Observing Techniques and Calibration

David Frayer (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 strategies depend on receiver and science needs
### Table 1: GBT Receivers

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

<table>
<thead>
<tr>
<th>Backend</th>
<th>Observing Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Versatile Green Bank Astronomical Spectrometer (VEGAS)</td>
<td>Continuum, pulsar, spectral line</td>
</tr>
<tr>
<td>Digital Continuum Receiver (DCR)</td>
<td>Continuum</td>
</tr>
<tr>
<td>Green Bank Ultimate Pulsar Processing Instrument (GUPPI)</td>
<td>Pulsar</td>
</tr>
<tr>
<td>Mark V Very Long Baseline Array Disk Recorder</td>
<td>Very Long Baseline Interferometry</td>
</tr>
<tr>
<td>Caltech Continuum Backend (CCB) (Ka-band)</td>
<td>Continuum</td>
</tr>
<tr>
<td>Zpectrometer (Ka-band)</td>
<td>Private PI instrument</td>
</tr>
<tr>
<td>Radar</td>
<td>Private PI instrument</td>
</tr>
</tbody>
</table>
### Observing Mode vs Backend Capabilities

<table>
<thead>
<tr>
<th>What are you doing?:</th>
<th>Continuum</th>
<th>Continuum full-stokes</th>
<th>Line</th>
<th>Pulsar</th>
<th>VLB</th>
<th>Radar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DCR</td>
<td>Mode-1 VEGAS</td>
<td>VEGAS</td>
<td>GUPPI</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CCB (Ka)</td>
<td>Mueller matrix calibration (function of parallactic angle)</td>
<td>{29 modes}</td>
<td>VEGAS-Pulsar</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mustang (3mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduction uses specialized scripts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The table above outlines various observing modes and their corresponding backend capabilities.
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.

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

<sup>a</sup> The useable bandwidth for this mode is 1250 MHz.
<sup>b</sup> The useable bandwidth for this mode is 850 MHz.
<sup>c</sup> 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:

\[ Ta = "antenna temperature" \]

• \( Ta(\text{total}) = T_{\text{source}} + \{Trx + T_{\text{bg}} + T_{\text{atm}} + T_{\text{spill}}\} \)
• Where \( \{….\} = \text{other contributions} \)
• Want \( T_{\text{source}} \), so carry out ON – OFF
• \( Ta(\text{ON}) = T_{\text{source}} + \{….\} \)
• \( Ta(\text{OFF}) = \{….\} \)
• So \( Ta(\text{ON}) - Ta(\text{OFF}) = T_{\text{source}} \)

⇒ 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

\[ F_{\text{Sky}} \]

\[ F_1 \]

\[ F_2 \]

\[ F_{\text{Sky}} - F_1 \]

\[ F_{\text{Sky}} - F_2 \]

\[ V_1 - V_2 \]

\[ V_2 - V_1 \]

Shift and Average to decrease noise by \( \sqrt{2} \)
Out-Of-Band Frequency Switching
Position Switching

**ON source**

\[ T_{\text{source}} + T_{\text{everything else}} \]

**OFF source**

\[ T_{\text{everything else}} \]
Position Switching: ON-OFF on Sky

\[ \text{ON - OFF} \]

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

Move telescope by the exact amount the beams are separated
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 ($T_{sys}$) for Typical Weather

Log-Log Plot of Expected $T_{sys}$ for Typical Weather Conditions

- With Typical Galactic Background
- No Galactic Background

Frequency (GHz):
- 0.29 - 0.40 GHz
- 0.39 - 0.52 GHz
- 0.51 - 0.69 GHz
- 0.91 - 1.23 GHz
- 1.15 - 1.73 GHz
- 1.73 - 2.60 GHz
- 3.95 - 8.0 GHz
- 8.0 - 10.0 GHz
- 12.0 - 18.0 GHz
- 26.0 - 39.5 GHz
- 38.2 - 49.8 GHz
- 88 - 100 GHz

Temperature ($T_{sys}$) (K):
- 100
- 10
- 1

Graph showing expected $T_{sys}$ levels for different frequency bands with and without typical galactic background.
GBT Surface Improved in 2009

- January 2009
- February 2009
- March 2009
- September 2009

Broken Actuators

Microns

$\Delta$Elev (deg)

0.75

0

$\Delta$CrossElevation (deg)

-0.75

0.75

11.7 GHz beam pattern

dB = -40 -20 0
GBT Aperture Efficiency and Gain (K/Jy)

Very good efficiency at lower-end of 3mm band
GBT Pointing and Surface Performance

- ~5-10 arcsec 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

\[
\frac{(\text{ON} - \text{OFF})}{\text{OFF}}
\]

\[
\left[ \left( T_{\text{source}} + T_{\text{everything else}} \right) - T_{\text{everything else}} \right] / T_{\text{everything else}}
\]

\[
= \frac{\text{(Source temperature)}}{\text{"System" temperature}}
\]
GBT Definition of $T_a$

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

- 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**

\[ T_{sys} = T_{cal} \times \frac{OFF}{(ON - OFF)} \]

**GBT: Flicker diode on/off**

\[ T_{sys} = T_{cal} \times \frac{OFF}{(ON - OFF)} + \frac{T_{cal}}{2} \]

Typically choose low $T_{cal}$ value to minimize $T_{sys}$ and high $T_{cal}$ value for very bright sources (for Rx that have two options)
Determining $T_{sys}$

Hot & Cold Loads

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

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

Example GBT 4mm Rx
Installation of 4mm calibration wheel and external cover

Look for this during GBT tour:
4mm Calibration Wheel

<table>
<thead>
<tr>
<th>Wheel Position (defined wrt Beam1)</th>
<th>Beam 1</th>
<th>Beam 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Observing</td>
<td>Sky</td>
</tr>
<tr>
<td>1</td>
<td>Cold1</td>
<td>Cold</td>
</tr>
<tr>
<td>2</td>
<td>Position2</td>
<td>1/4wave circ</td>
</tr>
<tr>
<td>3</td>
<td>Position3</td>
<td>Sky</td>
</tr>
<tr>
<td>4</td>
<td>Cold2</td>
<td>Warm</td>
</tr>
<tr>
<td>5</td>
<td>Position5</td>
<td>Sky</td>
</tr>
</tbody>
</table>
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:

\[ \frac{S(\text{source})}{S(3cX)} = \frac{T(\text{source})}{T(3cX)}, \]

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

![Graph showing GBT (Noise-Diodes)/VLA Ratio vs Frequency in GHz for 3C286, 3C295, and 3C123.](image)
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

<table>
<thead>
<tr>
<th>Band</th>
<th>GBT/VLA Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>340</td>
<td>0.50</td>
</tr>
<tr>
<td>800</td>
<td>1.17</td>
</tr>
<tr>
<td>L</td>
<td>0.92</td>
</tr>
<tr>
<td>S</td>
<td>0.88</td>
</tr>
<tr>
<td>C</td>
<td>1.32</td>
</tr>
<tr>
<td>X</td>
<td>1.00</td>
</tr>
<tr>
<td>Ku</td>
<td>0.87</td>
</tr>
<tr>
<td>KFPA</td>
<td>0.90</td>
</tr>
<tr>
<td>Ka</td>
<td>1.01</td>
</tr>
<tr>
<td>Q</td>
<td>0.83</td>
</tr>
</tbody>
</table>

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**
  - $$T_{sys} = T_{rcvr} + T_{spill} + T_{bg} \times \exp(-\tau A) + T_{atm} \times \left[\exp(-\tau A) - 1\right]$$
  - Air Mass $$A \sim 1/\sin(Elev)$$ (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 H₂O are ok for 3mm, 50% of time)
Background Information on Calibration
Temperature Scales

- $T_a = T_{sys} \ (ON-OFF)/OFF$  (uncorrected antenna temperature)
- $T_a' = T_a \ exp(\tau_o A)$
- $T_{mb} = T_a'/\eta_{mb}$  ($\eta_{mb} \sim 1.3 \ \eta_a$)
- $T_{a^*} = T_a'/\eta_l$  (mm-telescopes typically return $T_{a^*}$)
- $T_{r^*} = T_a'/\eta_l \ \eta_{fss}$
- $T_a'/S\nu = 2.84 \ \eta_a$  (for the GBT)
Calibration with Two Loads

Two loads “Direct” calibration, e.g., 4m Rx

\[ g = \frac{(T_{amb} - T_{cold})}{(V_{amb} - V_{cold})} \]

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

\[ T_A' = T_A e^{\frac{Z_a}{2}} \text{ need } \frac{Z_a}{2} \]
Calibration with One Load, $T_A^*$

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

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

\[
T_{cal} = \left[ \frac{T_{amb} - T_{A\,sky}}{T_{A\,sky}} \right] e^{z_2 A}
\]

\[
T_{cal} = T_{ATM} + (T_{amb} - T_{ATM}) e^{z_2 A}
\]

\[
\text{eq. A9 of KL91 re-written}
\]

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

Some have assumed $T_{cal} = T_{amb} = T_{ATM}$ with $T_A^*$ calibration.
Tssys for $T_A^*$ scale different than Tsys for $T_A$

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

where \( T_{sys}^* = T_{sys} \cdot e^{\frac{Z_0 A}{\eta L}} \) includes ATM

\[
T_A^* = T_A \cdot e^{\frac{Z_0 A}{\eta L}}
\]
Point-Source Calibration: Flux Density vs Antenna Temp

\[ P_{\text{rec}} = \frac{1}{2} A_e S_v \Delta v = k T'_a \Delta v \]

\[ A_e = \eta_a \left( \frac{\pi}{4} \right) D^2 \]

\[ \Rightarrow S_v = 3520 \frac{T'_a}{(\eta_a \text{ [D/m]}^2)} \]

i.e., \[ T'_a / S_v = 2.84 \eta_a \] for the GBT \( (\eta_a=0.71 \text{ at low } \nu) \)

Used for point-source calibration:

- Measure \( T_a \)
- Correct for atmosphere \( \Rightarrow T'_a \)
- Know \( S_v \)
- Derive \( \eta_a \)
Extended Sources: $T'_{mb}$ vs $T_{source}$

\[
T'_{A} = \frac{1}{\Omega_A} \int \int P_n(\theta, \phi) T_s(\theta, \phi) d\Omega
\]

compute using $T_{mb}$

\[
\frac{\Omega_{mb}}{\Omega_A} = \Pi_{mb} \quad ; \quad T'_{A} = \Pi_{mb} T_{mb}
\]

\[
T_{mb} = \frac{T'_{A}}{\Pi_{mb}} = \frac{1}{\Omega_{mb}} \int \int P_n(\theta, \phi) T_s(\theta, \phi) d\Omega
\]
If \( T_s \) is uniform, \( \Theta_s < \Theta_{mb} \Rightarrow 1/T_s \ll 1 \text{ over source:} \)

\[
T_{mb} = \frac{1}{T_s} \int_{\text{source}} \int \frac{P_{in}}{2_{MB}} \, d\Omega \\
= T_s \frac{\Theta_s}{2_{MB}} = \left( \frac{\Theta_s}{\Theta_{mb}} \right)^2
\]

Small source \( \Theta_s < \Theta_{mb} \)

"Filling Factor"  
"Beam dilution"
Gaussian Source

More general, assume $T_5$ Gaussian and beam Gaussian

$$\sigma_{\text{Gaussian}} = 1.133 \sigma_{\text{FWHM}}$$

$$T_{mb} = T_5 \left[ \frac{\Theta_5}{\sqrt{\Theta_{mb}^2 + \Theta_5^2}} \right]$$

$\Theta_{mb} \gg \Theta_5 \Rightarrow T_{mb} = T_5 \left( \frac{\Theta_5}{\Theta_{mb}} \right)^2 \checkmark$

$\Theta_5 \gg \Theta_{mb} \Rightarrow T_{mb} = T_5 \checkmark$
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.