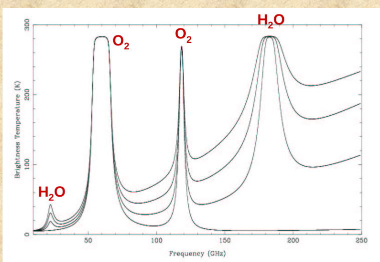
Techniques for Millimetre Interferometry

Tony Wong, ATNF
Synthesis School
2001

The trouble with mm-waves

- More stringent instrumental requirements
- Phase fluctuations due to H_2O in troposphere
- Tropospheric emission/opacity significant



R. Sault

Instrumental Challenges

1. **Surface accuracy**: If σ is r.m.s. surface error in μm, surface efficiency given by Ruze formula:

$$\eta_{sf} = \exp[-(4\pi\sigma/\lambda)^2]$$

For λ=3mm and σ=200 μm, η_{sf}=0.54. Antenna "holography" can be used to diagnose large-scale errors in dish shape.

2. **Field of view** (primary beam size):

$$\theta_{FWHM} \approx \lambda/D \approx 620''/D[m] \text{ at 3mm}$$

BIMA: D=6.1m, θ_{FWHM} = 100"
ATCA: D=22m, θ_{FWHM} = 30"

For large sources, **mosaicing** required.

Instrumental Challenges

3. **Pointing accuracy**: For mosaicing, want typical pointing error $\Delta\theta < \theta_{FWHM}/20$ (14% amplitude error at half power point). Thus need ~1.5" pointing accuracy at ATCA!
4. **Correlator bandwidth**:

$$1 \text{ MHz} \approx \lambda_{mm} \text{ km s}^{-1}$$

The same bandwidth covers only 1.4% of the velocity range at 3mm that it does at 21cm!

5. **Electronic phase noise**: tends to increase with frequency, and hard to calibrate (not antenna-based). For VLA at 22 GHz, ϕ_{rms}~10º.
6. **Baseline errors**: for a source-cal separation of 10º, Δb ~ 0.5mm leads to $\Delta\phi$ ~ 10º.

Amplitude Calibration

Recall that power is often given in temperature units (K) via the conversion:

$$P = k_B T \Delta\nu$$

Calibration of the visibility amplitude is typically performed by comparing it with the **system temperature**, the equivalent noise temperature presented to the detector:

$$T_{sys} = T_{rec} + T_{sky} + \cancelto{0}{T_{dish}} + \cancelto{0}{T_{src}}$$

The sky temperature can be determined via the radiative transfer equation:

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

Amplitude Calibration

In practice, we must correct T_{sys} for atmospheric absorption in order to estimate what the **unattenuated** celestial signal would be:

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

Example for T_{rec}=150 K, T_{atm}=290 K:

τ	0.2	0.8	2.0
T_{sys}	200	310	400
$T_{sys,eff}$	250	690	2960

The opacity τ at a given frequency depends on the column of precipitable water vapour (PWV).

Chopper Wheel Method

The standard method for measuring $T_{sys,eff}$ involves measuring the power received from the blank sky, then placing an ambient (295 K) load in front of the receiver (Kutner & Ulich 1981).

In both cases the output power is given by

$$P_{out} = m\,(T_{inp}\, e^{-\tau} + T_{sys}) = m\, e^{-\tau}\, (T_{inp} + T_{sys,eff})$$

where m is some scale factor and T_{inp} is the temperature of a "load" **above the atmosphere**.

For the blank sky measurement, T_{inp}=T_{CMB}=3 K.

For the ambient load measurement, T_{inp}=T_{amb}=295 K. (although the load isn't above the atmosphere, if the atmosphere is also at 295 K, its absorption and emission would cancel anyway)

Chopper Wheel Method

Combining the two measurements yields:

$$\frac{P_{amb}}{P_{sky}} = \frac{T_{amb} + T_{sys,eff}}{T_{cmb} + T_{sys,eff}}$$

$$T_{sys,eff} = \frac{(T_{amb} - T_{cmb})P_{sky}}{P_{amb} - P_{sky}} - T_{cmb} \approx \frac{(290\mathrm{K})P_{sky}}{P_{amb} - P_{sky}}$$

Hence, subject to the approximation $T_{amb} \approx T_{atm}$, the chopper wheel method gives $T_{sys,eff}$ directly even when T_{sys} and τ are not separately known!

Regular systemp measurements (every 15 min. or so) are needed to track variations in the receiver gains and atmosphere.

Absolute Flux Calibration

Good flux cals are unresolved, bright, and non-varying. But no such objects at mm wavelengths!

For planets there are reasonably good models for T_b which can be used, together with angular size, to derive a visibility model.

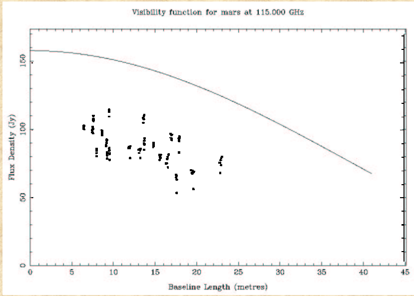
$$S_\nu = \frac{2kT_b}{\lambda^2}\Omega_{disk}$$

where Ω_{disk} is the angular size of the planet.

Usual method:

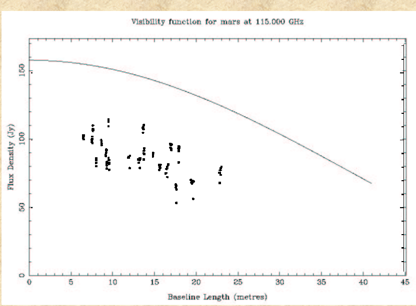
- Observe a planet during your track for 5-10 min.
- Bootstrap fluxes of phase calibrator & source using a model for the planet visibility structure.

Absolute Flux Calibration



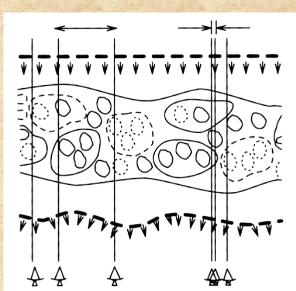
Problem: planets will generally be resolved out by the interferometer.

Absolute Flux Calibration



Possible solution: bootstrap in single-dish rather than interferometer mode.

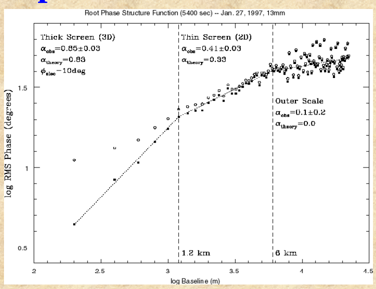
Atmospheric Phase Noise



Changes in refractive index of atmosphere due to precipitable water vapor (PWV) lead to "corrugations" in wavefront of an incoming plane wave.

Desai 1998

Atmospheric Phase Noise

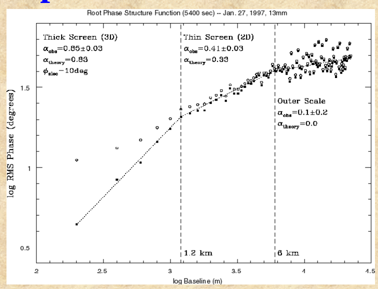


Carilli et al. 1999

- Atmospheric RMS phase noise (ϕ_{rms}) increases with **baseline length** because turbulence occurs on a range of length scales.

13

Atmospheric Phase Noise



Carilli et al. 1999

- Phase noise also increases with **frequency** because refractive effects are largely non-dispersive (constant in length units).

14

Effect on Visibility Data

Effect of phase noise on a visibility measurement can be expressed as

$$\langle V\rangle / V_0 = \exp\left(-\phi_{rms}^2 / 2\right)$$

where ϕ_{rms} is the RMS phase variation during the averaging time.

For ϕ_{rms}=1 rad, $\langle V\rangle/V_0=0.60$ and the visibility amplitude is reduced by 40% due to phase noise (also called decorrelation).

Since ϕ_{rms} increases with baseline length, visibility amplitude falls off in the outer **(u,v)** plane, degrading the angular resolution of the map (equivalent to optical “seeing”).

15

Phase Calibration

- Standard technique (**phase referencing**): observe a point source as phase calibrator every t_c~20-30 minutes, then apply interpolated phase gains to source.
- Can measure phase variations over timescales > $2t_c$ (Nyquist).
- OK for baselines up to ~100 m (looking through similar stuff) but time-averaged phase fluctuations too large on longer baselines.
- ATCA baselines range from 30m to 3km – **alternative techniques required.**

16

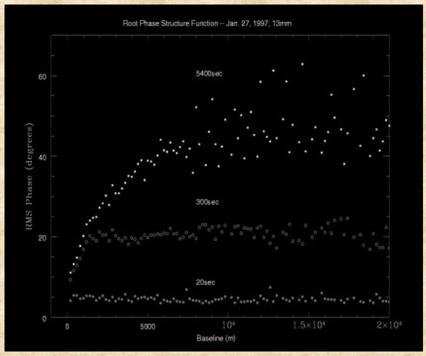
Phase Calibration

1. If source structure is simple and $n_{bsln} > 3$, can correct phase on much shorter timescales via **self-calibration** (limited by S/N ratio).
2. Otherwise, must switch back to phase calibrator rapidly (every few minutes) – **fast switching**.
3. With extra antennas, can observe calibrator continuously using a subarray – **paired array**.
4. Can make precise measurements of the water vapor column (PWV), proportional to the phase delay, by measuring H_2O lines at 22 or 183 GHz – **water vapor radiometry** (see Bob Sault's talk).

- **In the near term, fast switching will be the preferred method for ATCA.**

17

Effectiveness of fast switching



Carilli et al. 1999

18

Observing a test calibrator

In poor weather or when using long baselines, it may be unclear whether a non-detection is due to source weakness or to atmospheric phase decorrelation.

Procedure: observe a weaker (but detectable) "test" quasar near your source, in addition to a stronger quasar as the phase calibrator.

If phase gains transferred to the test quasar yield a good detection, your phase calibration is probably adequate.

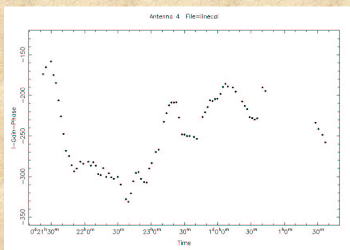
Example: **observe test quasar instead of source every third cycle (30 sec/cycle).**

```
source=m82,0841+708,1048+717
grid='ns(1,1,1,2,2,1,1,1,2,2,3,3,3,2,2)'
```

19

Instrumental Phase

- Phase variations can also result from variable instrumental delays, e.g. diurnal changes in effective cable length.
- A roundtrip phase measurement can be used to correct for these delays.

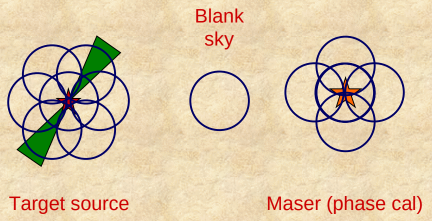


Four hours at BIMA

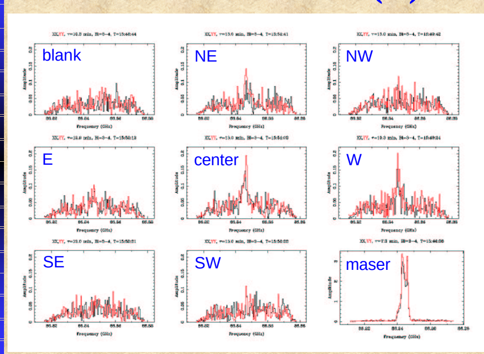
20

Sample Observing Scheme

1. Pointing pattern on SiO maser
2. 9-pt mosaic, 30 sec/point, repeated for 45 min.
3. Blank sky position serves as OFF for AC data



Results for NGC 6334 I(N)



Single-baseline ATCA, July 2001

Lecture Summary

- Interferometry at high radio frequencies places stringent demands on **pointing**, **surface accuracy**, and other instrumental properties.
- Amplitude calibration is complicated by varying **atmospheric opacity**, but can be corrected to first order using the chopper wheel method.
- Flux calibration relies on **planets** because quasars are variable at mm wavelengths.
- Phase calibration becomes increasingly difficult at **higher frequencies** and **longer baselines** due to turbulence in the tropospheric H_2O layer.
- **Observing programs need to allot adequate time for amplitude, flux, phase, and pointing calibrations in order to minimise map errors.**