Observing Techniques and Calibration 2

David Frayer (thanks to Ron Maddalena, Jim Condon, and Ryan Shannon for various slides)

GREEN BANK OBSERVATORY

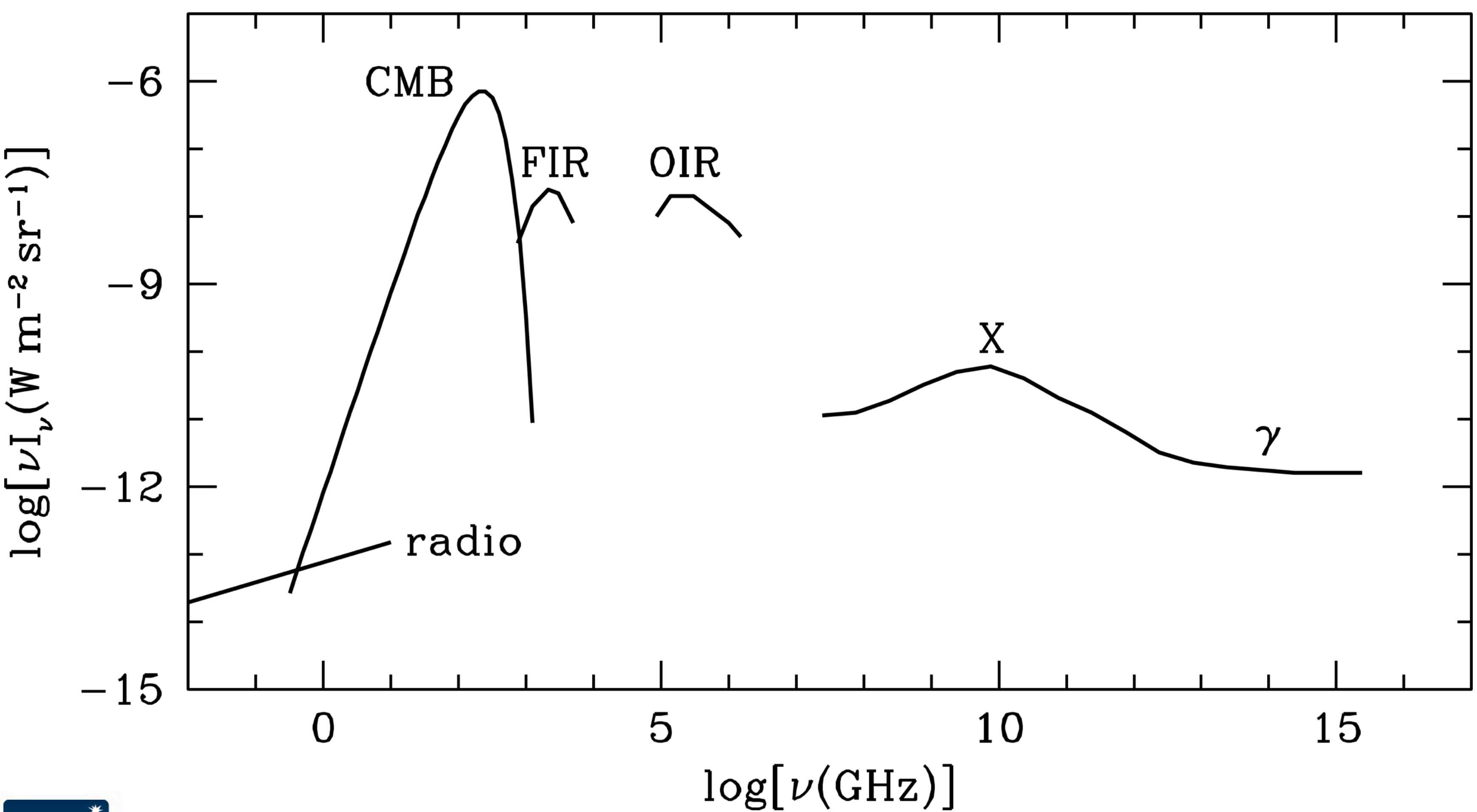
Topics for Talk 1 (Larry)

- Blackbody radiation
- Basic radiative transfer
- **Spectral Line Data Calibration**
- Calibration of Ta via noise diodes and definition of Tsys: Ta= Tsys*(ON-OFF)/OFF
- **ON-Ref observing techniques**: PS, FSW, BSW, NOD, SubBeamNod
- **Mapping Methods**: RALong/DecLat and Daisy OTF, Point-Map
- Nyquist Sampling

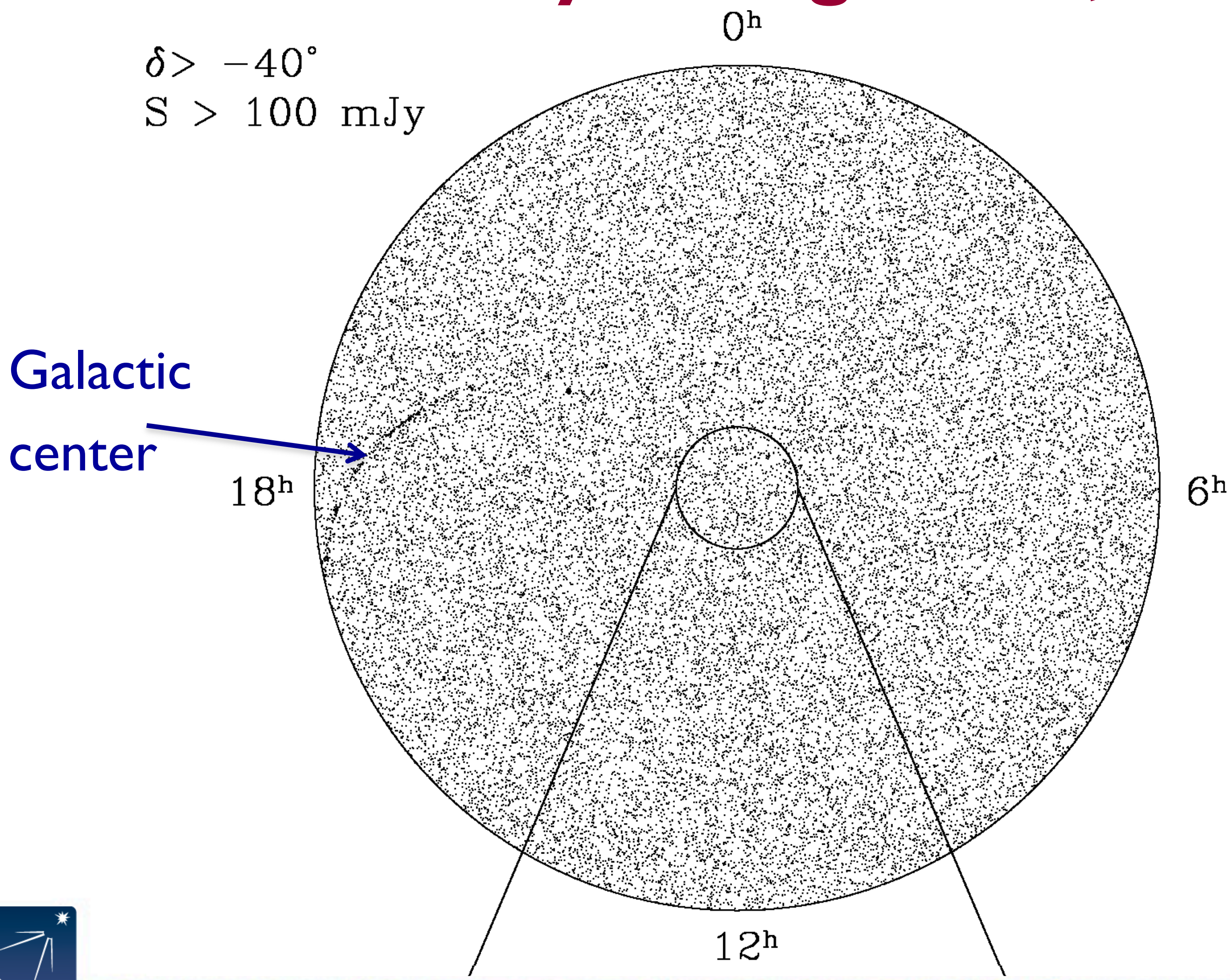
Topics for Talk 2 (David)

- **Continuum Observations**
- **1/f noise and confusion**
- Pulsar Observations
- Calibration into physical units Jy and K
- **Definition of the various telescope temperature scales and efficiencies**
- The effects of weather on data at high-frequency

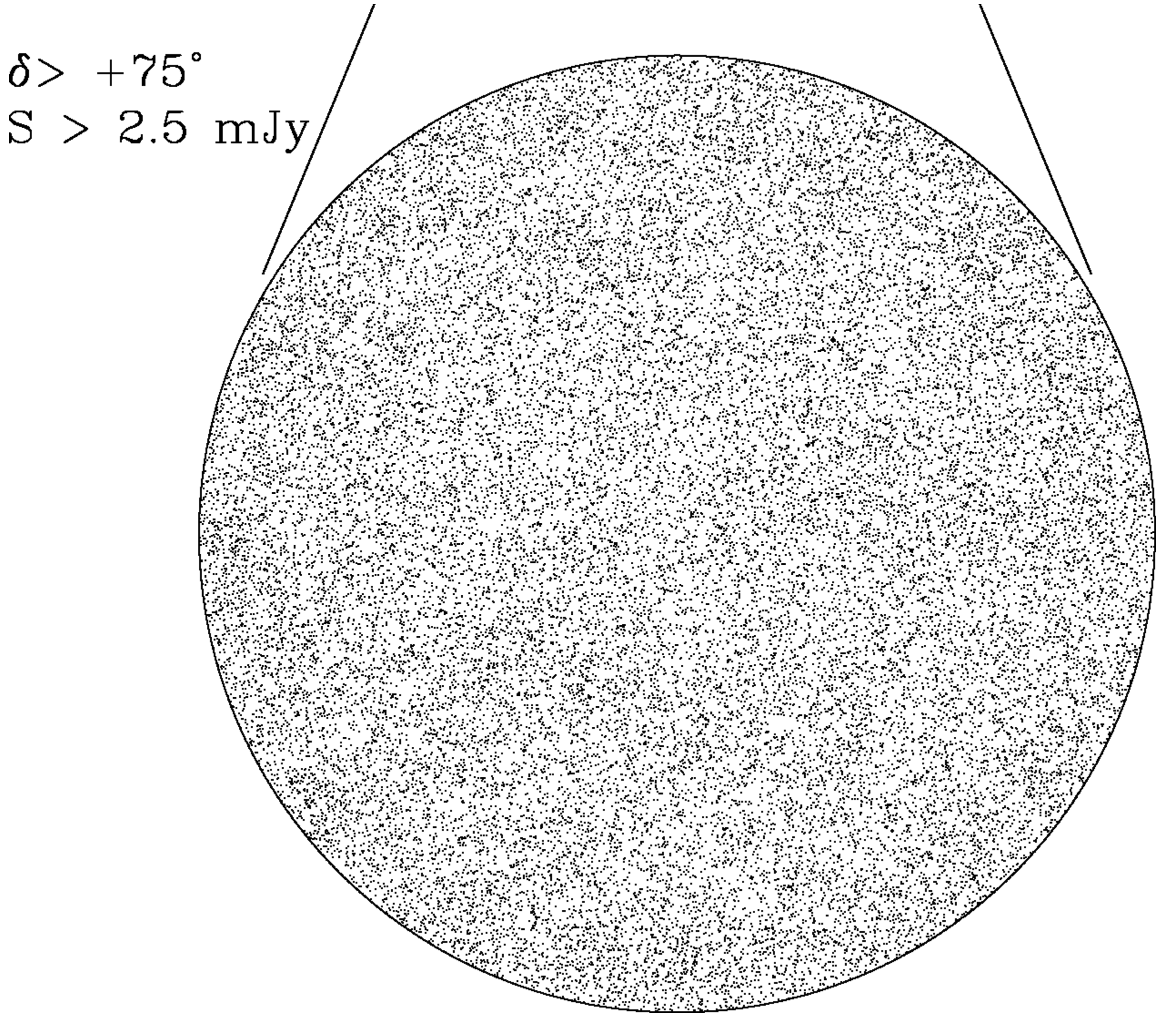
The spectrum of the universe



At 45 arcsec resolution, radio continuum sources are mostly extragalactic,

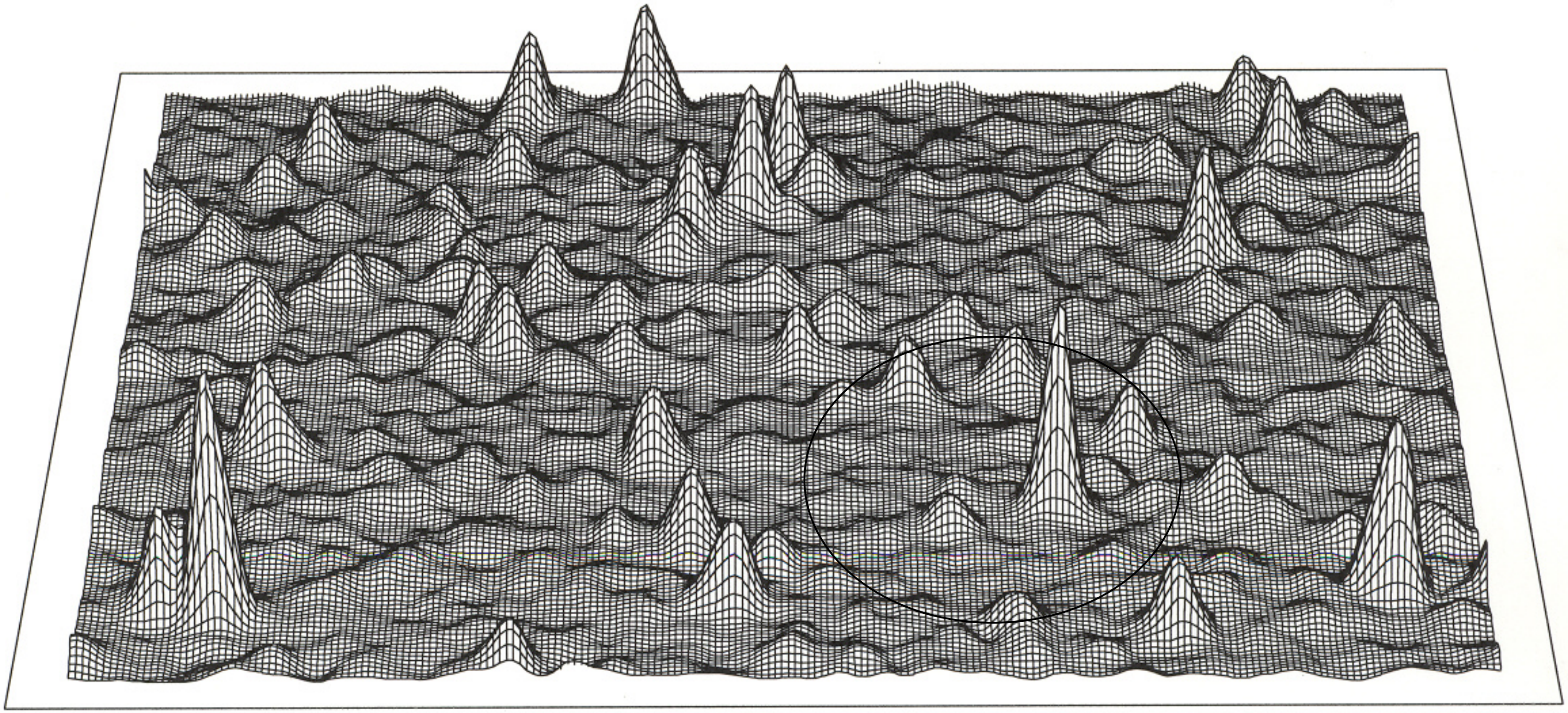


very isotropic, and hence very distant



"Confusion"

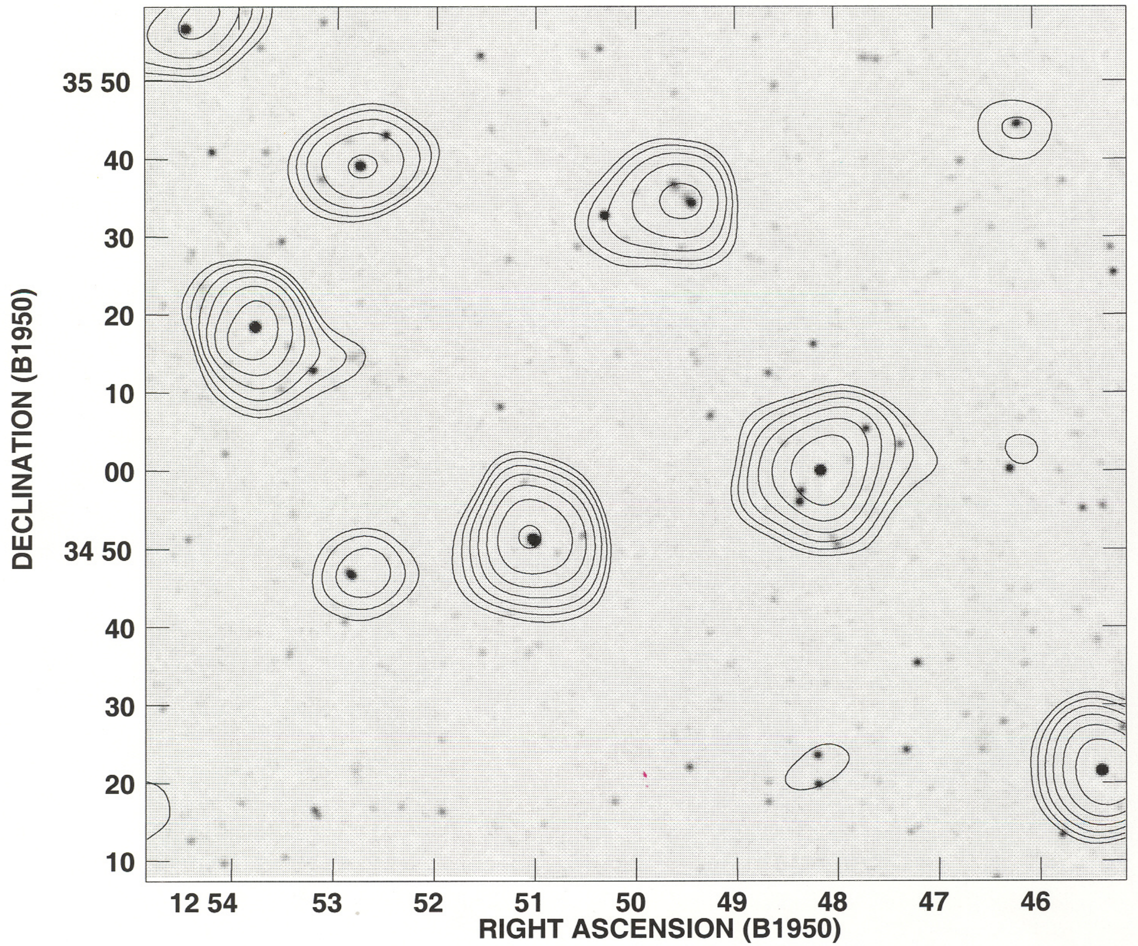
Profile plot of 45 deg^2 near the NGP imaged with 12′ resolution at 1.4 GHz. Strongest source S ≈ 1.5 Jy.



Confusion limit

NVSS (45 arcsec FWHM) grayscale

GB6 300' (12 arcmin FWHM) contours

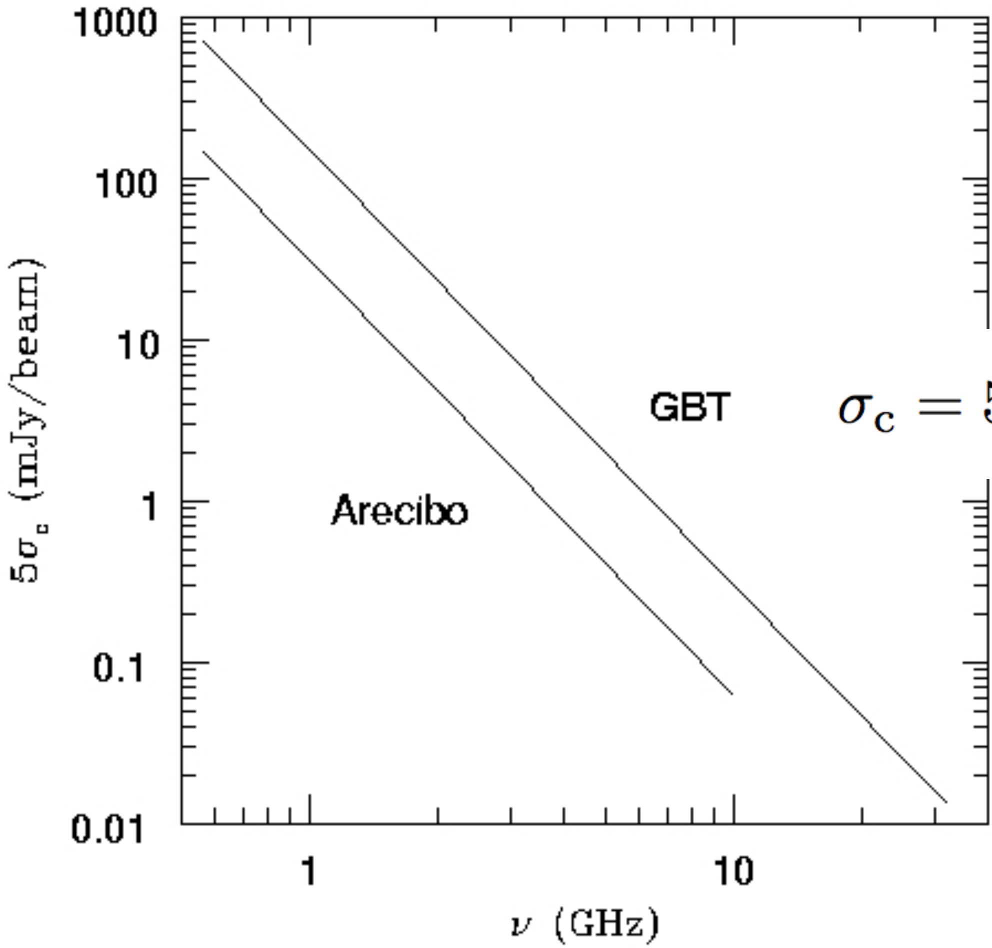


$$\left(\frac{\sigma_c}{\mathrm{mJy\ beam}^{-1}}\right) \approx 0.2\left(\frac{\nu}{\mathrm{GHz}}\right)^{-0.7}\left(\frac{\theta}{\mathrm{arcmin}}\right)^2$$

$S_{min} \approx 5\sigma_c$

NRAO

5σ confusion source detection limits at GBT and Arecibo



$$\sigma_c = 50 \text{ mJy } \cdot \nu^{-2.7} \text{ GHz}$$

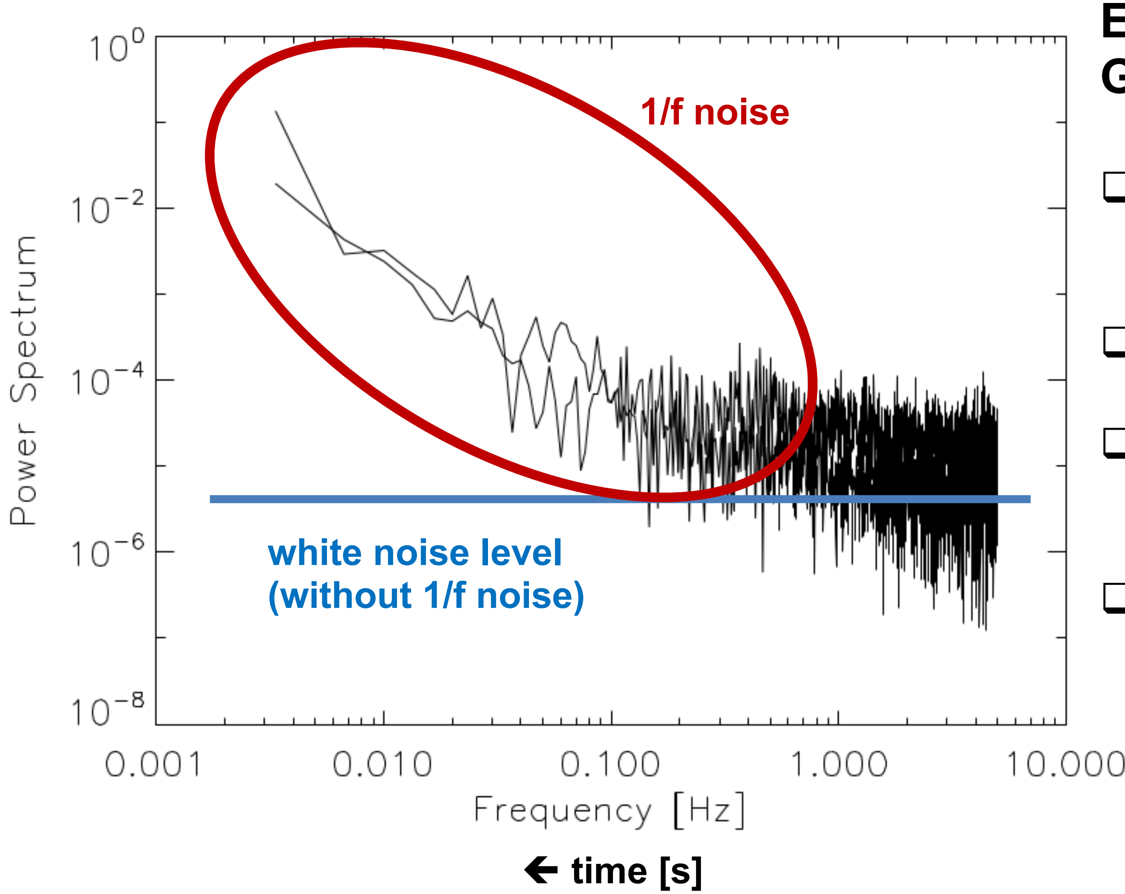
Continuum Radiometer Equation

$$\sigma_{Ta} = T_{SYS}\sqrt{\frac{1}{\Delta\nu \cdot t} + \left(\frac{\Delta G}{G}\right)^2}$$

Note (need to include confusion noise floor):
(sigma_Ta_total)^2 = (sigma_ta)^2 + (sigma_confusion)^2

- Receiver delta-G/G gain stability results in "1/f" noise.
- Baseline subtraction removes the 1/f noise for spectral-line observations.
- The 1/f noise dominates for single-dish continuum observations, except for receivers built with fast electronic beam-switching (e.g., CCB for Ka-band on the GBT).
- Need multiple scans over the source for continuum observations to decrease the noise (increasing the bandwidth does not help for single-dish continuum observations, unlike interferometer continuum observations where the gain instability does not correlate between antennae).

Electronic 1/f noise



The two lines in the figure are for the two polarization channels.

Example power spectrum for GBT 340 GHz receiver.

- The "white" noise level is ~10^-5 in power spectrum for frequencies >4Hz (time < 0.25 s).
- The 1/f noise dominates for time >1 sec.
- At 100sec the 1/f noise is ~1000x higher than the white noise.

- Would need to slew across point-sources at ~6deg/s to remove the 1/f noise for this Rx on the GBT and the GBT cannot slew nearly this fast.... ➔ would need a new Rx to measure continuum (which is actually under construction)

Effective Continuum Band-width limits for the GBT (GBT Memo#282 Mason 2013)

Receiver	$\frac{\Delta G}{G}(5\,\mathrm{Hz})$	$\Delta\nu_{eff.}$ [MHz]
PF(300 MHz)	$\sim 2.3 \times 10^{-3}$ *	2
PF(850 MHz)	$\sim 1.2 \times 10^{-3}$ *	7
L	$(3.7 \pm 2.4) \times 10^{-4}$	73
S	$(7.9 \pm 2.8) \times 10^{-4}$ *	16
C	$(1.5 \pm 0.8) \times 10^{-3}$	4
X	$(6.9 \pm 1.5) \times 10^{-4}$	21
Ku	$(1.6 \pm 1.2) \times 10^{-4}$	390
K	$(5.2 \pm 2.0) \times 10^{-4}$	37
Ka	$(5.0 \pm 2.1) \times 10^{-4}$	40
Q	$(4.1 \pm 1.1) \times 10^{-4}$	59
W	$(3.6 \pm 1.3) \times 10^{-4}$	77

Do not blindly assume the 1.5 GHz VEGAS Mode-1 bandwidth for continuum noise estimates. Use these tabulated bandwidths for sensitivity estimates based on Rx.

Example:
Ka-band and VEGAS/DCR limited to 40MHz. CCB (12GHz) with fast electronic switching is about (12000MHz/40MHz)^0.5 = 17x more sensitive based on effective bandwidth considerations....

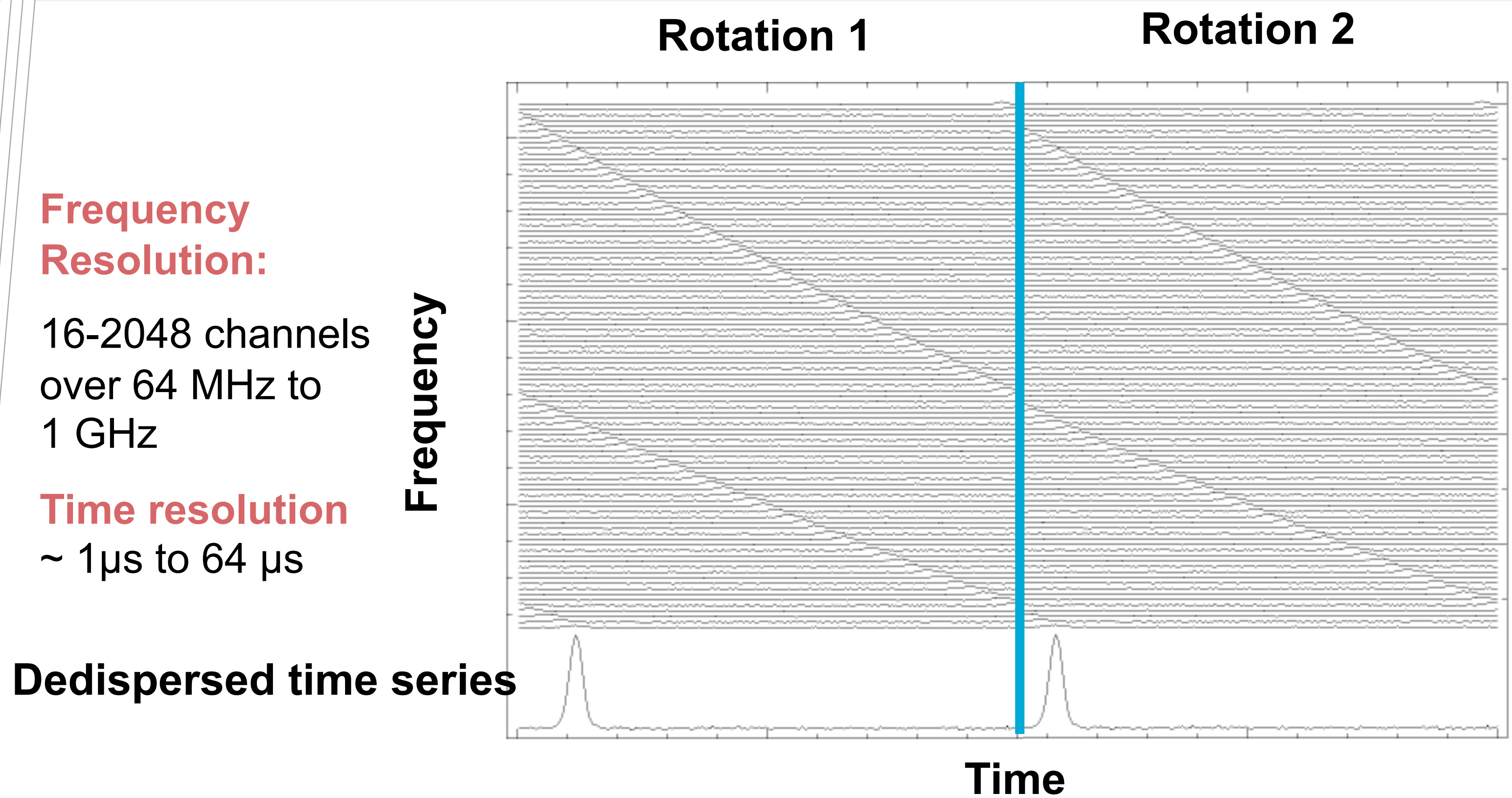
Pulsar Observations

Dynamic Spectra: Pulsar Radiation as a Function of Frequency and Time

Frequency Resolution:

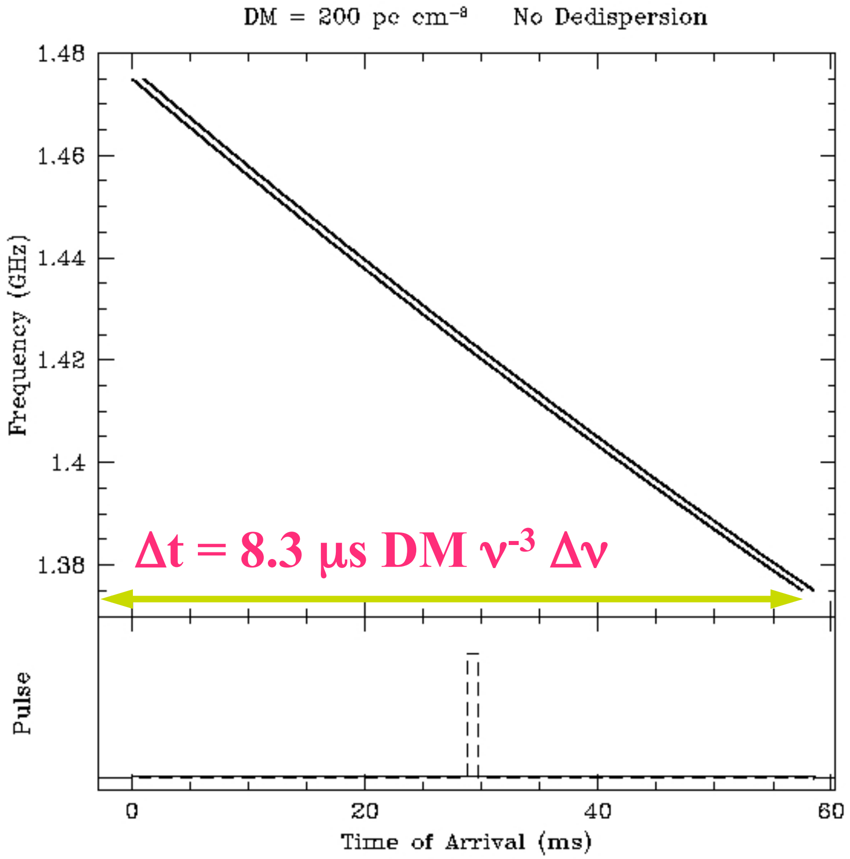
16-2048 channels over 64 MHz to 1 GHz

Time resolution
~ 1μs to 64 μs

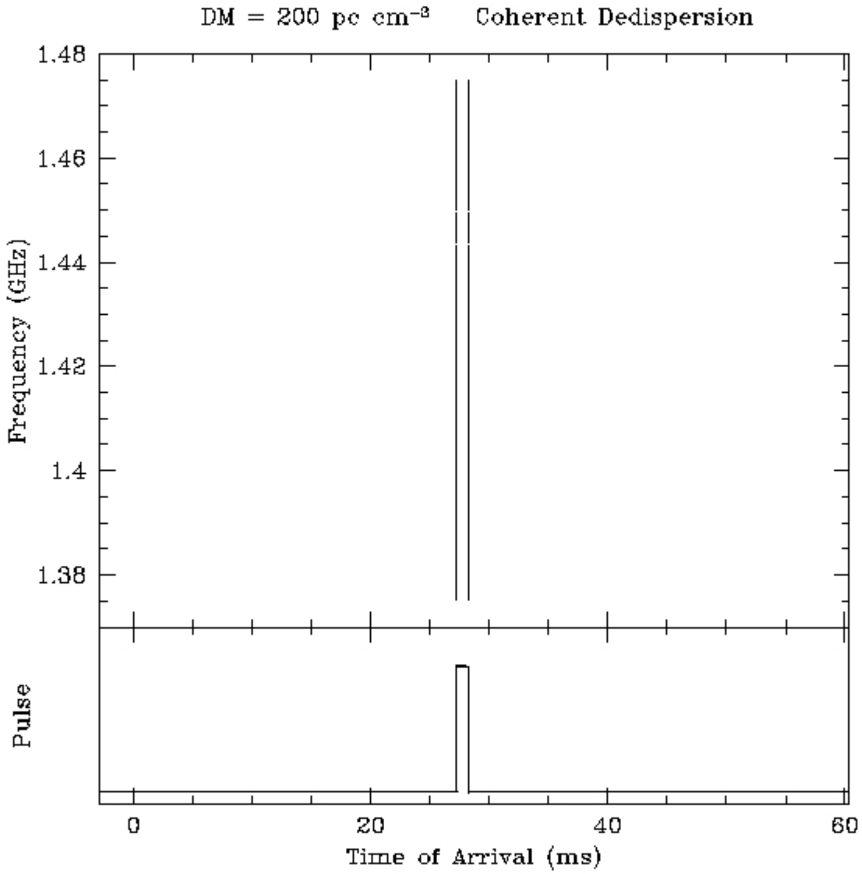


It is necessary to remove the effect of dispersion
1) **Increase SNR to detect pulsar; and**
2) **Best study pulsar**

Dispersed Pulse



Coherently dedispersed pulse



CSIRO

Calibration

Background Material:

$$P(\nu,\theta,\varphi,t) =$$

$$G_{RF}(\nu,t)G_{IF}(\nu,t)\cdot$$

$$[T_{Rcvr}(\nu,t) + T_A(\nu,\theta,\varphi,t)$$

$$\eta_l(E)\left(T_{CMB}e^{-\tau(\nu,t)A(E)} + T_{ATM}(\nu,t)\cdot\left(1 - e^{-\tau(\nu,t)A(E)}\right)\right) +$$

$$\left(1 - \eta_l(E)\right)\cdot T_{Spill}\,(E)]$$

$$T_{SYS}(\nu,\theta,\varphi,t) = [Everything\ between\ the\ square\ brackets]$$

$$T_A(\nu,\theta,\varphi,t) = \frac{\eta_R e^{-\tau(\nu,t)A(E)}}{\iint_{4\pi} f\,d\Omega}\iint_{4\pi} f(\theta-\theta',\varphi-\varphi')\,T_B(\theta',\varphi')\;d\theta'\;d\varphi'$$

$$S = \frac{2k}{\lambda^2}\iint_{\Omega_{SRC}} T_B\,d\Omega$$

$$S = \frac{2kT_A e^{\tau(\nu,t)A(E)}}{\eta_A A_G}\ (Point\ Source\ Only)$$

$$P_{Off}(\nu) = G_{RF}(\nu)G_{IF}(\nu) \cdot [T_{Rcvr}(\nu) + etc.]$$

$$P_{On}(\nu) = G_{RF}(\nu)G_{IF}(\nu) \cdot [T_{Rcvr}(\nu) + T_{Diode}(\nu) + etc.]$$

$$G_{RF}(\nu)G_{IF}(\nu) = \frac{P_{On}(\nu) - P_{Off}(\nu)}{T_{Diode}(\nu)}$$

Slight differences in calibration methods for continuum and spectral-line data:

Continuum:

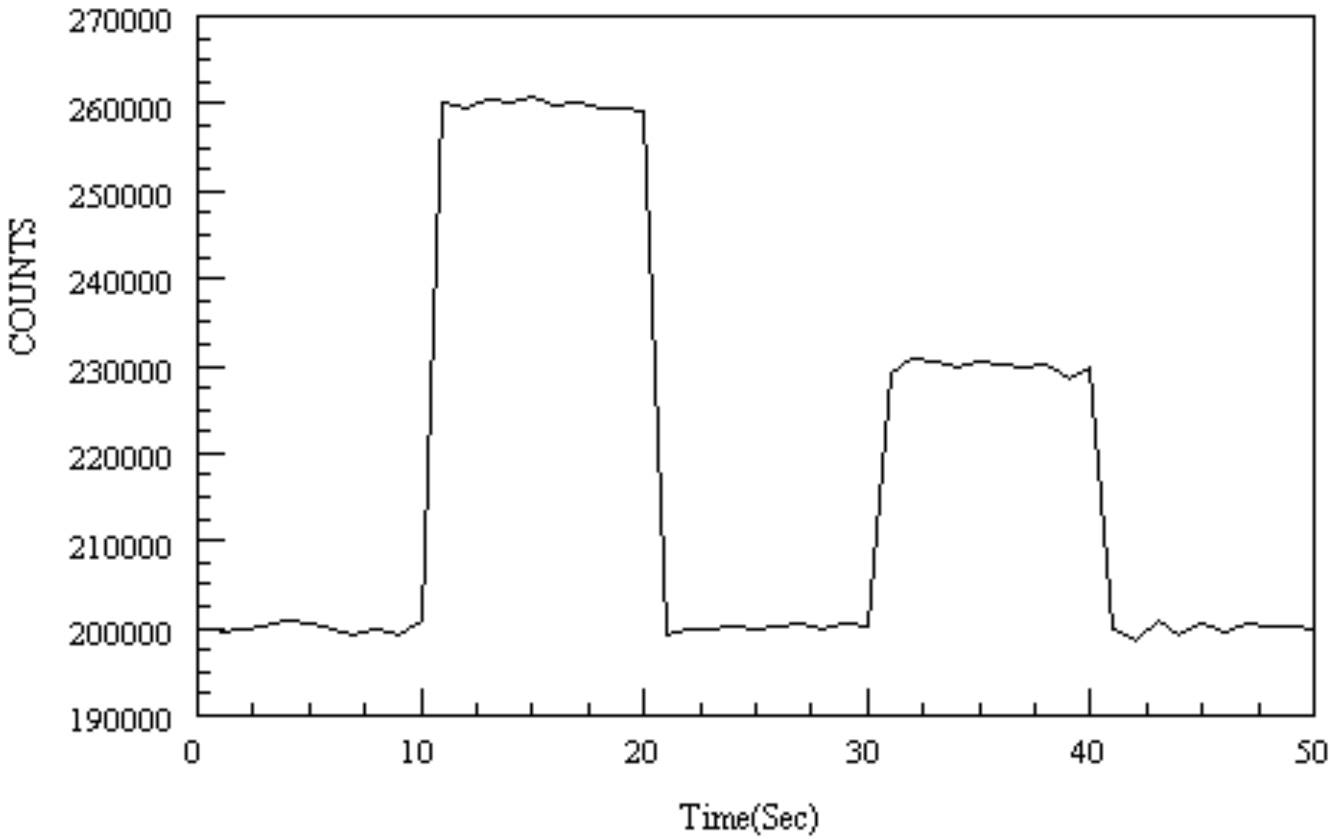
$$T_A = T_{Diode} \frac{P_{SIG} - P_{REF}}{P_{On} - P_{Off}}$$

Spectral Line:

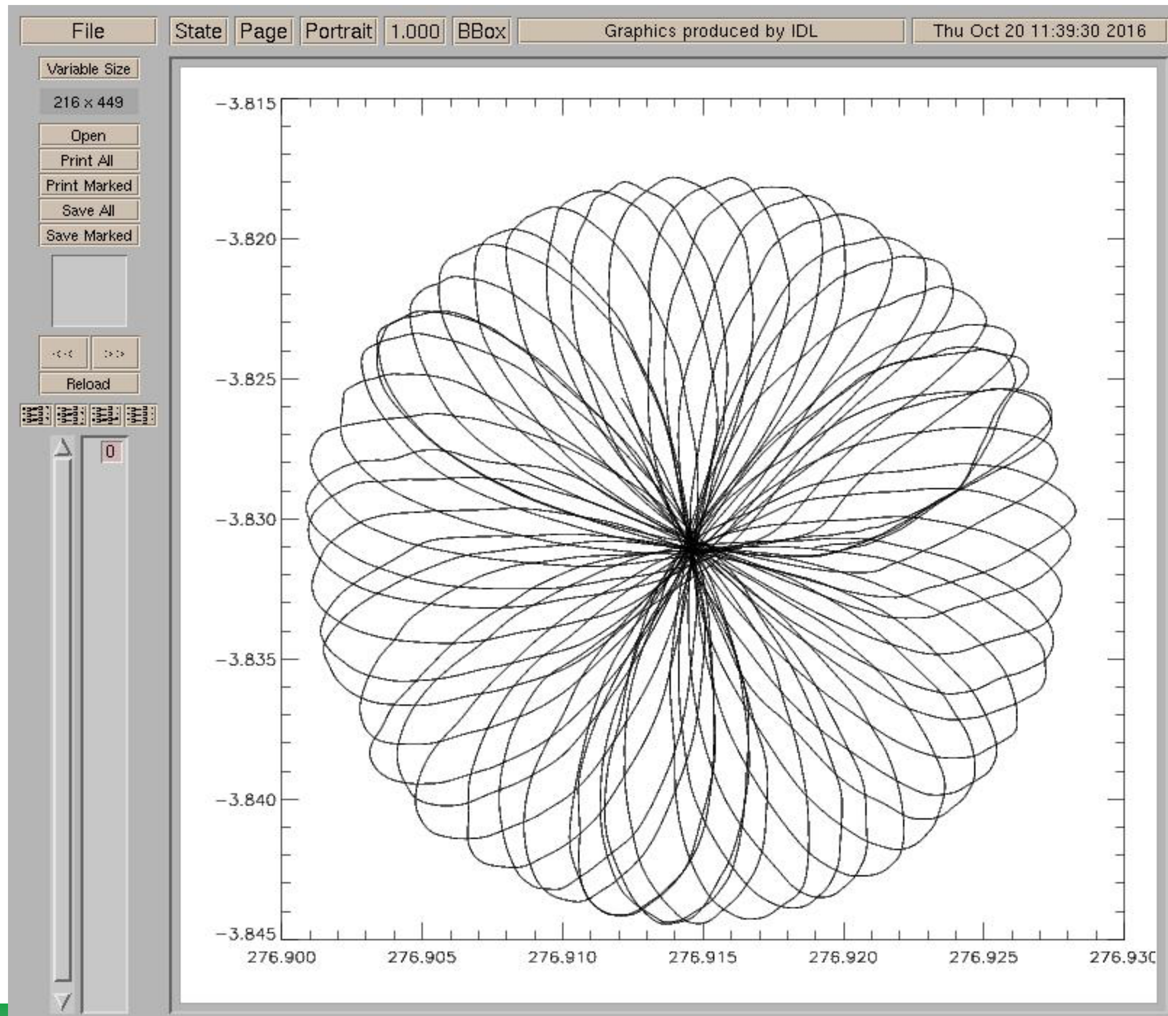
$$T_A(\nu) = \frac{P_{SIG}(\nu) - P_{REF}(\nu)}{P_{REF}(\nu)} \left\langle \frac{T_{Diode}(\nu) P_{REF}(\nu)}{P_{On}(\nu) - P_{Off}(\nu)} \right\rangle_{BW}$$

Continuum - Point Sources

On-Off Observing

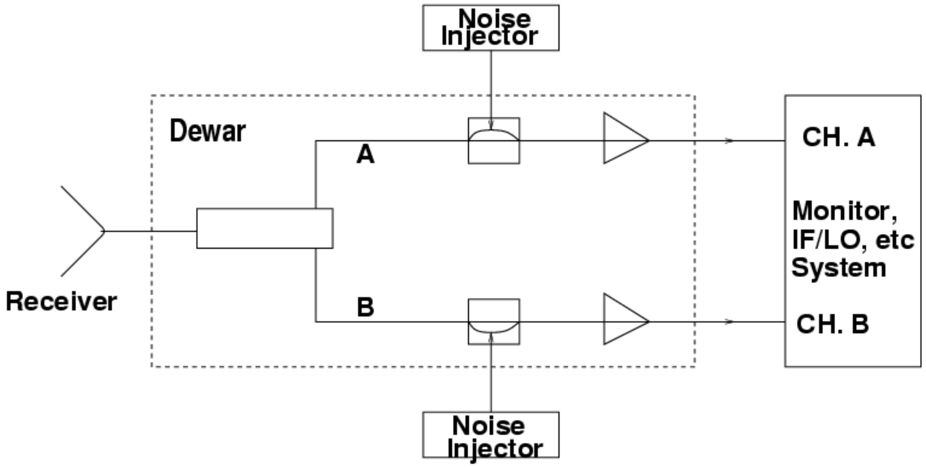


Daisy Scan Map: maximizes the number of passes over small source for continuum observations (i.e. avoid overheads of turning the telescope around as done in RA/Dec mapping)

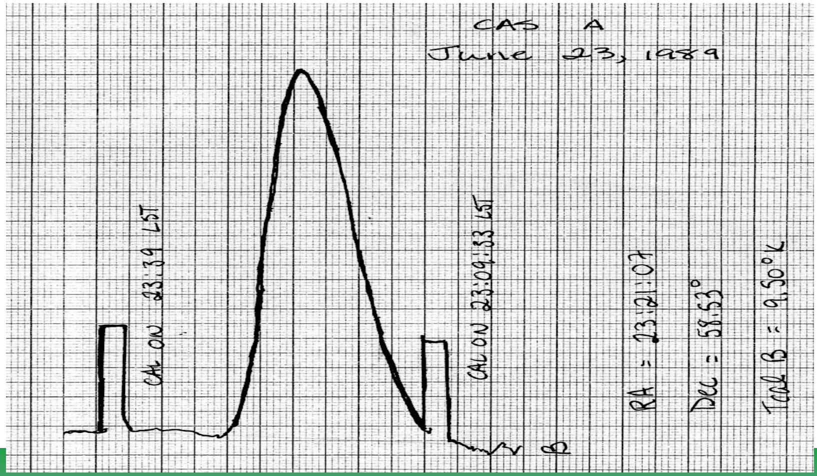


Calibration

Noise Diodes

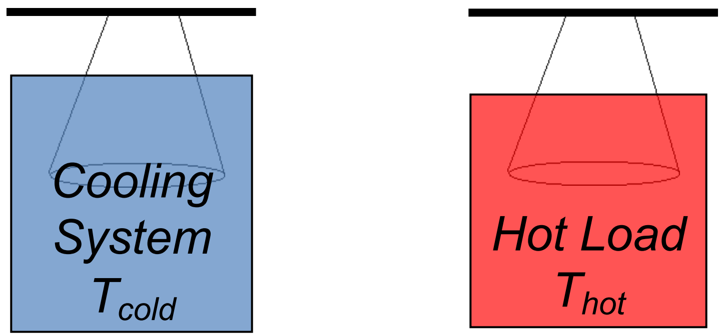


All GBT receivers besides 4mm, Argus, and Mustang use noise diodes.



Calibration

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

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

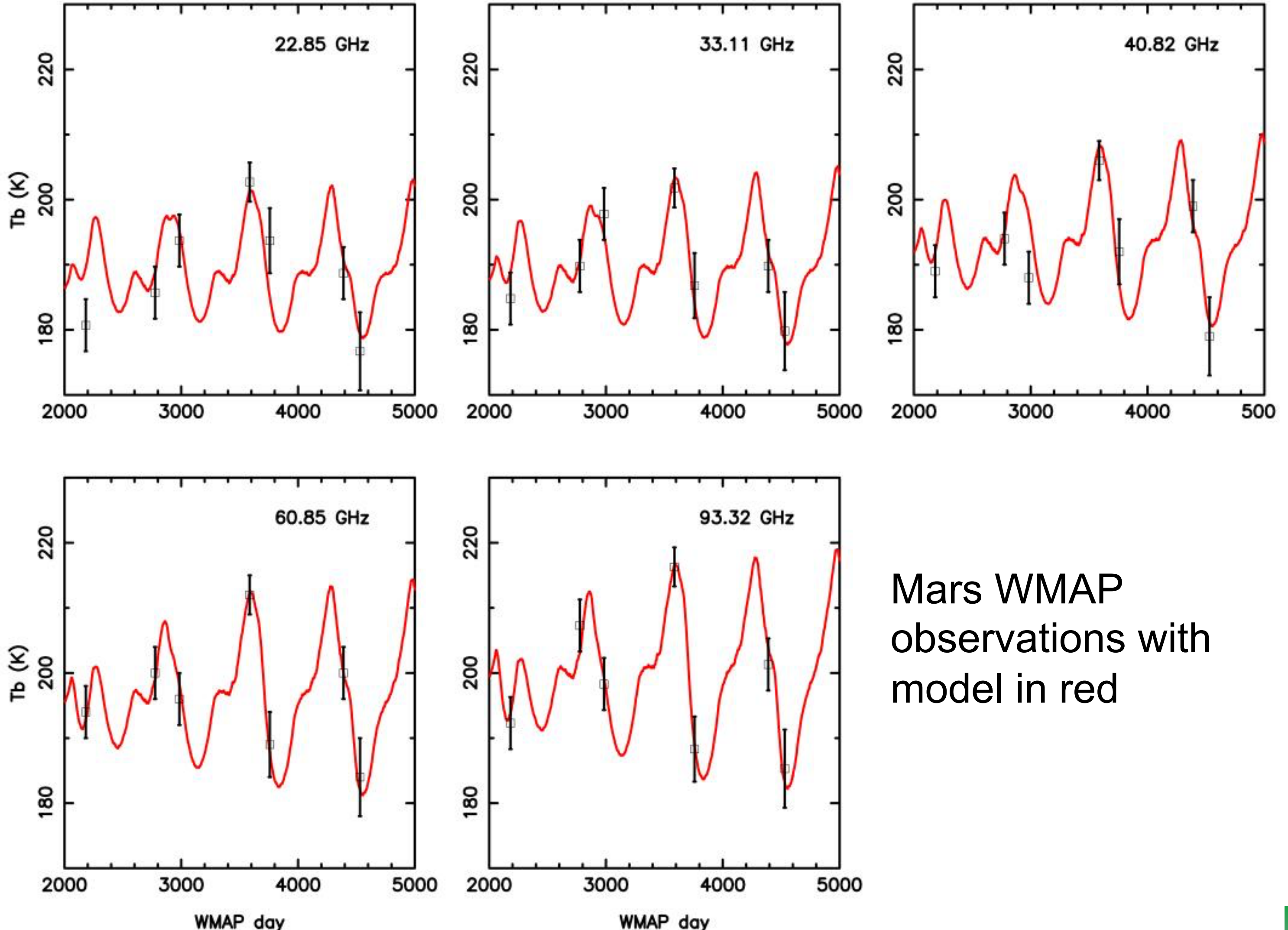
where S(3cX) is known and T(source) and T(3cX) are observed.

Absolute calibration typically known to 5-15%

Absolute Calibration tied to Mars via WMAP

VLA calibration (0.05-50 GHz):

Perley & Butler 2013, 2017



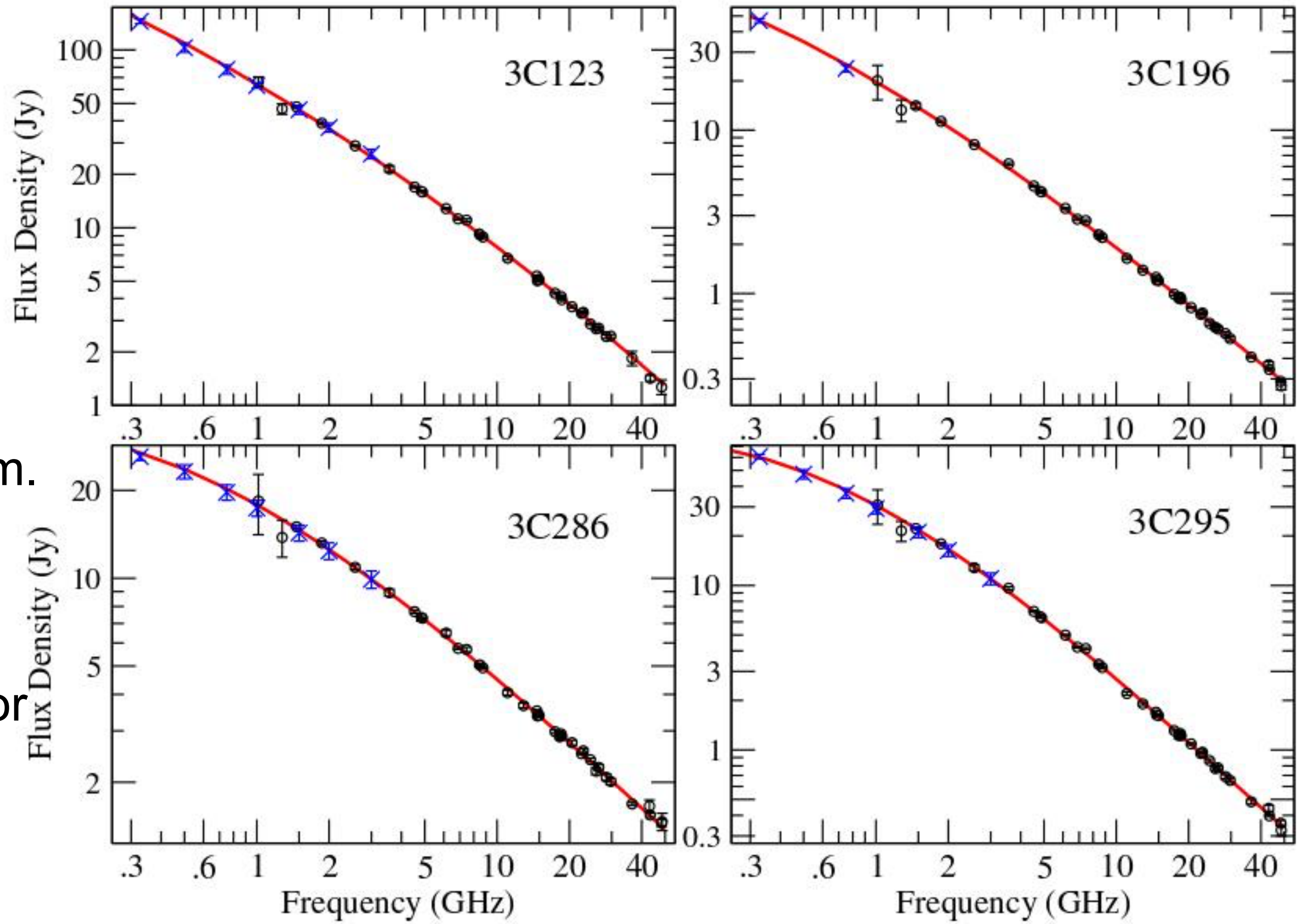
Mars WMAP observations with model in red

VLA Stable Calibrators

GBT Calibration:

GBT calibration tied to VLA calibration scale for <50 GHz, and is tied to ALMA absolute calibration at 3mm.

Mars and Uranus are the best sources (small) for GBT absolute planet calibration at 3mm.



Do not blindly assume the GBT Noise Diode Calibration

- Noise diodes are recommended to be sent back for re-calibration every 6 months to meet laboratory specs – we never do do this – we could expect drifts on time scale of 1-2 years.
- The KFPA has variable noise diodes.
- The noise diodes were last calibrated empirically for the GBT 10+ years ago…..
- There are significant variations in the noise diodes as a function of frequency.
- You should calibrate your data.

Flux Density vs Antenna Temp

$P_{rec} = ½ A_e S_v Δv = k T_a' Δv$

$A_e = η_a (π/4) D^2$

$\rightarrow S_v = 3520\ T_a' / (η_a [D/m]^2)$

i.e., $T_a'/S_v = 2.84\ η_a$ for the GBT ($η_a$=0.71 at low v)

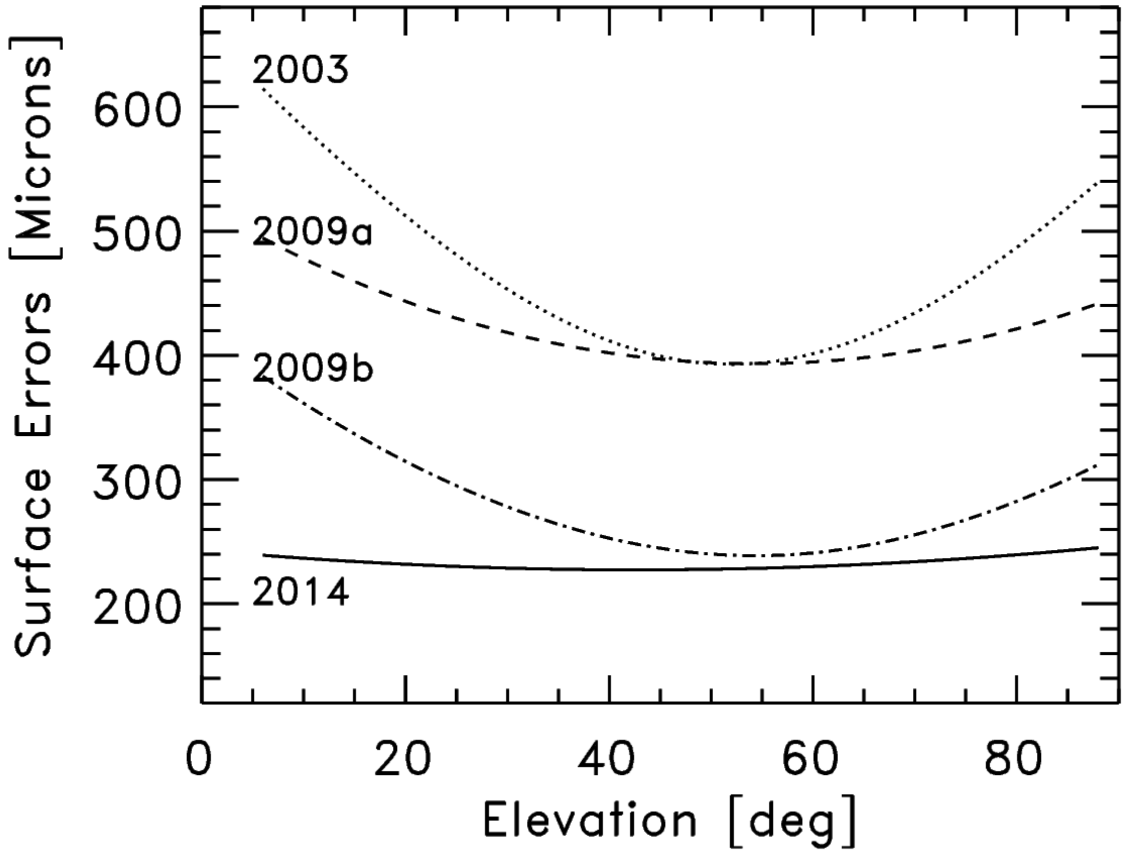
$$\eta_a = 0.352 \frac{T'_A}{S_\nu}.$$

Aperture efficiency for the GBT

Ruze Equation

$$\eta_a = \eta_0 \exp[-(4\pi\epsilon/\lambda)^2)],$$

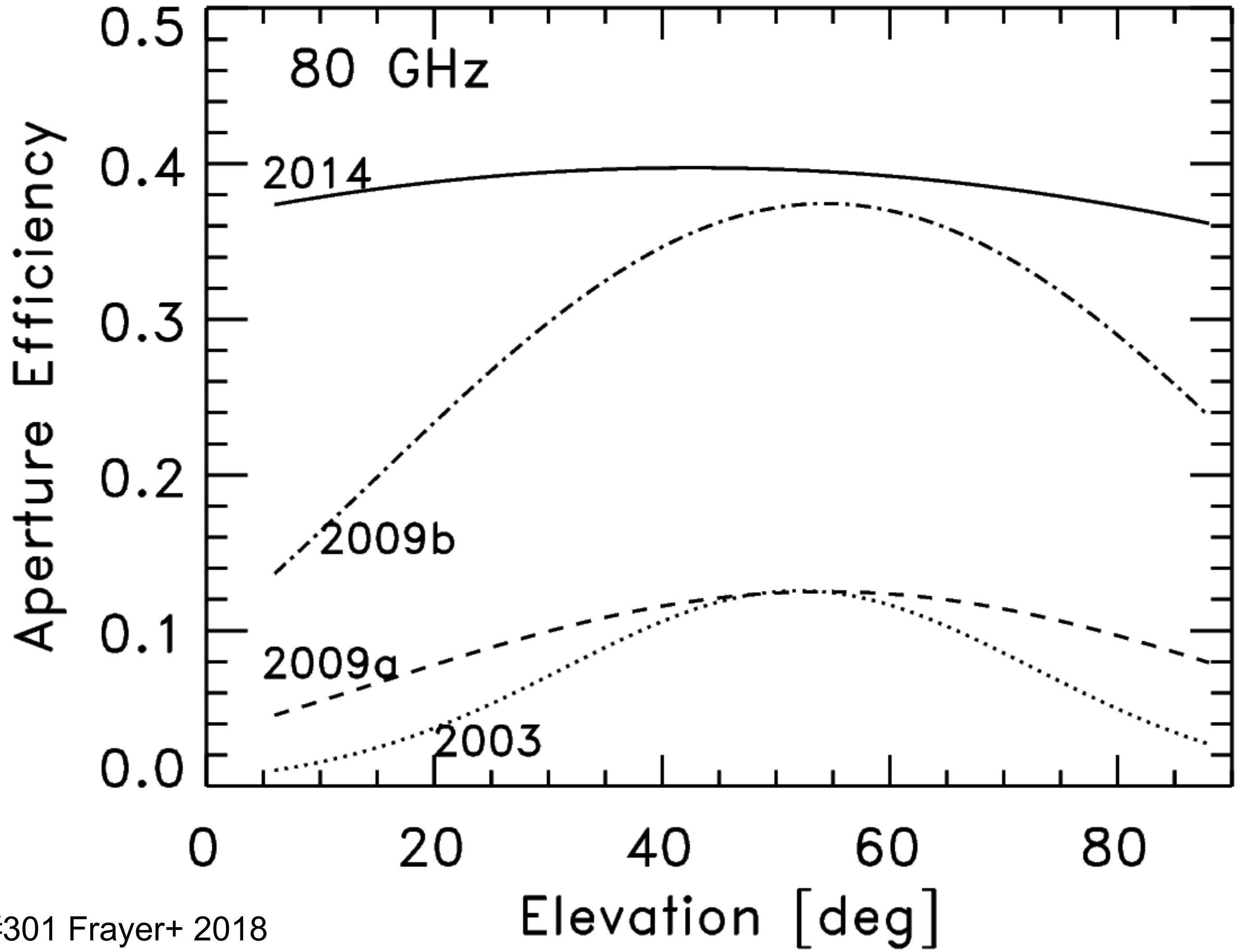
History of GBT Performance



Effective surface errors determines the aperture efficiency.

Surface errors of 235+/-15 microns were measured for 2017-2019 observing seasons

Gain-Curve: Improvements to Surface Models over time



GBT Memo #301 Frayer+ 2018

Telescope Efficiencies

$$\eta_{rss} = \frac{\iint_{2\pi} P_n(\Omega) d\Omega}{\iint_{4\pi} P_n(\Omega) d\Omega},$$

Rear-spillover and scattering efficiency -- fraction of power in the forward (on sky) 2pi direction

$\eta_l = \eta_r \eta_{rss}$, where the ohmic efficiency is $\eta_r \simeq 1.0$.

$$\eta_{fss} = \frac{\iint_{\Omega_D} P_n(\Omega) d\Omega}{\iint_{2\pi} P_n(\Omega) d\Omega},$$

Forward-spillover and scattering efficiency -- fraction of power in diffraction pattern including the error beam which is in the forward direction.

$$\eta_{mb} = \frac{\iint_{\Omega_{mb}} P_n(\Omega) d\Omega}{\iint_{4\pi} P_n(\Omega) d\Omega},$$

Main-beam efficiency – fraction of power in main-beam lobe (useful for small sources)

Antenna Temperature Scales

$$T'_A = T_A \, \exp(\tau_o \, A),$$ Measured antenna temperature corrected for ATM

$$T^*_A = \frac{T'_A}{\eta_l},$$ Measured antenna temperature in forward 2pi direction

$$T^*_R = \frac{T'_A}{\eta_l \, \eta_{fss}},$$ Measured antenna temperature associated with antenna diffraction pattern (including error beam) – corrected for both forward and rear-ward scattering and spillover

$$T_{mb} = \frac{T'_A}{\eta_{mb}}.$$ Measured antenna main-beam temperature

$$T'_A = \eta_{mb} \, T_{mb} = \eta_l \, T^*_A = \eta_l \, \eta_{fss} \, T^*_R.$$

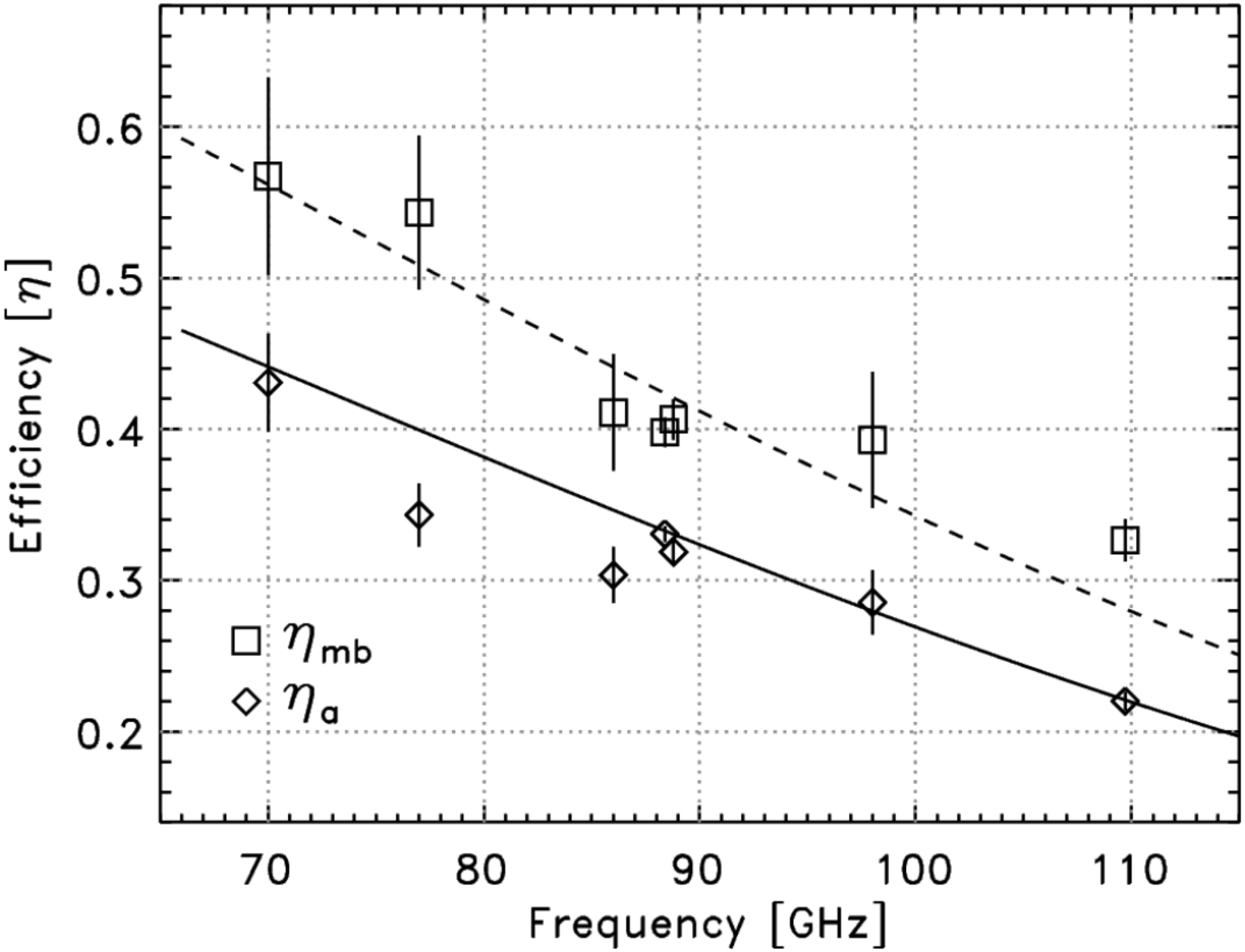
Point Source Calibration

$$\eta_a = 0.352 \frac{T'_A}{S_\nu}.$$

Assuming a Gaussian beam, the main-beam efficiency is related to the aperture efficiency by the following relationship:

$$\eta_{mb} = 0.8899 \eta_a \left(\theta_{FWHM} \frac{D}{\lambda} \right)^2,$$

Results from ~200 quasar measurements



$$\frac{\eta_{mb}}{\eta_a} = 1.274 \pm 0.035.$$

Average beam-size parameter:

$$\kappa \equiv \theta_{\mathrm{FWHM}} \left(\frac{D}{\lambda}\right) = 1.20,$$

GBT Memo #302 Frayer+ 2019

Extended Source Calibration

$$\eta_{\text{Source}} = \eta_c \eta_{fss} \eta_l,$$

$$T'_A = \eta_{\text{Source}} T_S.$$

$$\eta_c = \frac{\iint_{\Omega_{\text{Source}}} P_n(\Psi - \Omega) B_n(\Psi) d\Psi}{\iint_{\Omega_D} P_n(\Omega) d\Omega},$$

For extended sources larger than the main-beam, need to know the detailed beam error pattern and source structure to compute source “coupling” efficiency (eta_c)

Planet calibration (disk convolved to Gaussian beam). Works best for planets smaller than main-beam to avoid eta_c uncertainties.

$$\eta_{mb} = \frac{T'_a}{J_\nu(T_b)[1 - \exp(-x^2)]},$$

$$x = \sqrt{\ln 2}(\theta_S/\theta_{mb})$$

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

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

$$\Uparrow$$

source

$$\underline{\text{compute using } T_{mb}}$$

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

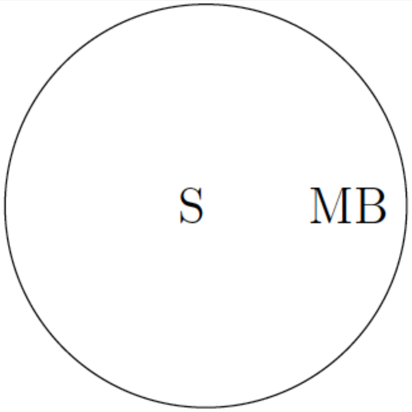
$$T_{mb} = \frac{T_A'}{\eta_{mb}} = \frac{1}{\Omega_{mb}} \iint P_n(\theta,\phi) T_s(\theta,\phi) d\Omega$$

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

$\Rightarrow P_n \approx 1$ over source:

$$T_{mb} = \frac{1}{\Omega_{mb}} T_s \iint_{source} P_n d\Omega$$
$$= T_s \frac{\Omega_s}{\Omega_{mb}} = \left(\frac{\theta_s}{\theta_{mb}}\right)^2$$

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



"Filling factor"
"Beam dilution"

Gaussian Source and Gaussian Beam approximation (with negligible error pattern)

More general, assume T_s is Gaussian and beam Gaussian

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

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

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

$\theta_s >> \theta_{mb}$ $\qquad T_{mb} = T_s$ ✓

Calibration with Two Loads

<u>Two loads</u> "Direct" Calibration, e.g. $4mRx$

$$g = \frac{T_{amb} - T_{cold}}{V_{amb} - V_{cold}}$$

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

$$T_A{}' = T_A e^{\tau_0 A} \qquad \underline{\underline{\text{need } \tau}}$$

$$T_{cold} = 54.0\,\mathrm{K} - 0.6[\mathrm{K/GHz}](\nu - 77.0\,\mathrm{GHz}),$$

Effective cold temperature for 4mm Rx
GBT Memo #302

Calibration with One Load, T_A^*

With a calibration vane with a temperature sensor, one can calibrate the approximate Ta* scale without any knowledge of the sky!!!

$$T_A^* = T_{cal}(C_{ON} - C_{OFF})/(C_{amb} - C_{OFF}),$$

$$T_{cal} = (T_{amb} - T_{OFF})\exp(\tau_o A)/\eta_l.$$

$$(T_{amb} - T_{OFF}) = T_{amb} - (\eta_l T_{sky} + (1-\eta_l) T_{spill})$$

$$T_{sky} = T_{ATM}(1 - \exp(-\tau_o A)) + T_{bg}\exp(-\tau_o A),$$

Doing some algebra Tcal reduces to:

$$T_{cal} = (T_{ATM} - T_{bg}) + (T_{spill} - T_{ATM})\exp(\tau_o A) + (T_{amb} - T_{spill})\exp(\tau_o A)/\eta_l.$$

$$\boxed{T_{cal} \simeq (T_{ATM} - T_{bg}) + (T_{amb} - T_{ATM})\exp(\tau_o A).}$$

Assuming either Tamb=Tspill or eta_l =1 which are both good approximations for the GBT.
We adopt the Tcal equation in the box for Argus using the Weather database for Tatm and tau_o.

$$T_{cal} \approx T_{amb}.$$

Average Tcal/Tamb ratio measured to be 0.997+/-0.018 for Argus observing sessions except for high ATM opacity.

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

- Opacity attenuates the signal and adds to the Tsys:

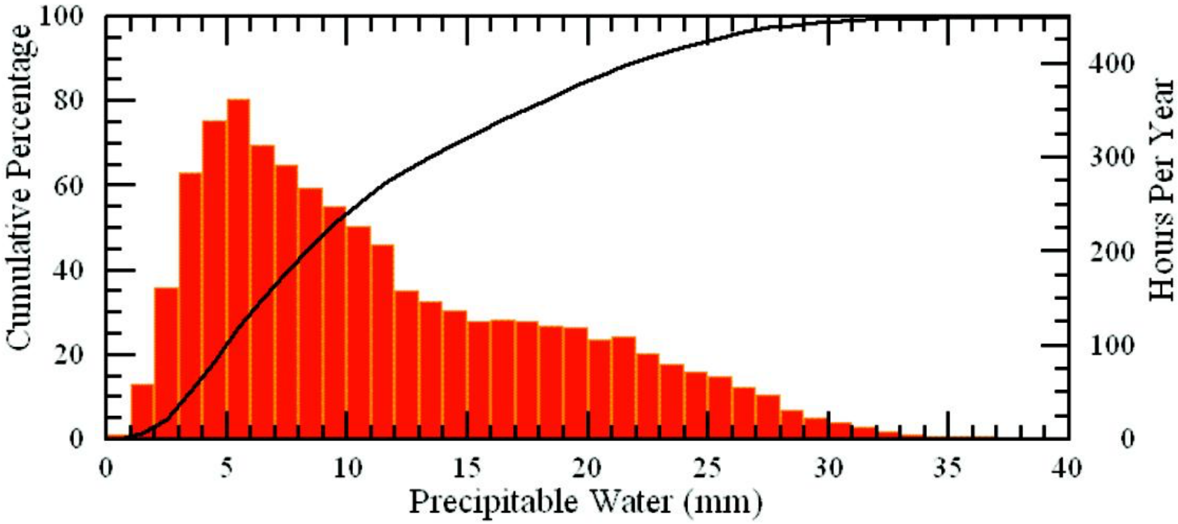
Tsys = Trcvr + Tspill +Tbg * exp(-tau*A) + Tatm * [exp(-tau*A) – 1]
Air Mass A~ 1/sin(Elev) (for Elev > 15°)

- Stability

Tsys can vary quickly with time

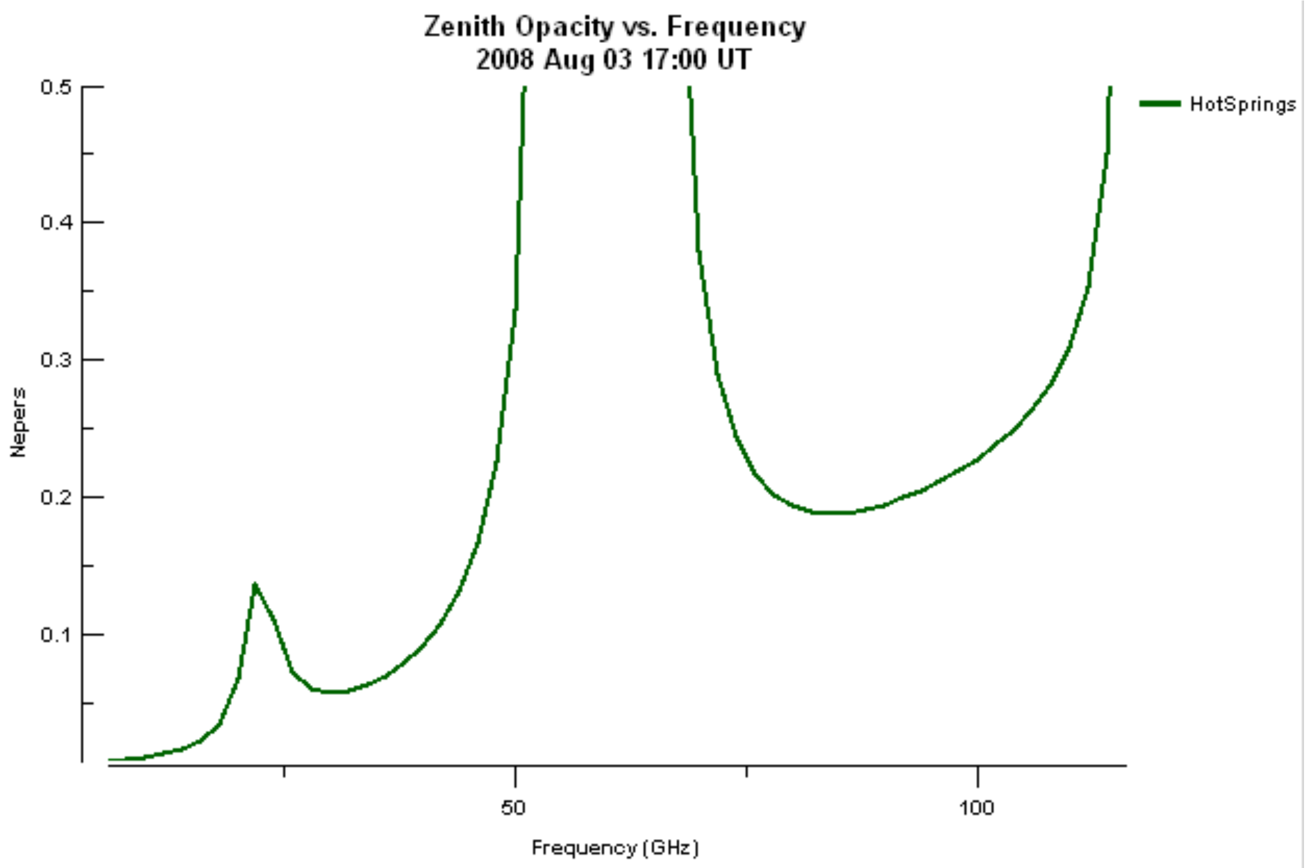
Worse when tau is high

- Atmosphere is in the near-field so the tau observed is similar for all beams for multi-beam receivers



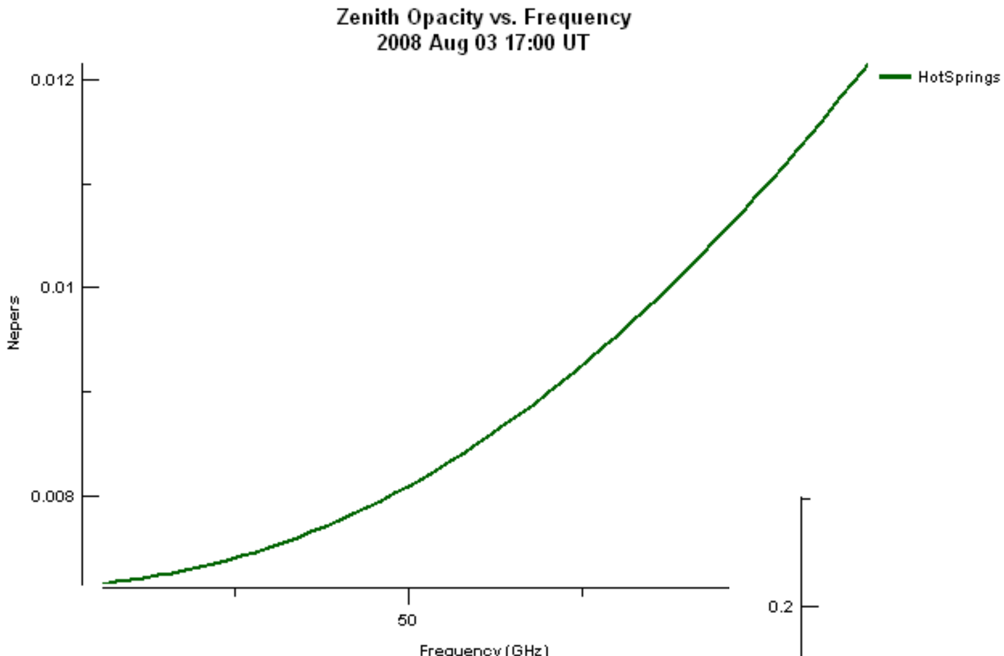
GBT site has many days with low water vapor per year ($<$10mm H_2O are ok for 3mm, 50% of time)

Opacity vs Frequency



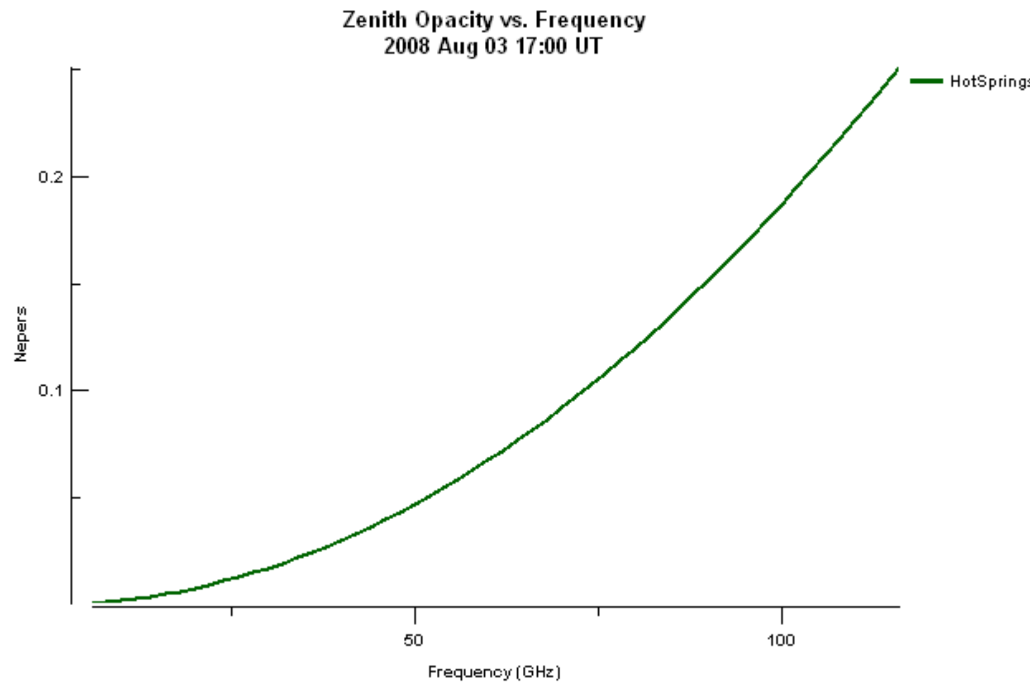
Total Opacity

Opacities from Various Atmosphere Components

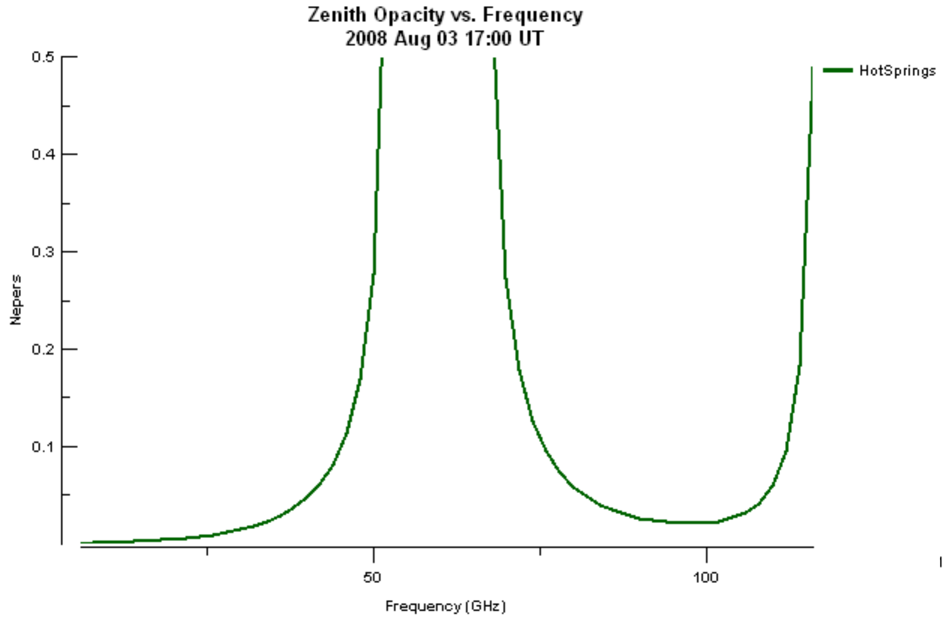


Dry Air Continuum

Water Continuum

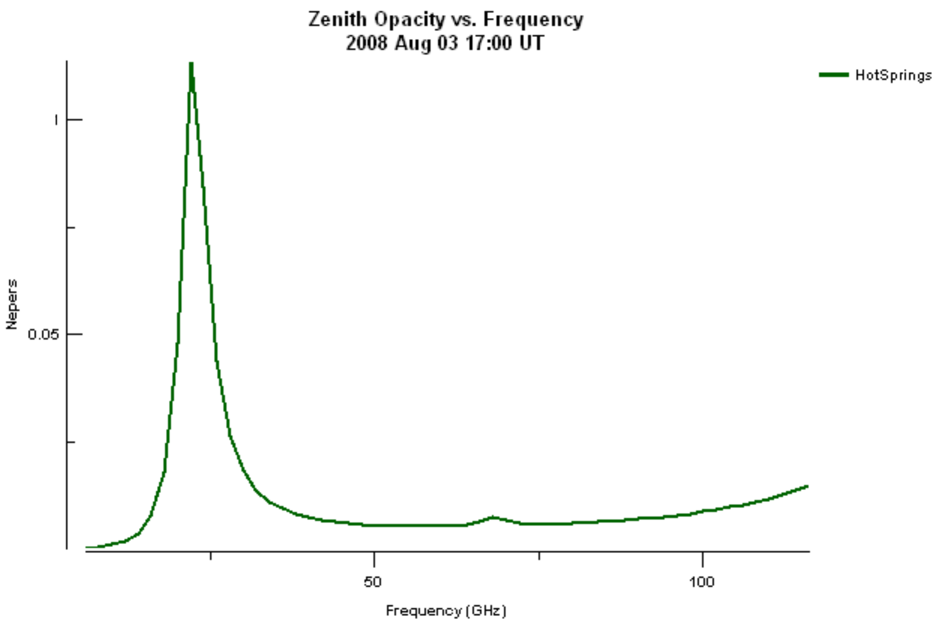


Opacities from Various Atmosphere Components

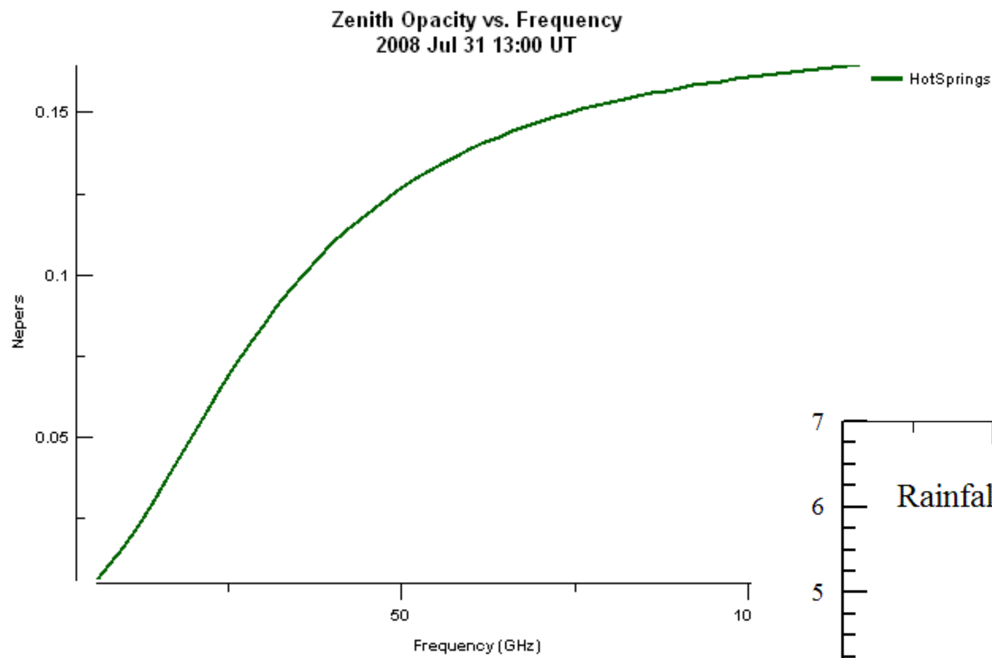


Oxygen Line

Water Line



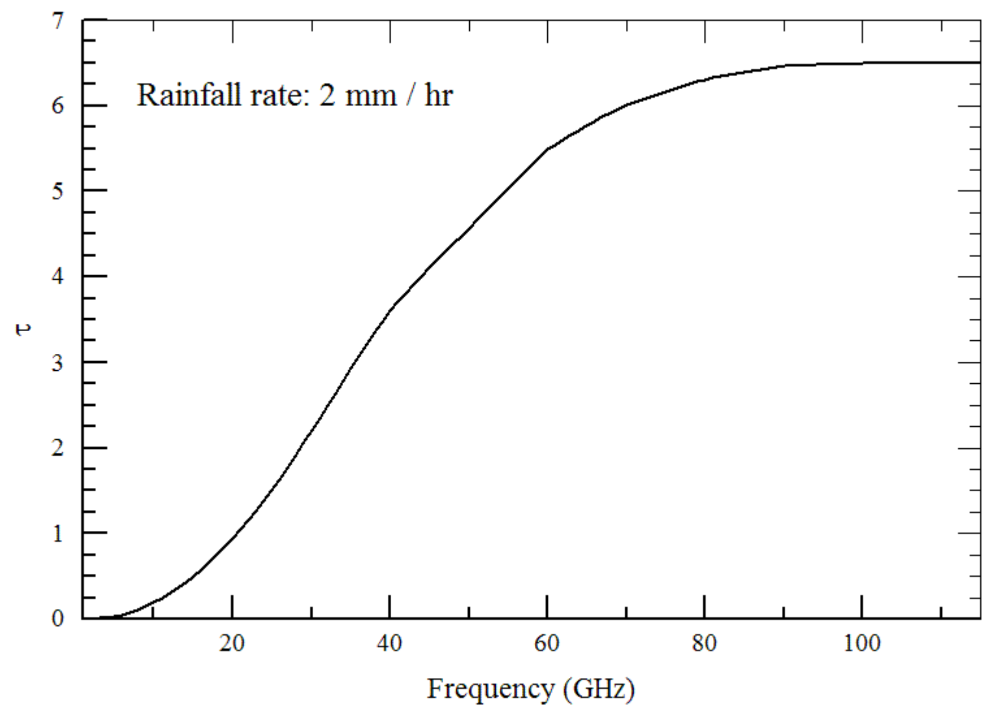
Opacities from Various Atmosphere Components



Hydrosols

water-soluable
componds

Rain



GBT 86 GHz Performance

Table 2: 86GHz GBT Efficiency and Calibration Parameters

Dish Diameter	D	100 m
RMS Surface Accuracy	ϵ	$235 \pm 15\,\mu$m
Beam Size Parameter	κ	1.20 ± 0.02
Aperture Efficiency	η_a	0.347 ± 0.032
Main-Beam Efficiency	η_{mb}	0.442 ± 0.043
Corrected Main-Beam Efficiency	η_M^*	0.465 ± 0.035
Jupiter Beam Efficiency(43″diameter)	$\eta_{\rm Jupiter}$	0.53 ± 0.05
Moon Beam Efficiency (32′ diameter)	$\eta_{\rm Moon}$	0.814 ± 0.029
Rear Spillover Efficiency[a]	η_l	0.985 ± 0.015
Forward Spillover Efficiency[b]	η_{fss}	0.965 ± 0.020

[a]Power in the forward 2π direction. [b]Factional power in the forward direction inside the $\sim 1^\circ$ diameter error pattern.

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