T_{atm} = physical temperature of the atmosphere, ~ 300 K

– "effective'' system noise temperature scaled to the top of the atmosphere (i.e., relative to the unattenuated celestial signal) is:

$$T_{sys}^{eff} = e^{\tau} \times [T_{atm} \times (1 - e^{-\tau}) + T_{rec}]^*$$

*ignoring spillover terms, etc.

Atmospheric opacity, continued…

•example: typical 1.3 mm conditions at OVRO

- – $\tau_0 = 0.2$, elevation = 30° ⇒ $\tau = 0.4$
- – $T_{sys}(\text{DSB}) = 1.5\,(100 + 50) = 225$ K
- – dominated by the atmosphere
- – if receiver is double side band and sideband gain ratios are unity, then

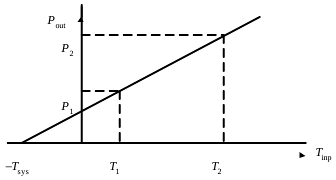
$T_{sys}(\text{SSB}) = 2\,T_{sys}(\text{DSB}) = 450$ K –very noisy

•so: atmosphere is noisy and is often the dominant contribution to T_{sys}; it is a function of airmass and changes rapidly, so need to calibrate often

Calibration of T_{sys}

•systems are linear ⇒ $P_{out} = m \times (T_{inp} + T_{sys})$

•if $P_{out} = 0$ then $T_{inp} = -T_{sys}$:



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

Calibration of T_{sys}, continued…

•at cm wavelengths loads T_1 and T_2 are the 3 K cosmic background radiation and a noise source with known noise temperature switched into the signal path

•at mm wavelengths we need two known loads above the atmosphere!

(1) 3 K cosmic background radiation

(2) T_{atm} obtained from a load placed in front of the feed at $T_{ambient} \sim T_{atm}$

load at T_{atm} → atmosphere → $T_{atm}e^{-\tau} + T_{atm}(1 - e^{-\tau}) = T_{atm}$

$\underbrace{\text{loss + emission}}$

cancel for $T_{load} = T_{atm}$

Absolute gain calibration

•there are no non-variable quasars in the mm/submm for setting the absolute flux scale; instead, have to use:

•planets: roughly black bodies of known size and temperature, e.g., Uranus @ 230 GHz has $S_\nu \sim 37$ Jy, diameter ~ 4″

- ▪problem: if the planet is resolved by the array, have to use single-dish (total power) calibration
- ▪if the planet is resolved by the primary beam, have to know its sidelobe pattern
- ▪S_ν is derived from models, can be uncertain by ~ 10%

•stars: black bodies of known size

- –e.g., the Sun at 10 pc: $S_\nu \sim 1.3$ mJy @ 230 GHz, diameter ~ 1 mas
- –problem: very faint! not possible for current arrays, but will be useful for ALMA

Atmospheric phase fluctuations

•at mm wavelengths variable atmospheric propagation delays are due to tropospheric water vapor (ionosphere is important for ν < 1 GHz)

•the phase change experienced by an electromagnetic wave is related to the refractive index of the air and the distance traveled by $\phi_e = 2\pi \times n \times D$

or in terms of an "electrical pathlength", $L_e = \lambda \times \frac{\phi_e}{2\pi} = n \times D$

•for water vapor $n \propto \frac{pwv}{DT_{atm}}$

so $L_e \approx 6.3 \times pwv$

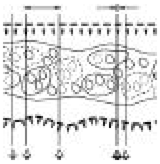
and $\phi_e \approx \frac{12.6\pi}{\lambda} \times pwv$

Atmospheric phase fluctuations, continued…

•variations in the amount of precipitable water vapor therefore cause

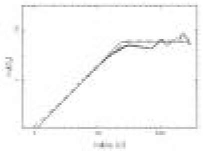
- –pointing offsets, both predictable and anomalous
- –delay offsets
- –phase fluctuations, which are worse at shorter wavelengths, and result in
  - •low coherence (loss of sensitivity)
  - •radio “seeing”, typically 1–3″ at $\lambda = 1$ mm

•effect of structure in the water vapor content of the atmosphere on different scales:



Atmospheric phase fluctuations, continued…

Phase noise as function of baseline length



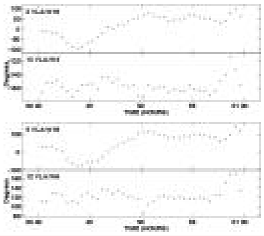
From Butler & Desai 1999

The position of the break and the maximum noise are weather dependent. Kolmogorov turbulence theory → $\phi_{rms} = Kb^{\alpha}/\lambda$, where α is a function of baseline length, and depends on the width of the turbulent layer

---

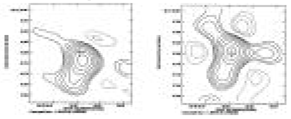
Atmospheric phase fluctuations, continued…

Antenna-based phase solutions using a reference antenna within 200 m of W4 and W6, but 1000 m from W16 and W18:

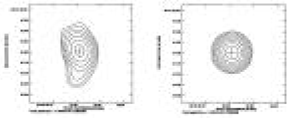


VLA observations of the calibrator 2007+404 at 22 GHz with a resolution of 0.1″:

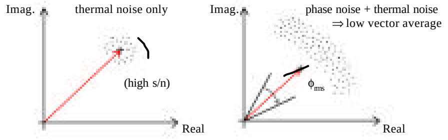
one-minute snapshots:



self-cal with t = 30min: self-cal with t = 30sec:



Phase fluctuations: loss of coherence



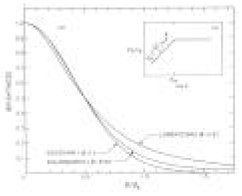
$$\text{coherence} = \frac{\text{vector average}}{\text{true visibility}}$$

measured visibility $V = V_0 e^{i\phi}$

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

if $\phi_{rms} = 1$ radian, coherence $= \frac{\langle V \rangle}{V_0} = 0.60$

Phase fluctuations: radio “seeing”



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

$$\langle V \rangle = V_0 \times \exp(-\phi^2_{rms}/2) = V_0 \times \exp(-[Kb^{\alpha}/\lambda]^2/2)$$

– measured visibility decreases with b

– source appears resolved, convolved with “seeing” function

Dependence of radio seeing on λ

- Consider observations at two frequencies, but the same resolution:

λ_1, b_1

$\lambda_2, b_2 = b_1(\lambda_2/\lambda_1)$ for the same resolution

then

$$\frac{(\phi_{rms})_1}{(\phi_{rms})_2} = \frac{b_1^{\alpha}/\lambda_1}{b_2^{\alpha}/\lambda_2} = \left(\frac{\lambda_2}{\lambda_1}\right)^{1-\alpha}$$

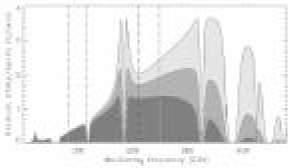
for example, $\alpha = 0.5$, $\lambda_1 = 1$ mm, $\lambda_2 = 6$ cm:

$$\frac{(\phi_{rms})_{1mm}}{(\phi_{rms})_{6cm}} \sim 8$$

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

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

- Radiometry: measure fluctuations in T_B^{atm} with a radiometer, use these to derive the fluctuations in *pwv*, and convert this into a phase correction using $\phi_e \approx \frac{12.6\pi}{\lambda} \times pwv$



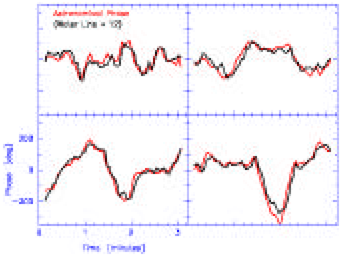
(from Bremer)

Monitor: 22 GHz H_2O line (OVRO, BIMA, VLA)

183 GHz H_2O line (CSO-JCMT, SMA, ALMA)

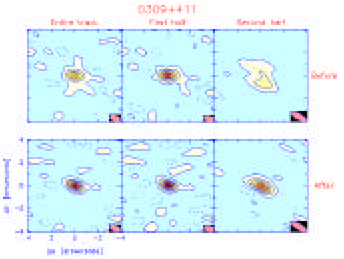
total power (IRAM, BIMA)

Examples of phase correction: 22 GHz Water Line Monitor at OVRO



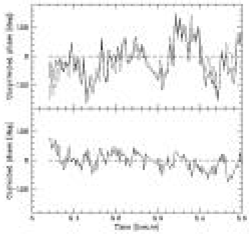
From Carpenter, Woody, & Scoville 1999

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



"Before" and "after" images from Woody, Carpenter, & Scoville 2000

Examples of phase correction: 183 GHz Water Vapor Monitor at the CSO-JCMT



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

Antenna requirements

- Pointing: for a 10 m antenna operating at 350 GHz the primary beam is ~ 18″
  - a 3″ error ⇒ Δ(Gain) at pointing center = 5%
  - Δ(Gain) at half power point = 22%
  - ⇒ need pointing accurate to ~1″
- Aperture efficiency: Ruze formula gives

$$\eta = \exp(-[4\pi\sigma/\lambda]^2)$$

  - ⇒ for η = 50% at 350 GHz, need a surface accuracy of 55 μm
- Baseline determination: phase errors due to errors in the positions of the telescopes are

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

Antenna requirements, continued…

where $\Delta\theta$ = angular separation between source and calibrator, and can be > 20° in mm/submm

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

e.g., for λ = 1.3 mm need Δb < 0.2 mm

Instrument stability

- Everything is more critical at shorter wavelengths.
  - –transmission line for the local oscillator should be stable to « λ
  - –needs to be temperature controlled
  - –round-trip path measurements can be ~ 1 turn/day, but quicker at sunrise/sunset
  - ⇒ calibrate instrumental phase every 20 to 30 mins

Summary of existing and future mm/submm arrays

Telescope	altitude (feet)	diam. (m)	No. dishes	A (m^2)	ν_{max} (GHz)
BIMA[1]	3,500	6	10	280	250
OVRO[1]	4,000	10	6	470	250
CARMA[1]	7,300	3.5/6/10	23	800	250
NMA	2,000	10	6	470	250
IRAM PdB	8,000	15	6	1060	250
JCMT-CSO[2]	14,000	10/15	2	260	650
SMA[3]	14,000	6	8	230	850
ALMA[4]	16,400	12	64	7200	850

[1] BIMA and OVRO will be combined and moved to a higher site to become CARMA

[2] First instrument to obtain submm fringes; will probably be used with the SMA

[3] Currently has 5 antennas, first fringes obtained in September 1999 at 230 GHz

[4] Currently under development, planned for full operation by 2010

Note:

- Existing millimeter instruments are on sites at 1,000 to 2,400 m altitude, with typically a few millimeters of precipitable H_2O
- Primary beam (field of view) ~ 40″ (IRAM) to 120″ (BIMA) at 115 GHz, resolution 1 to 2″. Note:
  - –very small fields of view
  - –not sensitive to extended emission on scales $\gtrsim \Omega_{PB}/3$
  - –mosaicing necessary for imaging even moderate-sized areas
  - –small number of antennas make it hard to build up good *uv*-coverage ⇒ not many *independent* pixels in the image plane

---

Practical aspects of observing at high frequencies with the VLA

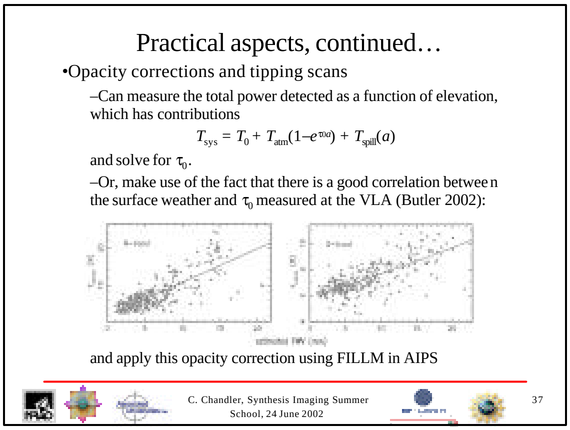
Note: details may be found at http://www.aoc.nrao.edu/vla/html/highfreq/

- 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
  - –Sources with a strong maser feature within the IF bandpass: monitor the atmospheric phase fluctuations using the maser, and apply the derived phase corrections to a continuum channel or spectral line channels; use short integration times, calibrate the instrumental phase offsets between the IFs being used every 30 mins or so

---

Practical aspects, continued…

- 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 $F_{8\,GHz} \geq 0.5$ Jy
- Calibrators at 22 and 43 GHz
  - –Phase: the spatial structure of water vapor in the troposphere requires that you find a phase calibrator $\lesssim$ 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
  - –Flux: 3C48/3C138/3C147/3C286. All are extended, but there are good models available for 22 and 43 GHz



Practical aspects, continued…

- Opacity corrections and tipping scans
  - Can measure the total power detected as a function of elevation, which has contributions

$$T_{sys} = T_0 + T_{atm}(1-e^{\tau_0 a}) + T_{spill}(a)$$

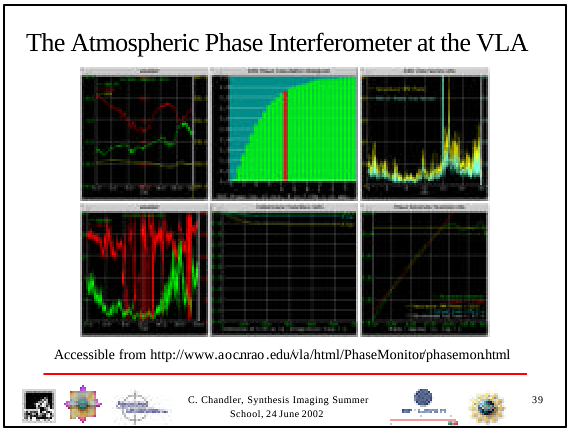
and solve for τ_0.

  - Or, make use of the fact that there is a good correlation between the surface weather and τ_0 measured at the VLA (Butler 2002):

and apply this opacity correction using FILLM in AIPS

Practical aspects, continued…

- 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 decorrelation of amplitudes by the atmospheric phase fluctuations



The Atmospheric Phase Interferometer at the VLA

Accessible from http://www.aoc.nrao.edu/vla/html/PhaseMonitor/phasemon.html

Summary

- 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/submm observatories around the world
  - Observing strategies should include measurements to quantify the effect of the phase fluctuations
- Instrumentation is harder for mm/submm
  - 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