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Millimetre Observations, Techniques and Considerations

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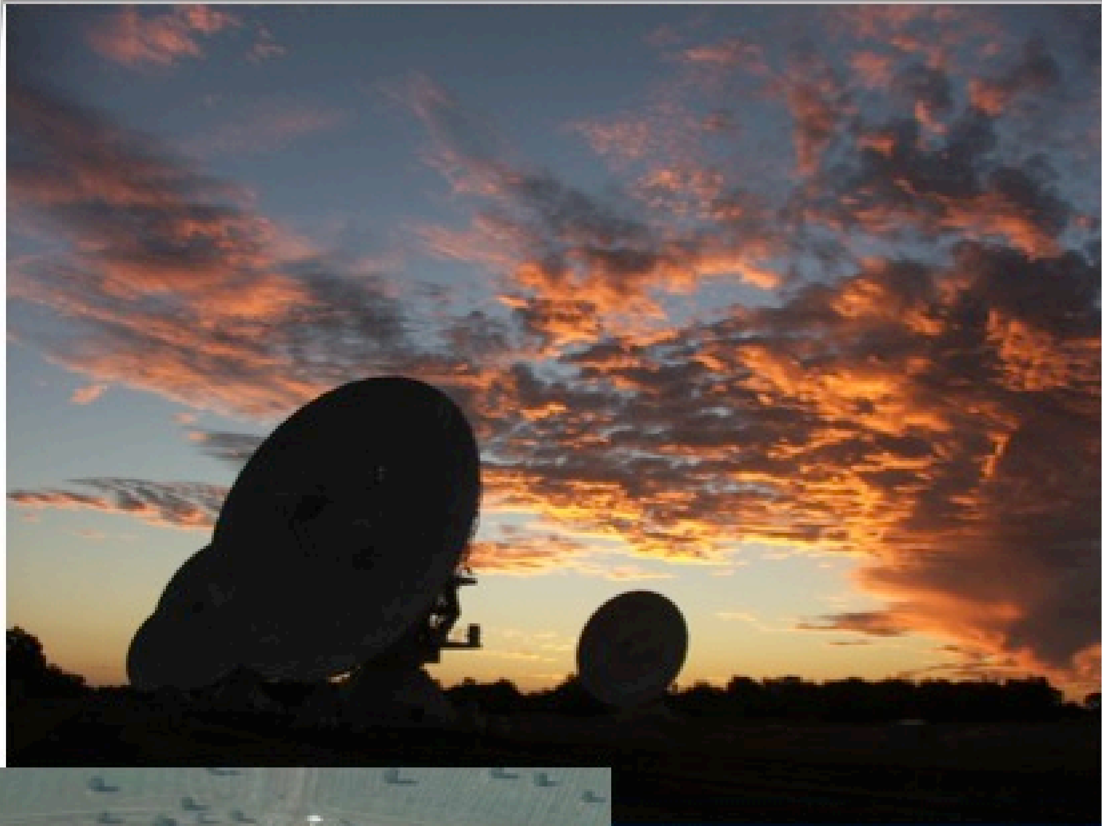
Outline

- Capabilities of ATNF instruments in mm
- Difference between mm and cm observations
    - Largely atmosphere
- Review of calibration
- Some practical aspects of mm observing and data reduction

Handy references (e.g. for more strict derivation):

- Kraus J.D., Radio Astronomy
- Talks by Dick Manchester and John Reynolds at this school
- Brooks K.J., Temperature scale and flux calibration, http://www.narrabri.atnf.csiro.au/mopra/TrainingDay08/Brooks_calibration.pdf
- Condon J.J., Ransom S.M., Essential Radio Astronomy, http://www.cv.nrao.edu/course/astr534/ERA.shtml

Australia Telescope at mm

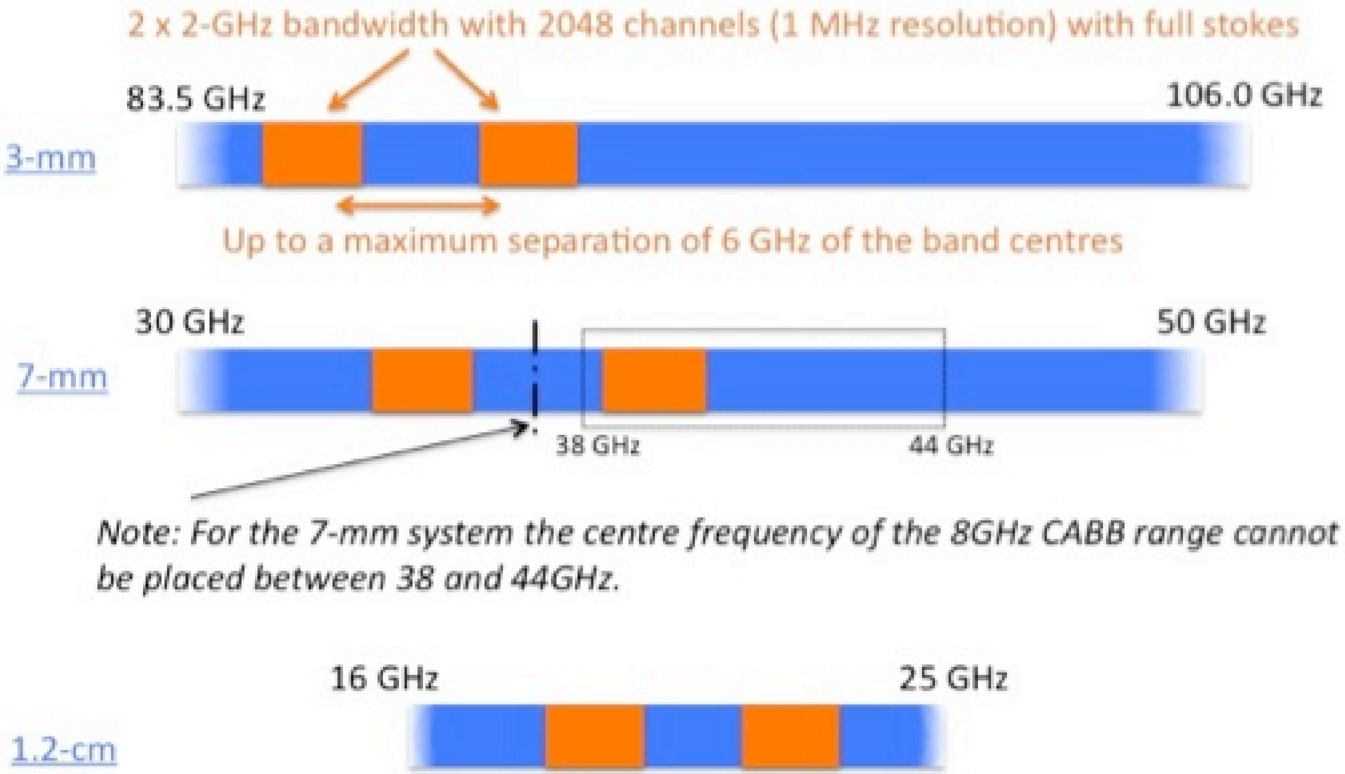


- Good set of receivers: 12mm, 7mm and 3mm
    - Mopra up to 117 GHz
    - Parkes only at 12mm
- Broadband backends available!
- Application for time via
  http://opal.atnf.csiro.au
- Proposal deadlines
    - June 15 (summer time)
    - December 15 (mm)

CABB - Present mm capabilities

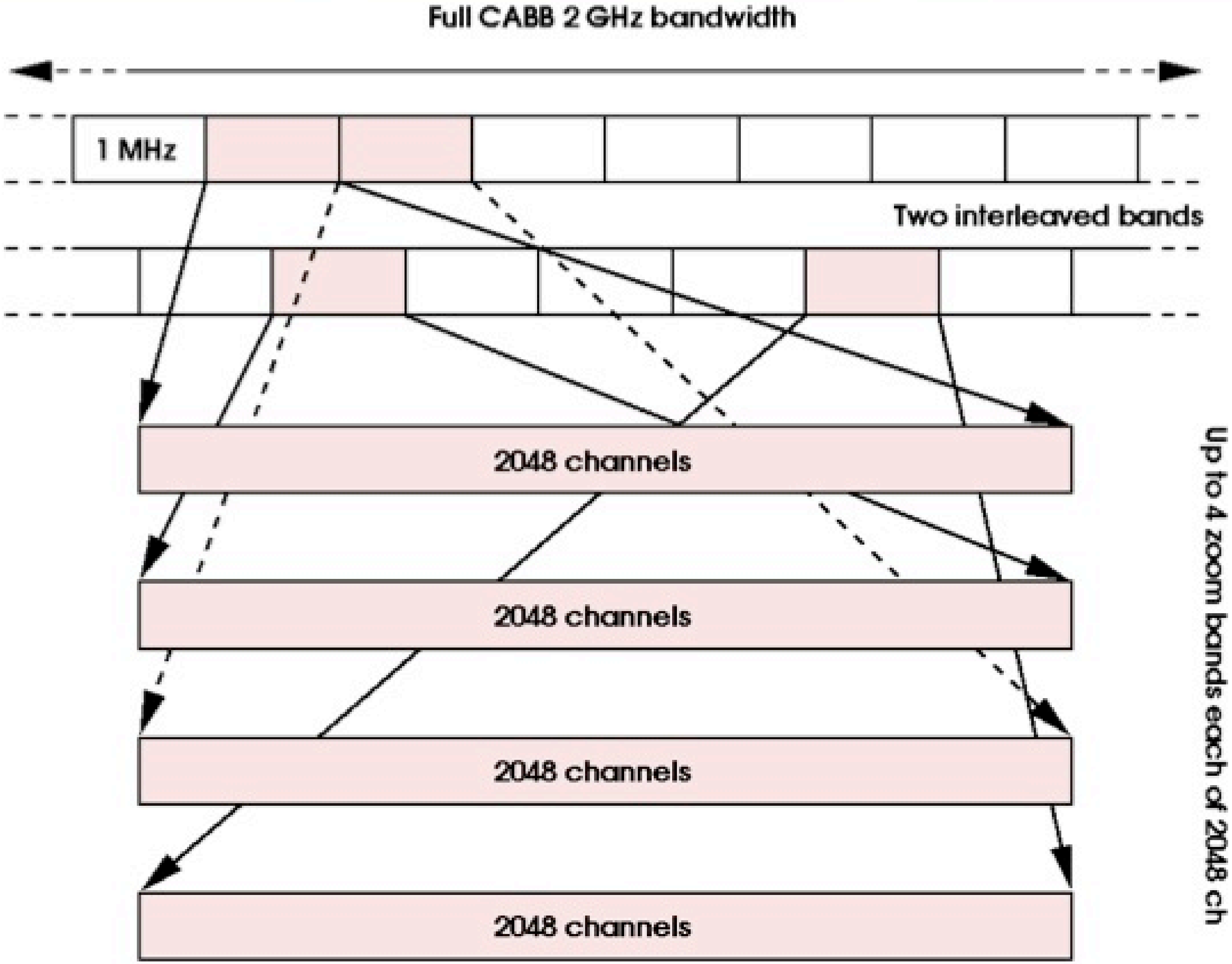
CABB wideband mode (mid Apr09 to mid Jul09)

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



More channels (16384) over each 2 GHz sub-band are technically feasible, but the timescale of implementation is uncertain at present

CABB - Zoom modes (example: 1 MHz zoom)



CABB - Zoom modes

- The width of a filter bank channel is the width of each zoom window
  - Coarse resolution of the wide sub-band = bandwidth of 1 zoom window
  - Stitching is possible (seamless, if interleaved windows are used)
- Initially up to 4 zoom windows per each 2 GHz sub-band
  - Eventually up to 16 zooms per sub-band will be available
  - Each 2 GHz sub-band (and all its zooms) can have different resolution

Resolution		Velocity Resolution			Velocity coverage		
Wide	Zoom	3mm	7mm	12mm	3mm	7mm	12mm
MHz	kHz	m/s			km/s		
1	0.5	1.6	3.8	7.1	3.1	7.5	14.3
4	2	6.3	15	29	12.6	30	57
16	8	25	60	114	51	120	229
64	32	101	240	457	202	480	914

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Mopra - a complementary single dish

- Similar set of receivers (but can go up to 117 GHz)
- Wide-band spectrometer (UNSW-MOPS) available (for a few years by now)

Available modes:

- Broad-band mode

continuous coverage of 8.3 GHz (0.25 MHz resolution = 0.8 km/s at 3mm) or

- Zoom mode

16 windows, 137.5 MHz each (0.03 MHz resolution = 0.1 km/s at 3mm)

What is so special about mm?

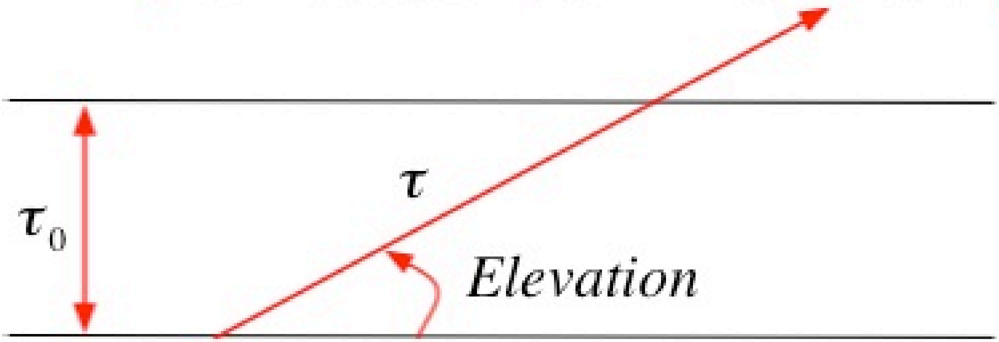
- Atmosphere becomes important
  - Absorbs astronomical signal
  - Emits its own radiation (contribution to Tsys)
  - Varies in time
  - Varies from one direction to another
  - Weather

Probably good

Most likely bad

Radiation transfer in the atmosphere

Tip: do not observe at mm below 30 deg of elevation



τ_0 zenith opacity

τ opacity in the direction of source

Homogeneous medium: opacity is proportional to the path: $\tau = \int \kappa_\nu d\ell$

$$\tau = \tau_0 / \sin(Elevation)$$

$$I_{below} = B_\nu(T)(1 - e^{-\tau}) + I_{above} e^{-\tau}$$

emission   absorption

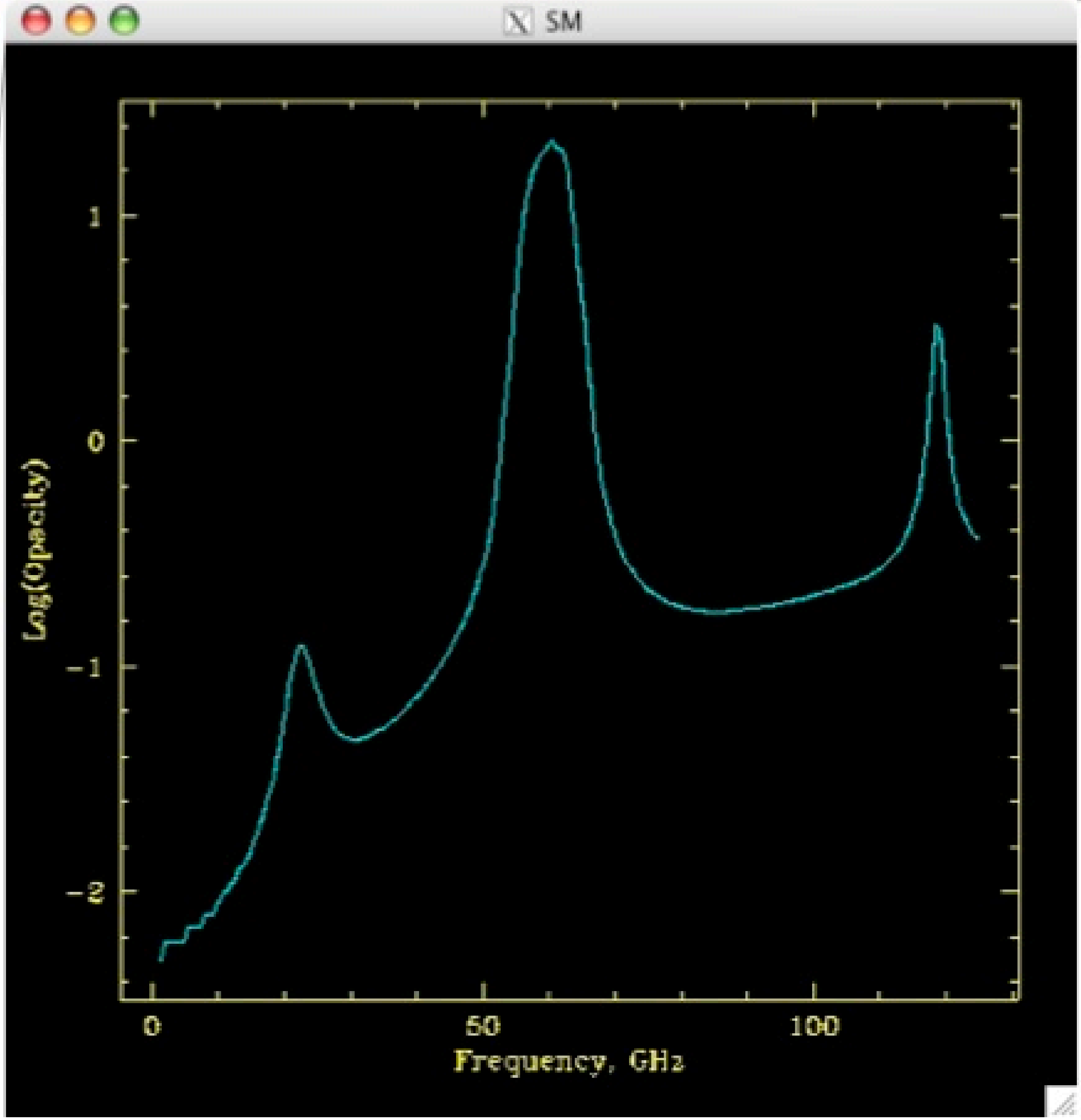
$$dI = \varepsilon_\nu d\ell - \kappa_\nu I d\ell$$

Intensity is often expressed in terms of the temperature (via Plank function). At low frequencies: $I \propto T$

$$\frac{\varepsilon_\nu}{\kappa_\nu} = B_\nu(T)$$ ← Plank function

$$T_{below} = T_{atm}(1 - e^{-\tau}) + T_{above} e^{-\tau}$$

Atmospheric transmission windows



- This plot shows the model of atmospheric opacity at Zenith (standard atmosphere and 20% humidity)
- Liebe's model: Radio Science, 1985, 20, 1069
- Dry component (i.e. oxygen)
- Wet component (water vapour), scale height of 1540m
- We can observe through 7mm and 3mm windows

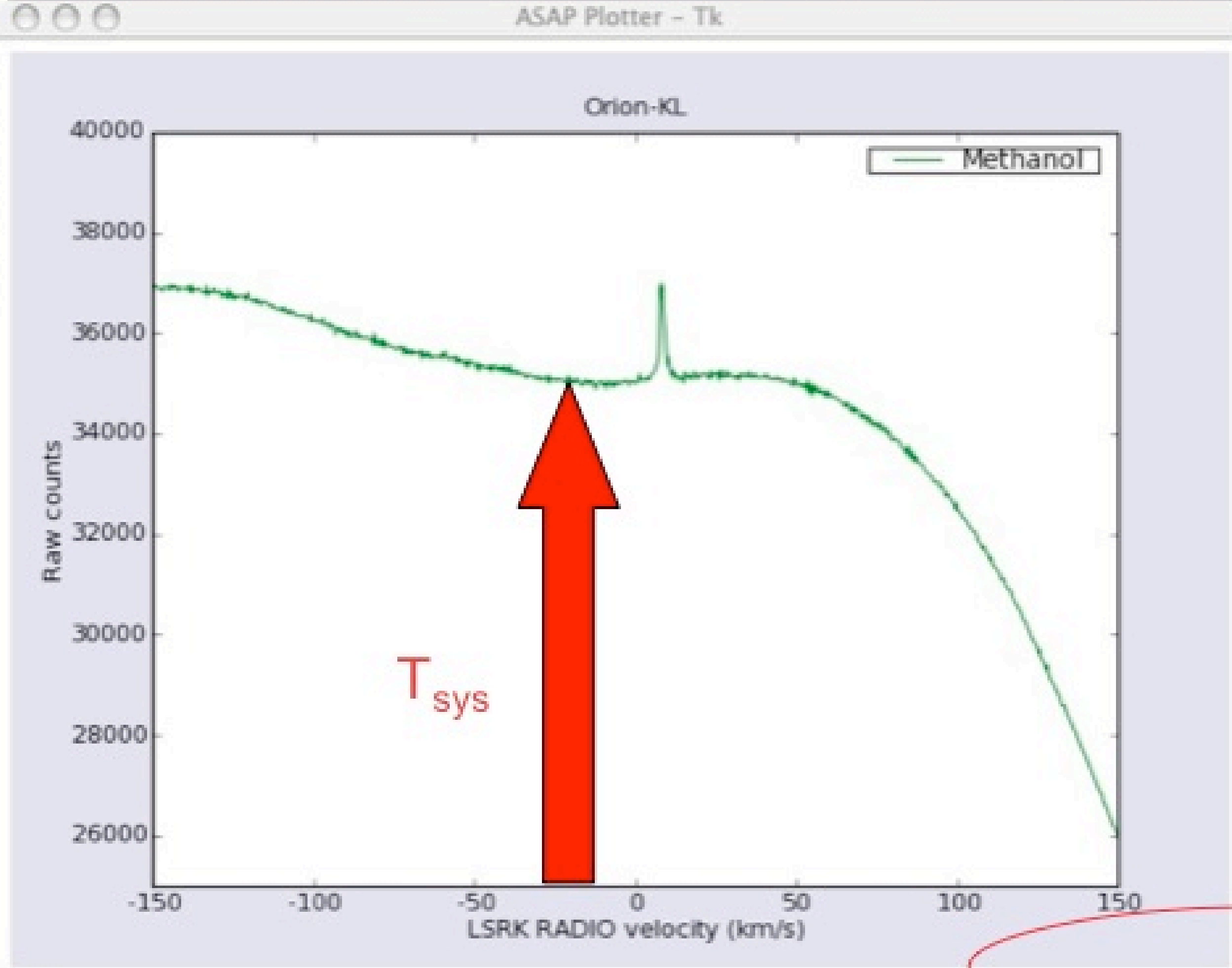
Atmosphere and interferometers

- For interferometers like ATCA atmospheric opacity is half of the evil
- Atmosphere causes phase variations as well (the effect is worse for extended arrays)

What is so special about mm?

- Atmosphere becomes important
  - Absorbs astronomical signal
  - Emits its own radiation (contribution to Tsys)
  - Vary in time
  - Vary from one direction to another
  - Weather
- Antenna performance becomes critical
  - Pointing
  - Focus/surface accuracy
  - Small beam means a small FOV (i.e. often need mapping)
- Very accurate calibration is difficult
  - Many small factors affect the calibration
  - Uncertainty is larger than for observations at cm-wavelengths

Raw single-dish spectrum



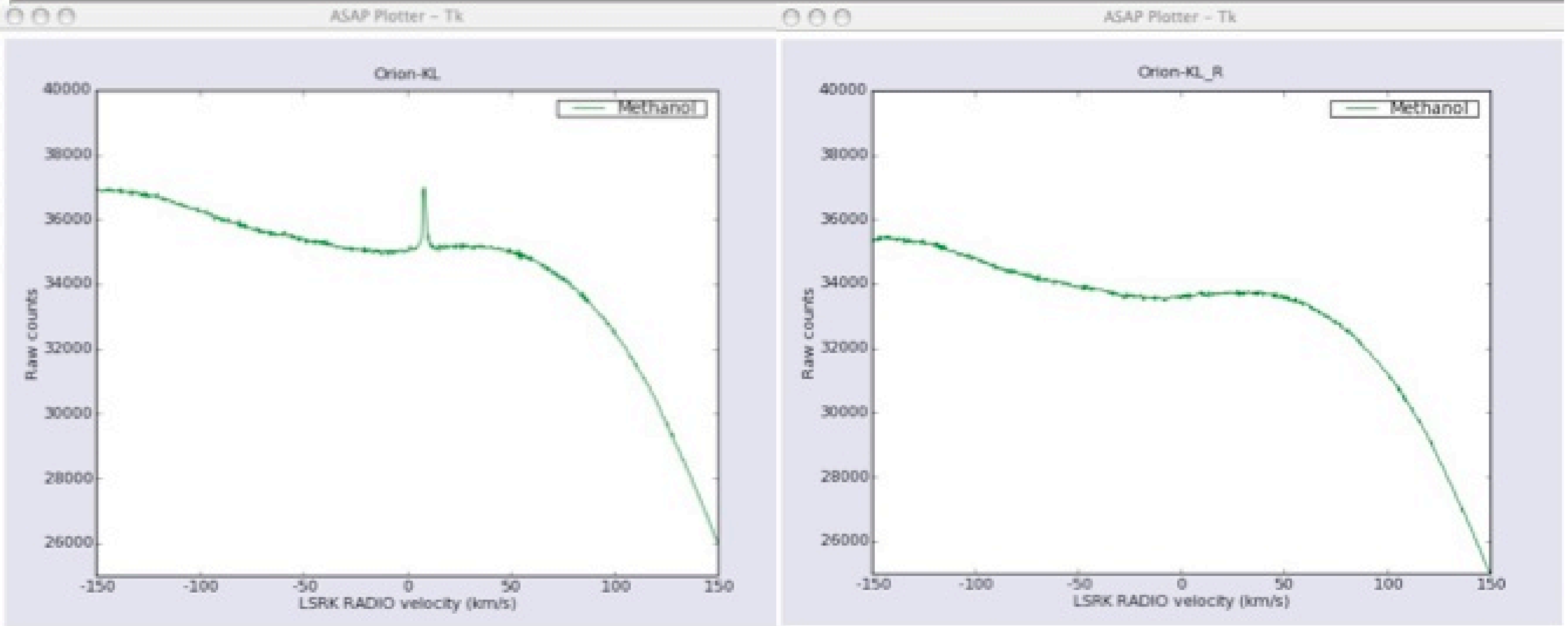
- Uncalibrated response to a spectral line source
- The raw units are usually scaled by the online system to match the Tsys
- Unscaled example is shown here as an extreme case of uncalibrated data

T_{sys} is usually referenced to above the atmosphere

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

Rayleigh-Jeans & 100% efficiency

Raw on and off spectra

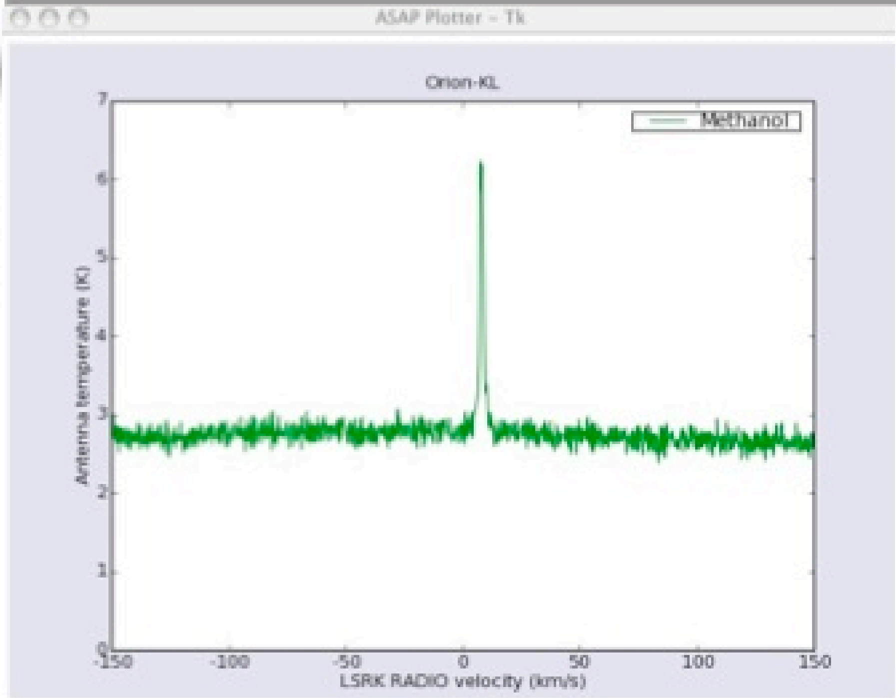


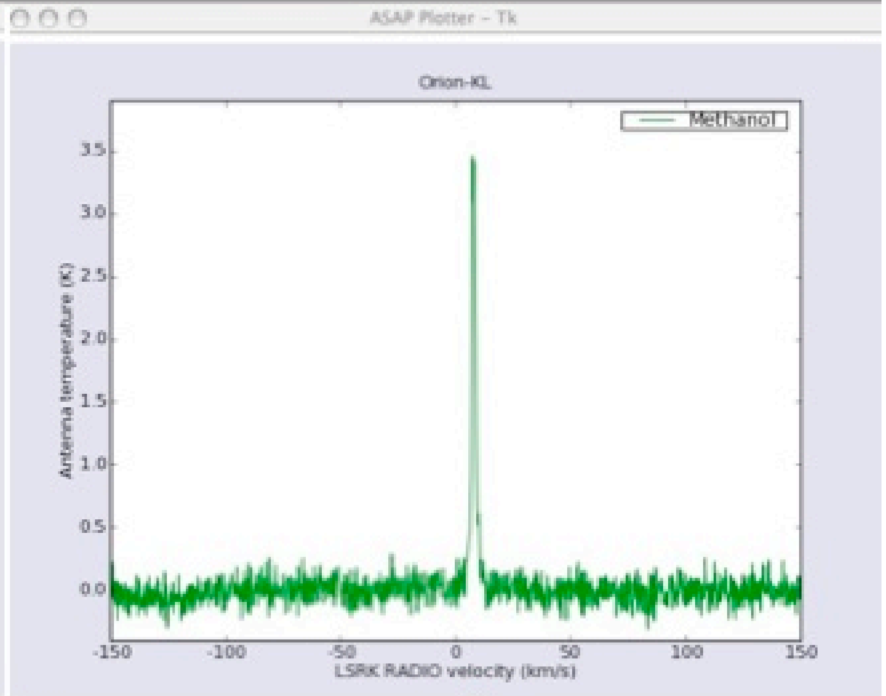
- Observe a reference position close to the target
- This method is known as position switching

$$T_a = \frac{ON - OFF}{OFF} T_{sys}$$

Quotient

Position switching, baselining

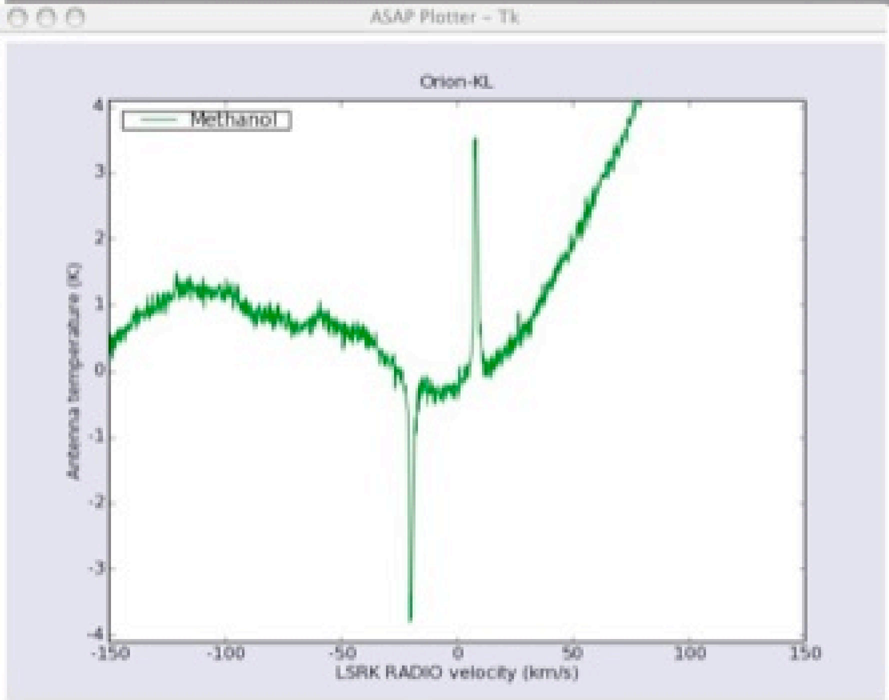


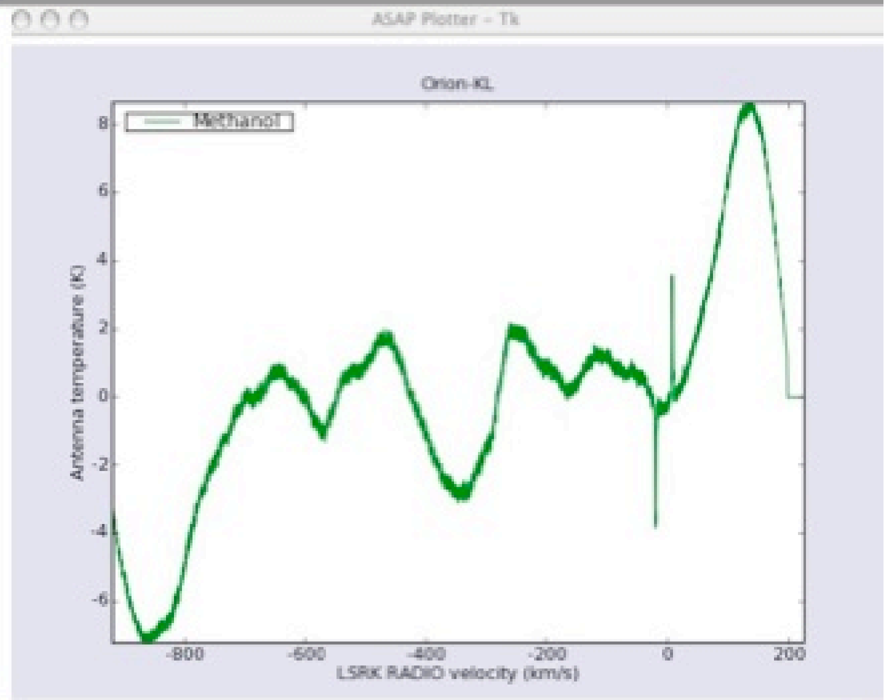


- Position switching gives good baselines, but
- Require twice as much observing time
- May be difficult for CO or HI in the Galaxy
- Systematics due to slightly different atmosphere for ON and OFF positions

Polynomial baseline removed

Frequency switching





- Frequency switching gives horrible baselines, especially if the source has a strong continuum emission and the telescope has a partially blocked aperture
- Does not allow to use all bandwidth
- Is not very suitable for broad-band instruments such as Mopra
- But it doesn't impose time penalty

Don't do it with ATNF instruments!

Position switching variations: MX-quotient

If you have two or more beams, loosing time is avoidable!

$$T_{a,1} = \frac{ON_1 - OFF_1}{OFF_1} T_{sys,1} \quad \text{average with} \quad T_{a,2} = \frac{ON_2 - OFF_2}{OFF_2} T_{sys,2}$$

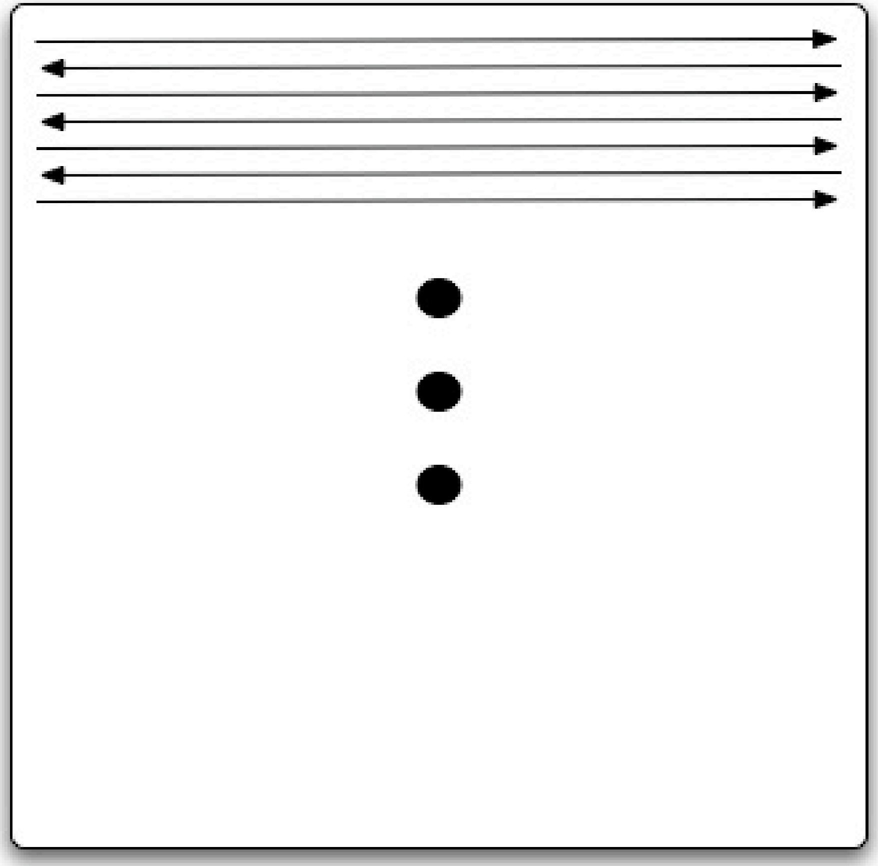
- Take median of all OFF positions if more than two beams are available
- This mode is used at Parkes with e.g. the methanol multibeam receiver
- There is a time overhead to change pointing/set up integration
- Not ideal for very short integrations (<1min per beam for Parkes)

Position switching variations: maps

- High frequency (Mopra)
  - Off-map reference position is observed once for each scan or two scans

- Low frequency and large maps (Parkes)
  - Reference spectrum is a median for the whole scan

livedata takes care of this!



Observer needs only to create an appropriate observing schedule!

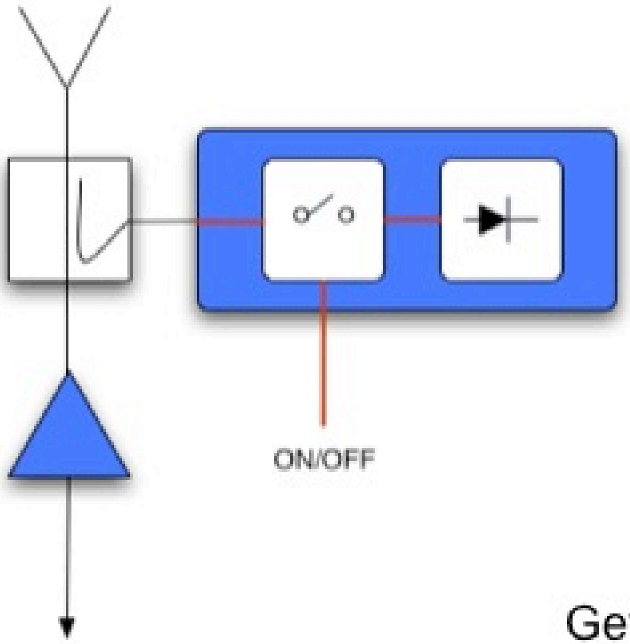
How to measure T_{sys}?

- Noise diode
  - Does not take the atmosphere into account
  - But it is good enough at low frequencies

$$P_{ON} \propto T_{diode} + T_{rec} + T_{atm}(1 - e^{-\tau}) + \cdots$$

$$P_{OFF} \propto T_{sys} e^{-\tau} \propto T_{rec} + T_{atm}(1 - e^{-\tau}) + \cdots$$

Above atmosphere value!



$$\frac{T_{sys} e^{-\tau}}{T_{diode}} = \frac{P_{OFF}}{P_{ON} - P_{OFF}}$$

Get T_{sys} if T_{diode} and opacity are known

Use hot and cold load to measure T_{diode} and T_{rec}

How to measure T_{sys}?

- Paddle
  - Without the atmosphere it would be a poor man's noise diode

$$P_{paddle} \propto T_{paddle} + T_{rec}$$

$$P_{sky} \propto T_{sys} e^{-\tau} \propto T_{rec} + T_{atm}(1 - e^{-\tau}) + \cdots$$

Above atmosphere value!

- Usual assumption: $T_{paddle} = T_{atm}$
- Hot and cold load method is more precise and gives opacity estimate

$$T_{sys} = \frac{P_{sky}}{P_{paddle} - P_{sky}} \left[(T_{paddle} - T_{atm}) e^{\tau} + T_{atm} \right]$$

- Noise diode allows to track T_{sys} variations caused by opacity:

$$\frac{T_{sys} e^{-\tau}}{T_{diode}} = \frac{P_{OFF}}{P_{ON} - P_{OFF}}$$

SKYDIP - a way to measure opacity

$$P_{ON} \propto T_{diode} + T_{rec} + T_{atm}(1 - e^{-\tau}) + \cdots$$

$$P_{OFF} \propto T_{sys} e^{-\tau} \propto T_{rec} + T_{atm}(1 - e^{-\tau}) + \cdots$$

Above atmosphere value!

Remember math we had for the noise diode…

$$\frac{P_{OFF}}{P_{ON} - P_{OFF}} = \frac{T_{rec} + T_{atm}(1 - e^{-\tau}) + \cdots}{T_{diode}}$$

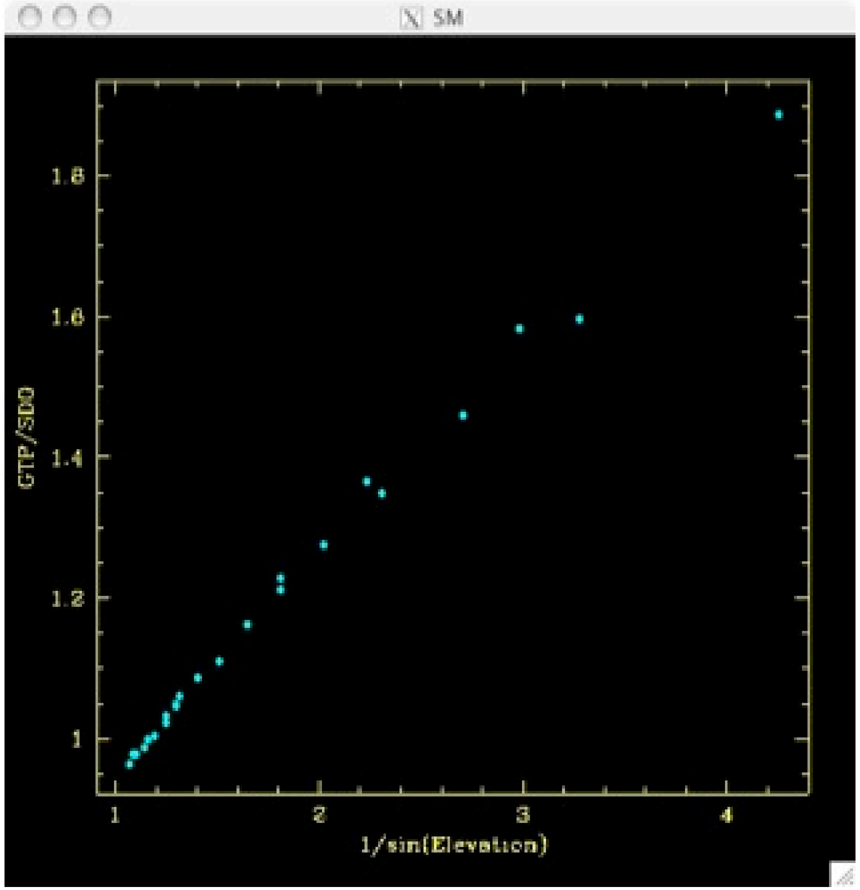
$$\frac{GTP}{SDO}$$

Gated Total Power

Synchronously Detected Output

$$\tau = \tau_0 / \sin(Elevation)$$

Linear dependence on 1/sin(elevation) for small optical depths



Correction for efficiency

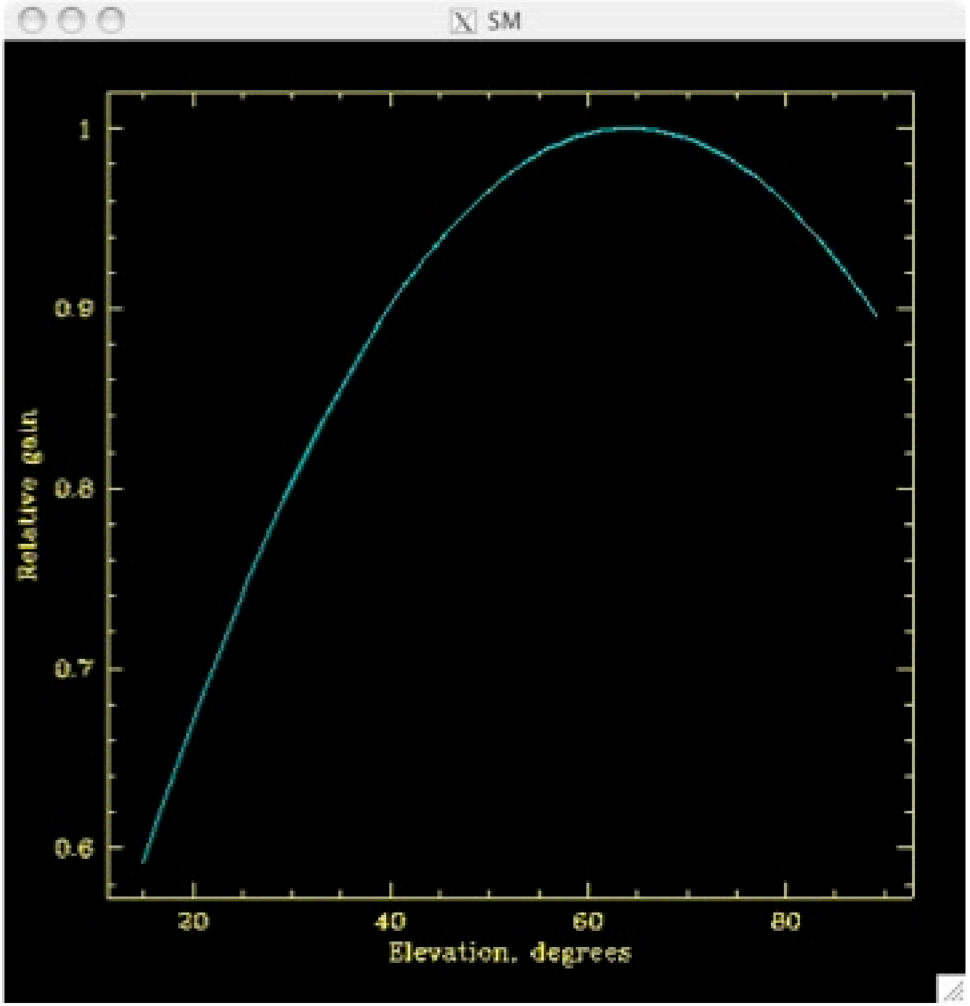
Paddle or noise diode do not allow us to account for all possible losses!

e.g., rearward scattering, spillover, blockage, focusing

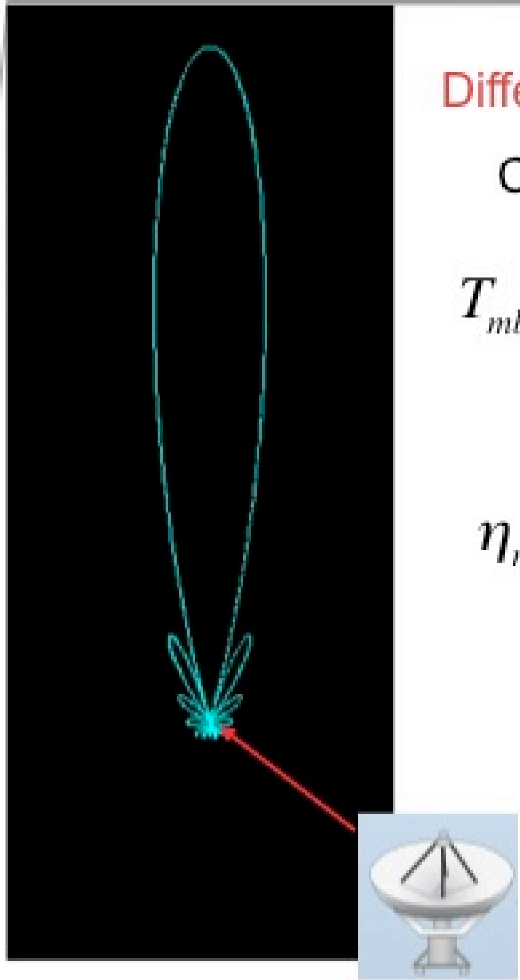
$$T_a^* = \frac{T_a}{\eta}$$ Corrected antenna temperature

- Elevation-dependent trends can be described as the gain-elevation curve
- It is often convenient to scale T_{sys} (and data) up in the online software
- Not totally independent from the main-beam efficiency (next slide)
- Moon as the natural paddle?

T_a^* is still an antenna-dependent quantity!



Main beam brightness temperature



Different telescopes have different beams

Considered isotropic radiation so far!

T_{mb} Accounts for the fraction of the power going into the main beam

$$\eta_{mb} = \frac{\int_{\Omega_{mb}} P(\Omega) d\Omega}{\int_{4\pi} P(\Omega) d\Omega}$$ Main beam efficiency

Normalized power pattern

$$T_{mb} = \frac{T_a^*}{\eta_{mb}}$$

Main beam brightness temperature of the same compact source measured with different instruments is expected to be the same!

Planets as standard sources

Planet	ATCA	Mopra
Mercury	Too close to the Sun	
Venus		
Mars	OK, but complex model	Too faint
Jupiter	Too big	OK, although big
Saturn	Has rings	
Uranus	Main calibrator at mm	Too faint
Neptune	Feasible	Too faint

Practical aspects of mm observing

- Do pointing solution from time to time
  - Once an hour or if moving to a different part of the sky
  - Pointing calibrator within 15 degrees from your target
  - SiO masers (at 7mm and 3mm) and H_2O masers at 12mm for Mopra
  - Continuum sources brighter than 0.5-1 Jy for ATCA
  - It may be acceptable for some 12mm science to use global pointing
- Do paddle calibration regularly if observing at 3mm
  - Once per 20 min or if moving to a different part of the sky
- ATCA: observe flux calibrator
  - 1934-638 for cm-wavelengths, 12mm and now 7mm as well
  - Uranus or Mars at 3mm and 7mm
  - Aim at observing close in time and elevation with your target
- Mopra: it wouldn't hurt to observe a standard source (Orion/M17) and/or Jupiter
  - But in general Mopra is not yet a well calibrated instrument
  - For 3mm look at Ladd et al., 2005, PASA, 22, 62

Mopra at 3mm

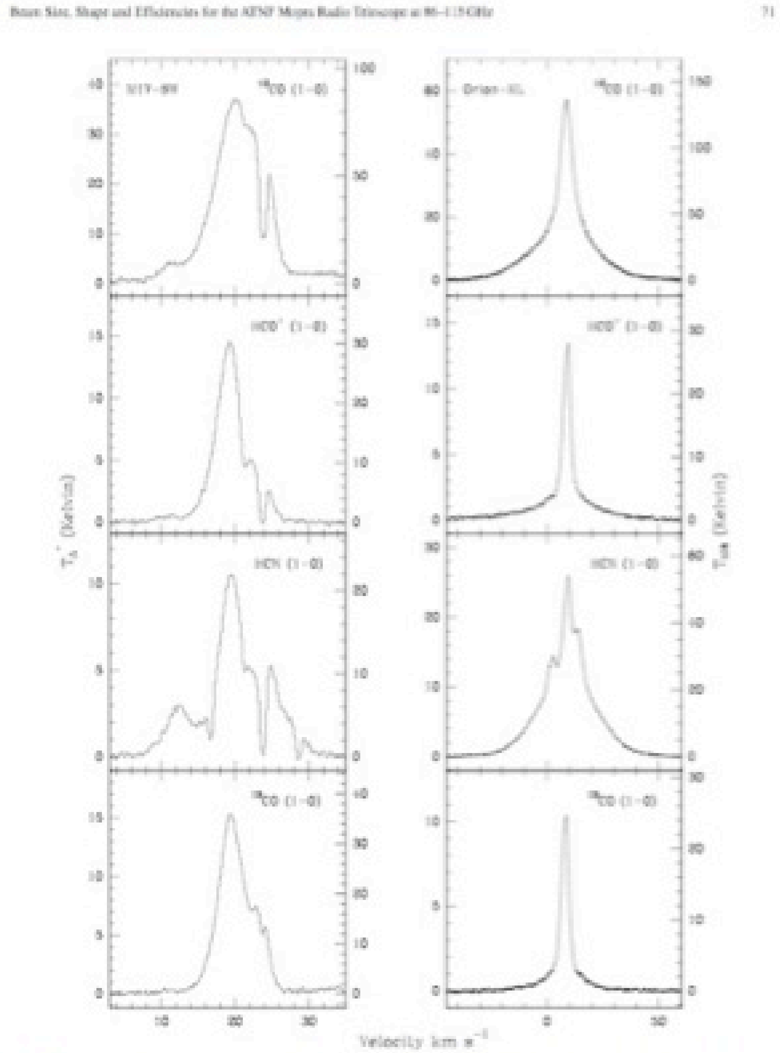


Figure 7 Standard spectra towards M17-SW and Orion-KL.

Ladd et al., 2005, PASA, 22, 62

- Standard spectra of Orion and M17 in both Ta* and Tmb scales
- Efficiencies at 3mm
- Beam maps

- Efforts are being made to extend this work to other bands

practical aspects of calibration in asap

- scantable.opacity(tau0)
  - Multiplies data and Tsys by $\exp(\tau_0/\sin(El))$
  - Required if Tsys is not corrected for atmosphere (12mm, 7mm)
  - User has to supply zenith opacity (tau0)
  - Miriad's task opplt can help to make an educated guess
  - Scripting required to account for time variations of tau0
- scantable.scale(factor,tsys=True)
  - Just scaling of data and optionally (if tsys is True) Tsys
  - Handy if you want a T_{mb} scale instead of T_a^*
- scantable.gain_el(poly=None, filename='',method='linear')
  - Divides the data and Tsys by the gain (efficiency) factor $T_a^* = \frac{T_a}{\eta}$
  - User can give polynomial coefficients (poly) or
  - External ascii table to be interpolated with the given method (filename) or
  - Rely on built-in models (for some instruments)

Summary

- ATCA and Mopra have receivers for 12mm, 7mm and 3mm with broadband backends
- Parkes can be used for 12mm observations of weaker sources
- Calibration is largely about understanding of your instrument
  - Many small factors, some of which are not well studied
  - Stable calibrators are continuum sources. Therefore it is easier to calibrate an interferometer than a single dish to a high accuracy
- Build an extra redundancy into your project
  - Observe known sources for cross-check
  - Calibrate more often than you need to achieve the science goal
- Try to observe in an appropriate season
  - i.e. no daytime observing in summer at 3mm

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Thank you