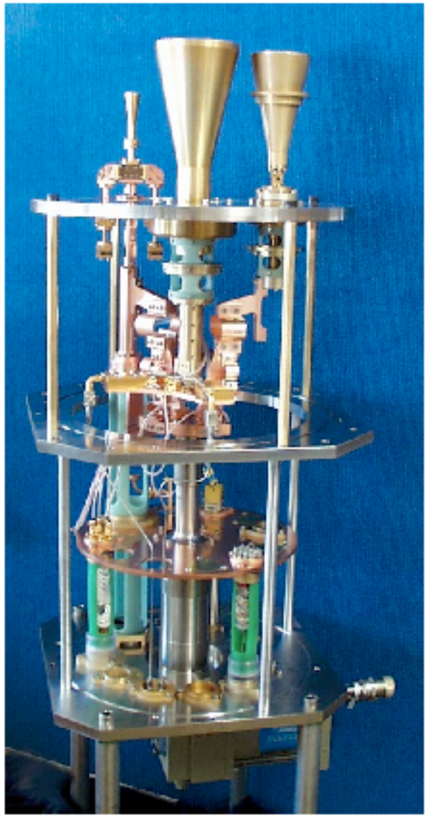

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Special Considerations for Millimetre Observing

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CASS Radio Astronomy School 28th September 2010

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Why the need for a talk on millimetre astronomy?

- Everything about interferometry is more difficult at higher frequencies
- Atmospheric opacity increases Tsys and attenuates the signal
- Fewer bright millimetre sources to use for calibrators
- Instrument stability is more difficult to maintain
- Antenna accuracy is less
- Field of view (antenna primary beam) is smaller

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Talk Outline

- Motivation for doing millimetre observations
- Capabilities of mmATCA
- Recap of observing strategies at centimetre wavelengths
- Highlight the differences for observing at higher frequencies
- Effects of the atmosphere
- Methods used by ATNF telescopes for atmospheric correction

Acknowledge presentations and contributions from Shari Breen, Cormac Purcell, Crystal Brogan, Debra Shepherd & Maxim Voronkov

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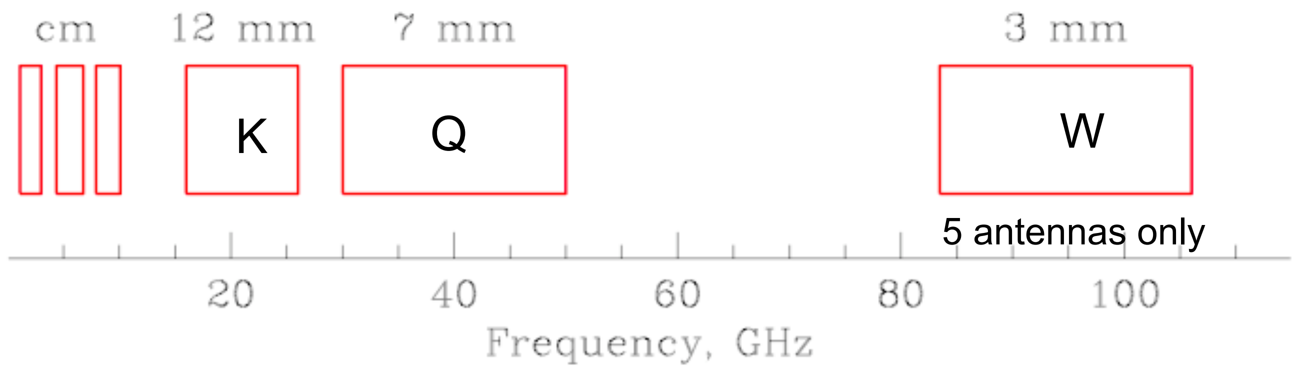
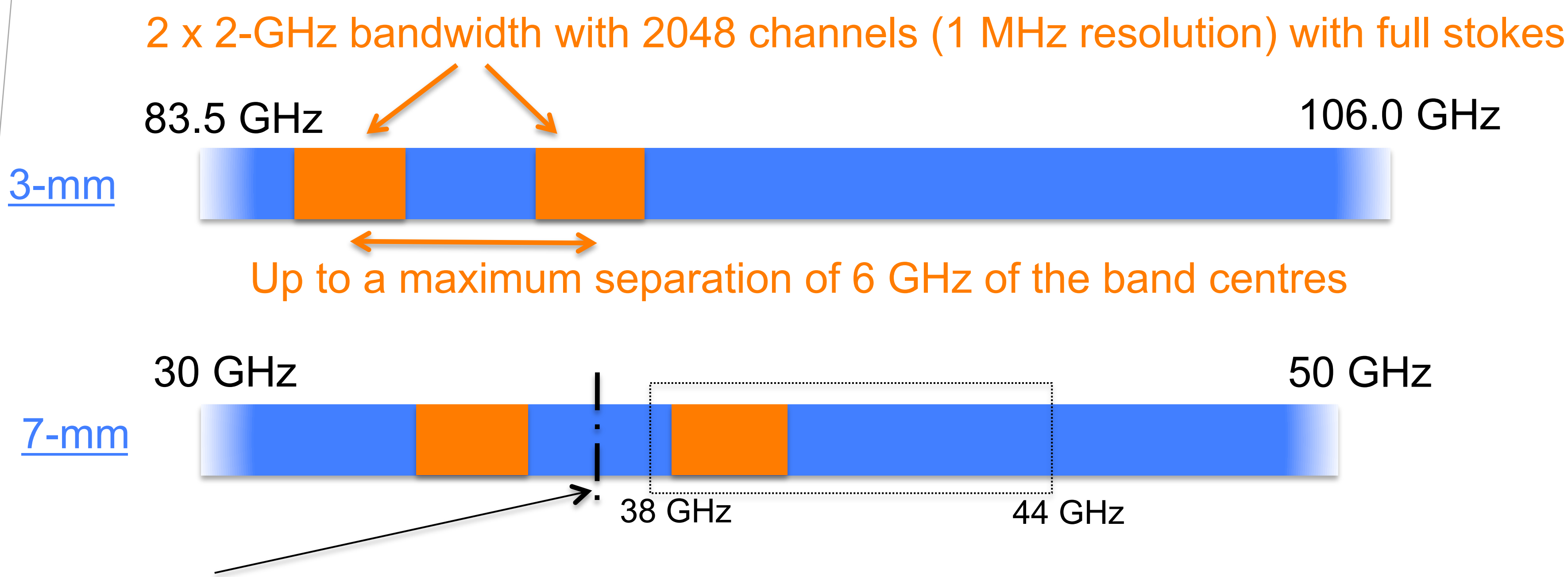
Motivation for millimetre astronomy



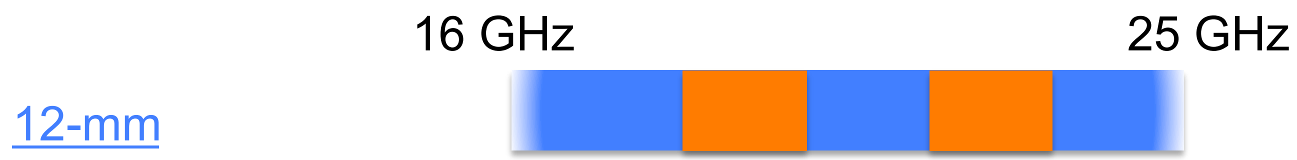
- Sensitive to thermal emission from dust, very dense ionized gas & molecular lines
- Probe of cool gas and dust in:
  - Molecular clouds
  - Dust in dense regions
  - Star formation in the high-red shift Universe
  - Recombination line emission from ionised gas
  - Thermal emission from dense, compact regions (young stars)

mmATCA with CABB

- 8 GHz CABB range over which two 2-GHz bands can be positioned



Note: For the 7-mm system the centre frequency of the 8GHz CABB range cannot be placed between 38 and 44GHz.



Observing restictions for mmATCA

- Stick with compact hypbrid array configurations (at least initially)
  - In most cases observations at 3mm using the 750X, 1.5X or 6X arrays will be severely hampered by atmospheric phase noise.
- The best time for millimetre observing is the APR observing semester from April 01 to September 30 (also referred to as the "winter season").
- For 3mm observing there is a 60-65% chance of weather suitable for 3mm observing during the winter season. Good conditions start in May and the weather starts falling apart in October. The height of summer is unsuitable.
- Observations at 12 and 7 mm may also be scheduled in the OCT observing semester, between October 01 to March 31.
  - If applying for time in this semester then it is recommended you request your observations to be scheduled in the months October or March or during the nightime of the remaining months (if your source LST range permits).

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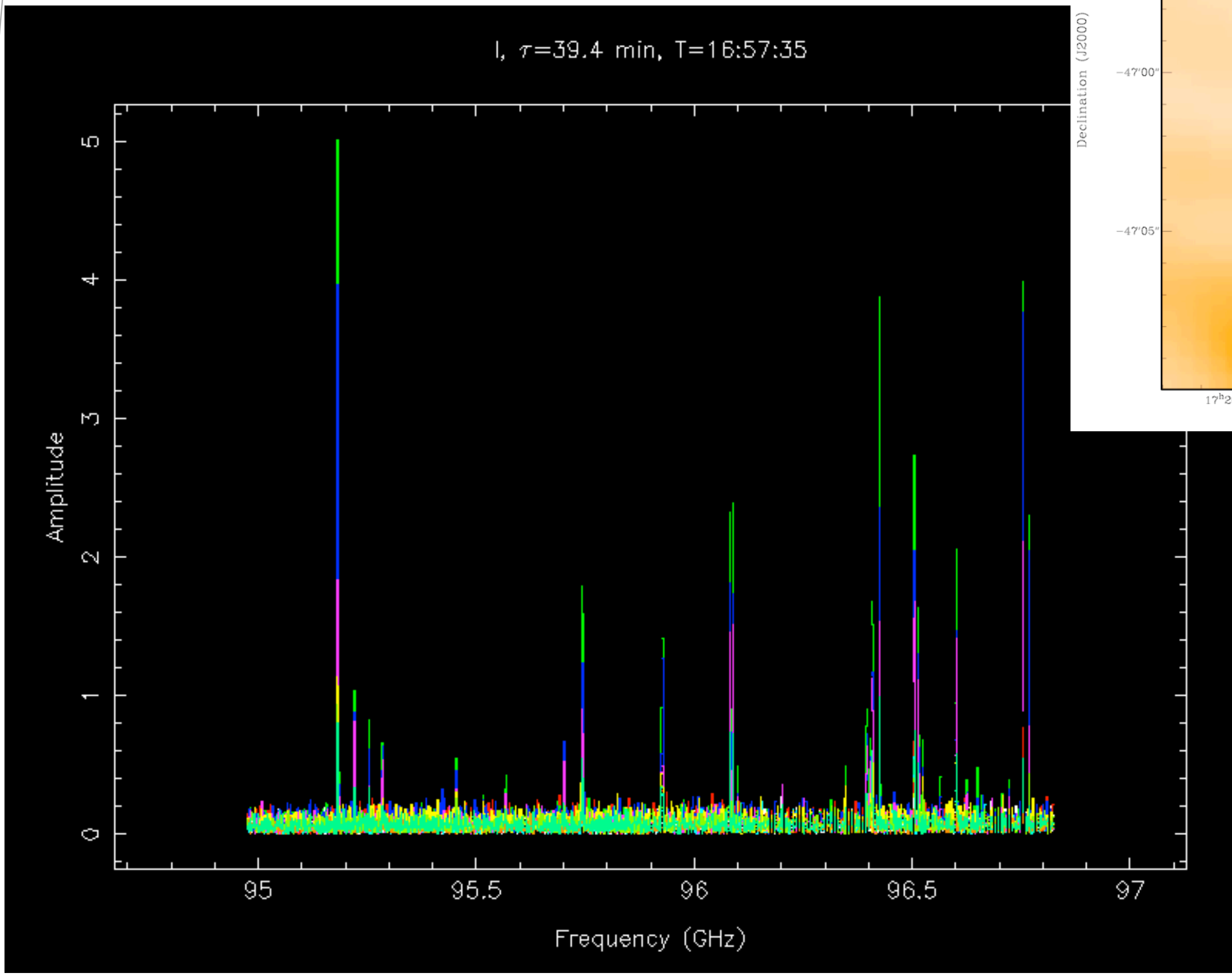
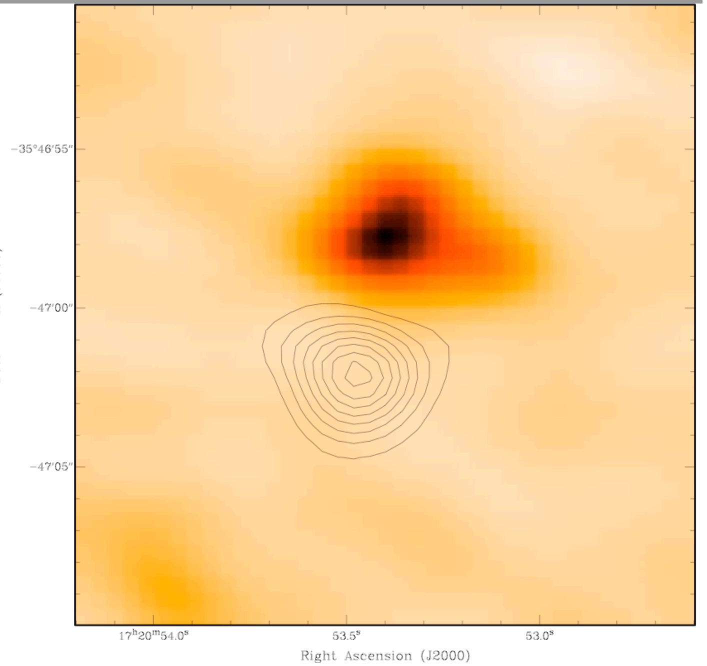
CABB observations of NGC6334I at 3mm

Work by Brooks, Titmarsh, Voronkov, Urquhart done as part of the CABB science commissioning





3mm continuum (contours) and $C^{34}S$ (2-1) (grayscale)

Calibration for cmATCA observations (≤ 8.6 GHz)

- Delay
- Bandpass
- Flux Scale
- Phase & Gain

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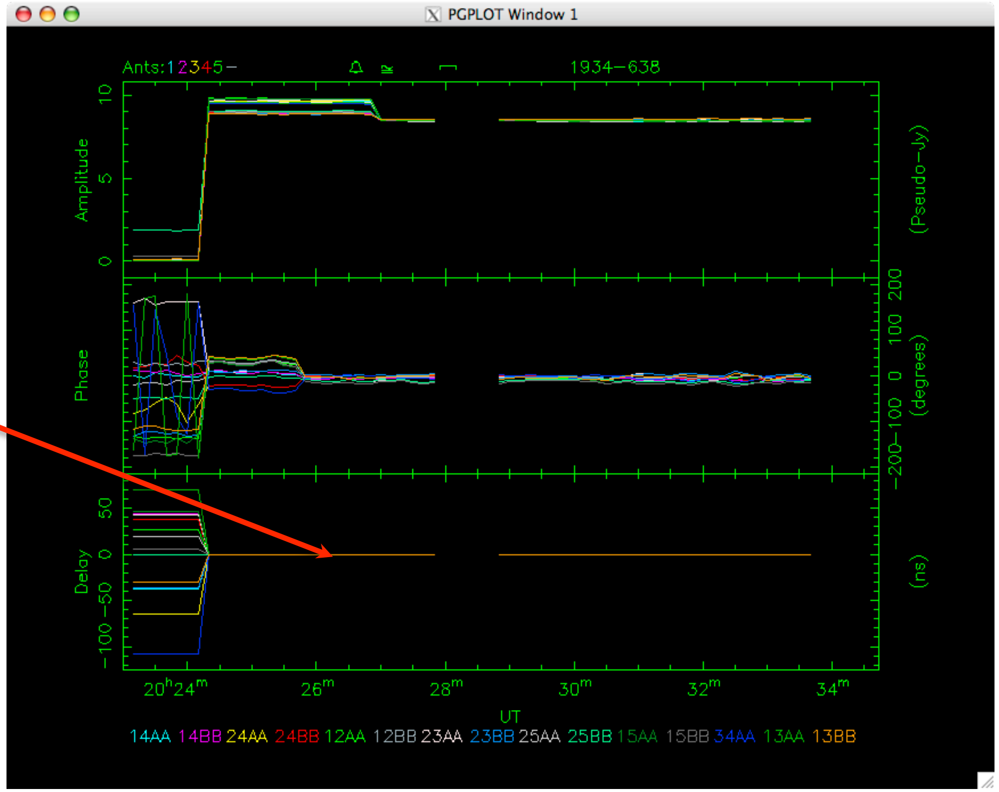
Delay Calibration - centimetre

- Bright “Startup” Calibrator

Source	RA	DEC	20cm	13cm	6cm	3cm
0823-500	08:25:26.869	-50:10:38.49	6.45	5.53	3.30	1.41
1253-055	12:56:11.166560	-05:47:21.524580	10.13	9.1	13.82	18.07
1934-638	19:39:25.026	-63:42:45.63	14.95	11.59	5.83	2.84

Delay Calibration
(set delays to zero)

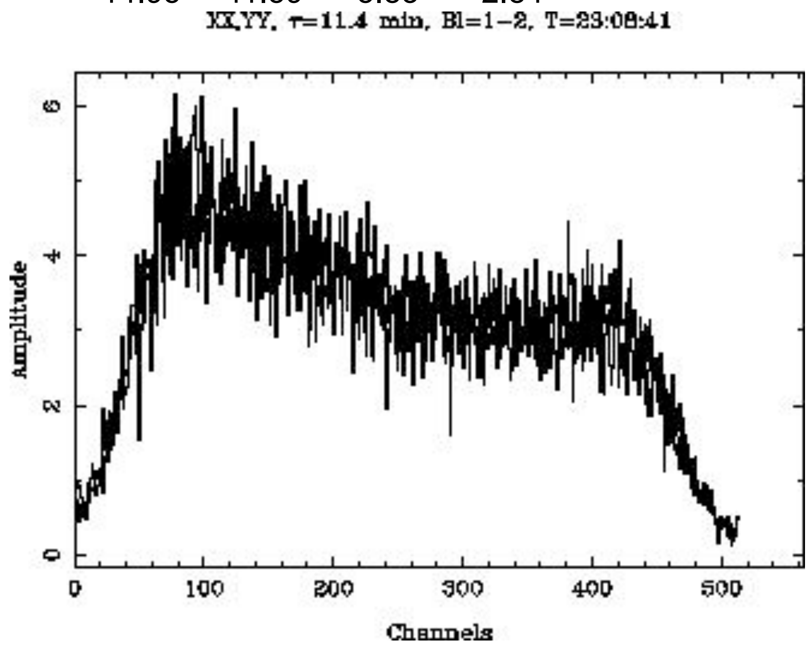


Bandpass Calibration - centimetre

Delay
Bandpass
Flux Scale
Phase

- Bright “Bandpass” Calibrator
- Correction of the different response across the band
- Observer at least once during each observing run for ~10mins

Source	RA	DEC	20cm	13cm	6cm	3cm
0823-500	08:25:26.869	-50:10:38.49	6.45	5.53	3.30	1.41
1253-055	12:56:11.166560	-05:47:21.524580	10.13	9.1	13.82	18.07
1934-638	19:39:25.026	-63:42:45.63	14.95	11.59	5.83	2.84

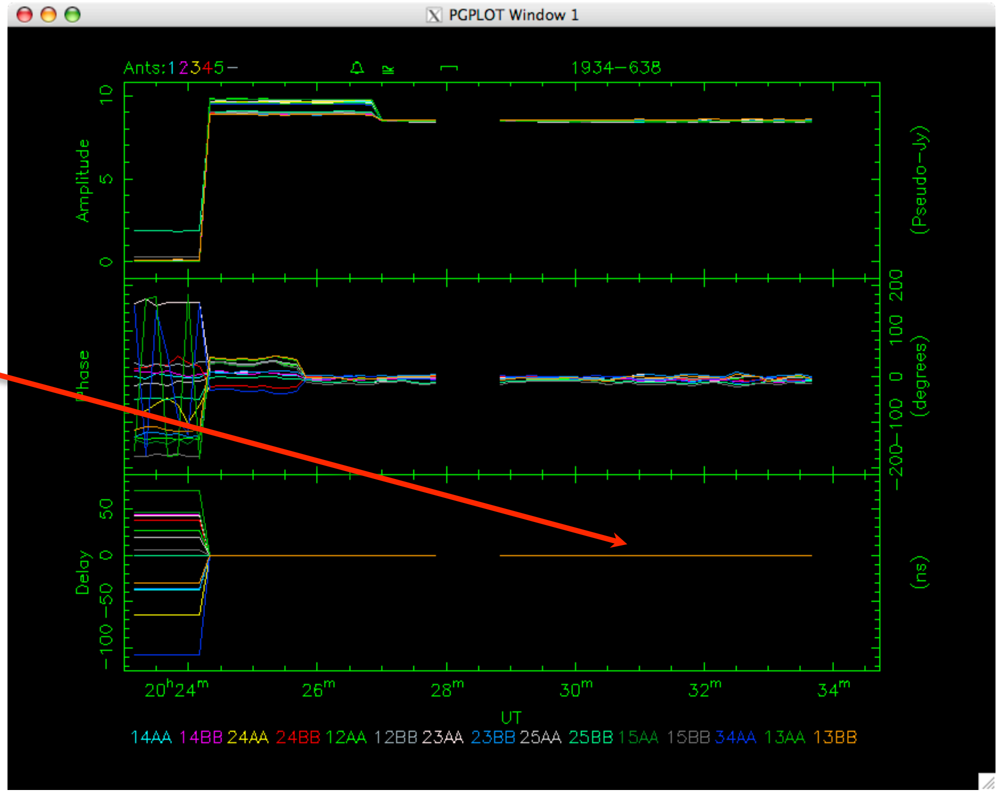


Flux Calibration- centimetre

- PKSB1934-638 is the "Primary Flux Calibrator"
- Observer at least once during an observing run for ~10mins
- Flux model in MIRIAD for 1934-638 between 408 and 8640 MHz

Source	RA	DEC	20cm	13cm	6cm	3cm
1934-638	19:39:25.026	-63:42:45.63	14.95	11.59	5.83	2.84

Startup, Flux & Bandpass Calibration using 1934-638



Phase & Gain Calibration - centimetre

Delay
Bandpass
Flux Scale
Phase

- Calibrator nearby to science target
- Sometimes called "secondary calibrator" or "gain calibrator"
- Must be unresolved (point source) for all baselines
- Should be ideally brighter than 0.5 Jy with an angular separation to the target of less than10 degrees
- Calibrators vary and so always have a couple of backups if the calibrators are close to the recommended flux limit
- Typically observe for ~2 min every 40 min (more frequently for higher frequencies)
- Always finish with a scan on the secondary calibrator

CALIBRATOR – TARGET - CALIBRATOR

The most up-to-date calibrator list is available by position or flux-limited online Search: http://www.narrabri.atnf.csiro.au/calibrators/

Calibration for mmATCA observations (≥ 16 GHz)

- Delay
- Bandpass
- Flux Scale
- Phase
- + Pointing
- + Atmosphere

Delay & Bandpass Calibration - millimeter

Delay
Bandpass
Flux Scale
Phase
Pointing
Atmosphere

- Bright "Startup" Calibrator and bright "Bandpass" calibrator

Source	RA	DEC	20cm	13cm	6cm	3cm	12m	7mm	3mm
0823-500	08:25:26.869	-50:10:38.49	6.45	5.53	3.30	1.41	**0.55**	**?**	**<0.12**
1253-055	12:56:11.166560	-05:47:21.524580	10.13	9.1	13.82	18.07	17.37	16.1	14.5
1934-638	19:39:25.026	-63:42:45.63	14.95	11.59	5.83	2.84	**1.03**	**0.38**	**0.03**

Too faint to use for mm observing

Source	RA	DEC	20cm	13cm	6cm	3cm	12m	7mm	3mm
0521-365	05:22:57.98465	-36:27:30.850920	12.09	6.60	3.84	3.00	2.59	3.9	4.1
0537-441	05:38:50.362	-44:05:08.94	4.54	3.92	2.99	3.04	8.35	10.2	9.2
1253-055	12:56:11.166560	-05:47:21.524580	10.13	9.1	13.82	18.07	17.37	16.1	14.5
1921-293	19:24:51.055957	-29:14:30.121150	9.06	10.45	11.85	13.59	10.98	9.5	7.0
2223-052	22:25:47.259291	-04:57:01.390730	5.95	5.96	6.12	6.28	7.48	8.8	6.6
2227-088	22:29:40.084346	-08:32:54.435410	1.00	0.84	1.32	1.42	4.14	4.7	5.4

1921-293 and 1253-055 are the favorites

Flux Calibration - millimetre

Delay
Bandpass
Flux Scale
Phase
Pointing
Atmosphere

Source	RA	DEC	20cm	13cm	6cm	3cm	12m	7mm	3mm
1934-638	19:39:25.026	-63:42:45.63	14.95	11.59	5.83	2.84	**1.03**	**0.38**	**0.03**

- For ATCA 12-mm & 7-mm flux calibration
  - 1934-638 is a suitable flux calibrator with CABB (just!)
- For ATCA 3-mm flux calibration (and backup for 12-mm and 7-mm)
  - Uranus is the preferred flux calibrator
- Flux model for Uranus is available in miriad
- Uranus is above an elevation of 30 degrees only for a few hours each day
- Flux calibration can be “boot-strapped” using calibrators 1921-293 or 1253-055
- Search for more flux calibrators is underway

Phase & Gain Calibration - millimetre

Delay
Bandpass
Flux Scale
Phase
Pointing
Atmosphere

- Calibrator nearby to science target (the closer the better)
- In principle > 1 Jy with an angular separation to the target of less than 5 degrees
- Fewer bright calibrators at higher frequencies
- In practice ~ 0.8 Jy with an angular separation up to 15 degrees
- Typically observe:
  - 2 min every 10 min at 90 GHz
  - 2 min every 15 min at 40 GHz
  - 2 min every 20 min at 20 GHz

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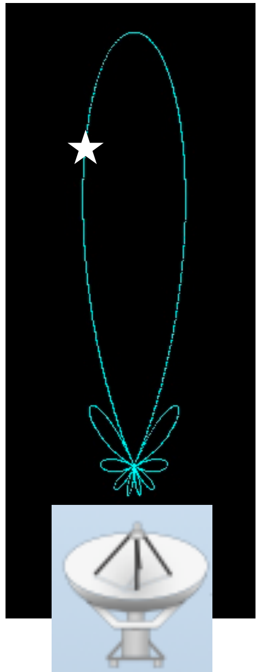
Pointing Calibration - millimetre

- Global pointing model for ATCA antennas achieves an uncertainty of ~10 arcsec
- Primary Beam ~ 1.22 λ/D
- Antenna response to flux is reduced if off target
- Additional pointing correction required for observations at 3 mm, 7 mm and (maybe) 12 mm
- Pointing should be corrected once per hour or if the antenna has slewed to a different part of the sky
- Use pointing scan (see Max's talk for details)



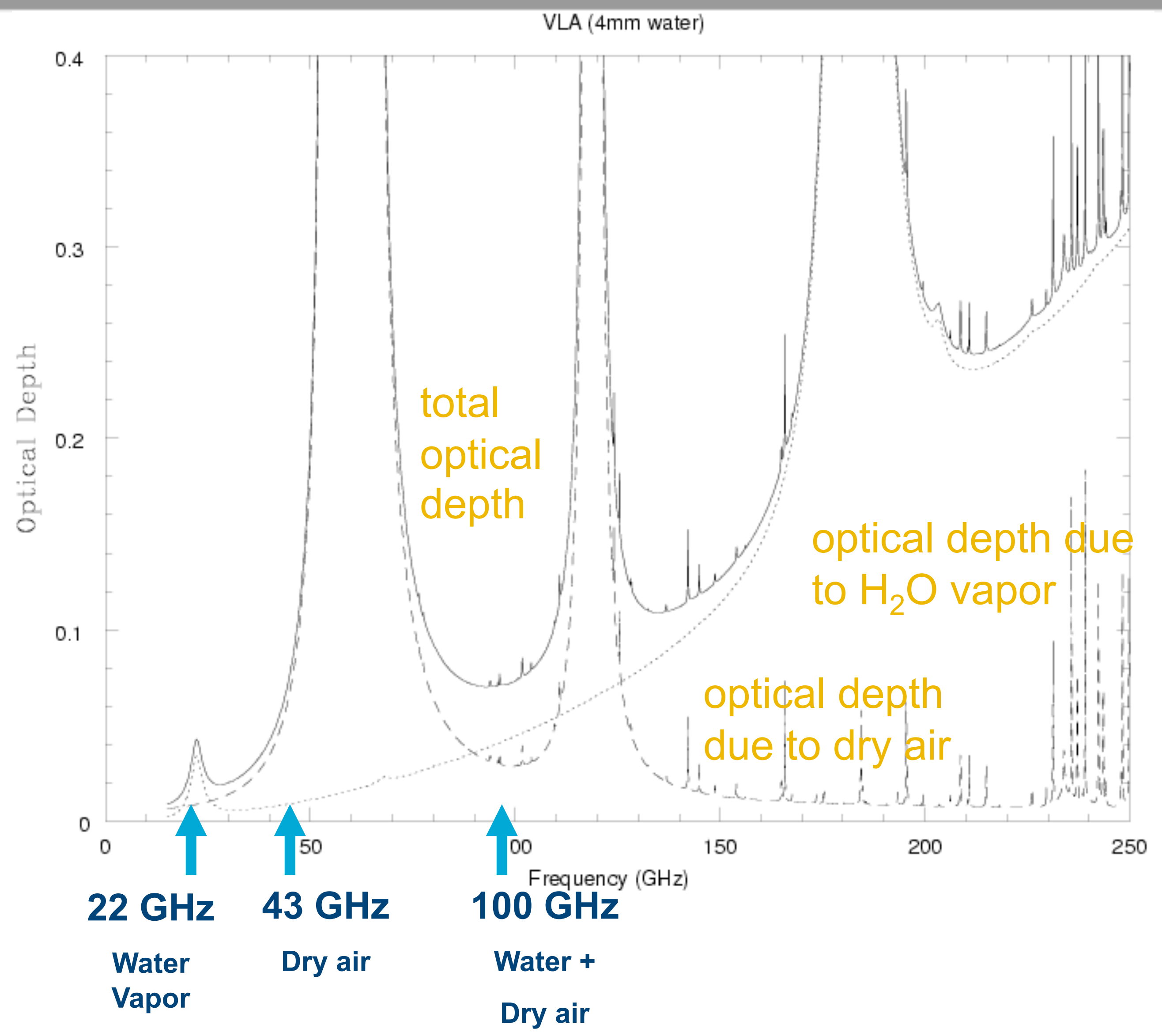
	1.3 GHz	2.2 GHz	4.5 GHz	8.0 GHz	16 GHz	30 GHz	90 GHz
Primary Beam	36 arcmin	21 arcmin	11 arcmin	6 arcmin	2 arcmin	95 arcsec	32 arcsec

Atmospheric Calibration - millimetre

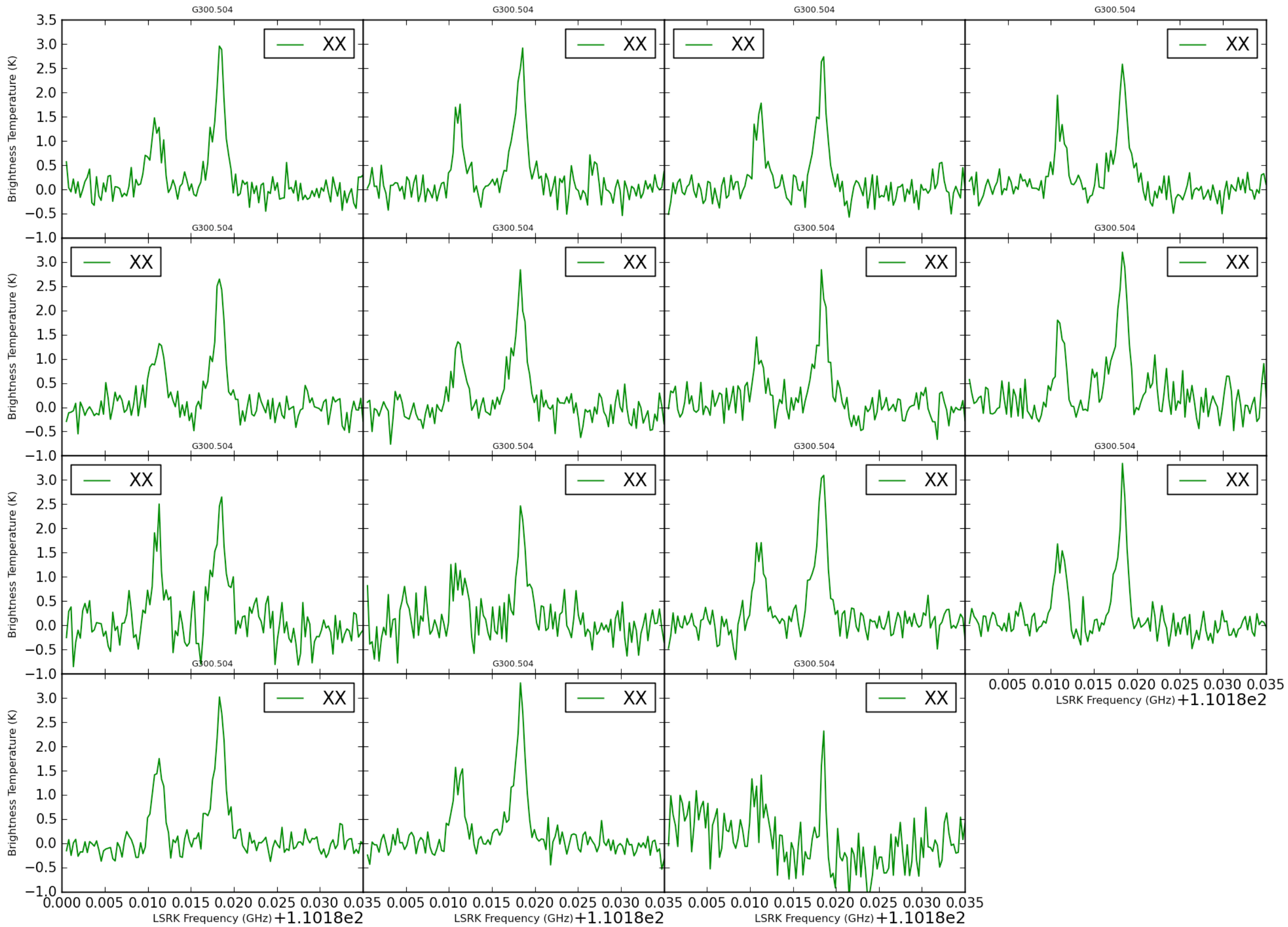
- Atmospheric opacity is significant below 1 cm
  - Raises Tsys and attenuations the source signal
  - Loss of visibility amplitude (co-herence)
- Opacity varies with frequency, altitude and weather conditions
  - Leads to significant phase fluctuations
- Opacity arises in the troposphere (lowest layer of the atmosphere, 7 – 10 km high

Atmospheric Calibration - millimetre

Delay
Bandpass
Flux Scale
Phase
Pointing
Atmosphere



Atmosphere adds noise and reduces signal



The less air and the less humidity the better

ALMA site – Chajnantor at 4600m - PWV 1mm

How to gauge dry observing weather

Plane trails - HUMID

How to gauge dry observing weather

Curly Hair - HUMID

How to gauge dry observing weather

ATCA seeing monitor

A two-element interferometer with an east-west baseline of 230m, tracking the 30.48GHz beacon on the geostationary satellite OPTUS-B3, at an elevation of 60 degrees.

The seeing monitor works by taking the difference between to successive phase measurements, computing the standard deviation of this difference, and converted into a path length in microns.

Results from the seeing monitor are updated in real time and displayed on MONICA in the control room.

This gives a measurement of the rms phase fluctuation caused by water vapour in the atmosphere.

Correcting for the atmosphere - Tau

Extinction is expressed in nepers (τ) and actual attenuation is given by $e^{-\tau}$

Transmission is inversely related to absorption as $1-e^{-\tau}$

The attenuation at an arbitrary zenith angle is given by the "sec z" term:

Attenuation = $e^{-\tau} = e^{-\tau_0 secz} = e^{-\tau_0/sin(el)} = e^{-\tau_0 A}$

where,

τ_0 = zenith optical depth

A = number of air masses (secz)

el = elevation angle

z = zenith distance (90 – el)

Atmospheric Model Outputs for tau

Using Miriad task “opplt”

For 22 GHz: tau = 0.4 to 0.2	x 1.5 to 1.2 (20%)
For 40 GHz: tau = 0.2 to 0.1	x 1.2 to 1.1 (9%)
For 50 GHz: tau = 0.6 to 0.3	x 1.8 to 1.3 (26%)
For 98 GHz: tau = 0.7 to 0.35	x 2.0 to 1.4 (30%)
For 115 GHz: tau = 1.35 to 0.7	x 3.8 to 2.0 (48%)

These were made with humidity = 70%, pressure = 1013 hPa and temperature = 300K.

For mmATCA observing stay above 35 degrees

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Simplified Sky Noise Equation

The measured antenna temperature from an astronomical source can be represented by:

$$T_{ON} = T_{rec} + T_{amb}\,(1 - e^{-\tau}) + T_{source}e^{-\tau} + T_{CMB}e^{-\tau}$$

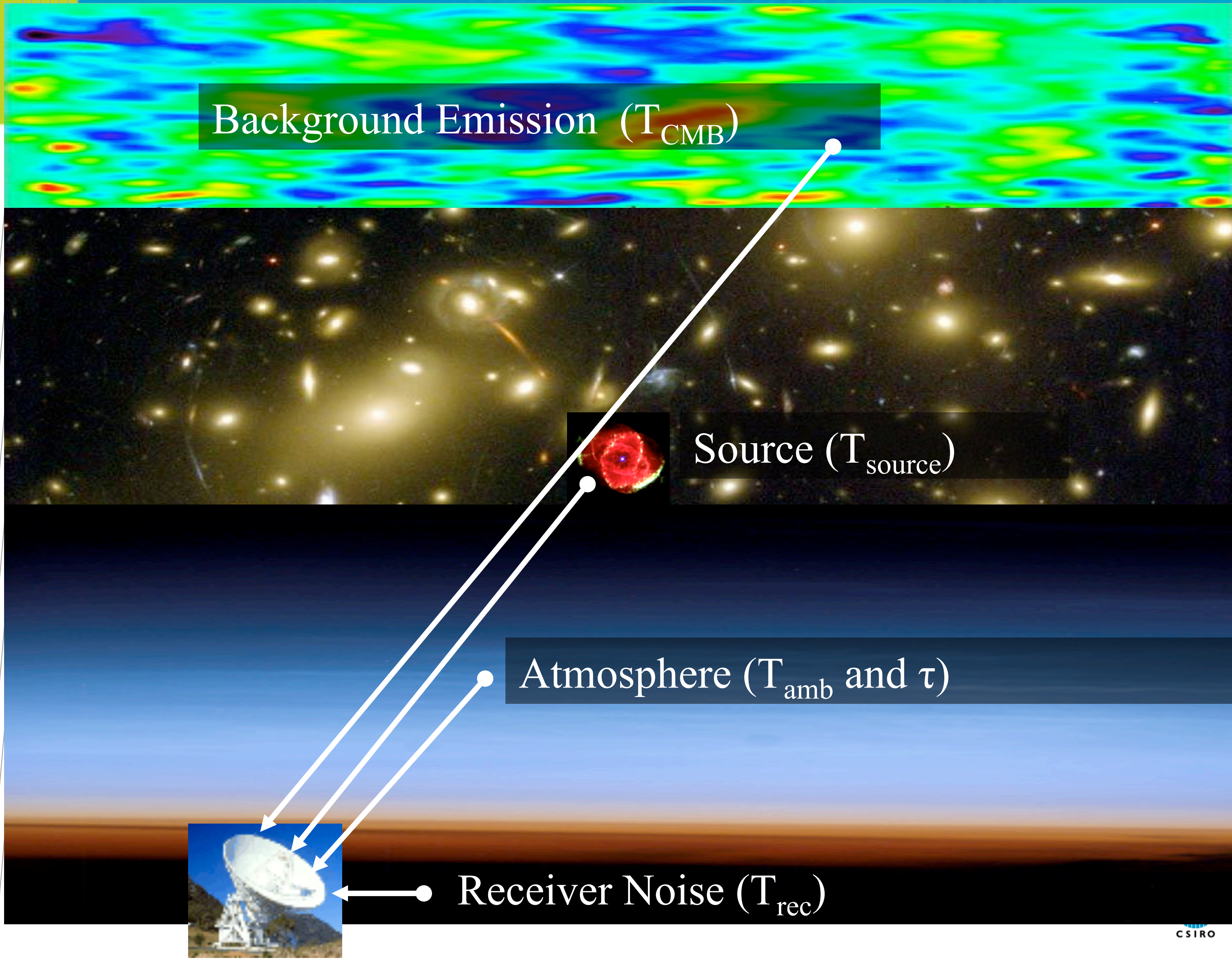
where,

T_{rec} = the receiver temperature

T_{source} = the source temperature

T_{amb} = ambient temperature

- T_{CMB} = the contribution to the signal from the cosmic background signal



Background Emission (T_{CMB})
Source (T_{source})
Atmosphere $(T_{amb}$ and $\tau)$
Receiver Noise (T_{rec})
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Correcting for the atmosphere – System Temperature

- The term "system temperature" is used to define the noise of the whole system.

  $Tsys = [T_{rec} + T_{atm} (1 - e^{-\tau}) + T_{CMB} e^{-\tau}]$

In good observing conditions the typical values for Tsys are:

12 mm ~ 60 K

7 mm ~ 120 K

3 mm ~ 220 K

For ATCA the primary contribution to Tsys is from the atmosphere

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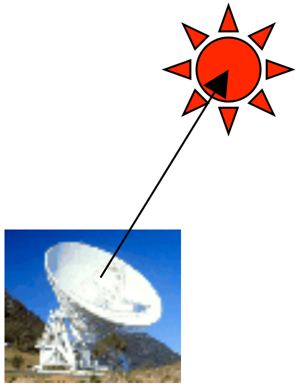
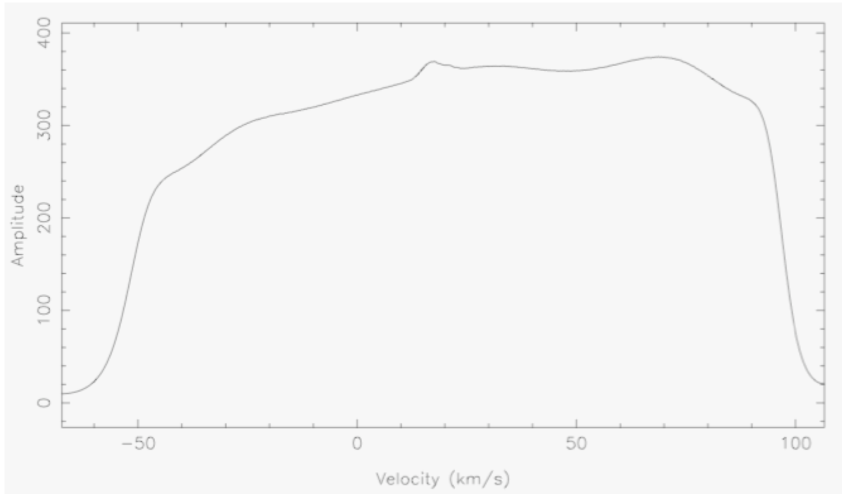
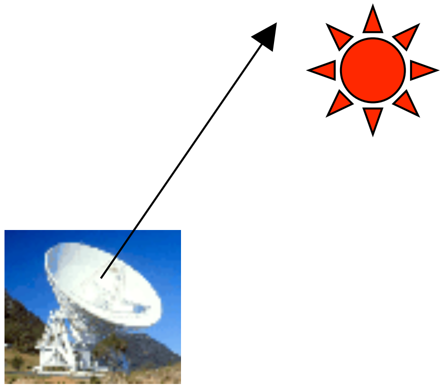
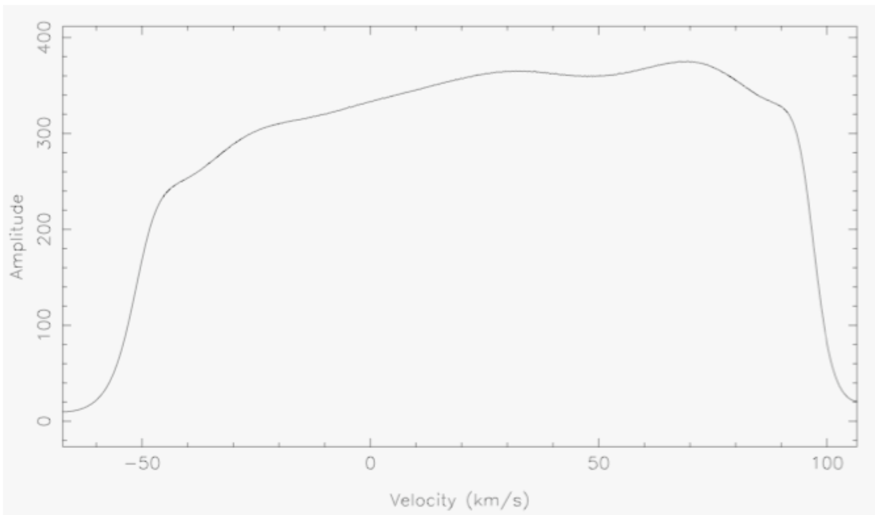
Consider single dish (Mopra) for a moment





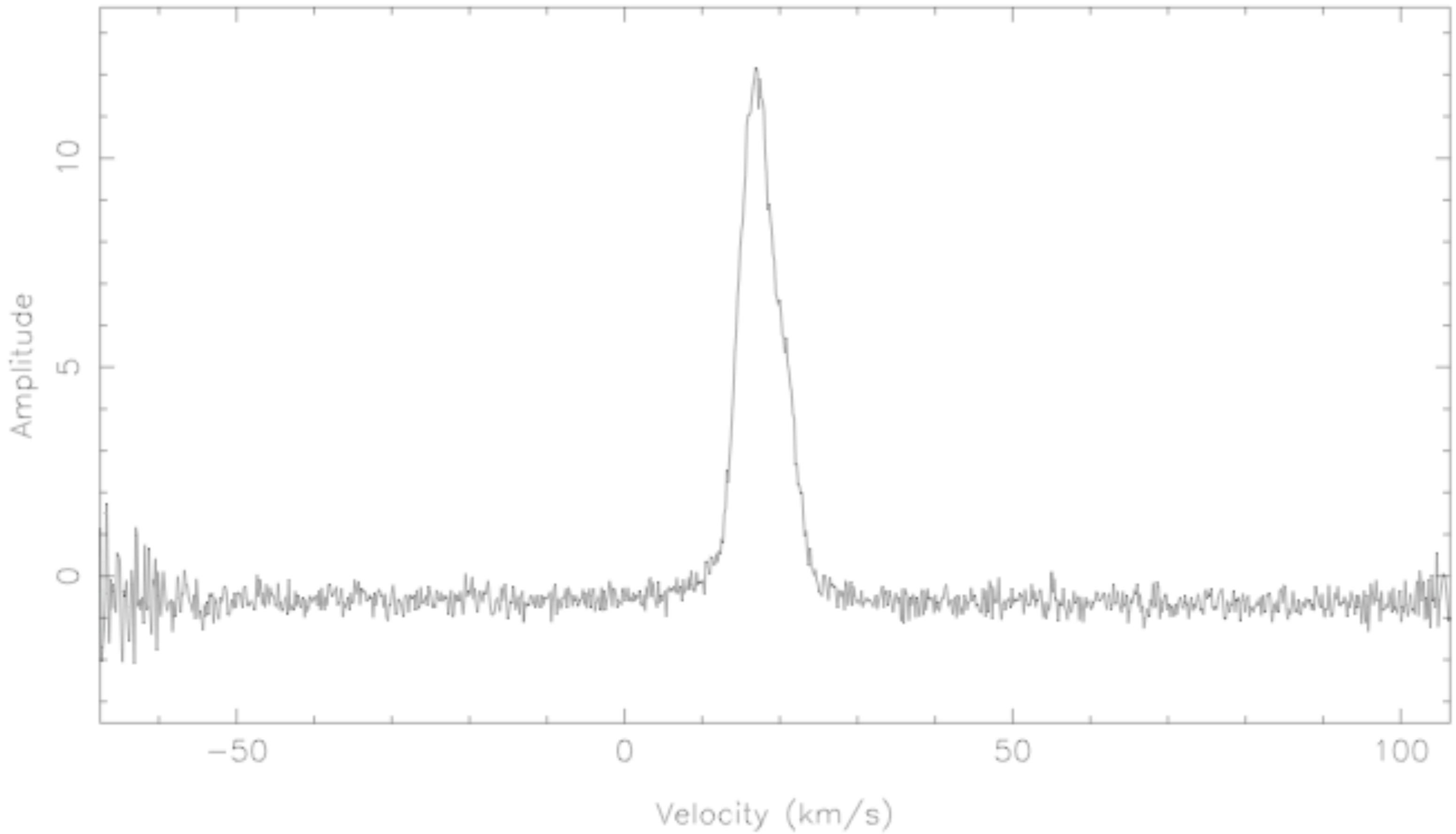
T_{ON}





T_{OFF}

Consider single dish (Mopra) for a moment



Output from ASAP: $T_{ON} – T_{OFF} / T_{OFF}$ = Quotient Spectrum

Consider single dish (Mopra) for a moment

Output from ASAP: $T_{ON} – T_{OFF} / T_{OFF}$ = Quotient Spectrum

Using: $T_{ON} = T_{rec} + T_{amb} (1 - e^{-\tau}) + T_{source}e^{-\tau} + T_{CMB}e^{-\tau}$
$T_{OFF} = T_{rec} + T_{amb} (1 - e^{-\tau}) + \quad + T_{CMB}e^{-\tau}$

Quotient Spectrum = $T_{source}e^{-\tau}$ / Tsys

Therefore to calibrate the flux scale for the spectral line produced by ASAP a measurement of Tsys and attenuation $e^{-\tau}$ are required.

Measuring the Tsys for Mopra 12 and 7 mm

- For the MOPS system on Mopra a switching noise diode is used to measure the change in Tsys
- We are continually tracking Tsys variations on one hot/cold load measurement taken at the start of the semester
- The noise diode is used to calculate the contribution of the receiver and the antenna to the Tsys measured at the feed aperture
- The noise diode adds a fixed and known contribution to the system
- The noise diode computes a new Tsys value for each 2-second integration cycle
- There is one Tsys value for each of the MOPS 2.2 GHz IF bands

Measuring the attenuation $e^{-\tau}$ for Mopra 12 & 7 mm

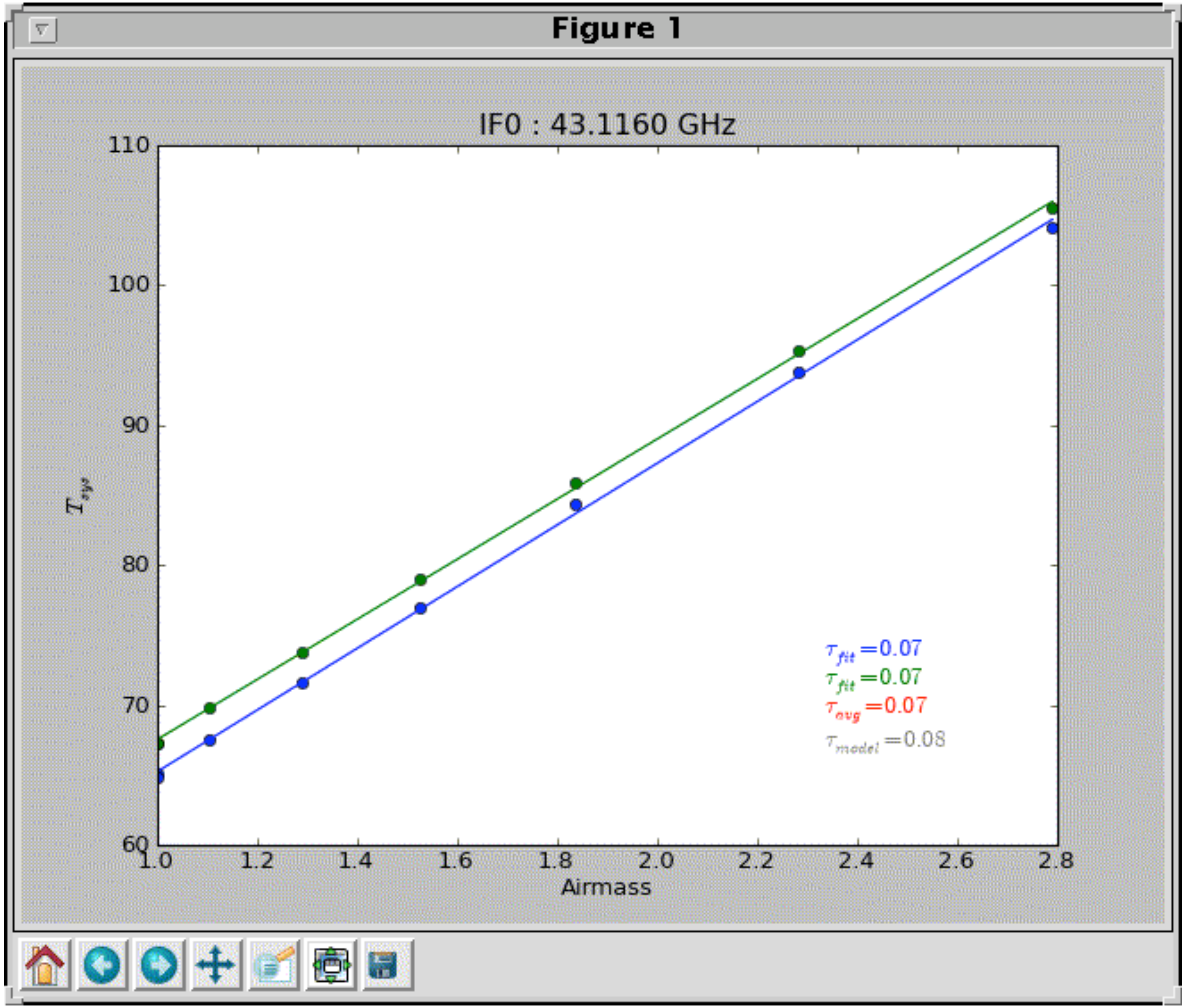
- For the MOPS 7- and 12-mm systems the atmospheric attenuation is measured via 2 independent methods:

1. Skydip measures the power of the atmosphere emission as a function of airmass while tipping the telescope from high to low elevation
   - Assuming that for each skydip procedure the values for T_{rec}, T_{atm} and T_{CMB} are constant then:

     $$Tsys(el) = A - (B)e^{-\tau_o/\sin(el)}$$

   - Time consuming and no good in bad (unstable) weather
2. Atmospheric Model
   - Inputs are: Temperature, Pressure, Humidity
   - This is the standard way to observe
   - Requires no observing time (offline correction in ASAP)

Measuring the attenuation $e^{-\tau}$ for Mopra 12 & 7-mm



Measuring the Tsys and attenuation $e^{-\tau}$ for Mopra at 3 mm

- For the MOPS 3-mm system the Tsys and the atmospheric attenuation is measured via the "Paddle" method
- This involves placing an ambient load (paddle) in front of the receiver horn for 30 sec.
- Assume that the temperature of the ambient load is equivalent to the temperature of the atmosphere obtain a value for Tsys corrected for atmospheric contributions
- CABB output temperature scale is automatically corrected each time a paddle measurement is made

Psky

$$T_{sys}^{eff} = (300\ \mathrm{K}) \frac{P_{sky}}{P_{abs} - P_{sky}}$$

Pabs

What happens for ATCA

- At 3-mm
  - Both the system temperature and the correction for tau is determined using the paddle method
  - The paddle measurement should be executed every 15min
  - The correction for tau is interpolated between paddle measurements
  - The CABB output temperature scale is automatically corrected to reflect the Tsys and tau values (1 value for the full 2GHz band)
- At 12 and 7 mm
  - The system temperature is determined by the noise diode
  - The correction for tau is determined offline (in miriad) using an atmospheric model

Calibration limitations – Flux uncertainty

- If you have data taken in good weather then expect the following uncertainties in your final flux measurements:
  - For 12 mm - 5 to 10 %
  - For 7 mm – 10 to 20 %
  - For 3mm – 30 to 50 %
- Be aware of these limitations and the sensitivity limitations of ATCA when you are preparing your observing proposal
- While observing unstable weather is your enemy.

Is all this extra effort worth it?

- One good thing for millimetre observing is that there is much less radio frequency interference
- Sensitive to thermal emission from dust, ionized gas & molecular lines
- Probe of cool gas and dust in the nearby and distant universe
- Observing with mmATCA gives you the skill set to use and work with the data products from the first of the next-generation astronomy mega-structures – ALMA

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Thank you

CSIRO Astronomy & Space Science
Australia Telescope National Facility
Kate Brooks
Millimetre Astronomy Research Scientist

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Measuring T_{sys} using the paddle method

Power measured from blackbody paddle:

$$P_{load} = C[I_{load} + I_{rx}]$$

Compare power from blank sky and known load:

$$\frac{P_{sky}}{P_{load} - P_{sky}} = \frac{J(T_{atm})(1-e^{-\tau}) + I_{bg}e^{-\tau} + I_{Rx}}{I_{load} + I_{Rx} - J(T_{atm})(1-e^{-\tau}) - I_{bg}e^{-\tau} - I_{Rx}}$$

Measuring T_{sys} using the paddle method

$$\frac{P_{sky}}{P_{load} - P_{sky}} = \frac{J(T_{atm})(1-e^{-\tau}) + I_{bg}e^{-\tau} + I_{Rx}}{I_{load} - J(T_{atm})(1-e^{-\tau}) - I_{bg}e^{-\tau}}$$

Assume: $T_{load} = T_{atm}$ i.e. $I_{load} = J(T_{atm})$

$$\frac{P_{sky}}{P_{load} - P_{sky}} = \frac{J(T_{atm})(1-e^{-\tau}) + I_{bg}e^{-\tau} + I_{Rx}}{J(T_{atm})\, e^{-\tau} - I_{bg}e^{-\tau}}$$

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Measuring T_{sys} using the paddle method

$$\frac{P_{sky}}{P_{load} - P_{sky}} = \frac{J(T_{atm})(1-e^{-\tau}) + I_{bg}e^{-\tau} + I_{Rx}}{J(T_{atm})\, e^{-\tau} - I_{bg}e^{-\tau}}$$

$$T_{sys} \rightarrow \frac{J(T_{atm})e^{\tau} - J(T_{atm}) + I_{bg} + I_{Rx}e^{\tau}}{J(T_{atm}) - I_{bg}}$$

$$\frac{P_{sky}}{P_{load} - P_{sky}} = \frac{T_{sys}}{J(T_{atm}) - I_{bg}}$$

Measured — Assumed : 300 K & < 1K

Calibration to T_A* scale

$$T_{sys} = \frac{P_{sky}}{P_{load} - P_{sky}} (J(T_{load}) - I_{bg})$$

Assumed 300 K
(Ambient temperature)

<1 K
From CMB

$$T_A^* = \frac{(P_{on\text{-}source} - P_{off\text{-}source})}{P_{off\text{-}source}} T_{sys}$$