Observing Techniques and Calibration

David Frayer (Green Bank Observatory)

GREEN BANK
OBSERVATORY

The GBT provides a lot of observing choices

- Pick receiver based on frequency
- Pick backend based on observing type (line, continuum, pulsar, ….)
- Pick observing techniques based on science goals (point source, large field, narrow lines vs broad lines….)
- Calibration stategies depend on receiver and science needs

Available GBT receivers

What frequency do you need?

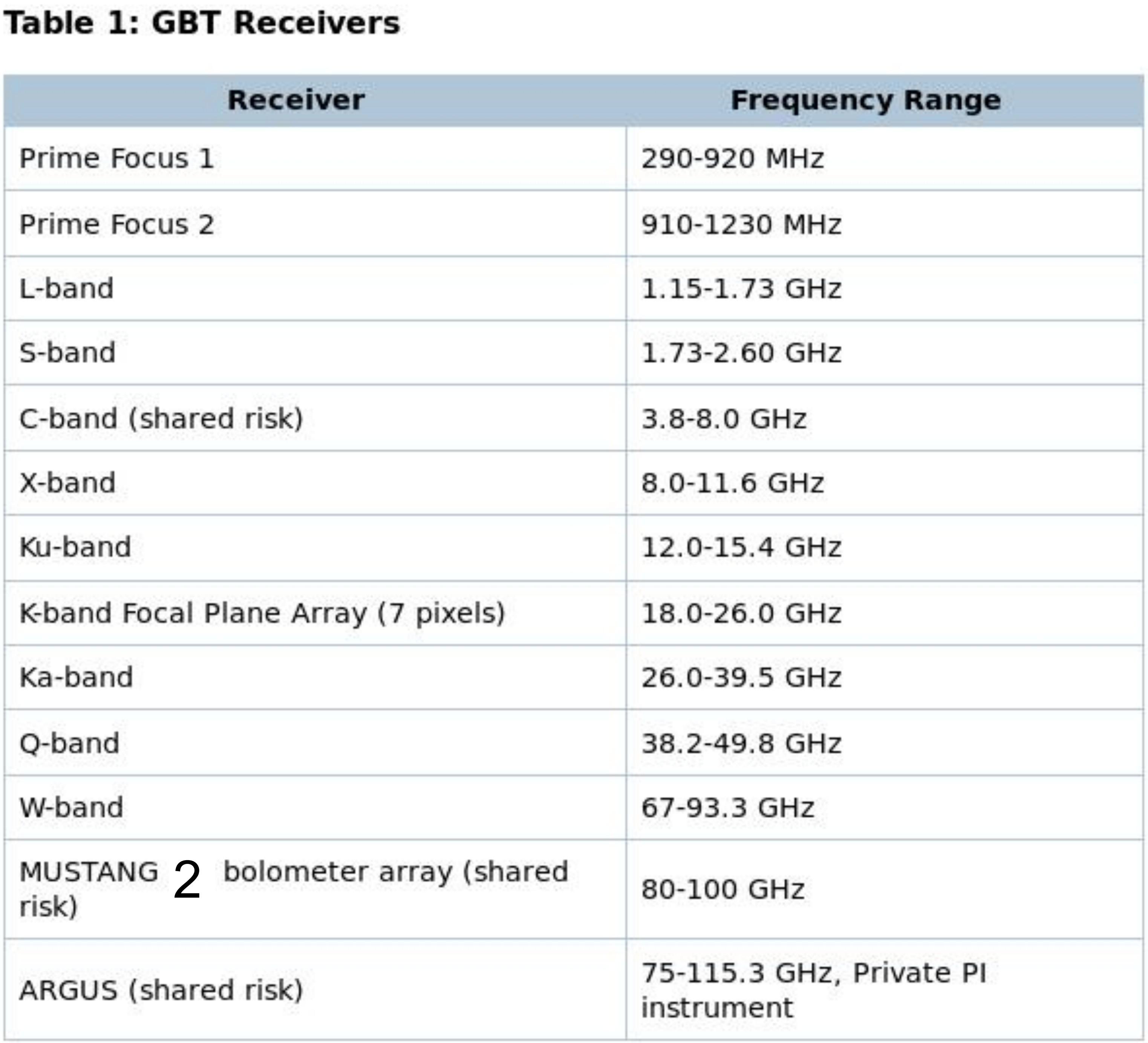


Table 1: GBT Receivers

Receiver	Frequency Range
Prime Focus 1	290-920 MHz
Prime Focus 2	910-1230 MHz
L-band	1.15-1.73 GHz
S-band	1.73-2.60 GHz
C-band (shared risk)	3.8-8.0 GHz
X-band	8.0-11.6 GHz
Ku-band	12.0-15.4 GHz
K-band Focal Plane Array (7 pixels)	18.0-26.0 GHz
Ka-band	26.0-39.5 GHz
Q-band	38.2-49.8 GHz
W-band	67-93.3 GHz
MUSTANG 2 bolometer array (shared risk)	80-100 GHz
ARGUS (shared risk)	75-115.3 GHz, Private PI instrument

Available GBT Backends

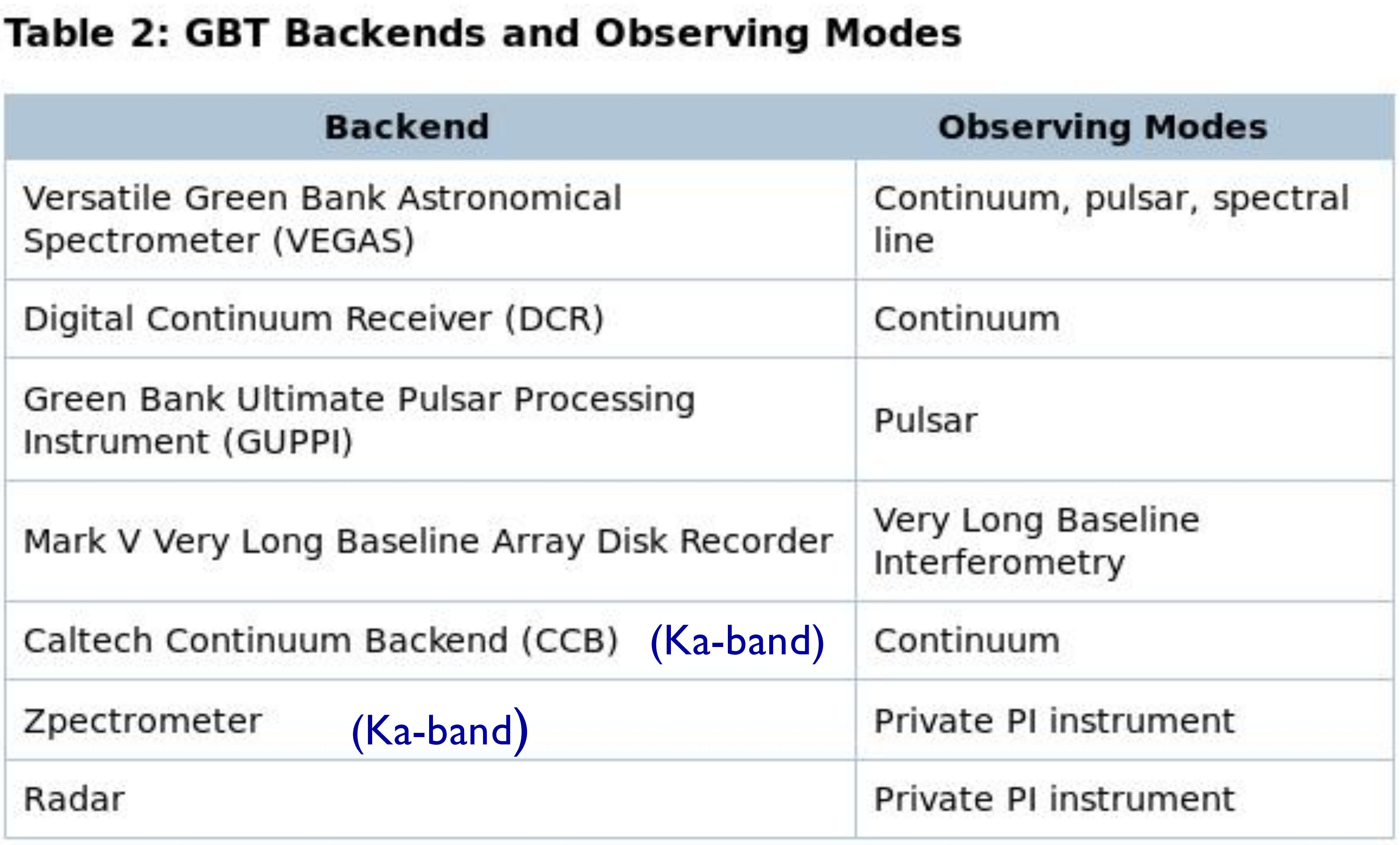


Table 2: GBT Backends and Observing Modes

Backend	Observing Modes
Versatile Green Bank Astronomical Spectrometer (VEGAS)	Continuum, pulsar, spectral line
Digital Continuum Receiver (DCR)	Continuum
Green Bank Ultimate Pulsar Processing Instrument (GUPPI)	Pulsar
Mark V Very Long Baseline Array Disk Recorder	Very Long Baseline Interferometry
Caltech Continuum Backend (CCB) (Ka-band)	Continuum
Zpectrometer (Ka-band)	Private PI instrument
Radar	Private PI instrument

Observing Mode vs Backend Capabilities

What are you doing?:	Continuum	Continuum full-stokes	Line	Pulsar	VLB	Radar
	DCR	Mode-1 VEGAS	VEGAS	GUPPI	Mark5 VLBA recorder	Radar backend
	CCB (Ka)	Mueller matrix calibration (function of parallactic angle)	{29 modes}	VEGAS-Pulsar		
	Mustang (3mm)		↑	{Search mode, timing mode}		
	Reduction uses specialized scripts					

VEGAS Modes:

16 separate spectrometer channels (8 dual polarization channels) that can be divided between beams and different frequencies as needed and can support up to 8 spectral sub-windows per spectrometer.

Maximum data rate ~160GB/s, but most projects at <1MB/s

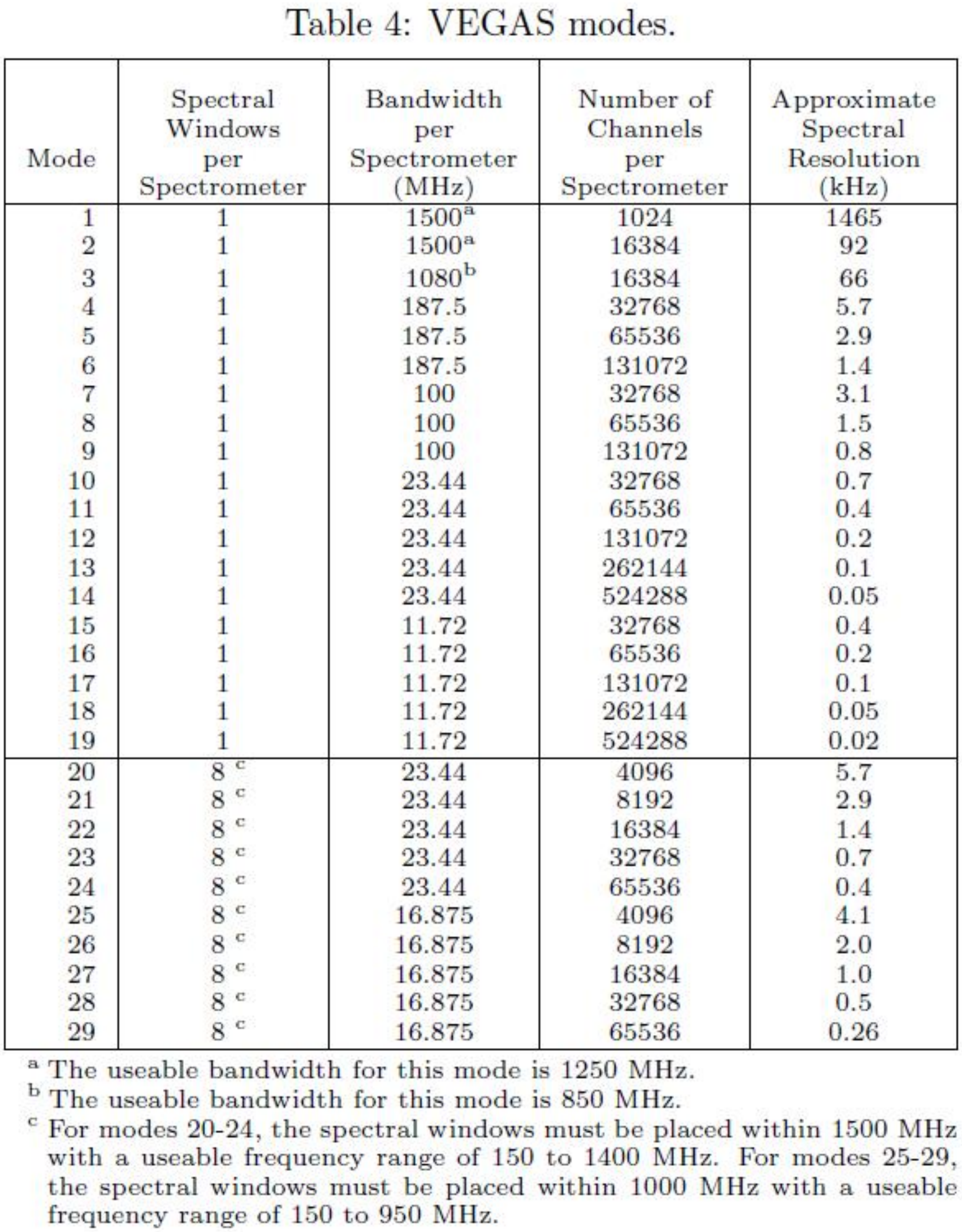


Table 4: VEGAS modes.

Mode	Spectral Windows per Spectrometer	Bandwidth per Spectrometer (MHz)	Number of Channels per Spectrometer	Approximate Spectral Resolution (kHz)
1	1	1500[a]	1024	1465
2	1	1500[a]	16384	92
3	1	1080[b]	16384	66
4	1	187.5	32768	5.7
5	1	187.5	65536	2.9
6	1	187.5	131072	1.4
7	1	100	32768	3.1
8	1	100	65536	1.5
9	1	100	131072	0.8
10	1	23.44	32768	0.7
11	1	23.44	65536	0.4
12	1	23.44	131072	0.2
13	1	23.44	262144	0.1
14	1	23.44	524288	0.05
15	1	11.72	32768	0.4
16	1	11.72	65536	0.2
17	1	11.72	131072	0.1
18	1	11.72	262144	0.05
19	1	11.72	524288	0.02
20	8 [c]	23.44	4096	5.7
21	8 [c]	23.44	8192	2.9
22	8 [c]	23.44	16384	1.4
23	8 [c]	23.44	32768	0.7
24	8 [c]	23.44	65536	0.4
25	8 [c]	16.875	4096	4.1
26	8 [c]	16.875	8192	2.0
27	8 [c]	16.875	16384	1.0
28	8 [c]	16.875	32768	0.5
29	8 [c]	16.875	65536	0.26

[a] The useable bandwidth for this mode is 1250 MHz.

[b] The useable bandwidth for this mode is 850 MHz.

[c] For modes 20-24, the spectral windows must be placed within 1500 MHz with a useable frequency range of 150 to 1400 MHz. For modes 25-29, the spectral windows must be placed within 1000 MHz with a useable frequency range of 150 to 950 MHz.

Picking your observing mode

The telescope measures:

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)

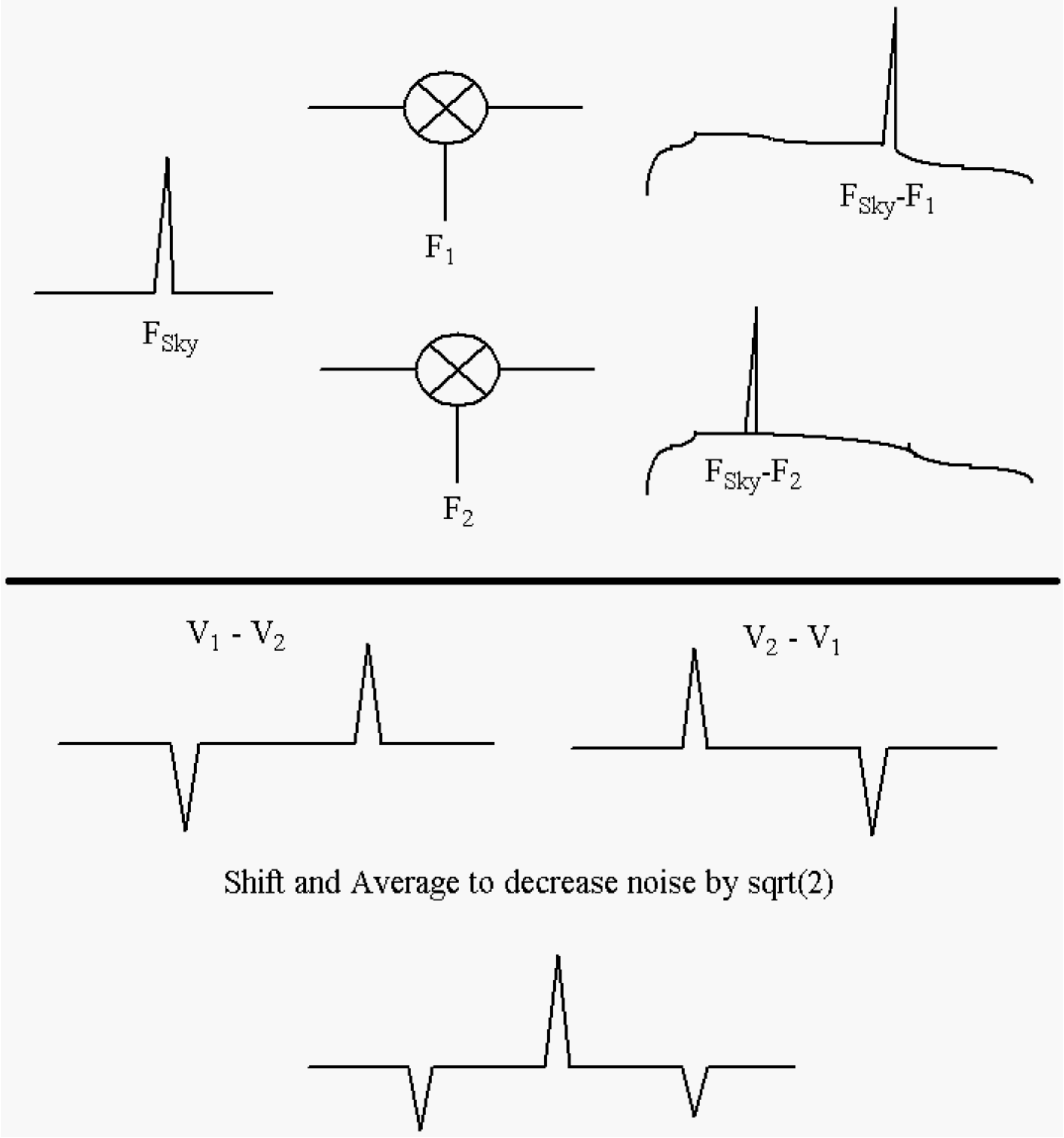
Types of reference observations

- Frequency Switching
  - In or Out-of-band

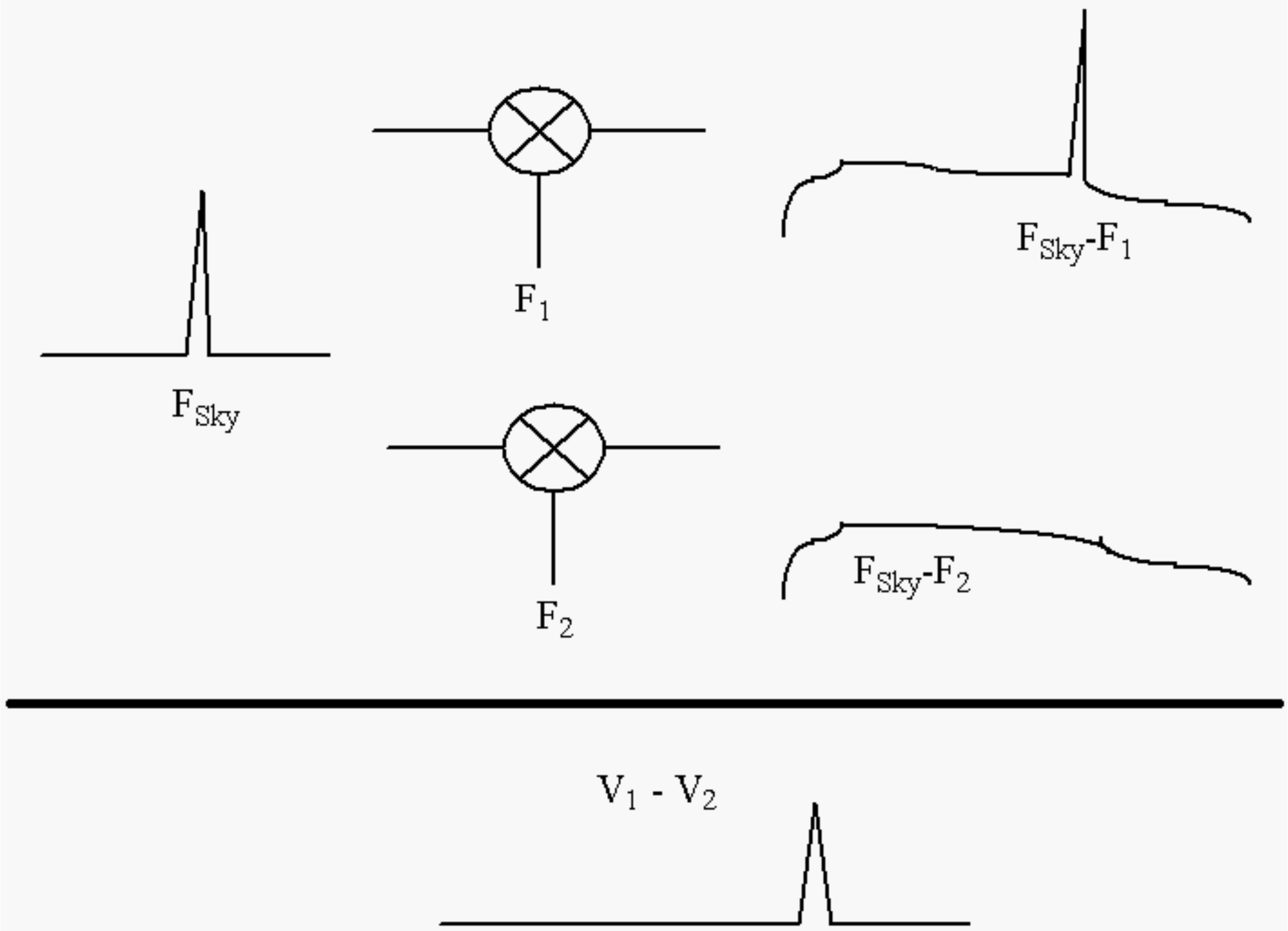
- Position Switching
  - Reference-Off
  - Mapping-Off

- Dual-Beam Position Switching
  - **Nod** -- Move telescope
  - **SubBeamNod** -- Move Subreflector

In-Band Frequency Switching



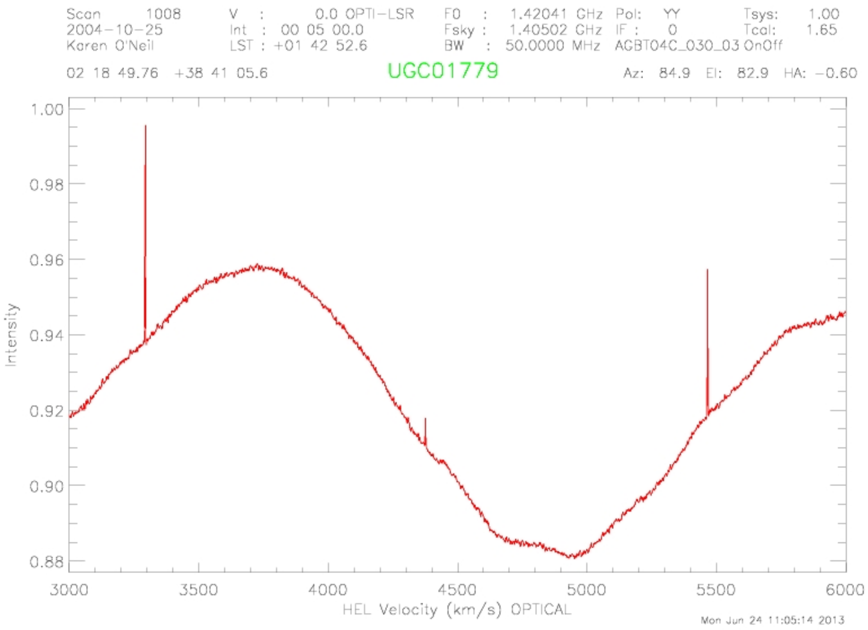
Out-Of-Band Frequency Switching



Position Switching

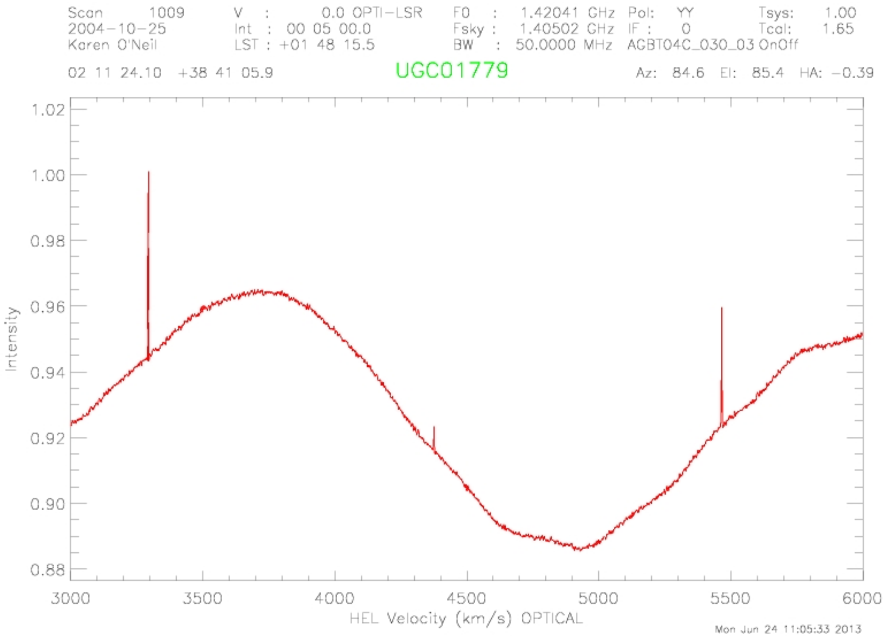
ON source

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



OFF source

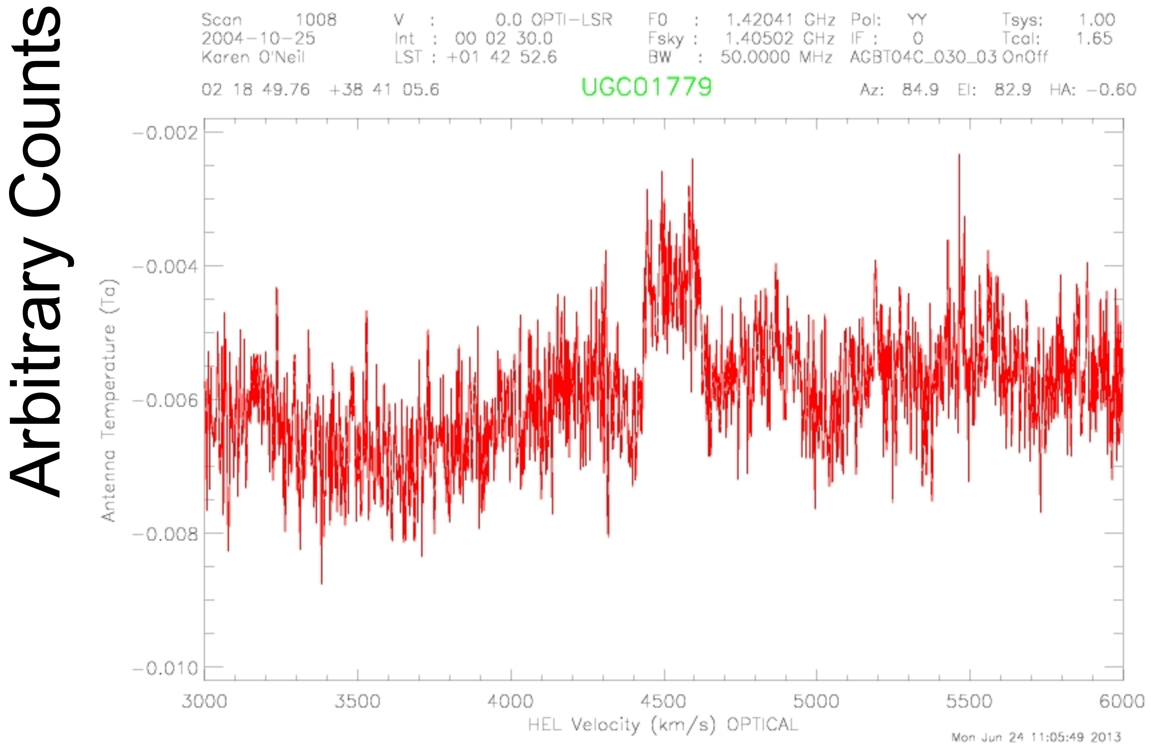
$T_{everything\ else}$



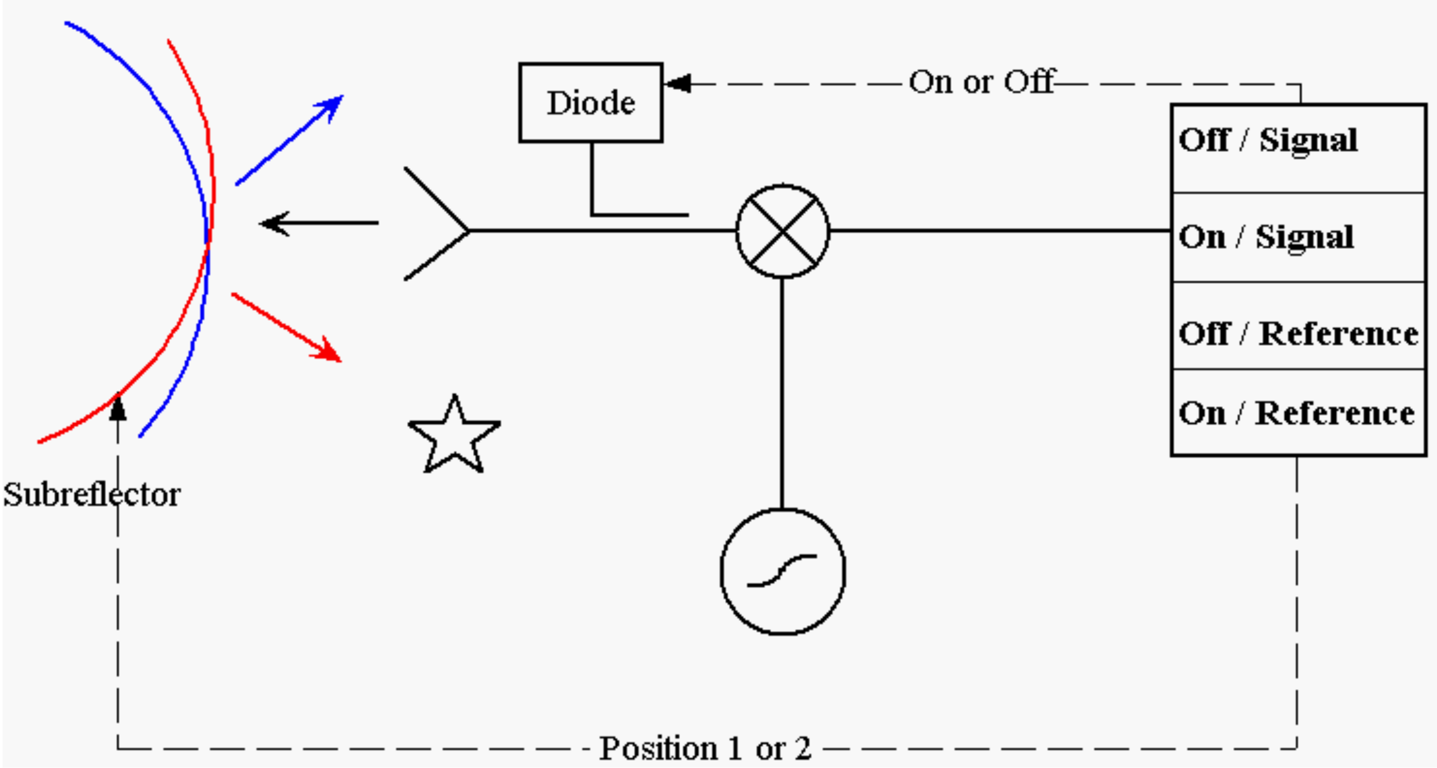
Position Switching: ON-OFF on Sky

ON - OFF

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

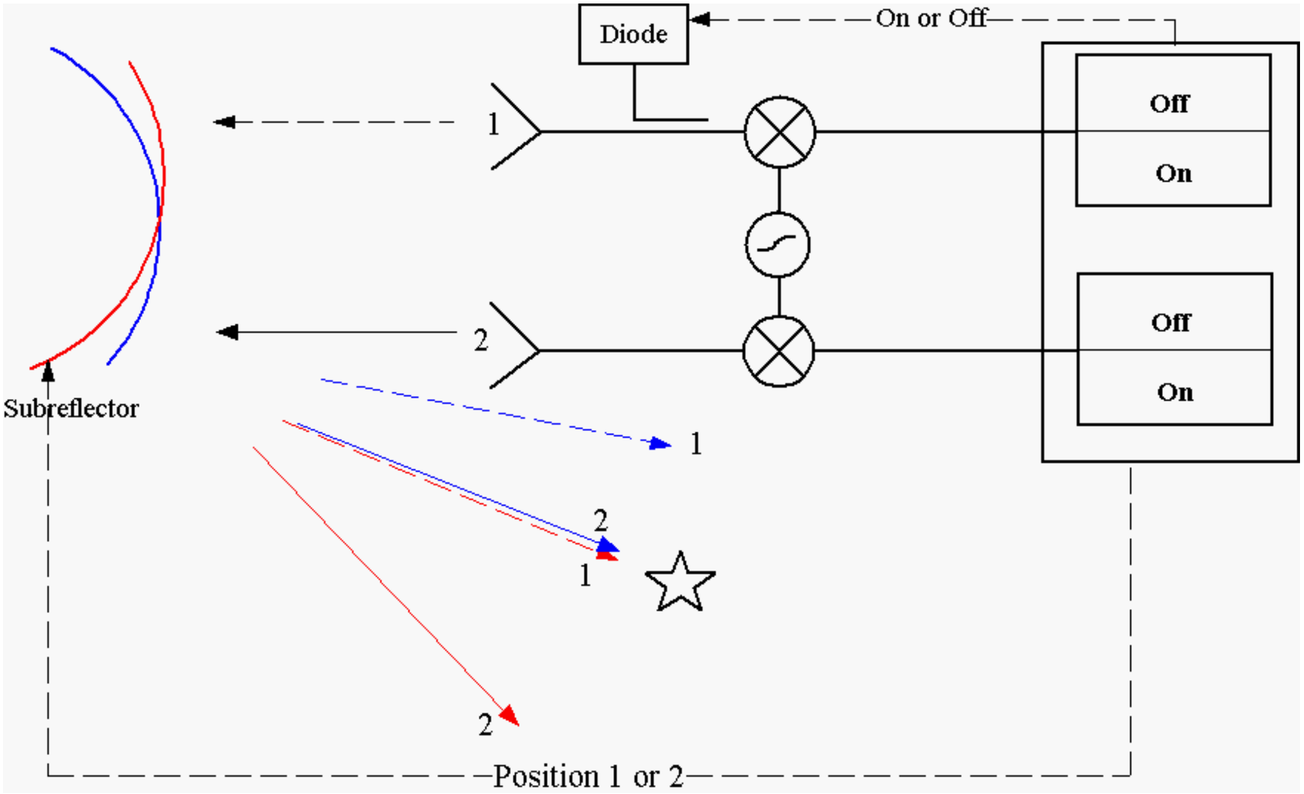


Beam Switching – Subreflector or tertiary mirror



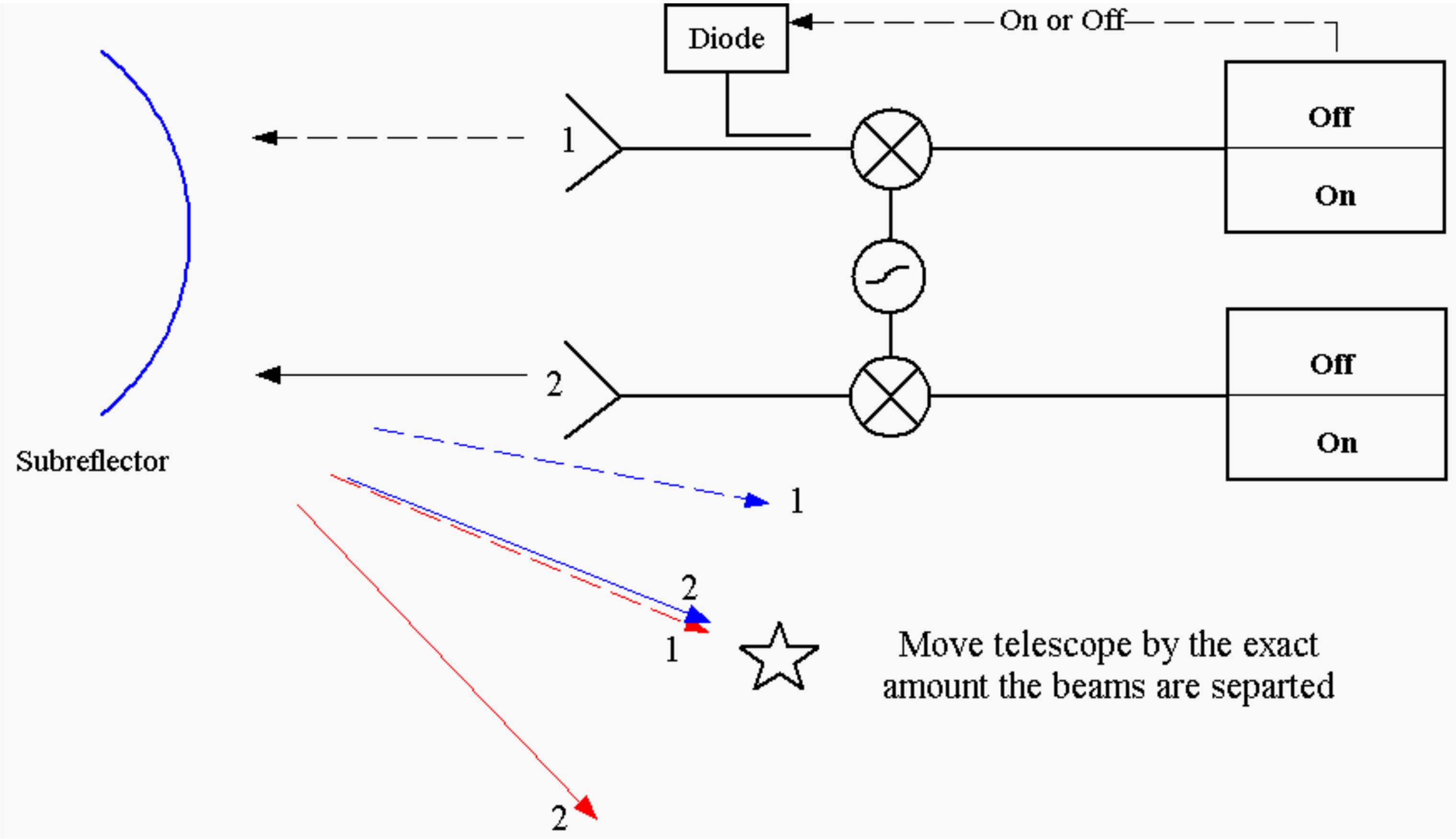
- Removes any ‘fast’ gain/bandpass changes
- Low overhead. ½ time spent off source

Subreflector Nodding with multi-beam receivers (SubBeamNod)



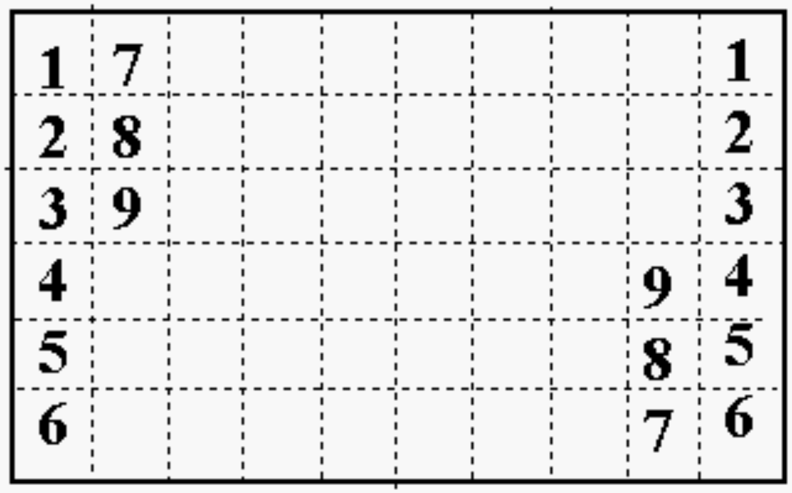
- Removes any ‘fast’ gain/bandpass changes
- Low overhead. ~All the time is spent on source

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



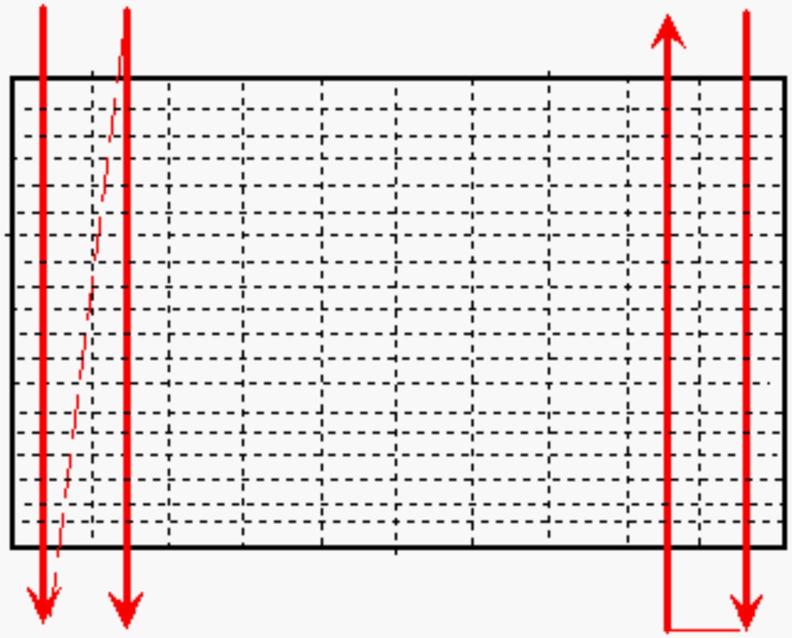
- Removes any ‘fast’ gain/bandpass changes
- Overhead from moving the telescope. All the time is spent on source

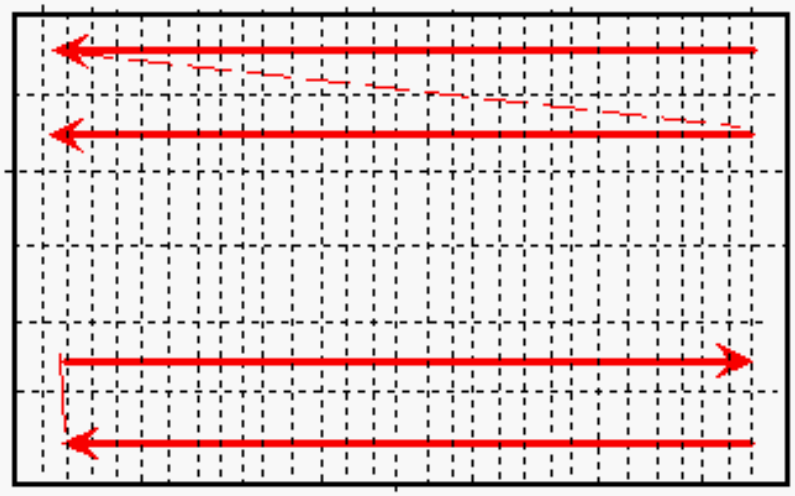
Mapping Techniques



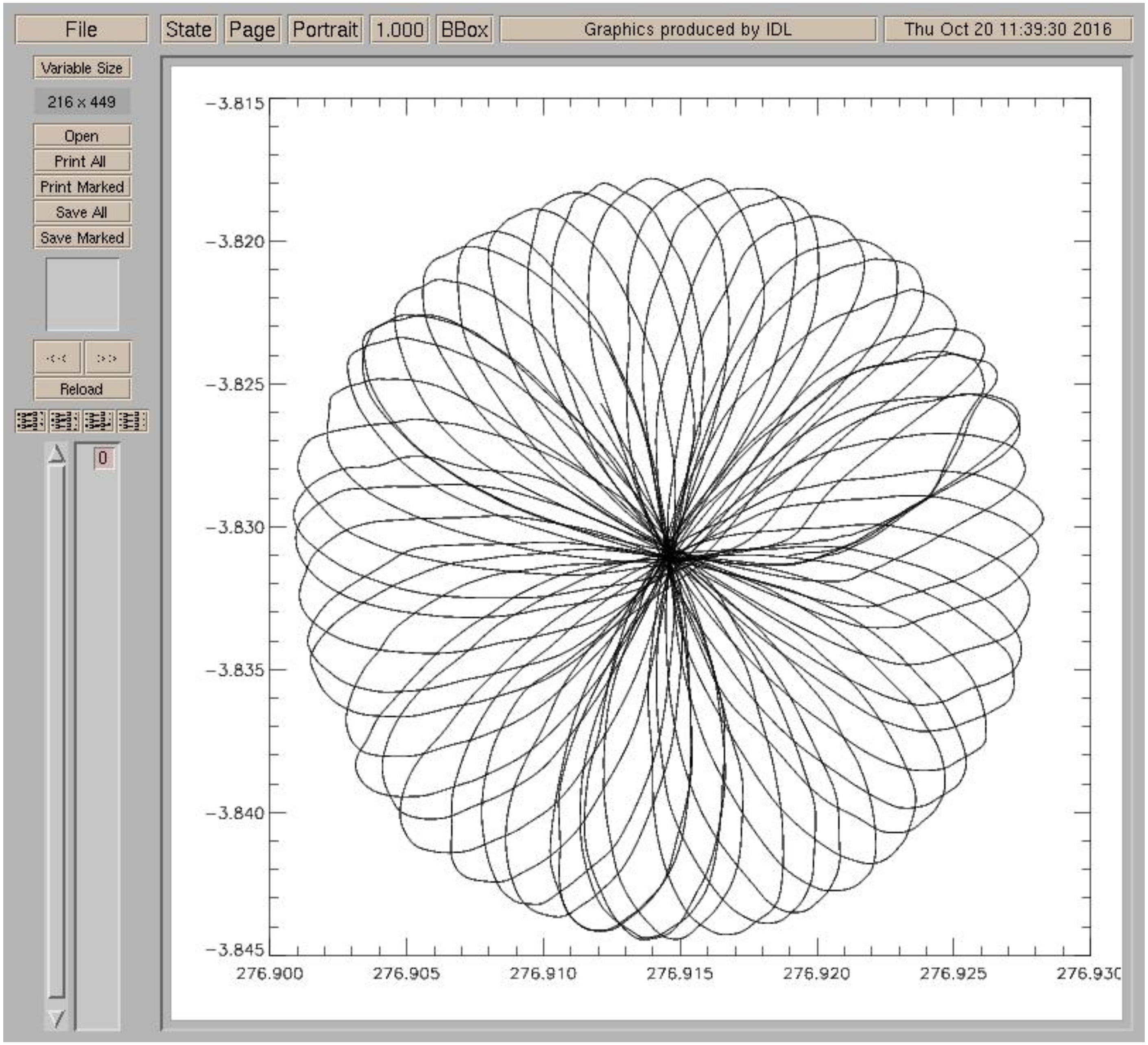
- **Point map**
  - •Sit, Move, Sit, Move, etc.
- **On-The-Fly Mapping**
  - •Slew a column or row while collecting data
  - •Move to next column row
  - •Basket weave
  - •Should oversample ~3x Nyquist along direction of slew

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





Example Daisy Scan Map



Frequency vs Position Switching

- Narrow line in non-crowded spectrum ➔ Frequency Switching (FS)
- Narrow line in crowded spectral region or significant RFI ➔ Position Switching (PS)
- Broad line ➔ PS

➢ Narrow line < 10 km/s

➢ Broad line > 100 km/s

Observing Mode – Small Source

If source size < beam, Line Obs, and PS:

- Nod {two beams} – if not limited by baselines
- SubBeamNod {two beams} – if baseline limited
- OnOff {one beam}
- Track (with and w/o offset)

If source size < beam, Line Obs and FS:

- Track

If source size < beam, Continuum Obs:

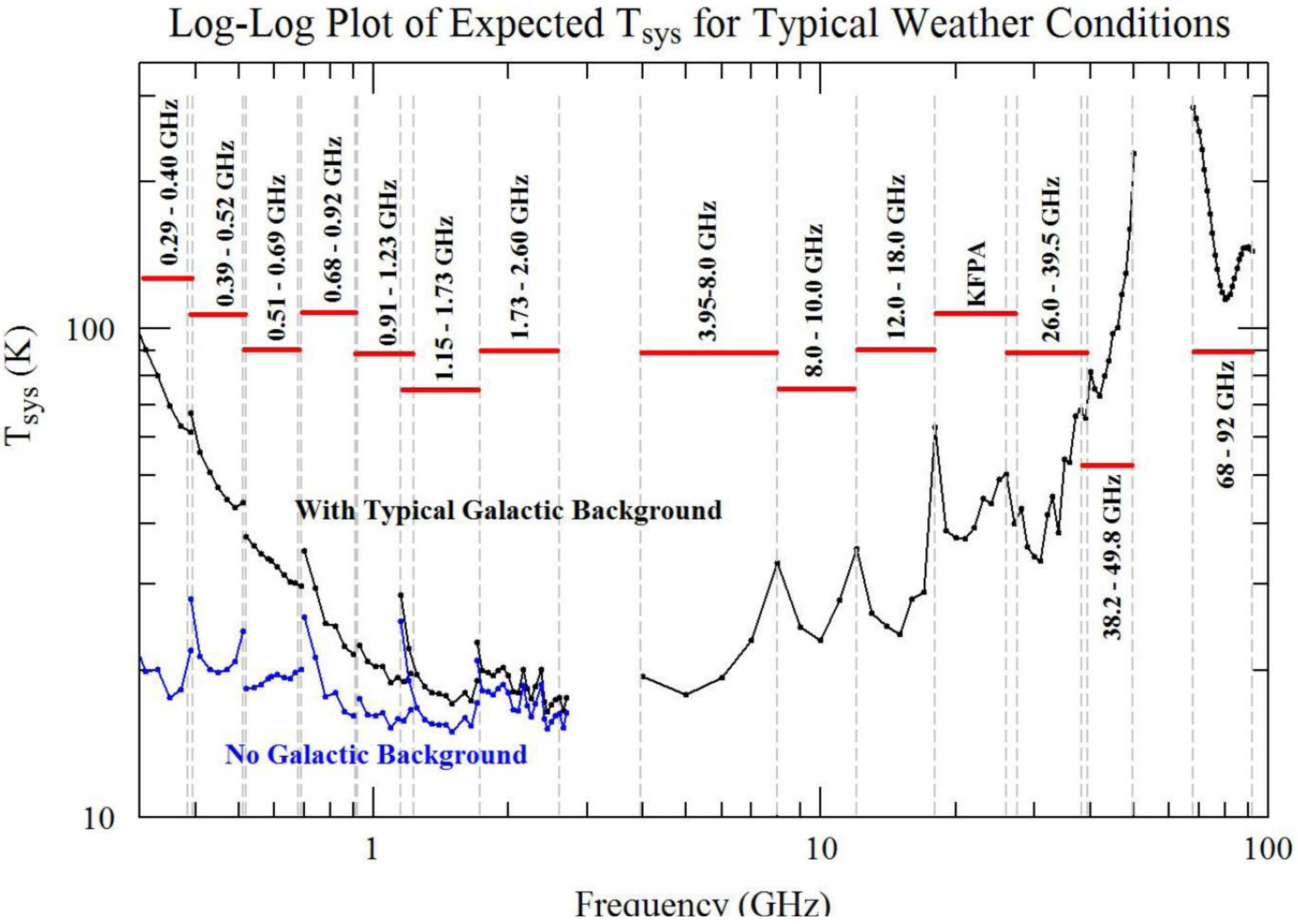
- Daisy map (efficient way to deal with 1/f noise)

Observing Mode – Large Source

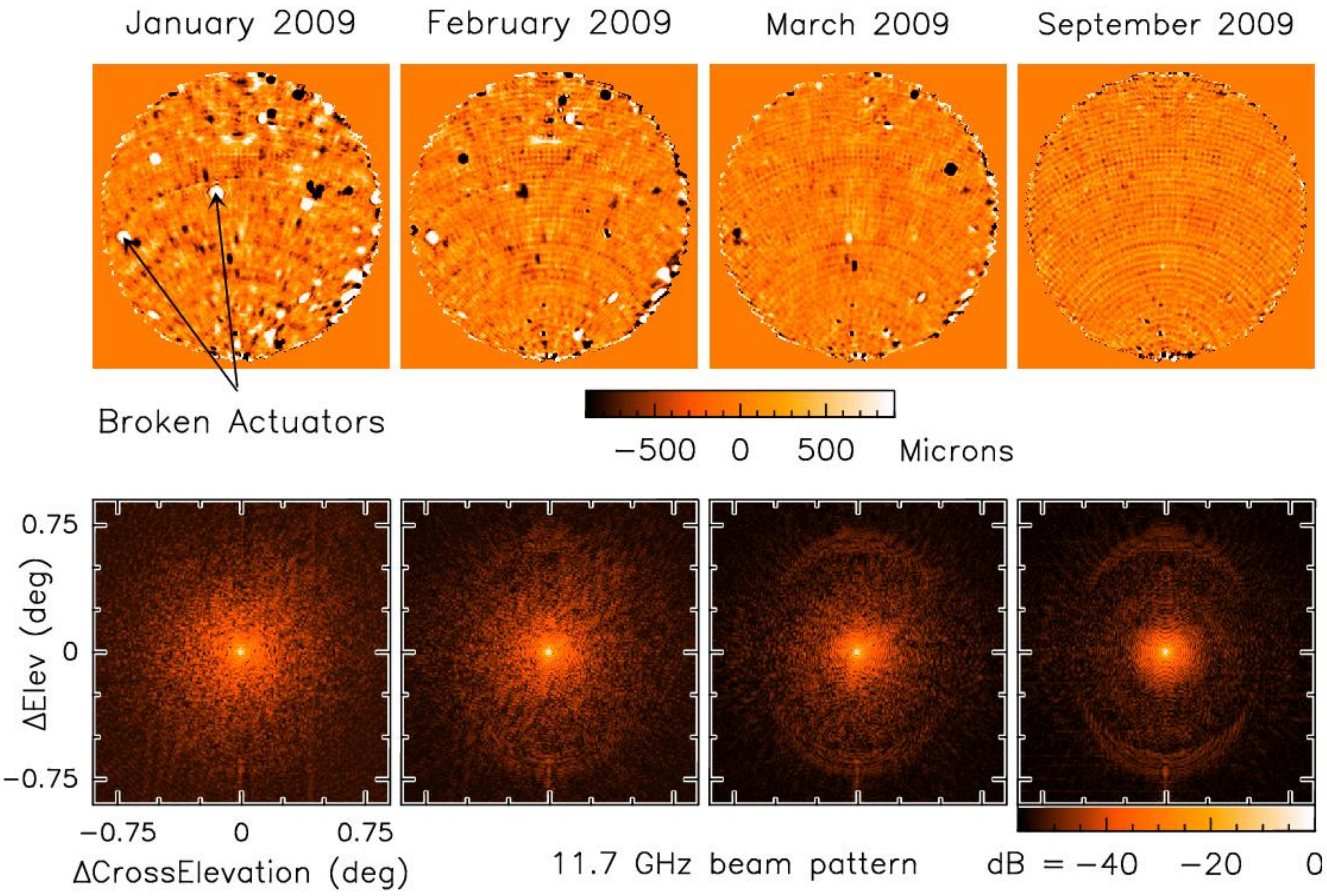
- ➢ Map > FOV of instrument
- RaLongMap and/or DecLatMap
- ➢ Map <~ FOV of instrument
- RaLong/DecLat mapping
- Daisy
- Box scans
- PointMap (Grid) if needing a deep spectrum

Performance of the GBT

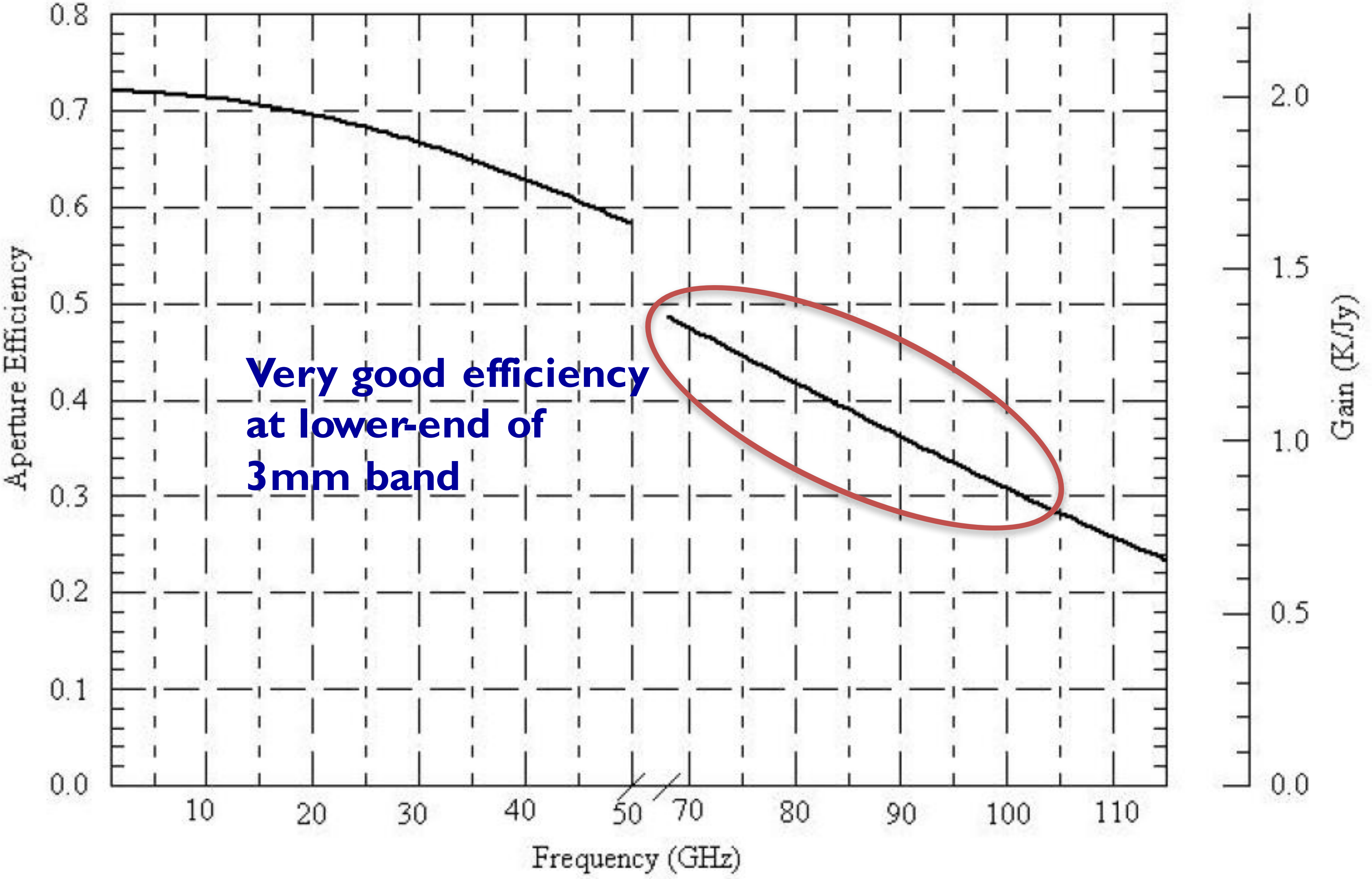
Noise Levels (Tsys) for Typical Weather



GBT Surface Improved in 2009



GBT Aperture Efficiency and Gain (K/Jv)



Very good efficiency at lower-end of 3mm band

GBT Pointing and Surface Performance

- ~5-10 arcscec blind pointing
- ~2 arcsec offset pointing
- ~1 arcsec tracking accuracy
- Rms (surface) ~ 0.35mm – no corrections during day
- Rms (surface) ~ 0.3mm – no corrections during night
- Rms(surface) ~0.23mm with corrections at night
- Long-term Goal: Rms(surface)~0.20mm

Observing: Antenna Optimization

- Should point+focus every 30min-1hr depending on frequency and time of day (point+focus takes ~5min)
- AutoOOF (which takes ~30min) is used to correct the surface for thermal effects for Q-band and W-band at night.
- Daytime surface changes <1hr time scales and the AutoOOF solutions can cause more harm than good after ~1hr from the AutoOOF (so it is typically not useful to use the "thermal" corrections during the day).

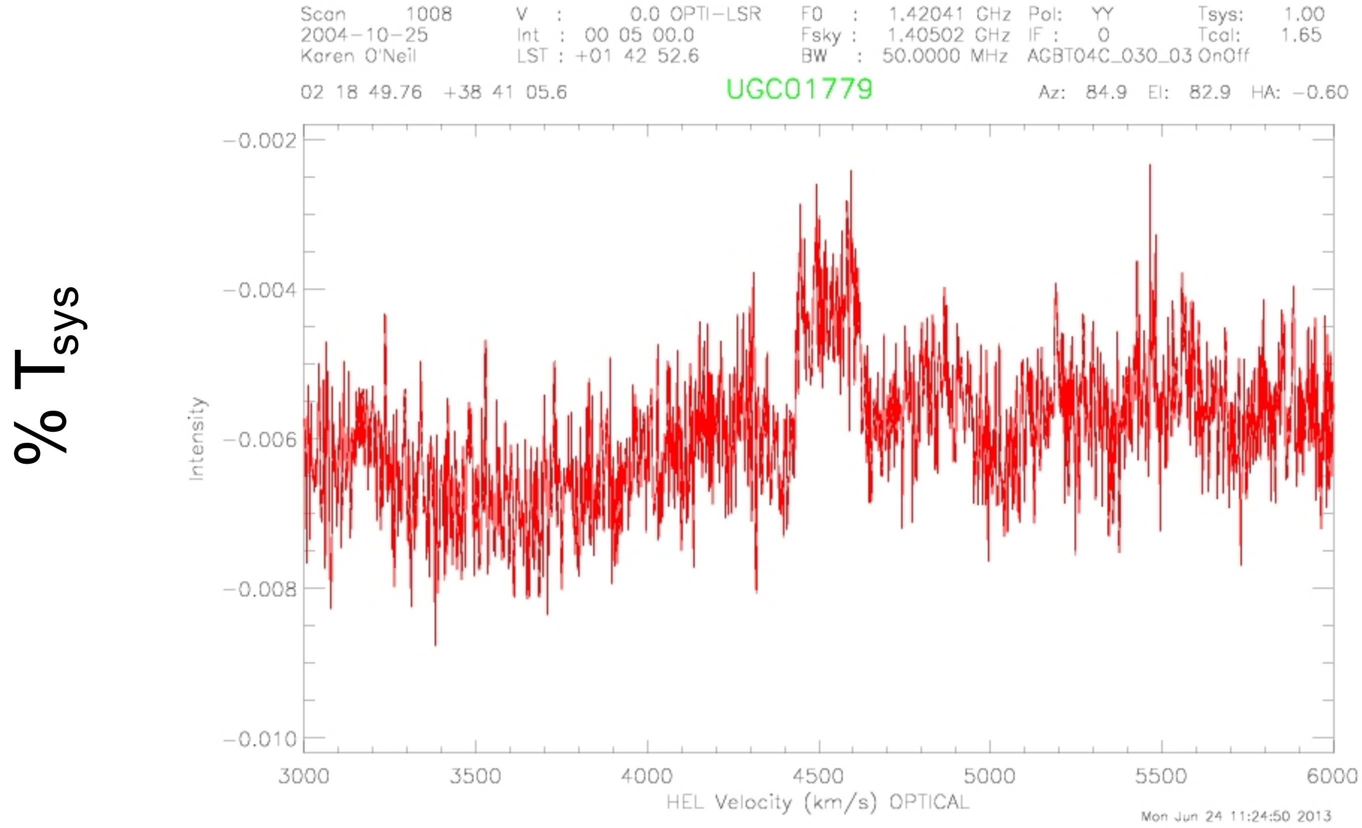
Calibration

Calibration of Data

(ON - OFF)/OFF

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

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



GBT Definition of Ta

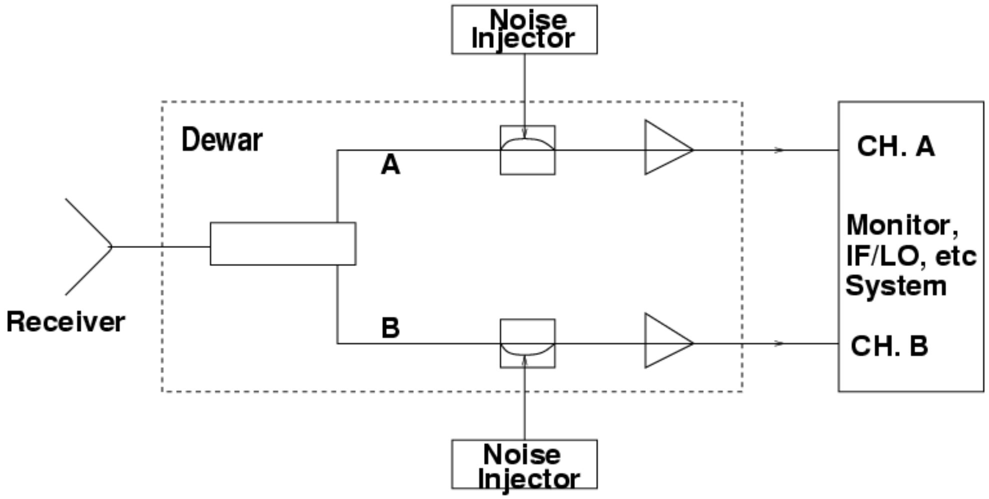
$$T_a = \frac{(\mathrm{ON} - \mathrm{OFF})}{\mathrm{OFF}} \, T_{system}$$

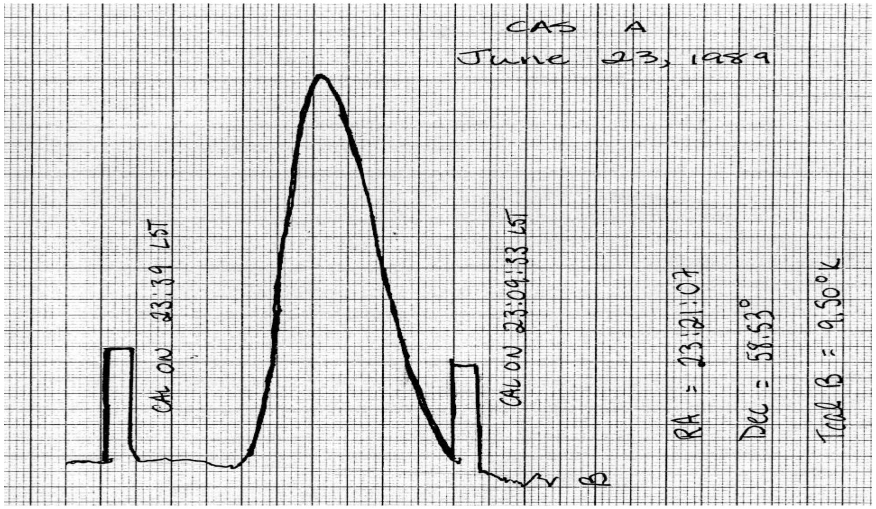
Blank Sky or other

From diodes, Hot/Cold loads, etc.

Determining T_{sys}

Noise Diodes





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

Determining T_{sys}

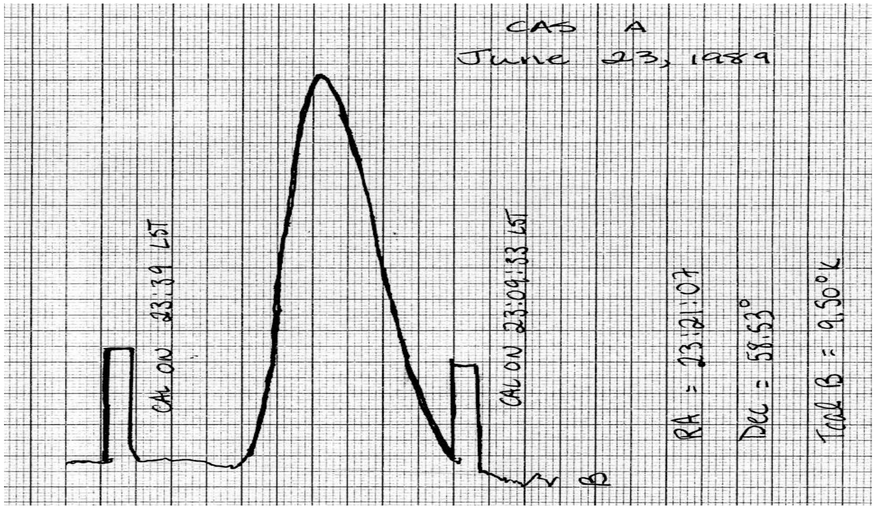
Noise Diodes

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

GBT: Flicker diode on/off

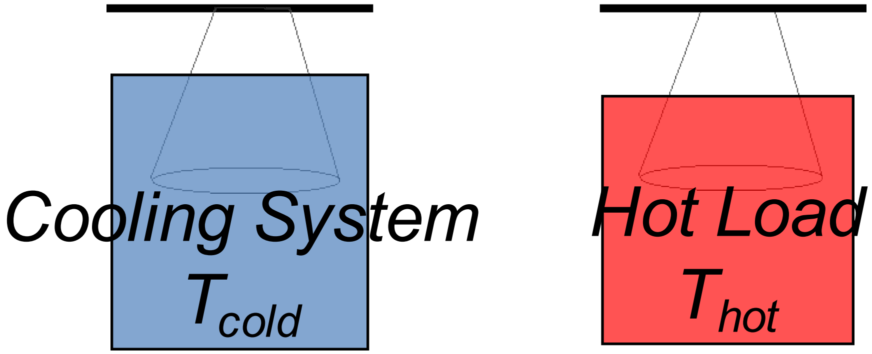
$$T_{sys} = T_{cal} * OFF/(ON - OFF) + T_{cal}/2$$

Typically choose low Tcal value to minimize Tsys and high Tcal value for very bright sources (for Rx that have two options)



Determining T_{sys}

Hot & Cold Loads

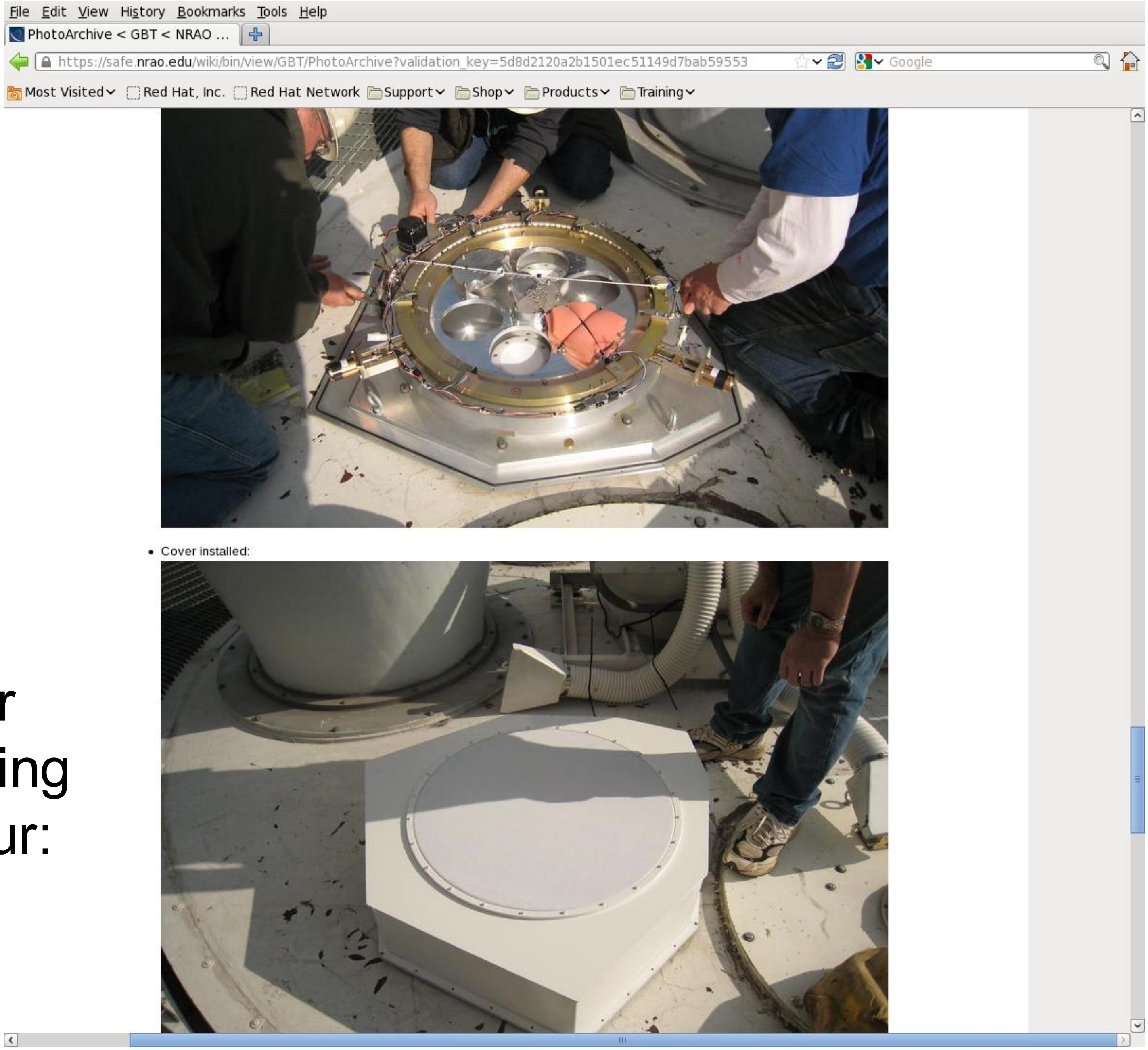


Gain: $g = (T_{hot} - T_{cold})/(V_{hot} - V_{cold})$ [K/Volts]

$T_{sys} = g\, V_{off}$

Example GBT 4mm Rx

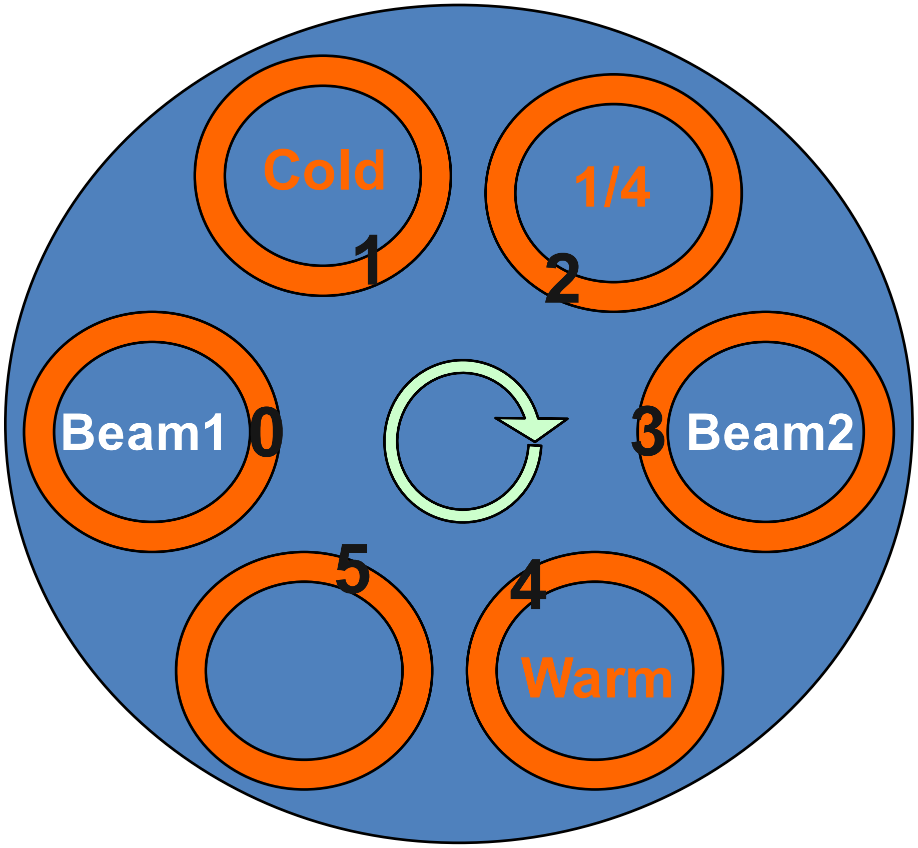
Installation of 4mm calibration wheel and external cover



- Cover installed:

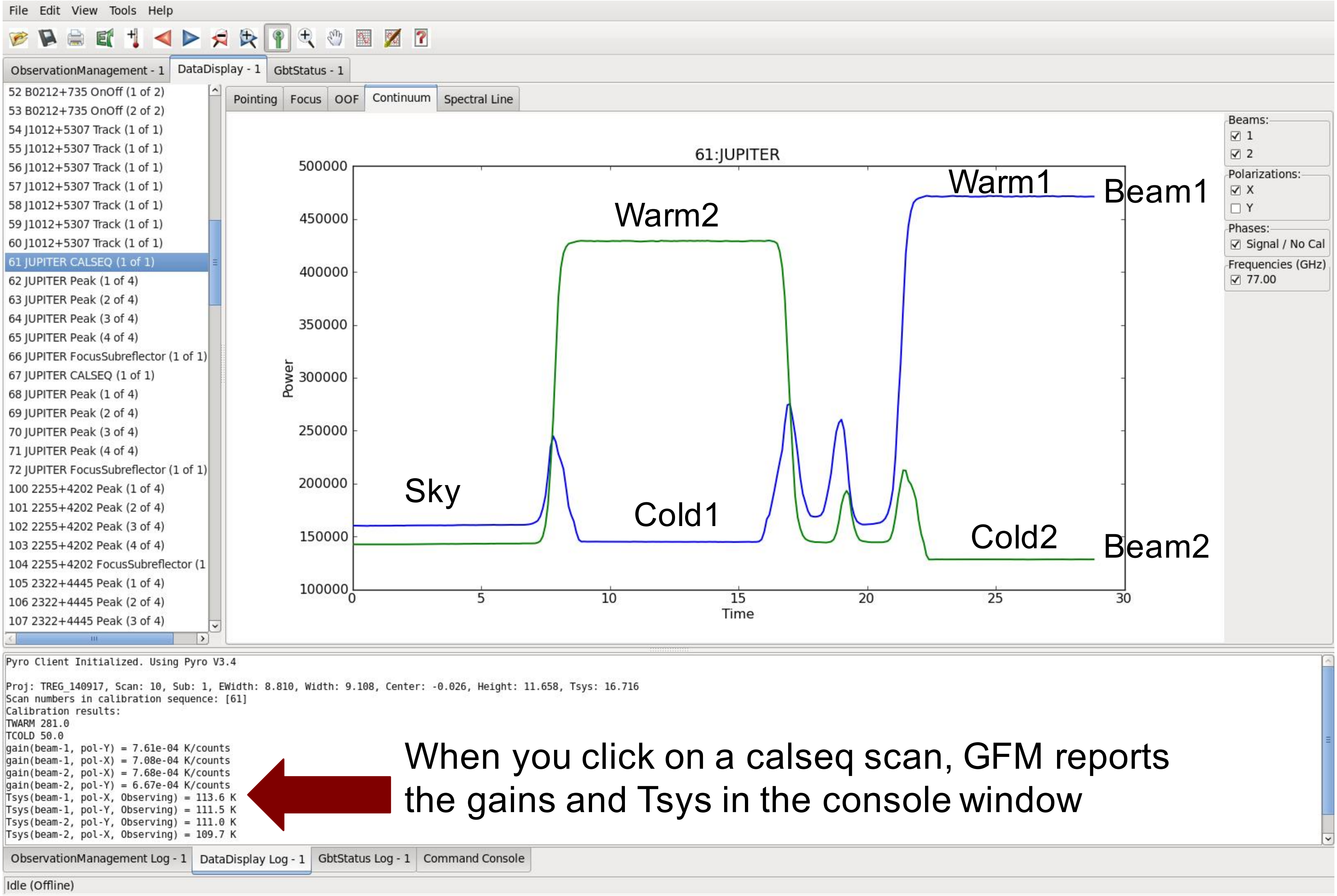
Look for this during GBT tour:

4mm Calibration Wheel



	Wheel Position (defined wrt Beam1)	Beam 1	Beam 2
0	Observing	Sky	Sky
1	Cold1	Cold	Warm
2	Position2	1/4wave circ	Sky
3	Position3	Sky	Sky
4	Cold2	Warm	Cold
5	Position5	Sky	1/4wave Circ

CalSeq-auto Scan (GFM display)



52 B0212+735 OnOff (1 of 2)
53 B0212+735 OnOff (2 of 2)
54 J1012+5307 Track (1 of 1)
55 J1012+5307 Track (1 of 1)
56 J1012+5307 Track (1 of 1)
57 J1012+5307 Track (1 of 1)
58 J1012+5307 Track (1 of 1)
59 J1012+5307 Track (1 of 1)
60 J1012+5307 Track (1 of 1)
61 JUPITER CALSEQ (1 of 1)
62 JUPITER Peak (1 of 4)
63 JUPITER Peak (2 of 4)
64 JUPITER Peak (3 of 4)
65 JUPITER Peak (4 of 4)
66 JUPITER FocusSubreflector (1 of 1)
67 JUPITER CALSEQ (1 of 1)
68 JUPITER Peak (1 of 4)
69 JUPITER Peak (2 of 4)
70 JUPITER Peak (3 of 4)
71 JUPITER Peak (4 of 4)
72 JUPITER FocusSubreflector (1 of 1)
100 2255+4202 Peak (1 of 4)
101 2255+4202 Peak (2 of 4)
102 2255+4202 Peak (3 of 4)
103 2255+4202 Peak (4 of 4)
104 2255+4202 FocusSubreflector (1
105 2322+4445 Peak (1 of 4)
106 2322+4445 Peak (2 of 4)
107 2322+4445 Peak (3 of 4)

```
Pyro Client Initialized. Using Pyro V3.4

Proj: TREG_140917, Scan: 10, Sub: 1, EWidth: 8.810, Width: 9.108, Center: -0.026, Height: 11.658, Tsys: 16.716
Scan numbers in calibration sequence: [61]
Calibration results:
TWARM 281.0
TCOLD 50.0
gain(beam-1, pol-Y) = 7.61e-04 K/counts
gain(beam-1, pol-X) = 7.08e-04 K/counts
gain(beam-2, pol-X) = 7.68e-04 K/counts
gain(beam-2, pol-Y) = 6.67e-04 K/counts
Tsys(beam-1, pol-X, Observing) = 113.6 K
Tsys(beam-1, pol-Y, Observing) = 111.5 K
Tsys(beam-2, pol-Y, Observing) = 111.0 K
Tsys(beam-2, pol-X, Observing) = 109.7 K
```

When you click on a calseq scan, GFM reports the gains and Tsys in the console window

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.

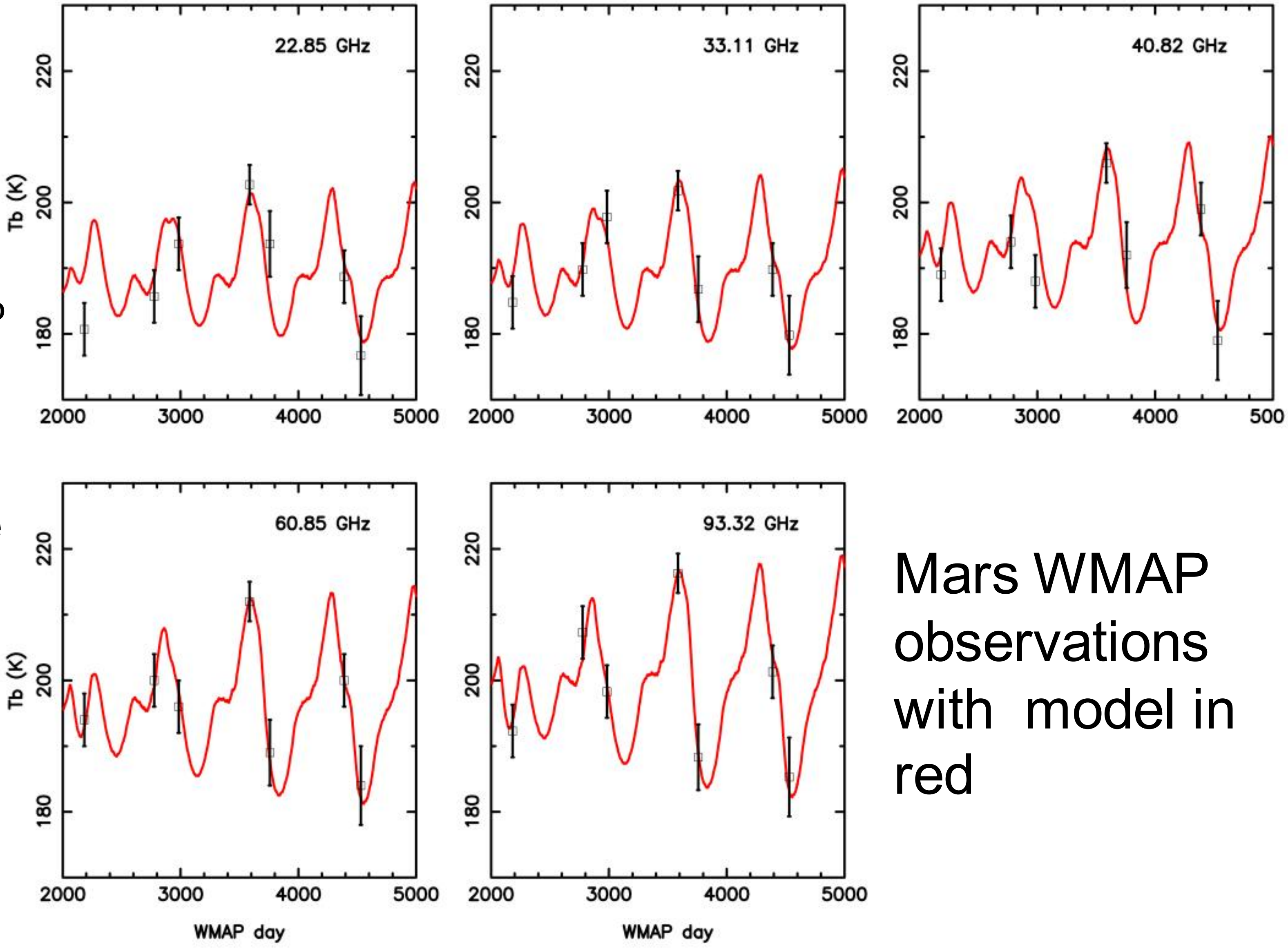
Absolute calibration typically known to 5-15%

Absolute Calibration tied to Mars via WMAP

VLA calibration (1-50 GHz):

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

Perley & Butler 2013

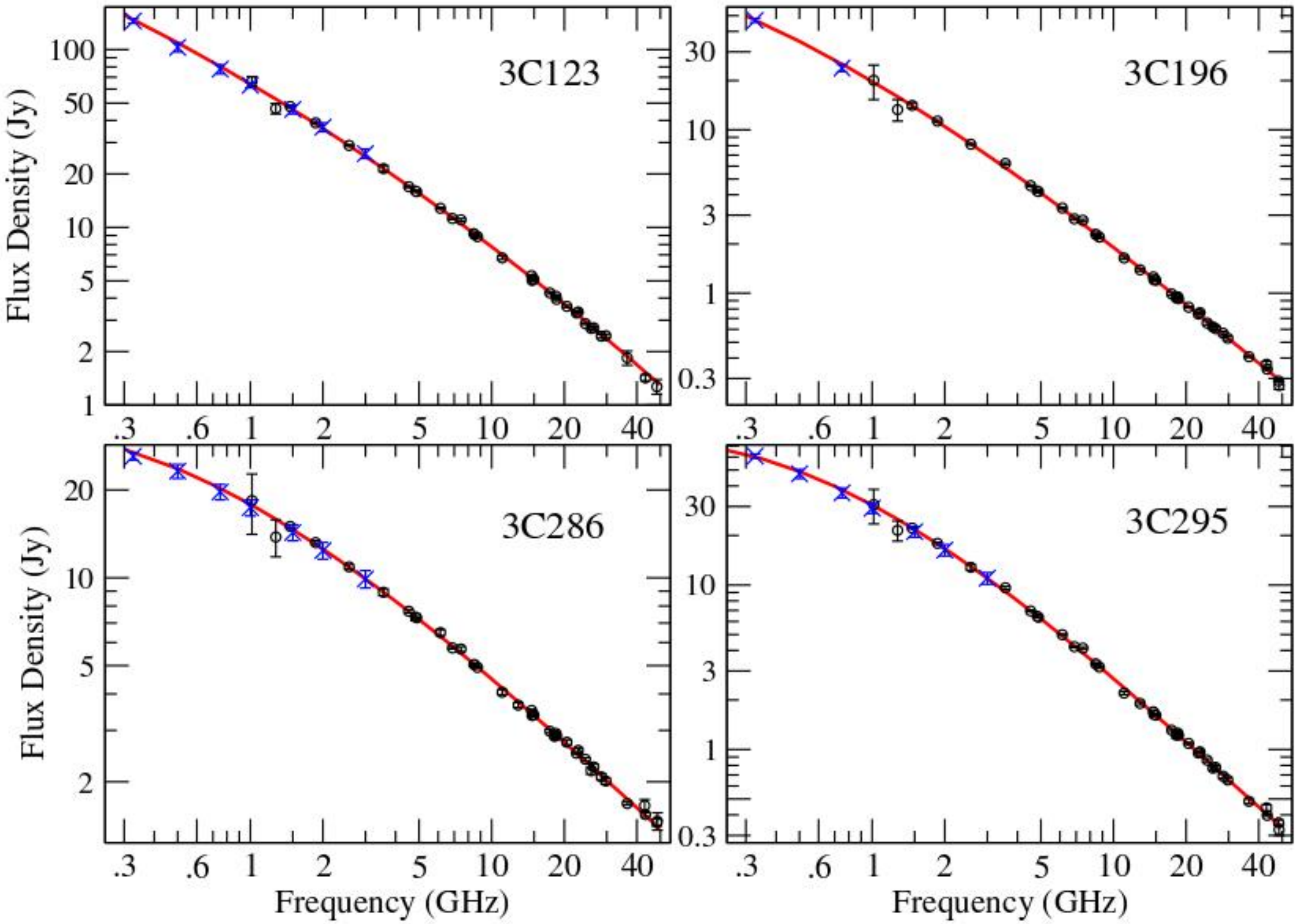


Mars WMAP observations with model in red

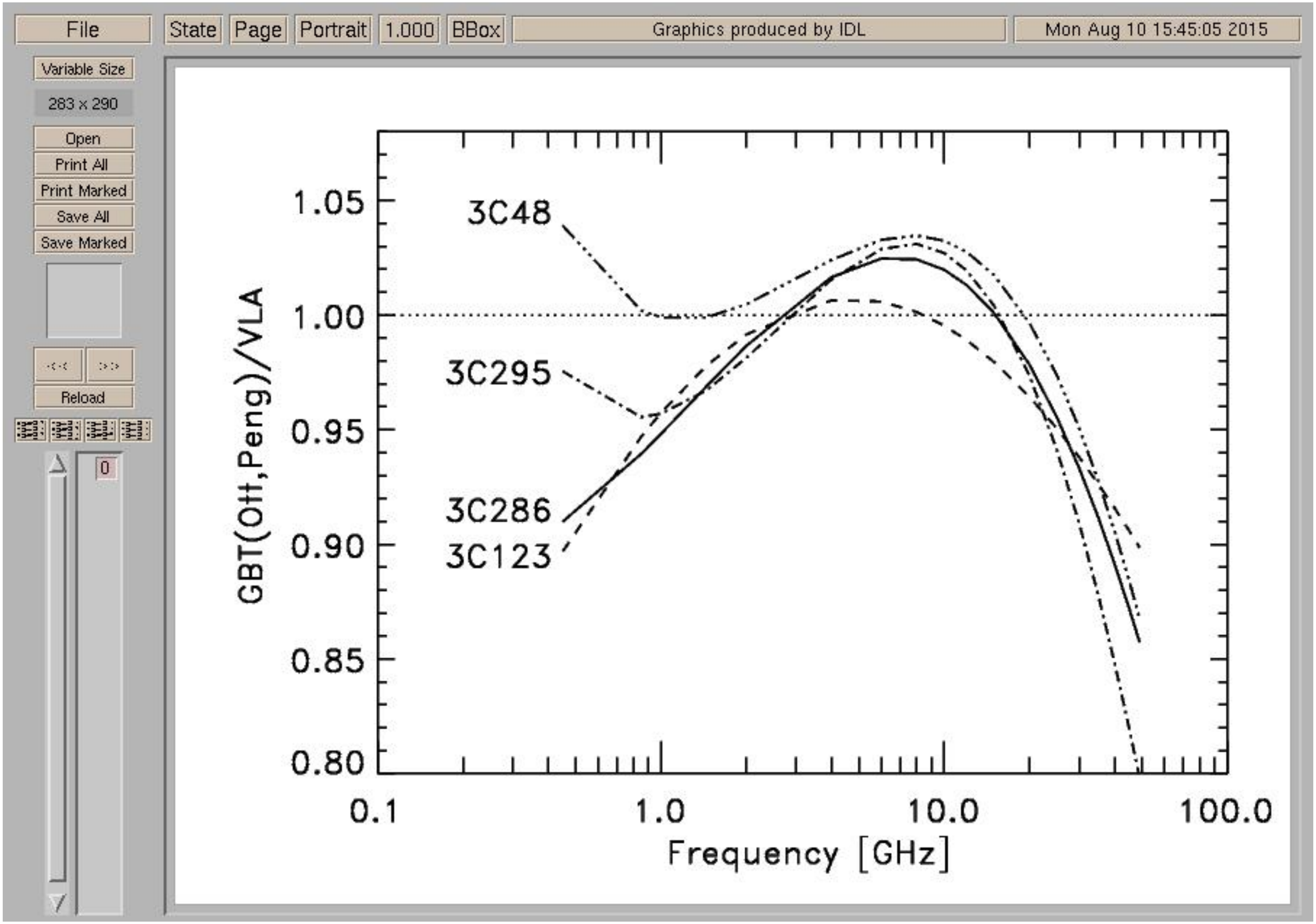
VLA Stable Calibrators

GBT Calibration "Plan":

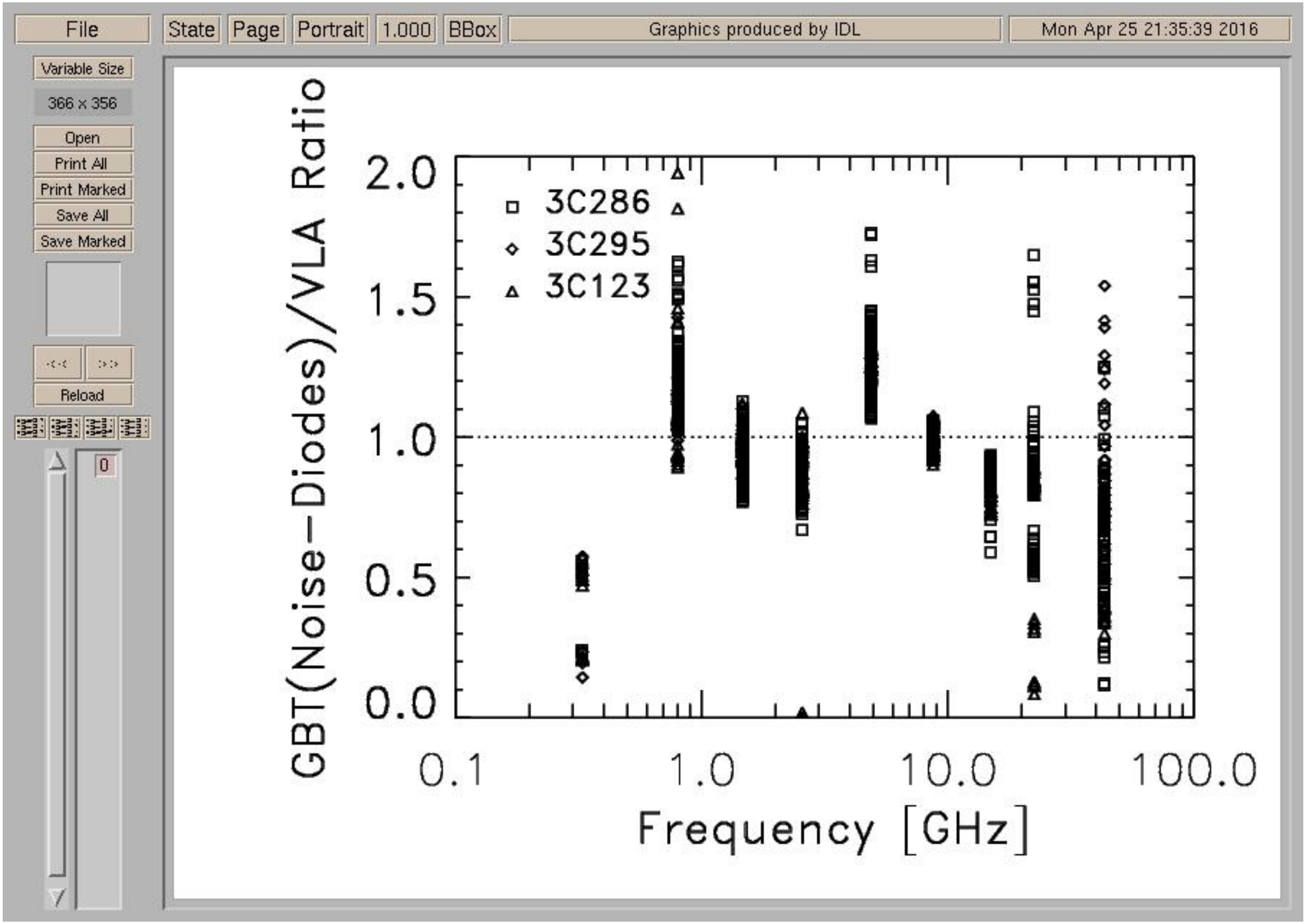
Eventually tie GBT to VLA calibration scale for 1-50 GHz, and we will use ALMA for 3mm absolute calibration



Comparison of Calibration Scales (Ott 1994 vs VLA 2013)



GBT Calibration Measurements 2015-2016



Do not blindly accept 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.

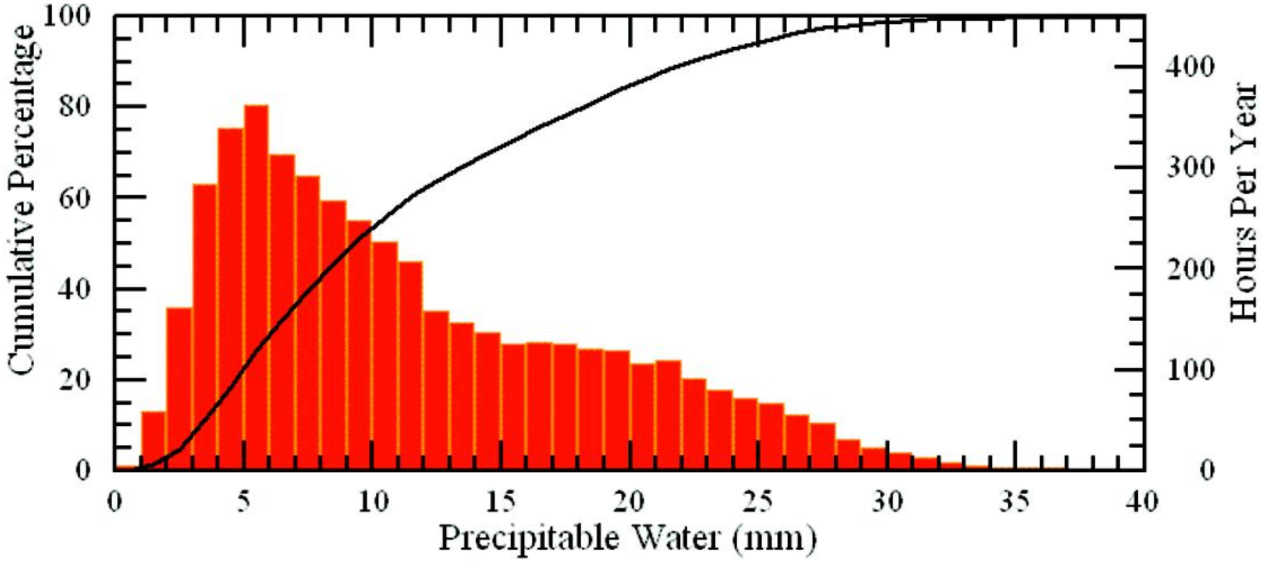
Estimate of Error in GBT Calibration

Band	GBT/VLA Calibration
340	0.50
800	1.17
L	0.92
S	0.88
C	1.32
X	1.00
Ku	0.87
KFPA	0.90
Ka	1.01
Q	0.83

Based on 15A486 calibration program and ongoing observing programs over 2015-2016. Results based on averaging both polarizations.

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



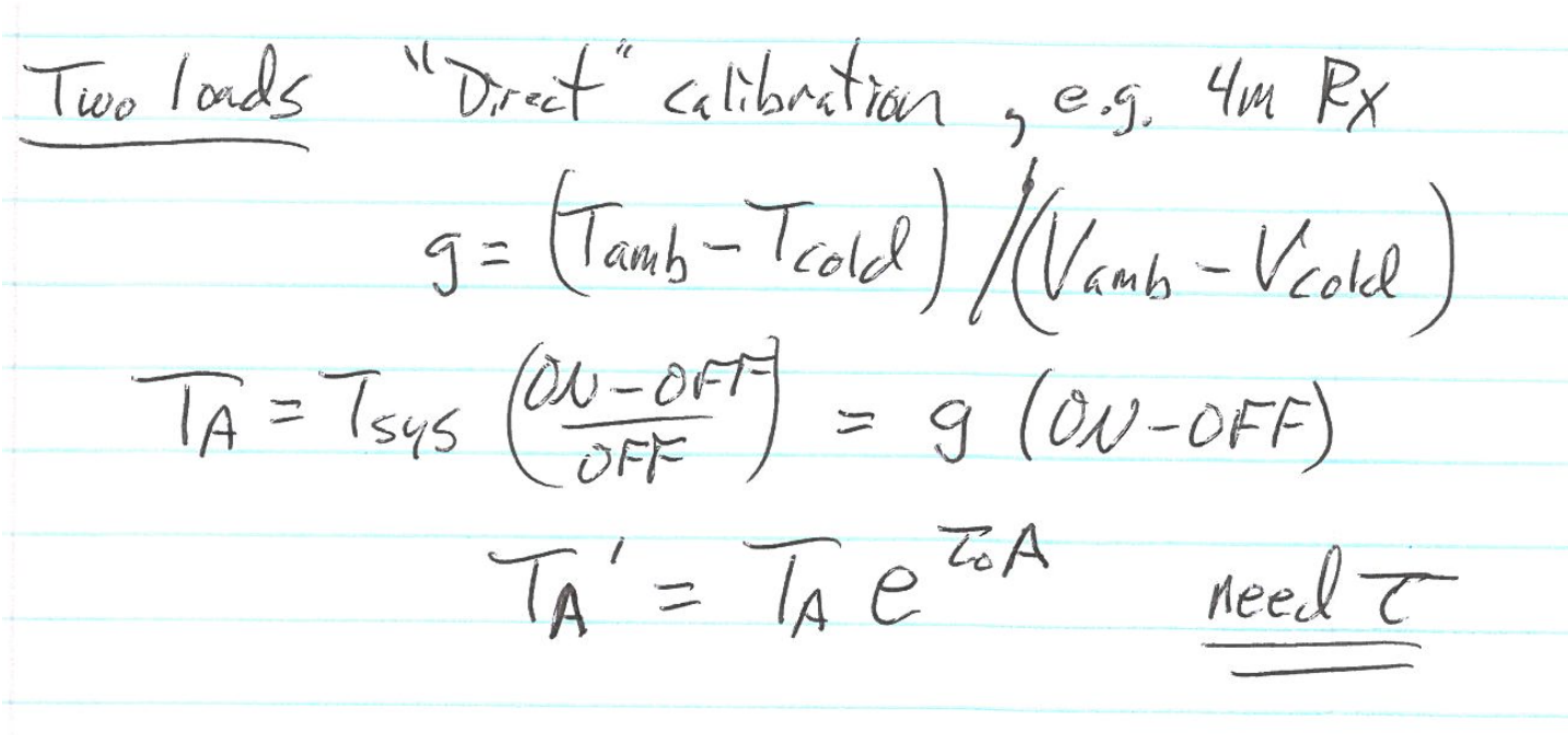
GBT site has many days with low water vapor per year (<10mm H_2O are ok for 3mm, 50% of time)

Background Information on Calibration

Temperature Scales

- $Ta = Tsys\ (ON\text{-}OFF)/OFF$ (uncorrected antenna temperature)
- $Ta' = Ta\ \exp(\tau_o A)$
- $T_{mb} = Ta'/\eta_{mb}$ (η_{mb}~1.3 η_a)
- $Ta^* = Ta'/\eta_l$ (mm-telescopes typically return Ta*)
- $Tr^* = Ta'/(\eta_l\ \eta_{fss})$
- $Ta'/S\nu = 2.84\ \eta_a$ (for the GBT)

Calibration with Two Loads



Two loads "Direct" calibration, e.g. 4m Rx

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

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

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

need τ

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}

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

; yuk, but:

Algebra =>

$$\boxed{T_{cal} = \underset{\underset{\text{model}}{\uparrow}}{T_{ATM}} + \left(T_{amb} - T_{ATM}\right) e^{\tau_o A}}$$

what Argus will use.

eq. A9 of KU91 re-written

assumes $T_{spill} \simeq T_{amb}$ 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

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

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

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

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

<u>compute using T_{mb}</u>

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

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

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"

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
- Users should correct for atmosphere at all frequencies, but it is crucial at high freq.
- Users should observe a known calibrator once per semester per target frequency to calibrate the noise diodes and instrumental effects empirically.
- Absolute calibration should be done in good weather.