Single Dish Observing Techniques and Calibration

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{some slides taken from past presentations of Ron Maddalena and Karen O'Neil}

What does the telescope measure:

Ta = "antenna temperature"

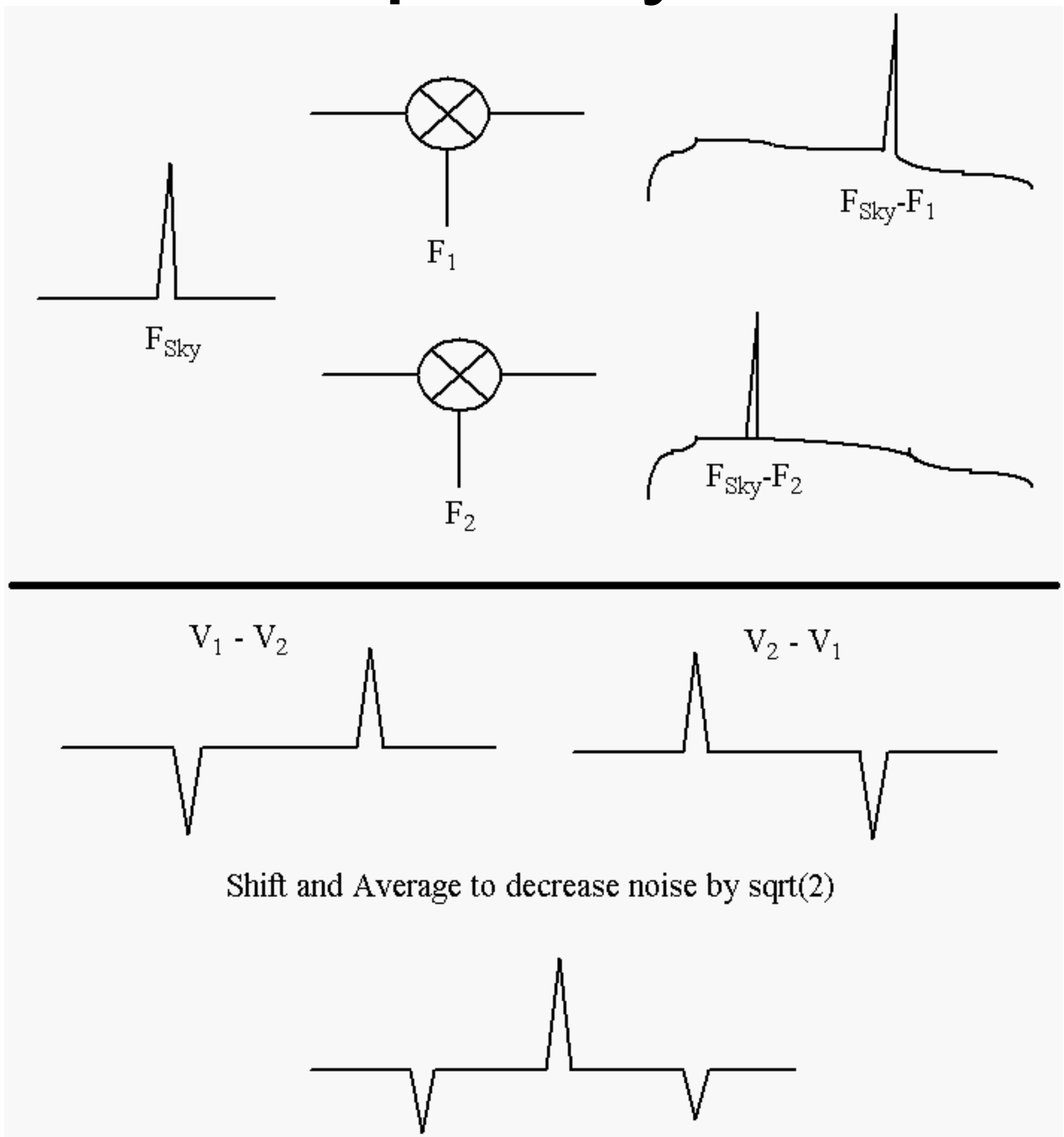
- Ta(total) = Tsource + {Trx + Tbg + Tatm + Tspill}
- Where {....} = other contributions
- Want Tsource, so carry out ON – OFF
- Ta(ON) =Tsource + {....}
- Ta(OFF) = {....}
- So Ta(ON)-Ta(OFF) = Tsource

➔ Need to carry out ON-OFF observations and there are different observing techniques for measuring ON-OFF

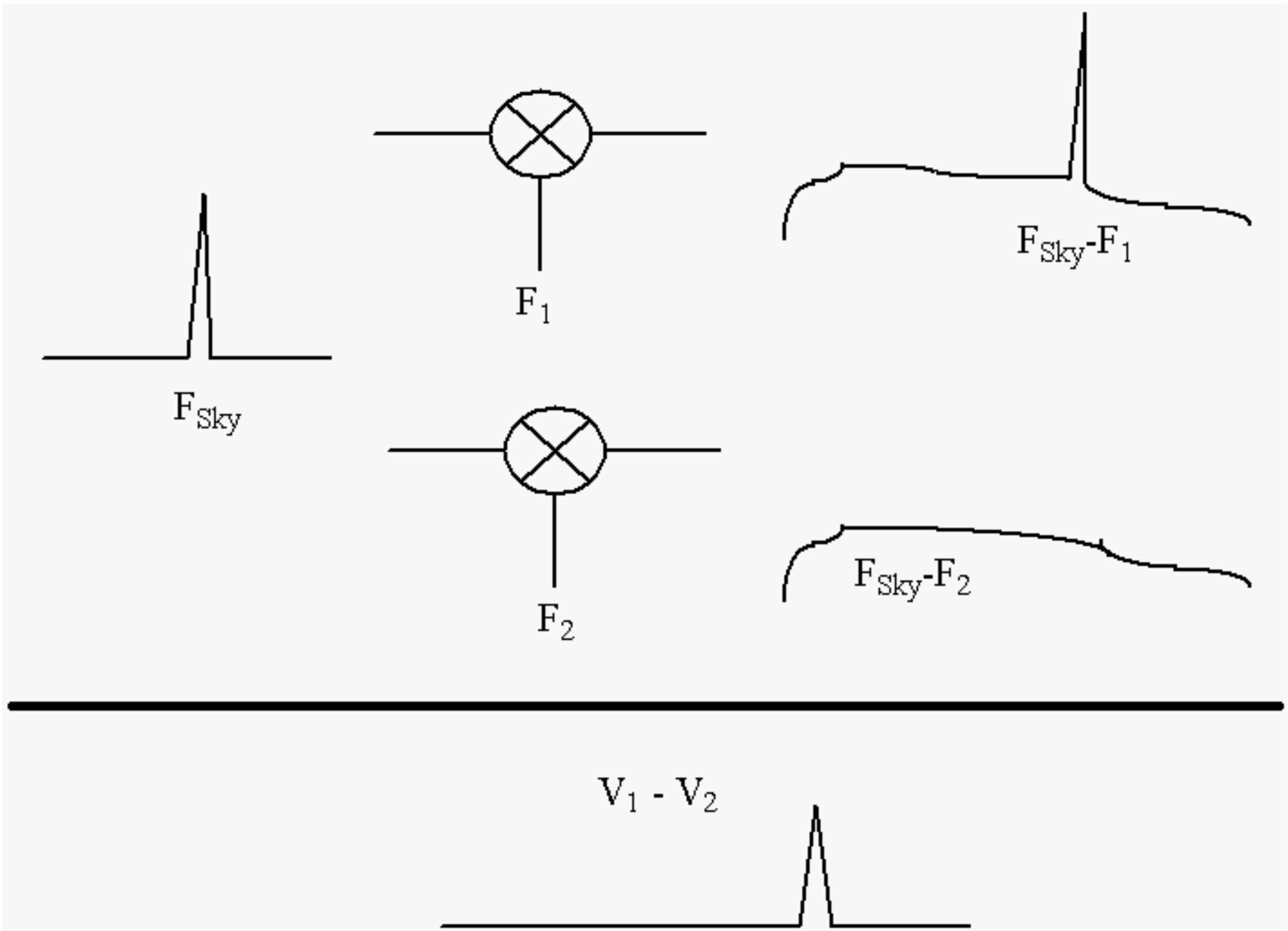
Different Observing Modes to derive the reference data (OFF)

- Types of reference observations
  - Frequency Switching
    - In or Out-of-band
  - Position Switching
  - Beam Switching
    - Move Subreflector
    - Receiver beam-switch
  - Dual-Beam Nodding
    - Move telescope
    - Move Subreflector

In-Band Frequency Switching



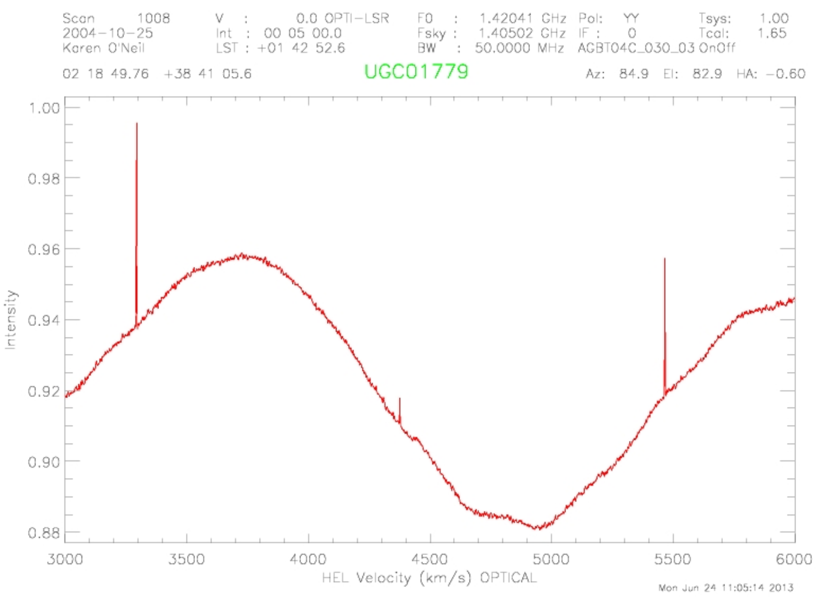
Out-Of-Band Frequency Switching



Position Switching

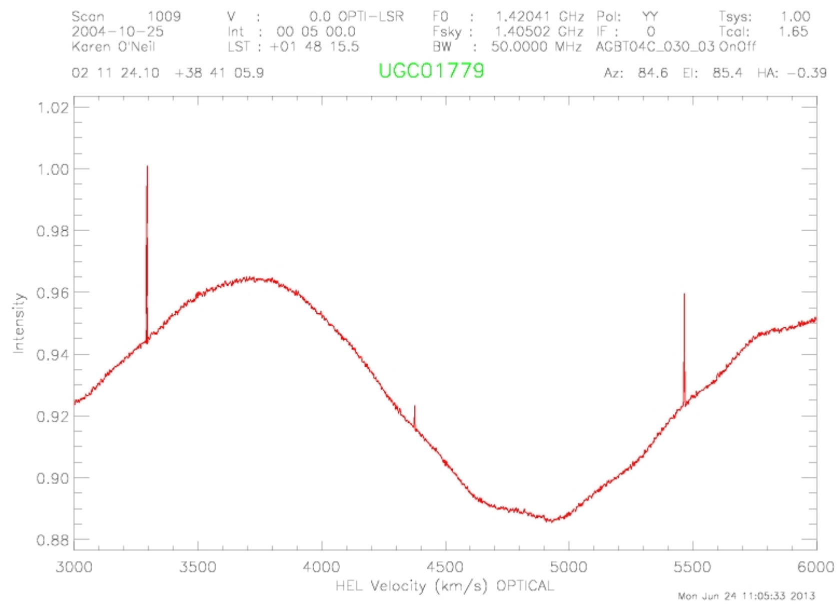
ON source

$T_{source} + T_{everything\ else}$



OFF source

$T_{everything\ else}$

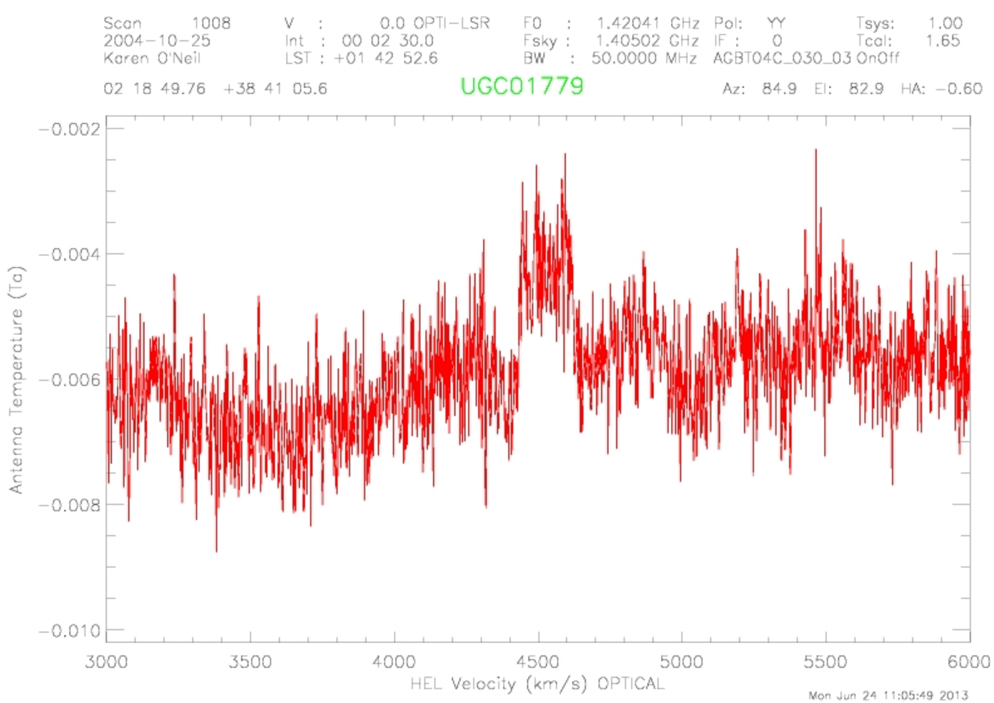


Position Switching: ON-OFF on Sky

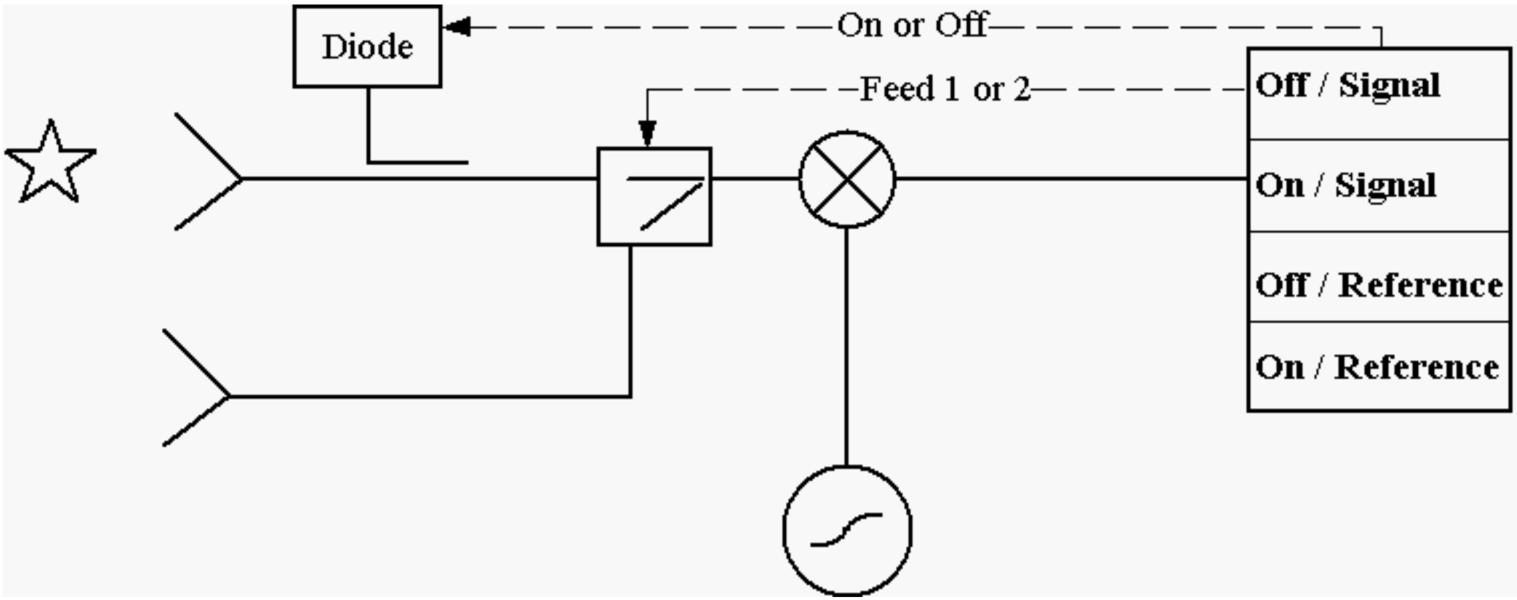
ON - OFF

$$(T_{source} + T_{everything\ else}) - (T_{everything\ else})$$

Arbitrary Counts

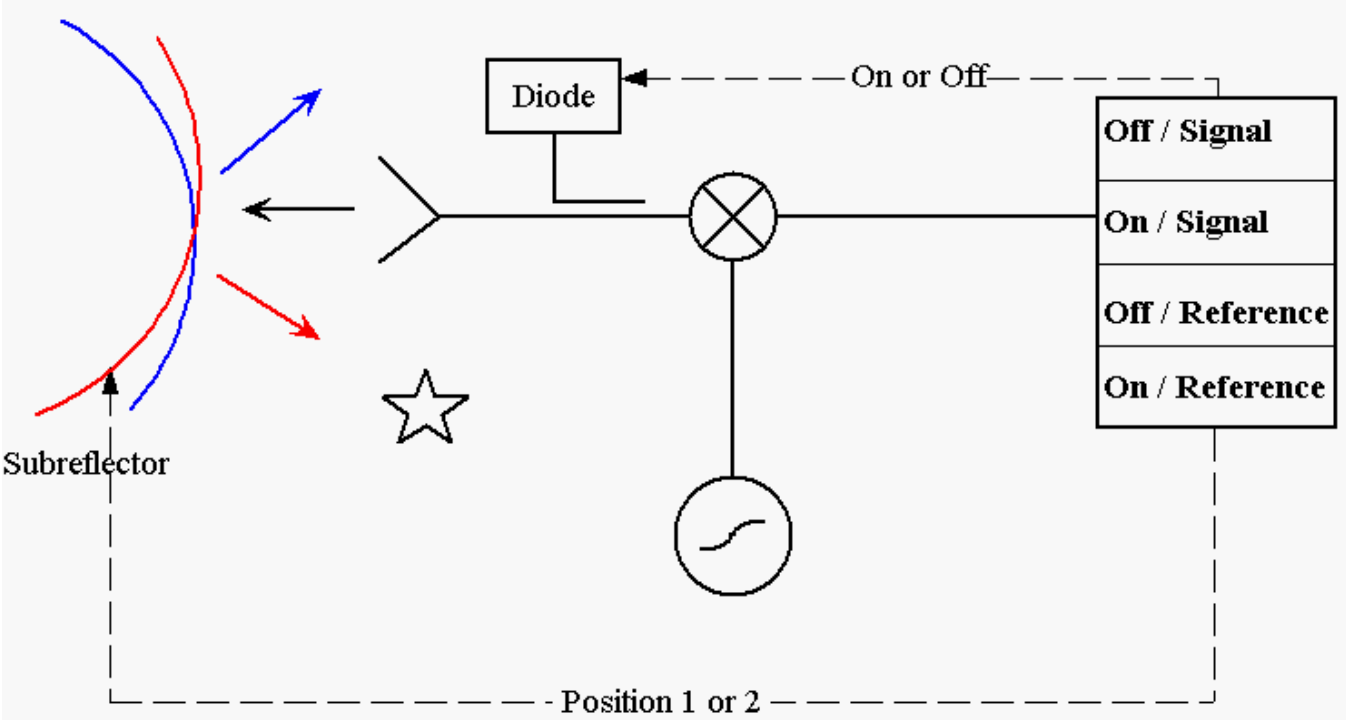


Beam switching – Internal switching ("Dicke switching")



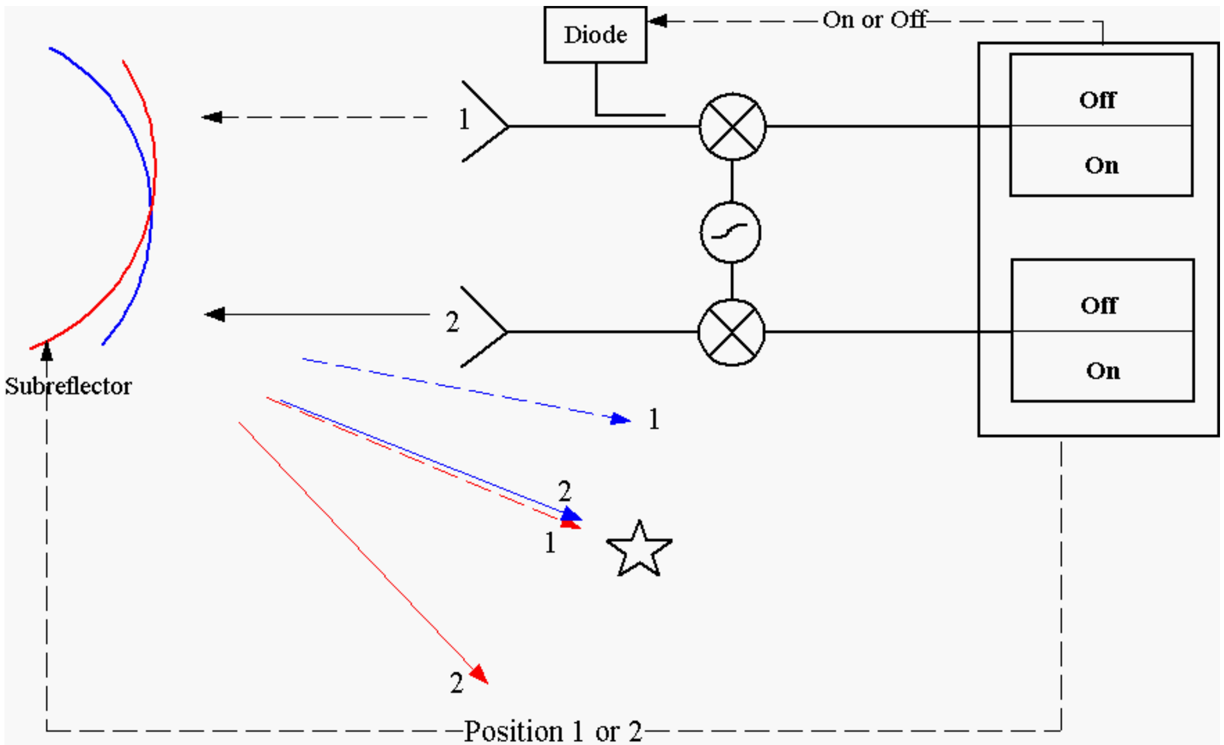
- Difference spectra eliminates any contributions to the bandpass from after the switch
- Residual will be the difference in bandpass shapes from all hardware in front of the switch.
- Low overhead but ½ time spent off source

Beam Switching – Subreflector or tertiary mirror



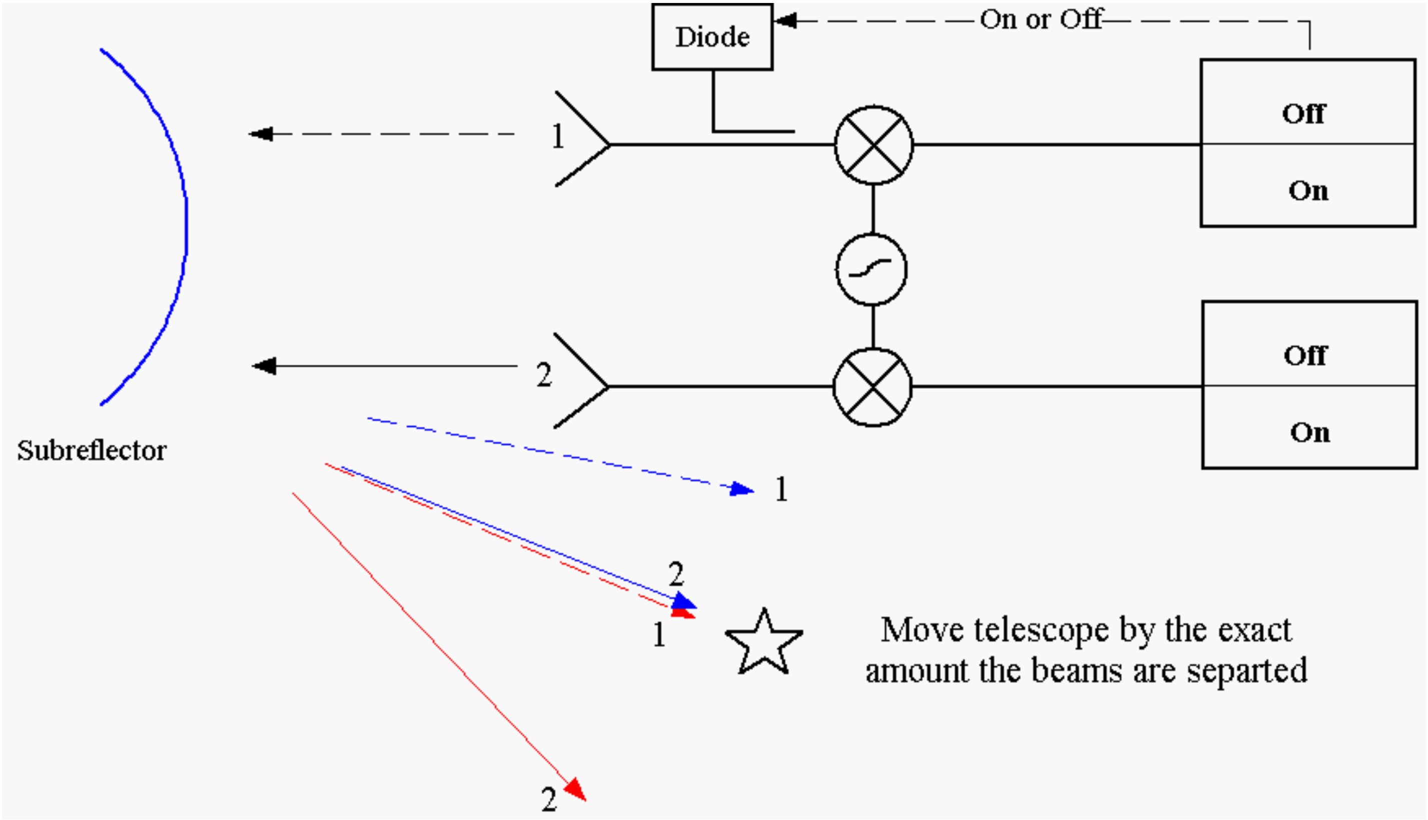
- Removes any ‘fast’ gain/bandpass changes
- Low overhead. ½ time spent off source

Nodding with dual-beam receivers - Subreflector or tertiary mirror (SubBeamNod)



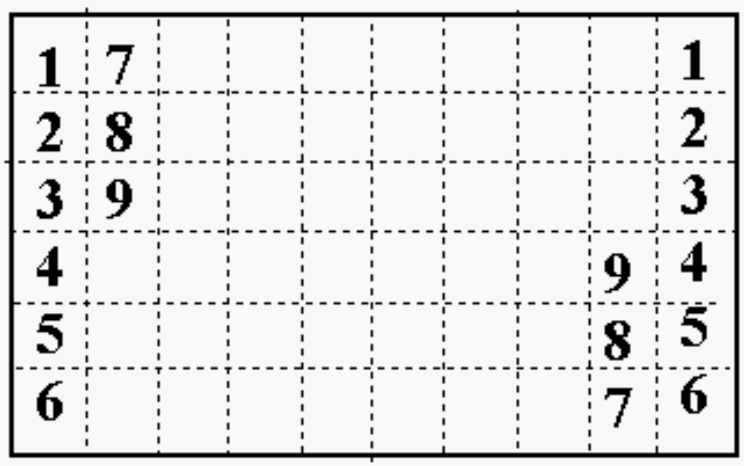
- Removes any ‘fast’ gain/bandpass changes
- Low overhead. All the time is spent on source

Nodding with dual-beam receivers - Telescope motion (NOD)



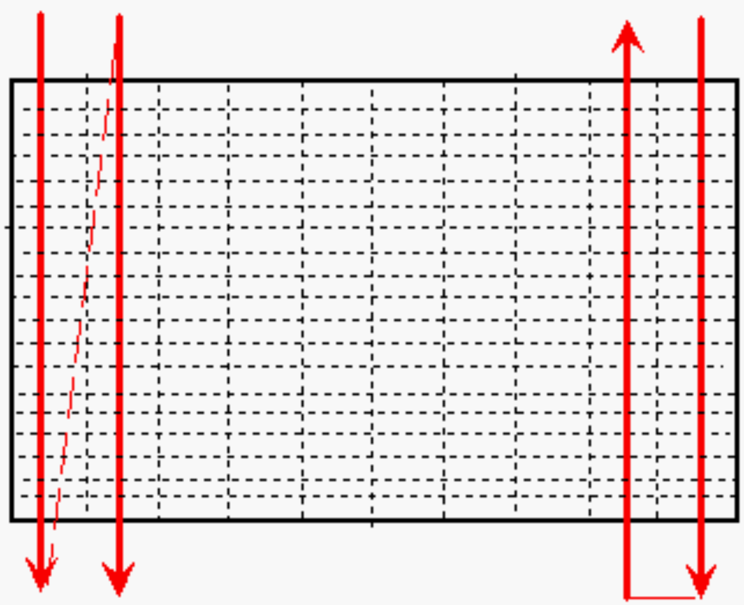
- Removes any ‘fast’ gain/bandpass changes
- Overhead from moving the telescope. All the time is spent on source

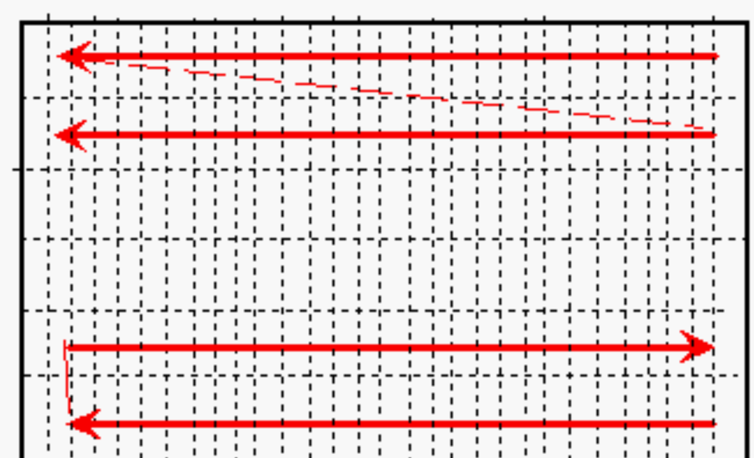
Mapping Techniques



- **Point map**
  - •Sit, Move, Sit, Move, etc.
- **On-The-Fly Mapping**
  - •Slew a column or row while collecting data
  - •Move to next column row
  - •Basket weave
  - •Should oversanple ~3x Nyquist along direction of slew

    Reference/OFF from a "source-free" map position or separate "OFF" spectrum taken.





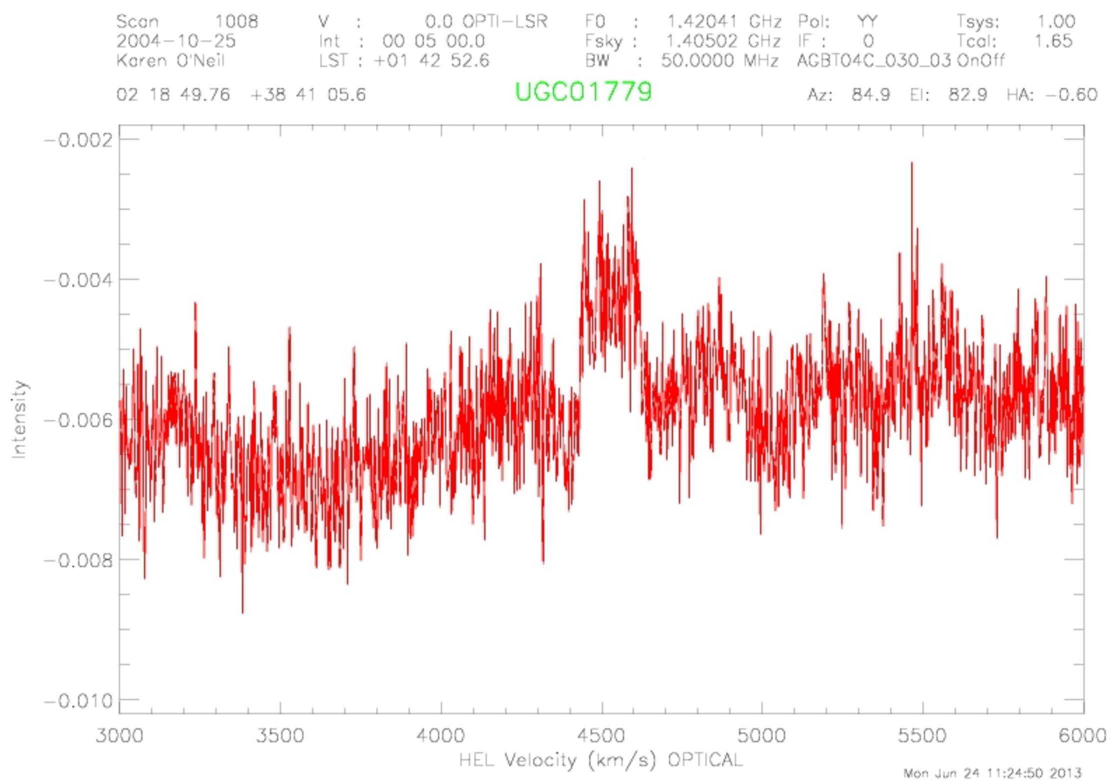
Calibration of Data

(ON - OFF)/OFF

$$[(T_{source} + T_{everything\ else}) - (T_{everything\ else})]/\ T_{everything\ else}$$

=(Source temperature)/("System" temperature)

% T_{sys}



Determining T_a

$$T_a = \frac{(\mathrm{ON} - \mathrm{OFF})}{\mathrm{OFF}} \, T_{system}$$

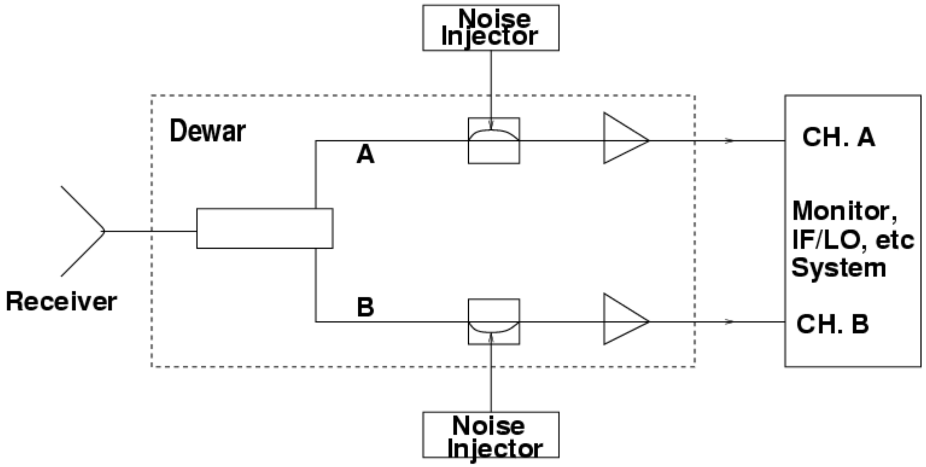
Blank Sky or other

From diodes, Hot/Cold loads, etc.

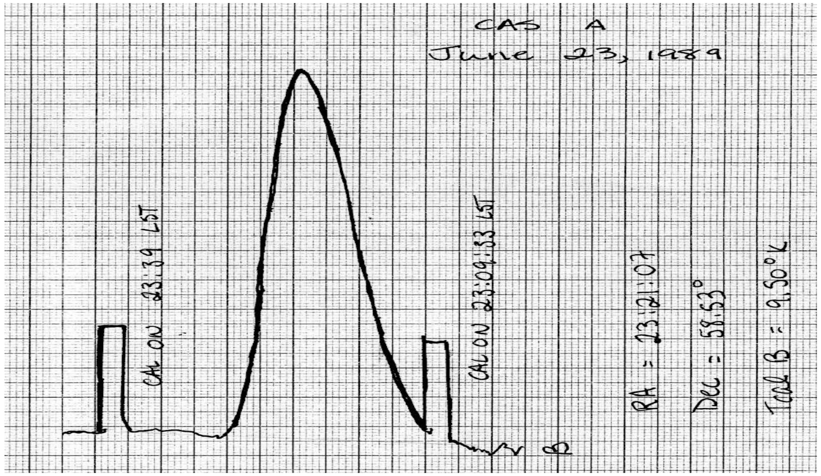
GBT definition of Ta

Determining T_{sys}

Noise Diodes



All GBT receivers besides 4mm and Mustang use noise diodes.



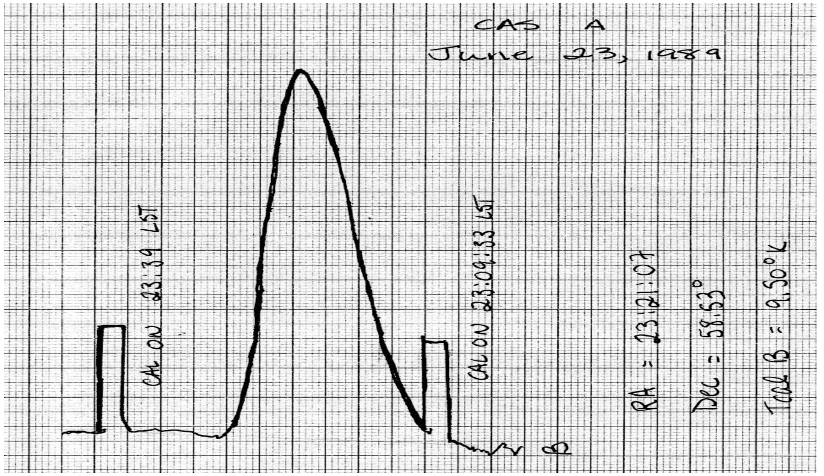
Determining T_{sys}

Noise Diodes

$$T_{sys} = T_{cal} * OFF/(ON - OFF)$$

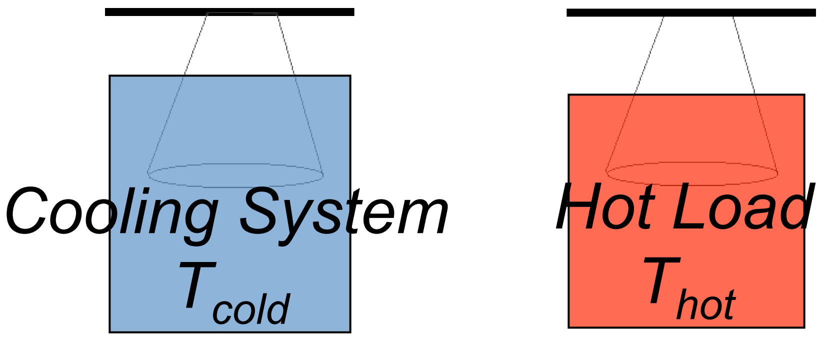
GBT: Flicker diode on/off

$$T_{sys} = T_{cal} * OFF/(ON - OFF) + T_{cal}/2$$



Determining T_{sys}

Hot & Cold Loads



Gain: g =(Thot – Tcold)/(Vhot –Vcold) [K/Volts]

Tsys = g Voff

Example GBT 4mm Rx

Absolute Calibration on known astronomical sources (point sources)

➔ Corrects for any errors in the adopted Tdiode/gains measured in the lab and corrects for the telescope response

Observe and process source and known calibrator (3cX) source data in the same way, then the flux density of the source S(source) is simply:

S(source)/S(3cX) = T(source)/T(3cX),

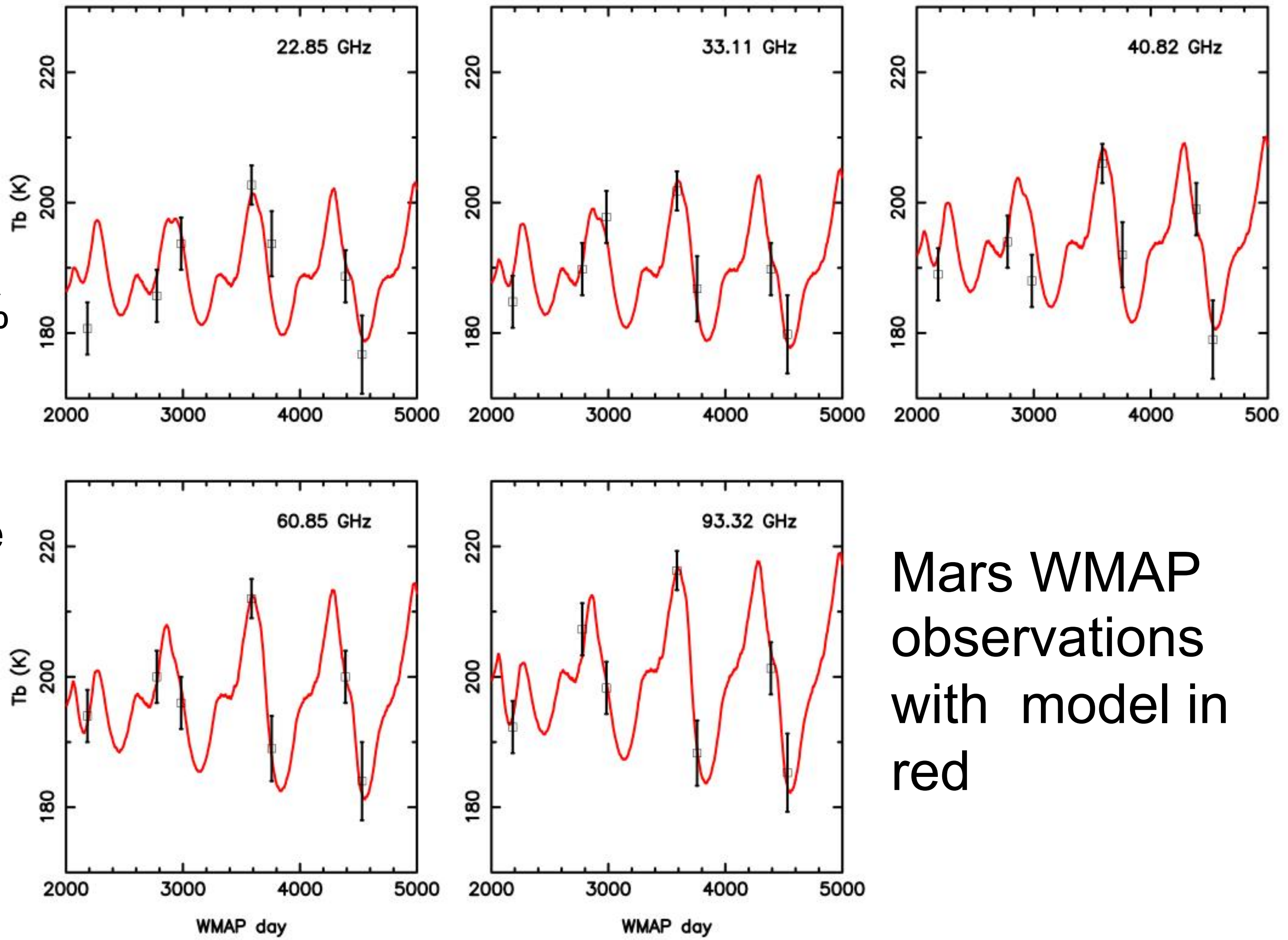
where S(3cX) is known.

Absolute Calibration tied to Mars via WMAP

VLA calibration (1-50 GHz):

- <20 GHz ~1% accurate
- 20-50 GHz: ~3% accurate

Perley & Butler 2013

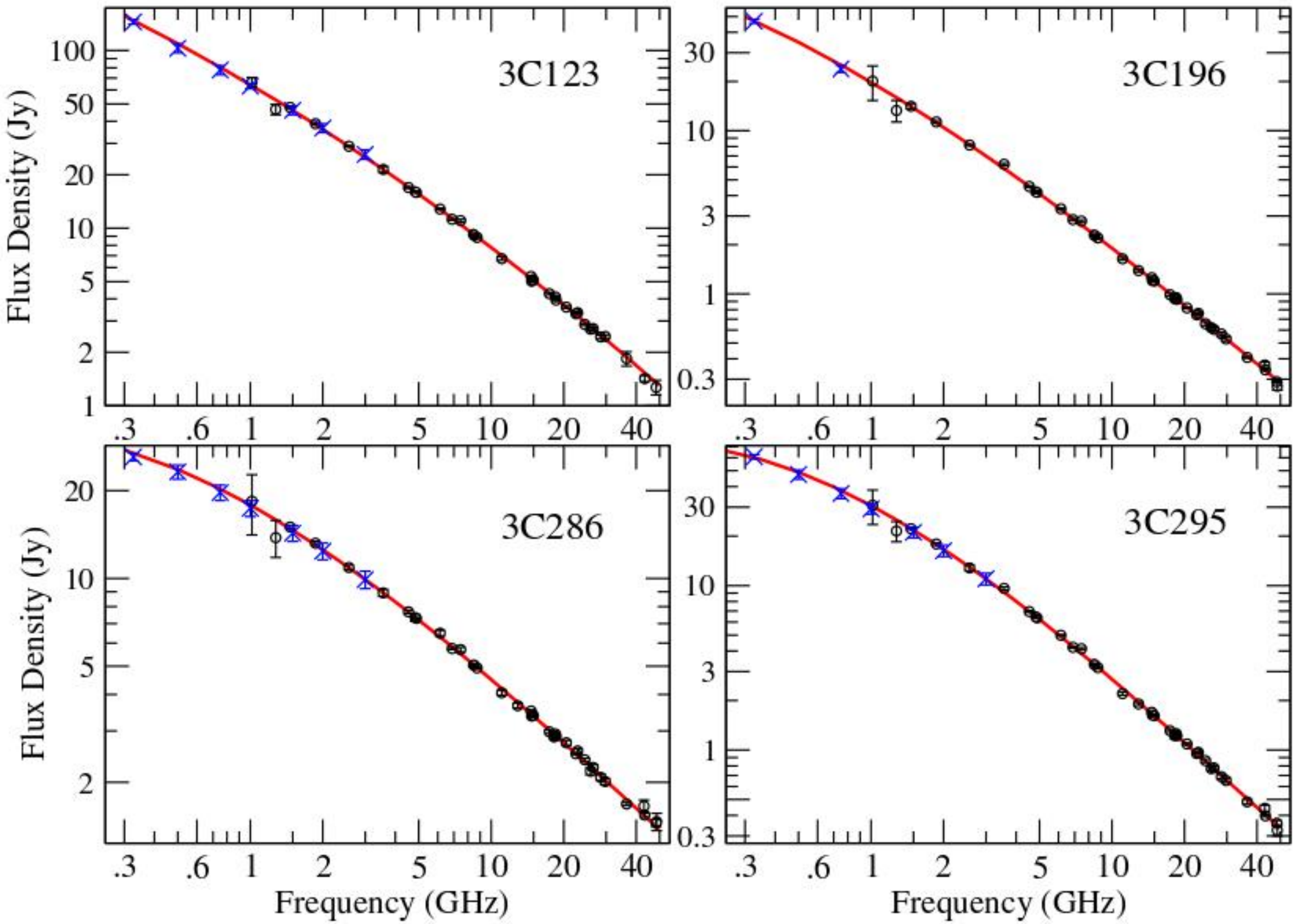


Mars WMAP observations with model in red

VLA Stable Calibrators

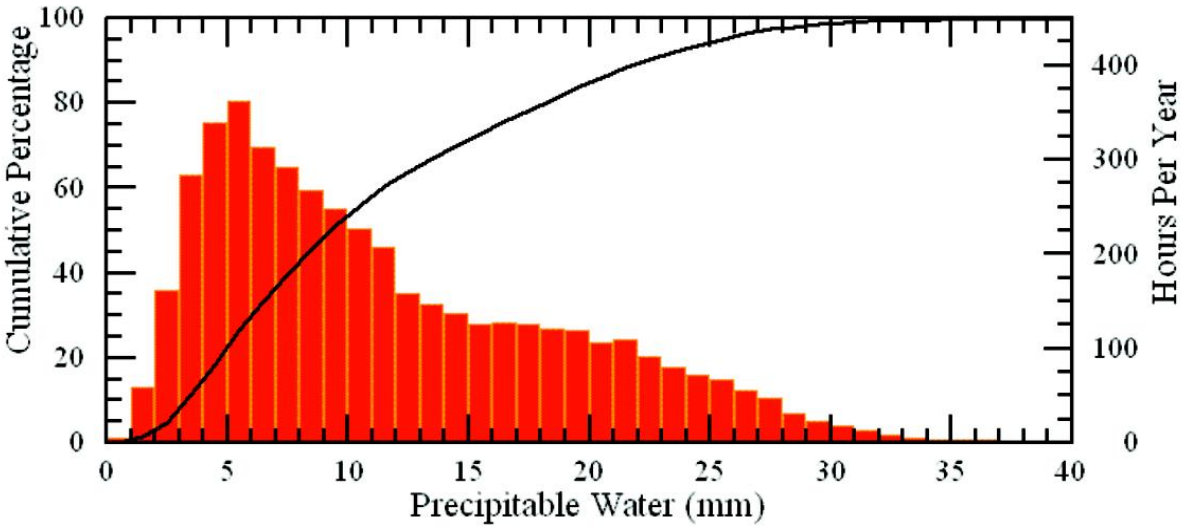
GBT Calibration "Plan":

Tie GBT to VLA calibration for 1-50 GHz, and we will use ALMA for 3mm absolute calibration (CARMA in the past)



The atmosphere is important at high frequency (>10 GHz)

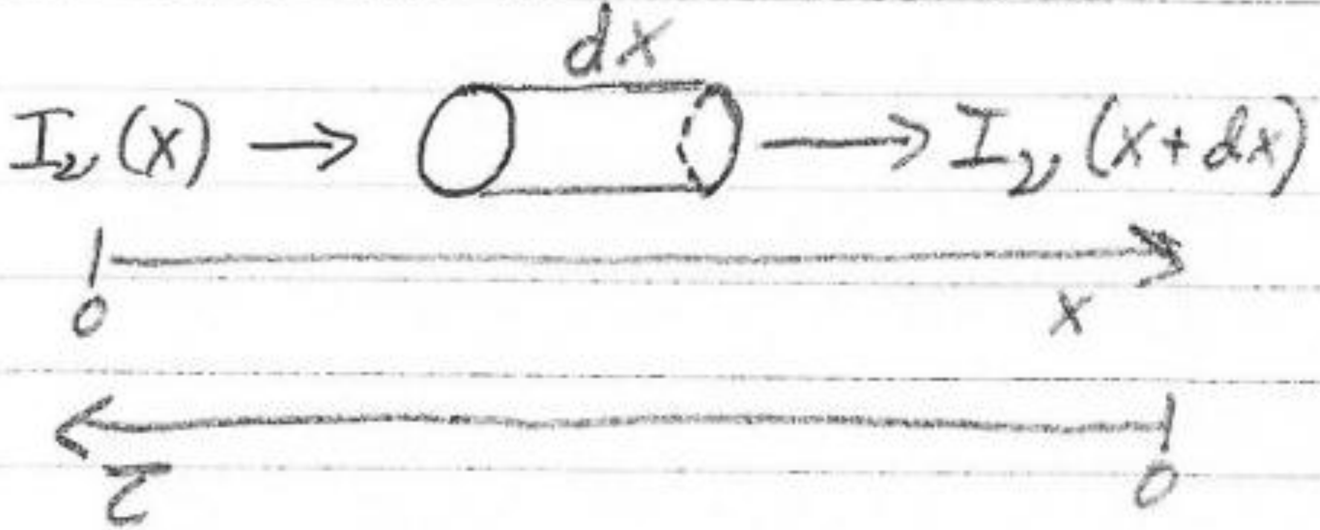
- Opacity
  - Tsys = Trcvr + Tspill +Tbg * exp(-tau*A) + Tatm * [exp(-tau*A) – 1]
  - Air Mass A~ 1/sin(Elev) (for Elev > 15°)
- Stability
  - Tsys can vary quickly with time
  - Worse when Tau is high



GBT site has many days with low water vapor per year (<10mm H_2O are ok for 3mm, 50% of time)

Radiative Transfer

Radiative Transfer



$$\frac{dI_\nu}{dx} = -\kappa_\nu I_\nu + \varepsilon_\nu$$

absorption emission

Thermal Equilibrium

$$\frac{dI_\nu}{dx} = \underbrace{-\kappa_\nu I_\nu}_{\text{absorption}} + \underbrace{\varepsilon_\nu}_{\text{emission}}$$

Thermal Equilibrium

$$\frac{dI_\nu}{dx} = 0, \quad I_\nu = \underbrace{B_\nu(T) = \frac{\varepsilon_\nu}{\kappa_\nu}}_{\text{"Kirchhoff's law"}}$$

Blackbody Equation

Blackbody eq:

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\left[\frac{1}{e^{h\nu/kT} - 1}\right]$$

$$B(T) = \int B_\nu(T)\,d\nu = \sigma T^4$$

"Stefan-Boltzmann" law

Rayleigh-Jeans Approximation

Rayleigh-Jeans Approximation:

$h\nu << kT$

$$\Rightarrow B_\nu(T) \simeq \frac{2\nu^2}{c^2} kT = \frac{2kT}{\lambda^2} = I_\nu \text{ (Thermal-RJ)}$$

Good for 3mm and longer wavelengths

Temperature Scales

- Ta= Tsys (ON-OFF)/OFF (uncorrected antenna temperature)
- Ta' = Ta exp(τ_oA)
- T_{mb} = Ta'/η_{mb} (η_{mb}~1.3 η_a)
- Ta* = Ta'/η_l (mm-telescopes typically return Ta*)
- Tr* = Ta'/(η_l η_{fss})
- Ta'/Sν =2.84 η_a (for the GBT)

Antenna Theorem

Power Received = Power Transmitted

$P_{rec}(\theta,\phi) = \frac{1}{2} A_e P_n(\theta,\phi) S_\nu \Delta\nu$ (½ from single pol.)

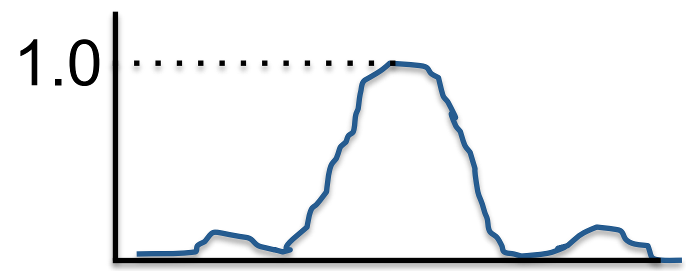
S_ν = flux density [W/m²/Hz] $= I_\nu \delta\Omega = (2kT/\lambda^2)\, \delta\Omega$

$P_{rec} = \frac{1}{2} A_e \Delta\nu (2kT/\lambda^2) \iint P_n(\theta,\phi) d\Omega$

$P_{trans} = k\, T\, \Delta\nu$

$\frac{1}{2} A_e\ \Delta\nu\ (2kT/\lambda^2)\Omega_a = k\, T\, \Delta\nu$

→ $\mathbf{A_e\ \Omega_a = \lambda^2}$, where



Antenna Solid angle: $\Omega_a = \iint_{4\pi} P_n(\theta,\varphi) d\Omega$

P_n = antenna power pattern normalized to the peak; $P_n(0,0)=1.0$

Point-Source Calibration: Flux Density vs Antenna Temp

$P_{rec} = ½ A_e S_\nu \Delta\nu = k T_a' \Delta\nu$

$A_e = \eta_a (\pi/4) D^2$

→ $S_\nu = 3520\, T_a'/(\eta_a [D/m]^2)$

i.e., $T_a'/S_\nu = 2.84\, \eta_a$ for the GBT (η_a=0.71 at low ν)

Used for point-source calibration:

- Measure T_a
- Correct for atmosphere → T_a'
- Know S_ν
- Derive η_a

Telescope "Gain"

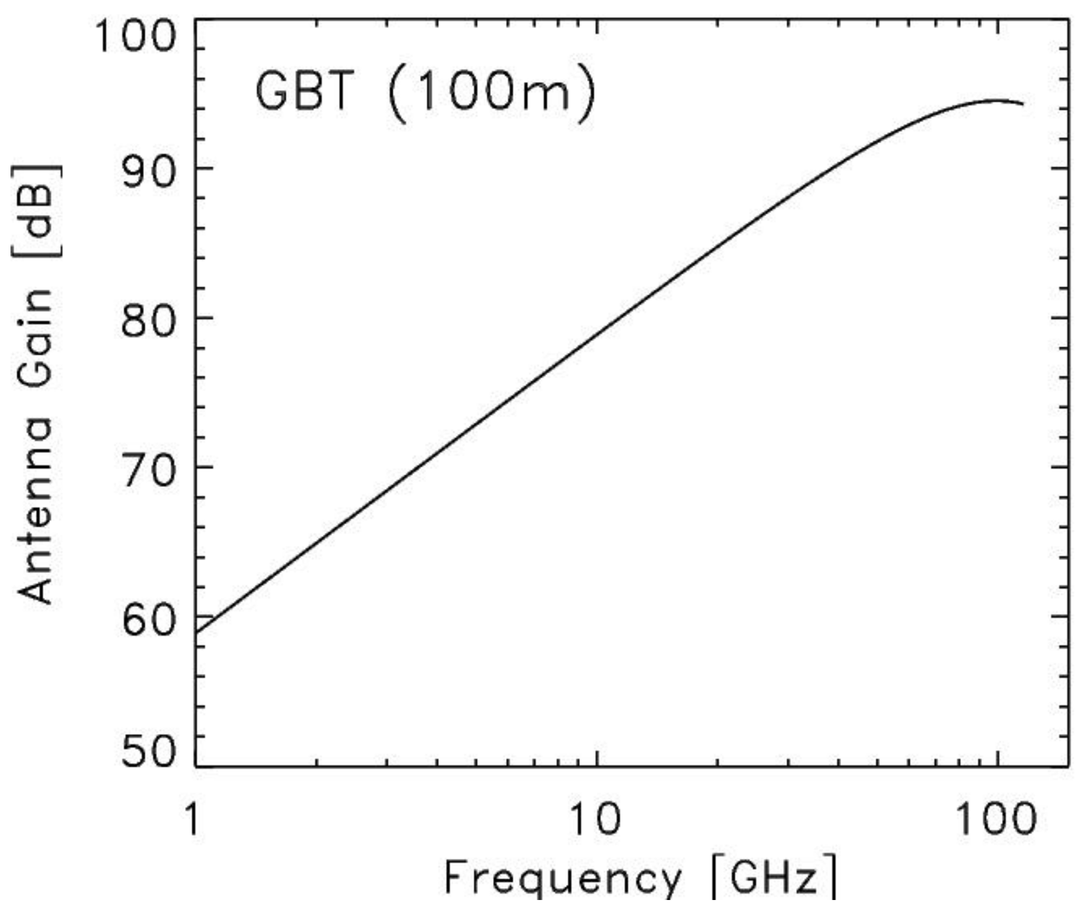
Astronomers:

Gain = T_a'/S_ν in units of K/Jy

Engineers: Gain as given by the Antenna Theorem

➔ $G = 4\pi A_e/\lambda^2$ in units of dB

(antenna viewed as a big amplifier)



T_R^*

$$T_A' = T_R^* \, \eta_r \left[\underbrace{\iint_{\Omega_d} P_n \, d\Omega \Big/ \iint_{4\pi} P_n \, d\Omega}_{\text{Fraction of power not lost in spillover + scattering}} \right]$$

Kutner + Ulich 1981
12m, "US" definitions

$\eta_r \simeq 1$ radiative efficiency

$$\eta_{fss} \equiv \iint_{\Omega_d} P_n \, d\Omega \Big/ \iint_{2\pi} P_n \, d\Omega$$ "Foward" scattering + spillover eff.

$$\eta_{rss} \equiv \underbrace{\iint_{2\pi} P_n \, d\Omega}_{\text{Forward hemisphere}} \Big/ \iint_{4\pi} P_n \, d\Omega$$ "Rearward" scattering + spillover eff.

$$\Rightarrow T_A' = T_R^* \eta_r \eta_{fss} \eta_{rss} = T_R^* \eta_{fss} \eta_\ell$$

$$\eta_\ell = \eta_r \eta_{rss}$$

$\eta_\ell = F_{eff}$ "forward efficiency" IRAM/Class

η_ℓ = fraction of power on sky in forward direction

$(1-\eta_\ell)$ = fraction of power that "see's" the ground

T_A^*

"Chopper-wheel" Calibration gives T_a^*

$$T_a^* = T_a'/\eta_l = \eta_{fss} \cdot T_R^*$$

IRAM: $T_{mb} = \frac{F_{eff}}{B_{eff}} T_a^*$

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

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

$\eta_l = F_{eff}$

$B_{eff} = \eta_{mb}$

Calibration Two Loads vs One Load

<u>Two loads</u> "Direct" calibration, e.g. 4m Rx

$$g = (T_{amb} - T_{cold}) / (V_{amb} - V_{cold})$$

$$T_A = T_{sys} \left(\frac{ON - OFF}{OFF} \right) = g\,(ON - OFF)$$

$$T_A' = T_A\, e^{\tau_0 A}$$

<u>need τ</u>

Calibration with One Load, T_A^*

With a chopper wheel/ vane and a simple temperature sensor, one can calibrate to the approximate Ta* scale without any knowledge of the sky.

One load chopper calibration:

$$T_A^* = T_{cal} \left[\frac{V_{on} - V_{off}}{V_{amb} - V_{off}} \right]$$

need T_{ATM}

$$T_{cal} \equiv \left[\frac{T_{amb} - T_A^{sky}}{\eta_l} \right] e^{\tau_0 A}$$

; yuk, but:

Algebra ⟹

$$\boxed{T_{cal} = T_{ATM} + (T_{amb} - T_{ATM})\, e^{\tau_0 A}}$$

what Argus will use.

model

eq. A9 of KU91 re-written

assumes $T_{spill} \approx T_{amb}$ and ignoring T_{bg}

Some have assumed $T_{cal} = T_{amb} = T_{ATM}$ with T_A^* calibration

Tsys for T_A^* scale different than Tsys for T_A

$$T_A^* = T_{sys}^* \left(\frac{ON-OFF}{OFF} \right)$$

where $T_{sys}^* = T_{sys} \cdot \frac{e^{\tau_0 A}}{\eta_\ell}$ includes ATM

ie

$$T_A^* = T_A \cdot \frac{e^{\tau_0 A}}{\eta_\ell}$$

Definitions of Ω's

$$\Omega_A \equiv \iint_{4\pi} P_n(\theta,\phi)\, d\Omega$$

$$\eta_{mB} = \frac{\Omega_{mB}}{\Omega_A}$$

$$\Omega_{MB} \equiv \iint_{MB} P_n(\theta,\phi)\, d\Omega$$

$$\eta_{rss} = \frac{\Omega_F}{\Omega_A} \simeq \eta_\ell = F_{eff}$$

$$\Omega_d \equiv \iint_{\Omega d} P_n(\theta,\phi)\, d\Omega$$

$$\eta_{fss} = \frac{\Omega_d}{\Omega_F}$$

$$\Omega_F \equiv \iint_{2\pi} P_n(\theta,\phi)\, d\Omega$$

$$\Omega_{Source} = \iint_{Source} P_n(\theta,\phi)\, d\Omega$$

Note:
$\Omega_d = \Omega_{mb}$
(different authors/
conventions)

Extended Sources: T_{mb} vs T_{source}

$$T_A' = \frac{1}{\Omega_A} \iint P_n(\theta,\phi)\, T_s(\theta,\phi)\, d\Omega$$

source

compute using T_{mb}

$$\frac{\Omega_{mb}}{\Omega_A} = \eta_{mb} \quad ; \quad T_A' = \eta_{mb} T_{mb}$$

$$T_{mb} = \frac{T_A'}{\eta_{mb}} = \frac{1}{\Omega_{MB}} \iint P_n(\theta,\phi)\, T_s(\theta,\phi)\, d\Omega$$

case 1. If T_s is uniform, $\theta_s < \theta_{mb} \Rightarrow \Omega_s \ll \Omega_{MB}$

$\Rightarrow P_n \approx 1$ over source:

$$T_{mb} = \frac{1}{\Omega_{MB}} T_s \iint_{\text{source}} P_n \, d\Omega$$

$$= T_s \frac{\Omega_s}{\Omega_{MB}} = \left(\frac{\theta_s}{\theta_{mb}}\right)^2$$

$$\boxed{T_{mb} = T_s \left(\frac{\theta_s}{\theta_{mb}}\right)^2}$$

small source $\theta_s < \theta_{mb}$

"Filling factor"

"Beam dilution"

$$T_{mb} = \frac{1}{\Omega_{mb}} \iint P_n \cdot T_S \, d\Omega$$

Case 2: $\theta_S = \theta_{mb}$, T_S uniform

$$T_{mb} = T_S \frac{1}{\Omega_{mb}} \underbrace{\iint_{mb} P_n \, d\Omega}_{\Omega_{mb}}$$

$$\boxed{T_{mb} \equiv T_S \qquad \theta_S = \theta_{mb}}$$

How about $\theta_S > \theta_{mb}$:

$$\Rightarrow \boxed{T_{mb} \simeq T_S \qquad \theta_S > \theta_{mb}} \qquad \text{case 3}$$

Note: For beams with significant side-lobes the measured Ta' increases with source size outside the main-beam and the relationship between T_{mb} and T_S depends on the details of how η_{mb} is derived and the coupling of the source to the main beam.

Gaussian Source

More general, assume T_s Gaussian and beam Gaussian

$$\Omega_{Gaussian} = 1.133\,\theta_{FWHM}^2$$

$$T_{mb} = T_s\left[\frac{\theta_s^2}{\theta_{mb}^2 + \theta_s^2}\right]$$

$\theta_{mb} \gg \theta_s$ $\quad T_{mb} = T_s\left(\theta_s/\theta_{mb}\right)^2$ ✓

$\theta_s \gg \theta_{mb}$ $\quad T_{mb} = T_s$ ✓

Concluding Remarks

- To observe weak signals, one needs to measure ON-OFF
- Several different observing techniques can be used to give ON-OFF (freq-switched, position switched)
- At cm wavelengths, we use noise diodes to calibrate the data, while at mm wavelengths ambient/cold loads are used
- At low-freq, the Ta scale is used, while at high freq, one must correct for atmosphere (Ta')
- The Ta* scale is typically used with one ambient load at mm wavelengths (chopper technique)
- Point sources are typically calibrated to flux density [Sν] Jy units, while extended sources are typically calibrated to the T_{mb} [K] temperature scale