Cryogenic Receiver Technology

Steven White
Green Bank Observatory
• GBT Optics
• Feeds
• GBT Receivers
• Focal Plane Array
• Phase Array Feed Receivers
• Ultra Wide Band Feeds
Specify diameter:  100 m
Set focal distance:  60 m
Specify dish center:  54 m

Cone: $\theta_H = 39.005^\circ$
Cone: $\theta_o = 42.825^\circ$

Specify Optics:  Gregorian
Specify ellipse:  $e = 0.528$
Specify focal distance:  11 m  (7.55x7.95 m)
Feed Half Angle:  15 °

600 m Paraboloid
Focal Point=  60 m
• 100 meter Offset design from a 600 meter paraboloid

• Weight: 17,000,000 lbs.

• Focal Length 60 meters.

• Surface Accuracy: < 240 μm meters

• Track Flatness: +/- 125 μm meters

• Delta height of track: 0.1 mm
Losses:
- Blockage efficiency: $\eta_b$ (GBT = 0)
- Illumination efficiency: $\eta_t$
- Spillover efficiency: $\eta_s$
- Phase efficiency: $\eta_p$
- xPolarization efficiency: $\eta_x$

Real telescope:
$$\eta_a = \eta_b \eta_i \eta_s \eta_p \eta_x$$
\[ \eta_t \eta_s = 0.815 \quad \text{11dB edge taper} \]

\[ \eta_t \eta_s = 0.700 \quad \text{15dB edge taper (GBT)} \]

\[ T_s = (1 - \eta_s) T_{\text{ground}} \degree K \quad \sim 11.6 \degree K \text{ at PF,} \quad \sim 1 \degree K \text{ at Gregorian} \]

Maximize \( A[m^2] / \eta_a \) or \( G/T \)
Fourier transform relationship

Far-field beam pattern is Fourier transform of aperture plane electric field distribution
Corrugated Horns

Analytical Expressions are closed form.

Defined Edge Taper

Good Impedance Match

Diameter $\sim 3 \lambda$ GBT Optics
Corrugated Feed Horn Fields

Design and Measurement of Conical Corrugated Feed Horns for the BIMA Array, Xiaolei Zhang, 1991, Memo 17
Prime Focus Feed

Cross Dipole 290-395 MHz
Gregorian Feeds

S, Ku (2x), L

KFPA Feed

W band feed
Receiver Noise Power

\[ N_{RX} = k T_{eq} B \text{ [Watts]} \]

Raleigh Jeans Law

- \( k \): Boltzmann's Constant
- \( T \): Temperature
- \( B \): Bandwidth
Amplifier Equivalent Noise

\[ P_o = GkBT_s + K \]

Define \( K = GkBT_e \)

Then, \( P_o = GkB(T_s + T_e) \)

\( T_e \) is the amplifier *Equivalent Input Noise Temperature*
Input Losses

0.1 dB ~ 7K at room temperature (290 K)
Linear Polarization

Orthomode Transducer
Circular Polarization
Typical Heterodyne Receiver
Radio Source Properties

• Total Power (continuum: cmb, dust)
  – Correlation Radiometer Receivers (Ka Band)
  – Bolometers Receivers (MUSTANG)

• Frequency Spectrum (Spectroscopy: HI, Astrochemistry, Pulsars)
  – Heterodyne
  – Prime 1 & 2, L, S, C, X, Ku, K, Ka, Q, W

• Dual Polarization (magnetic fields, stokes parameters)
  – Requires OMT
  – Circular requires OMT & Phase Shifter, Septum Polarizer, or Hybrid.
  – Limits bandwidth raises $T_{RX}$

• Very Long Baseline Interferometry (VLBI)
  – Phase Calibration
The GBT

System Temperature - TYPICAL weather conditions (includes spillover, atmosphere, Galactic background, CMB)

Frequency (GHz)

System Temperature (K)
Prime Focus Receivers

<table>
<thead>
<tr>
<th>Receiver</th>
<th>Frequency</th>
<th>$T_{sys}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF1.1</td>
<td>0.290 - 0.395</td>
<td>46 K</td>
</tr>
<tr>
<td>PF1.2</td>
<td>0.385 - 0.520</td>
<td>43 K</td>
</tr>
<tr>
<td>PF1.3</td>
<td>0.510 - 0.690</td>
<td>30 K</td>
</tr>
<tr>
<td>PF1.4</td>
<td>0.680 - 0.920</td>
<td>22 K</td>
</tr>
<tr>
<td>PF2</td>
<td>0.910 - 1.230</td>
<td>20 K</td>
</tr>
<tr>
<td>Frequency [GHz]</td>
<td>WG Band</td>
<td>Temperature [° K]</td>
</tr>
<tr>
<td>----------------</td>
<td>---------</td>
<td>------------------</td>
</tr>
<tr>
<td>1.3-1.8</td>
<td>L</td>
<td>20</td>
</tr>
<tr>
<td>2-3</td>
<td>S</td>
<td>22</td>
</tr>
<tr>
<td>4-6</td>
<td>C</td>
<td>23</td>
</tr>
<tr>
<td>8-10</td>
<td>X</td>
<td>27</td>
</tr>
<tr>
<td>12-15</td>
<td>Ku</td>
<td>30</td>
</tr>
<tr>
<td>18-26.5</td>
<td>K</td>
<td>30-40</td>
</tr>
<tr>
<td>26-40</td>
<td>Ka</td>
<td>35-45</td>
</tr>
<tr>
<td>40-52</td>
<td>Q</td>
<td>67-134</td>
</tr>
<tr>
<td>68-92</td>
<td>~E</td>
<td>30-90</td>
</tr>
<tr>
<td>75-115</td>
<td>W</td>
<td>&gt;100</td>
</tr>
<tr>
<td>80-100</td>
<td>W</td>
<td>NEP: $\sim 10^{-31}$ [W²/Hz]</td>
</tr>
</tbody>
</table>
GBT Receivers

Ka Band

W Band (2 Pixel)

Q band
Inside Receiver Room
Focal Plane Arrays
K Band Focal Plane Array
3 HPBW
K Band $f = 22 \text{ GHz}$

$0.177 \text{ HPBW/mm} = 13.36 \text{ mm}$

GBT Beam Spatial Coverage/Resolution

K Band $f = 22 \text{ GHz}$ \quad $\lambda = 13.36 \text{ mm}$

GBT Aperture Spacing

$0.177 \text{ HPBW/mm}$
K Band Single Pixel

Feed

Thermal Transition

Phase Shifter

OMT

Noise Module

Isolators

LNA

Sliding Transition
7 Pixel K band Receiver
Star Formation in a Filament in Taurus

Dust

GBT NH₃ Compared to Moon

1 pc

Galactic Longitude

Intensity [mJy/σ]

Integrated NH₃ (1,1) [K km s⁻¹]
ARGUS

16-pixel W-band Feed Array; 75-116 GHz

- 16 InP MMIC RF amplifiers cooled to 15 K
- Noise temperature < 50-60 K
- Open for general use

- A collaborative effort: S. Church [PI], M. Sieth, K. Devaraj, P. Voll (Stanford); A. Readhead, K. Cleary, R. Gawande (Caltech); L. Samoska, P. Kangaslahti, T. Gaier, P. Goldsmith (JPL), A. Harris (U. Maryland); J. Gunderson (U. Florida)

- Receiver described in Seith et al. 2014, Proc. SPIE 9153
ARGUS

![Image of a circuit board and a graph showing noise and gain vs. frequency.]

<table>
<thead>
<tr>
<th>Component</th>
<th>Physical Temp. (K)</th>
<th>Gain (dB)</th>
<th>Contrib. to Rec. Noise Temp (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat window</td>
<td>300</td>
<td>-0.07</td>
<td>4.9</td>
</tr>
<tr>
<td>Entrance feedhorns</td>
<td>20</td>
<td>-0.04</td>
<td>0.2</td>
</tr>
<tr>
<td>MMIC module</td>
<td>20</td>
<td>25.0</td>
<td>33.9</td>
</tr>
<tr>
<td>Module to 20K board</td>
<td>20</td>
<td>-1.0</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>20 K board</td>
<td>20</td>
<td>-3.3</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>IF flex line</td>
<td>20-77</td>
<td>-1.4</td>
<td>0.1</td>
</tr>
<tr>
<td>77 K Board</td>
<td>77</td>
<td>-1.8</td>
<td>0.4</td>
</tr>
<tr>
<td>IF Amplifier</td>
<td>77</td>
<td>15</td>
<td>1.8</td>
</tr>
<tr>
<td>77 K Board</td>
<td>77</td>
<td>-1.8</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>IF flex line</td>
<td>77-300</td>
<td>-5.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Projected Receiver Gain/ Temperature</td>
<td>25.1 dB</td>
<td>42 K</td>
<td></td>
</tr>
</tbody>
</table>
ARGUS

HCO+ 10 min snapshot; 8″ <-> 0.005 pc at Taurus
MUSTANG-2

223 Feedhorn Bolometer Array
4’ FoV; 10” beam
63 $\mu$Jy; 0.062 mK ($T_A^*$) across a 5’ × 5’ field in 1 hour
Sunyaev–Zel’dovich effect

Collaboration: University of Pennsylvania (M. Devlin, PI), National Institute of Standards, Green Bank Observatory, National Radio Astronomy Observatory, University of Michigan, Cardiff University

Orion Molecular Cloud complex: GBT+MUSTANG image of dust (orange) against the visible light (purple).
Phased Array Feed
Cryogenic PAF

\[ \text{Survey Speed} \propto N \left( \frac{\eta}{T_{\text{sys}}} \right)^2 \]

Sample aperture: \( \frac{f \lambda}{D} \)

Performance of a Highly Sensitive, 19-element, Dual-polarization, Cryogenic L-band Phased-array Feed on the Green Bank Telescope

**Authors:**


• **Formed L Band Phased Array GBT Feed**

• The March 2017 GBT test was successful, demonstrating:
  – Seven low-noise beams on sky
  – Tsys/eff of central beam <30K
  – Close correspondence between measured result and model

• *Digital Data Links (DDL)*
• *BeamFormer Backend.*
NRAO and Green Bank Observatory break the record for the coldest, most sensitive phased array feed system on Earth!
Ultrawideband Receiver
Ahmed Akgiray Thesis

Figure 4.11: Three-dimensional CAD drawings of the high-gain quad-ridge horn. Feed diameter is 82 cm ($1.6\lambda_d$) and length is 73.2 cm ($1.7\lambda_d$) with $f_{ls} = 0.7$ GHz

4.3 High-Gain QRFH
Fused Quartz

Aluminium

PTFE

0.7GHz

4.2GHz
• Wideband Feed Development

• 0.7 to 4 GHz
• Corrugation
• Quartz Spear
• Quartz Vacuum Window
UWBR Photographs