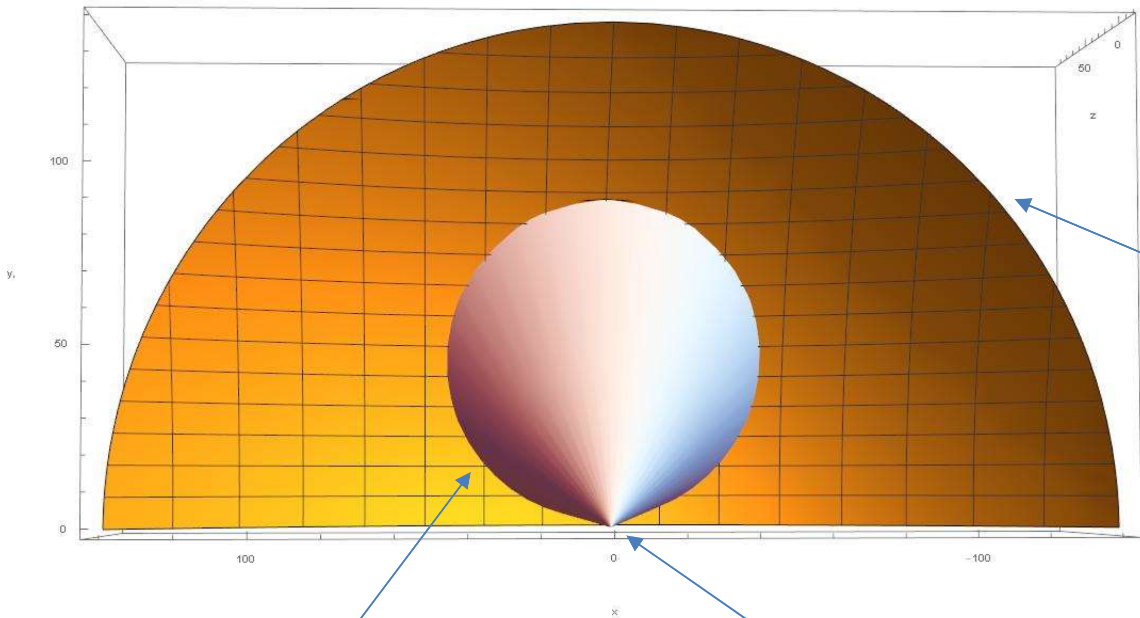
Cryogenic Receiver Technology

Steven White

Green Bank Observatory

- GBT Optics
- Feeds
- GBT Receivers
- Focal Plane Array
- Phase Array Feed Receivers
- Ultra Wide Band Feeds



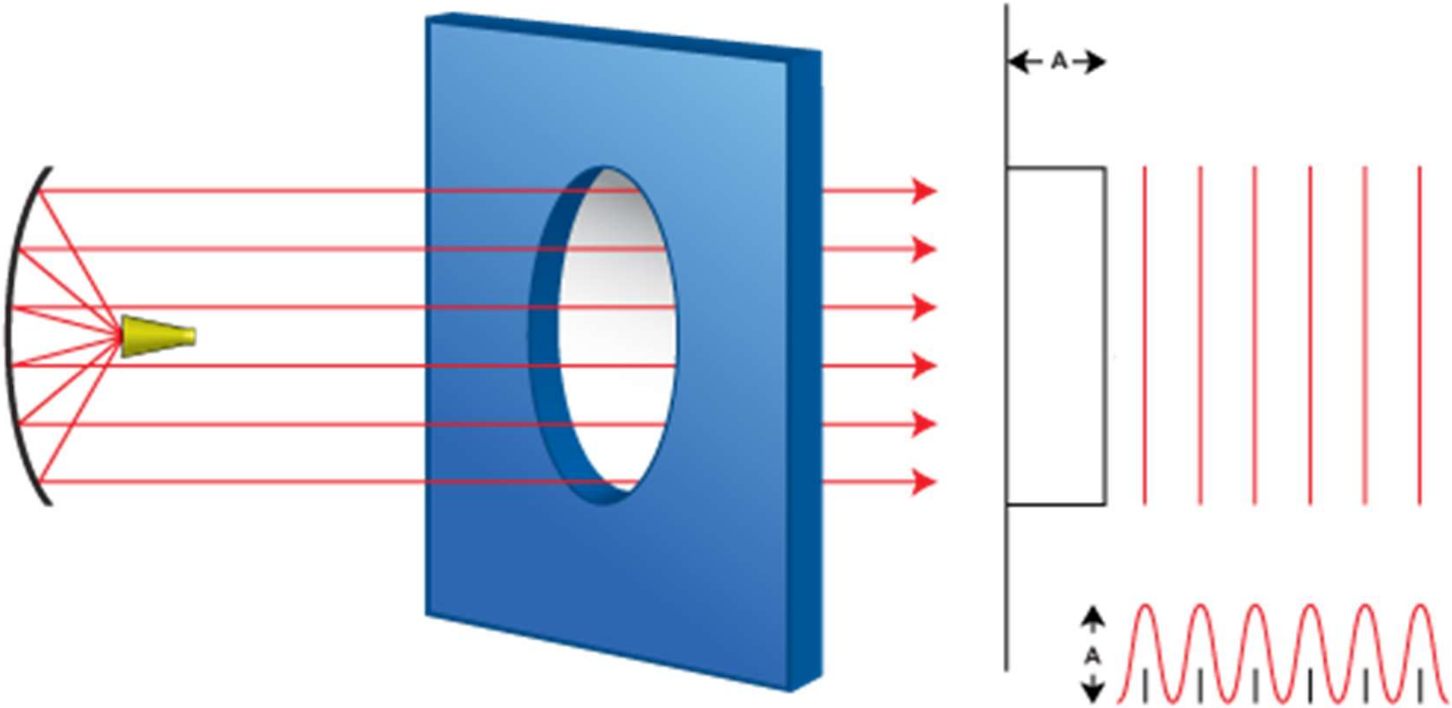
600 m Paraboloid
Focal Point= 60 m

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

Specify diameter: 100m
Set focal distance: 60 m
Specify dish center: 54 m

Cone: $\theta_H = 39.005°$
Cone: $\theta_o = 42.825°$

- 100 meter Offset design from a 600 meter paraboloid
- Weight: 17,000,000 lbs.
- Focal Length 60 meters.
- Surface Accuracy: < 240 μ meters
- Track Flatness: +/- 125 μ meters
- Delta height of track: 0.1 mm

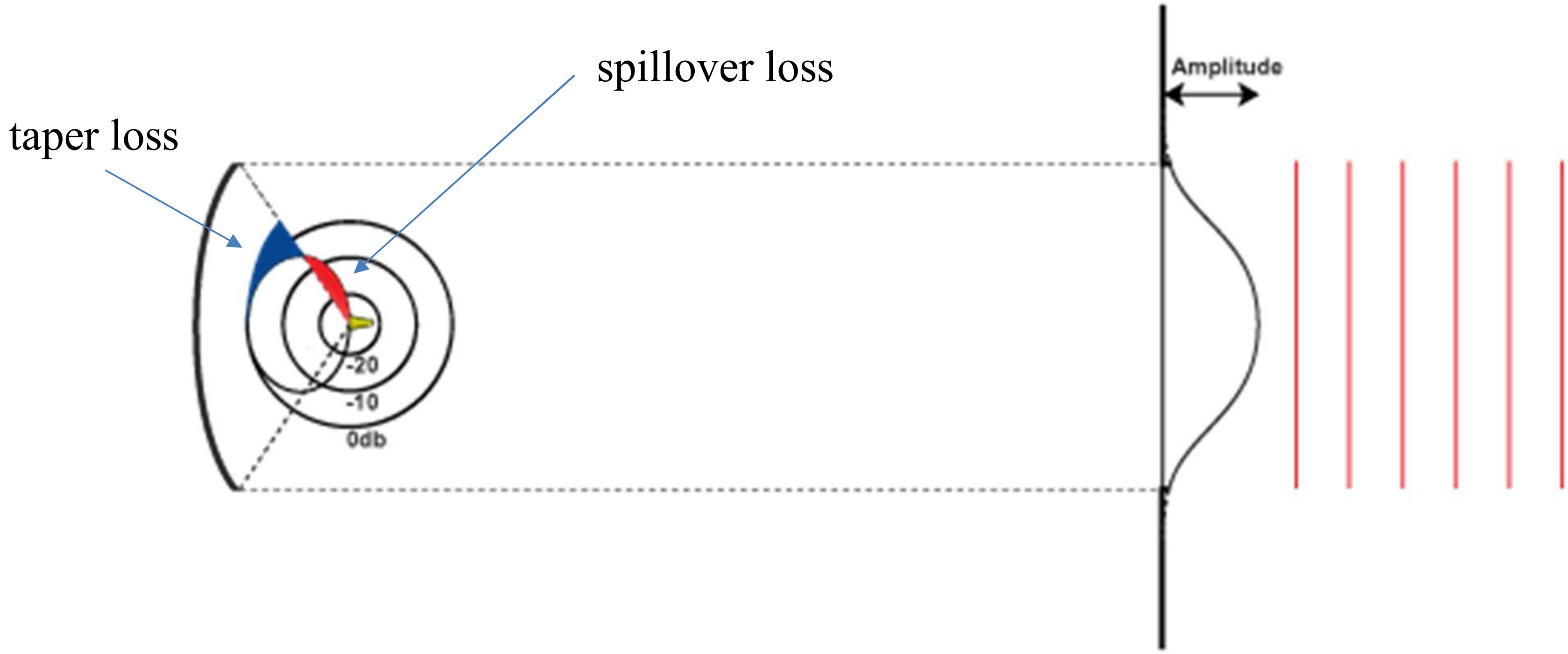


Losses:

- Blockage efficiency: η_b (GBT =0)
- illumination efficiency: η_t
- Spillover efficiency: η_s
- Phase efficiency: η_p
- xPolarization efficiency: η_x

Real telescope:

$$\eta_a = \eta_b \eta_i \eta_s \eta_p \eta_x$$



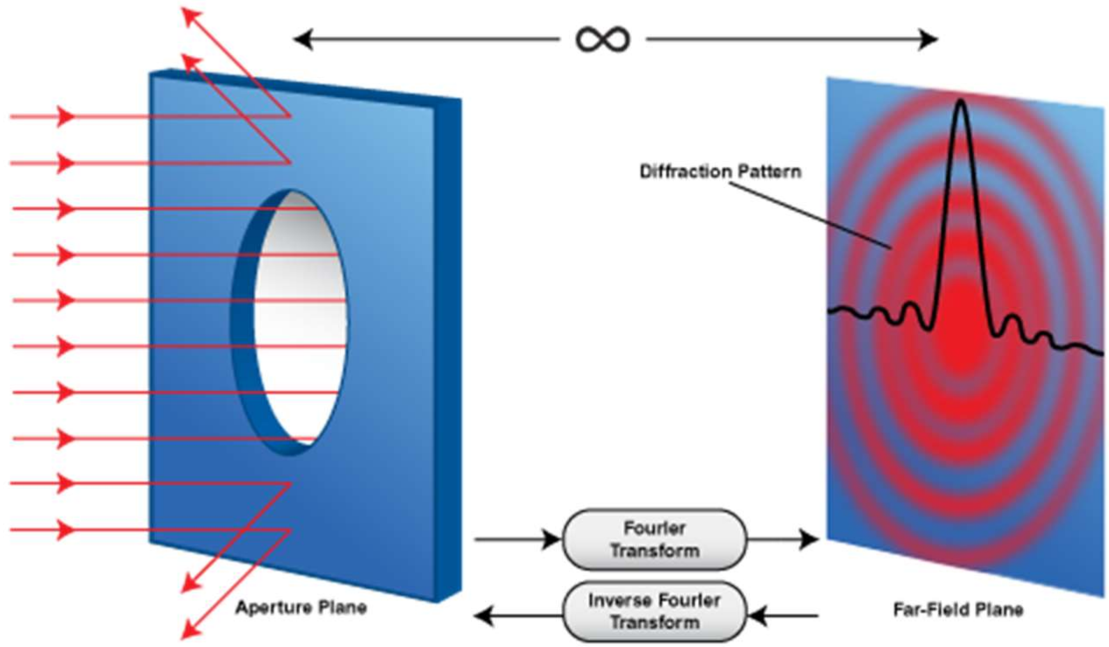
$\eta_t \eta_s = 0.815$ 11dB edge taper

$\eta_t \eta_s = 0.700$ 15dB edge taper (GBT)

$T_s = (1 - \eta_s)\, T_{ground}\ ^oK$ ~ 11.6 ^oK at PF, ~ 1 ^oK at Gregorian

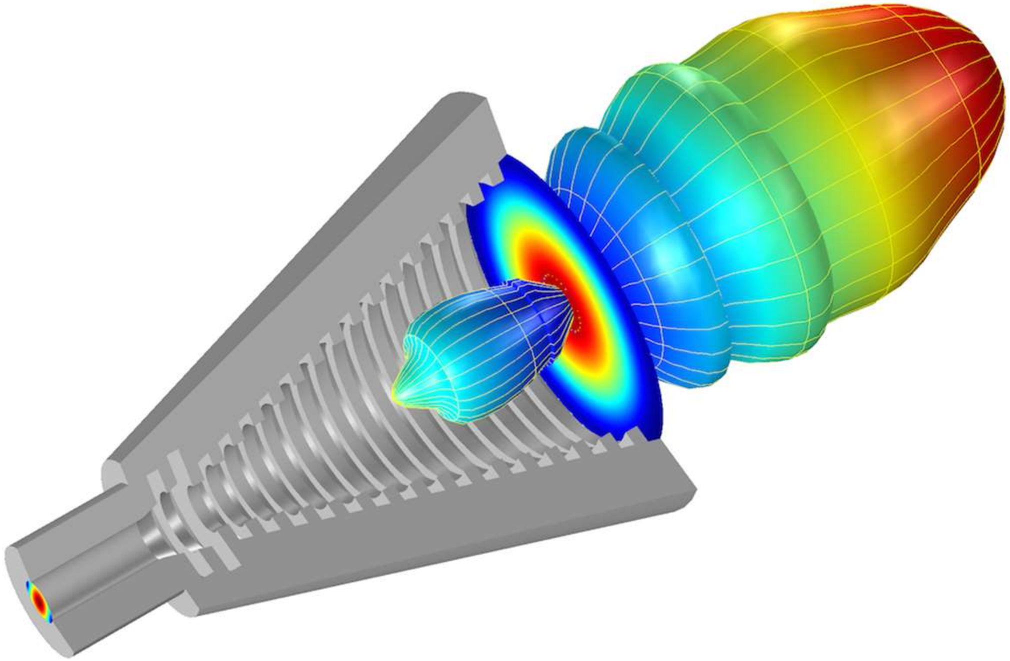
Maximize A[m^2] / η_a or G/T

Fourier transform relationship



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

Corrugated Horns



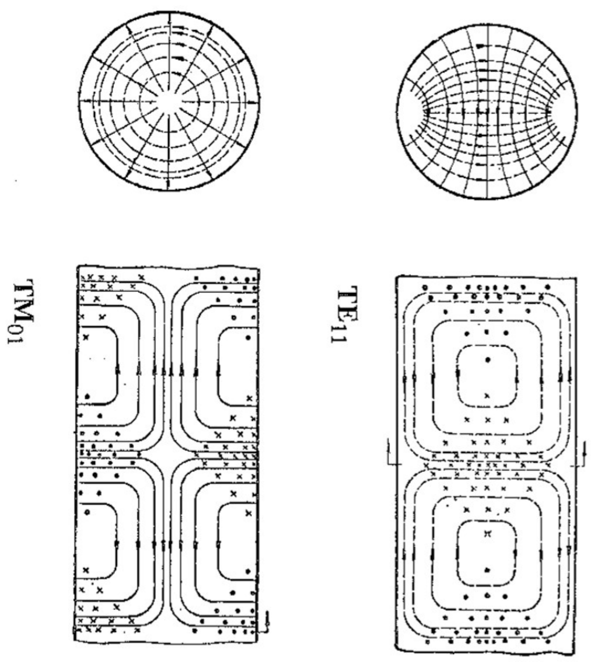
Analytical Expressions are closed form.

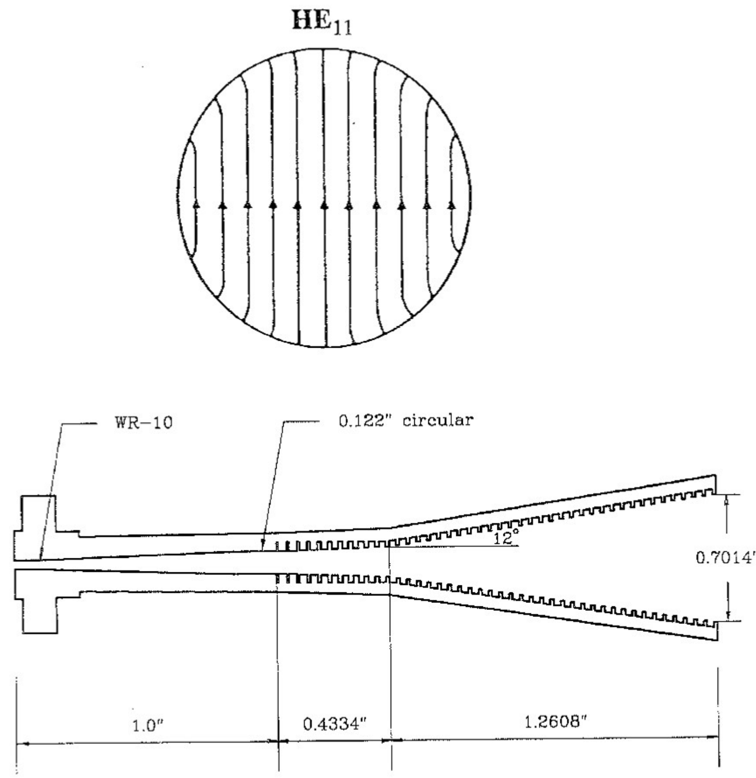
Defined Edge Taper

Good Impedance Match

Diameter ~ 3 λ 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

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

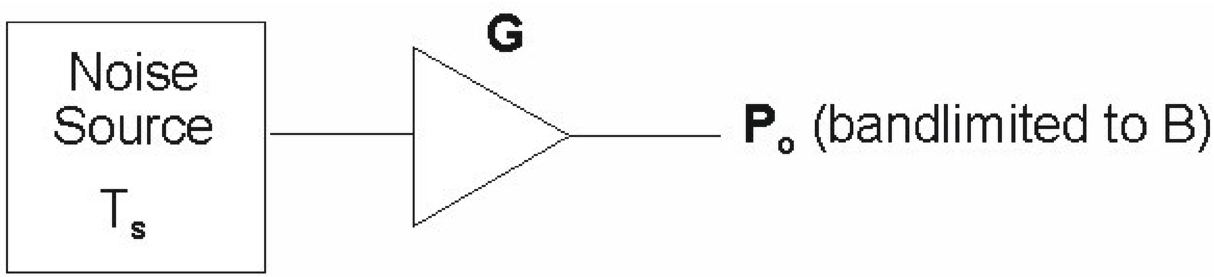
Raleigh Jeans Law

k: Boltzmann's Constant

T: Temperature

B: Bandwidth

Amplifier Equivalent Noise



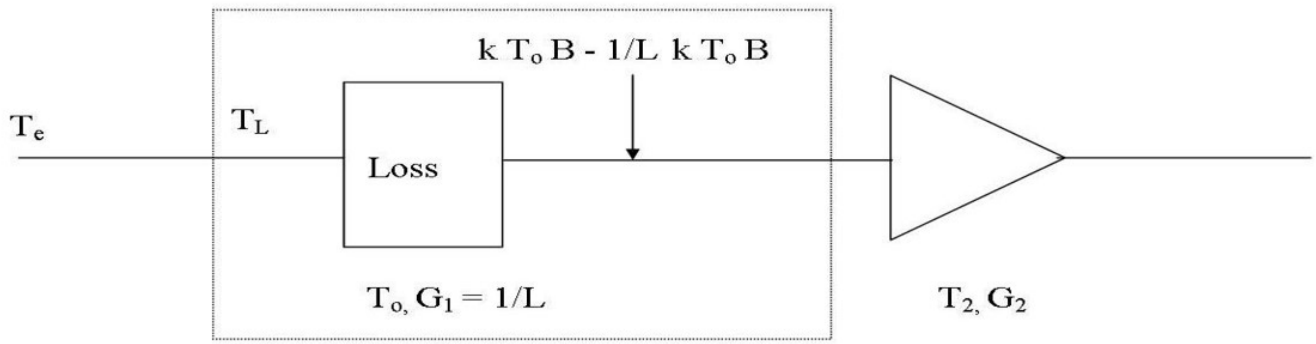
$P_o = GkBT_s + K$

Define $K = GkBT_e$

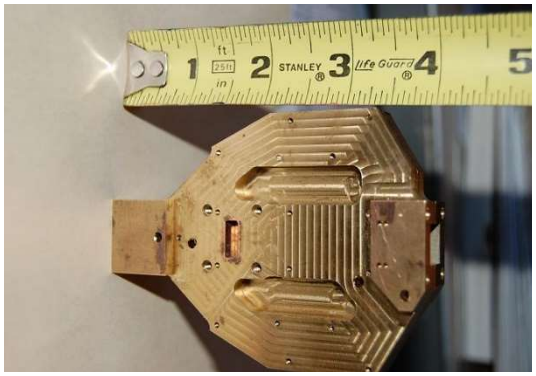
Then, $P_o = GkB(T_s + T_e)$

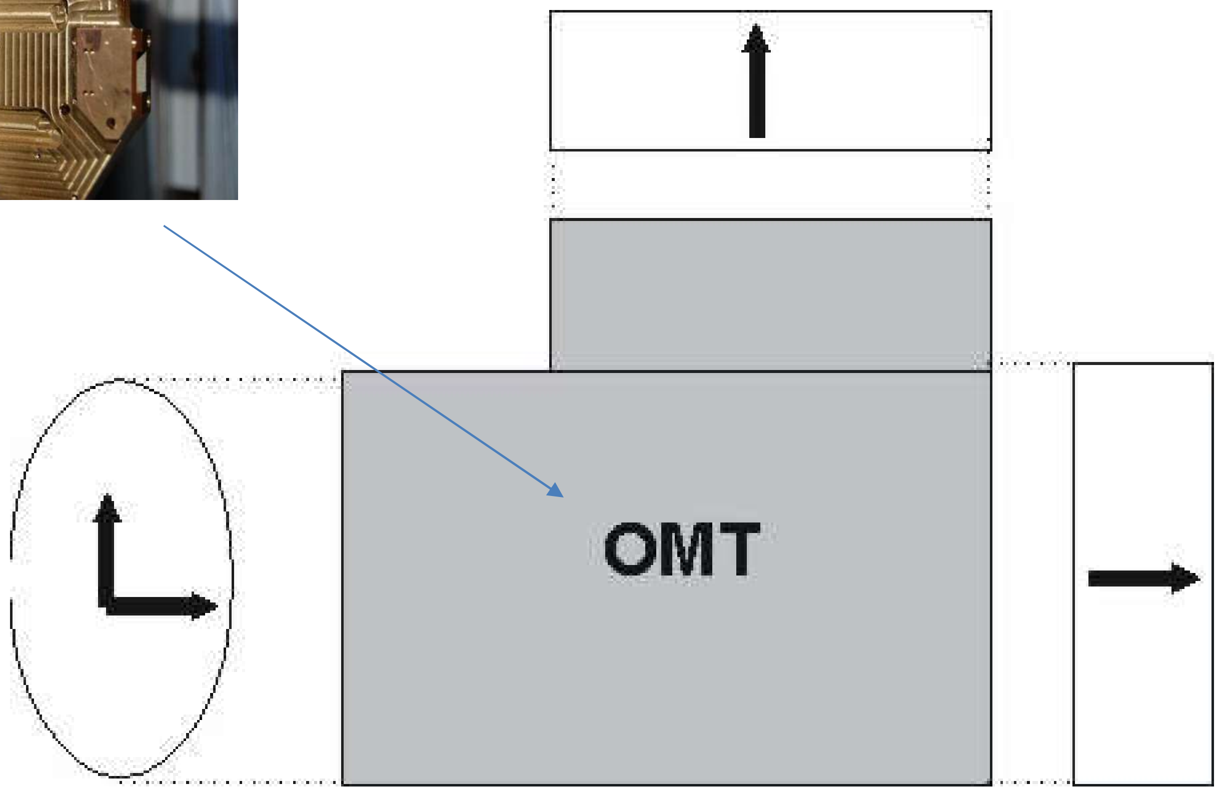
T_e is the amplifier *Equivalent Input Noise Temperature*

Input Losses
0.1 dB ~ 7K at room temperature (290 K)



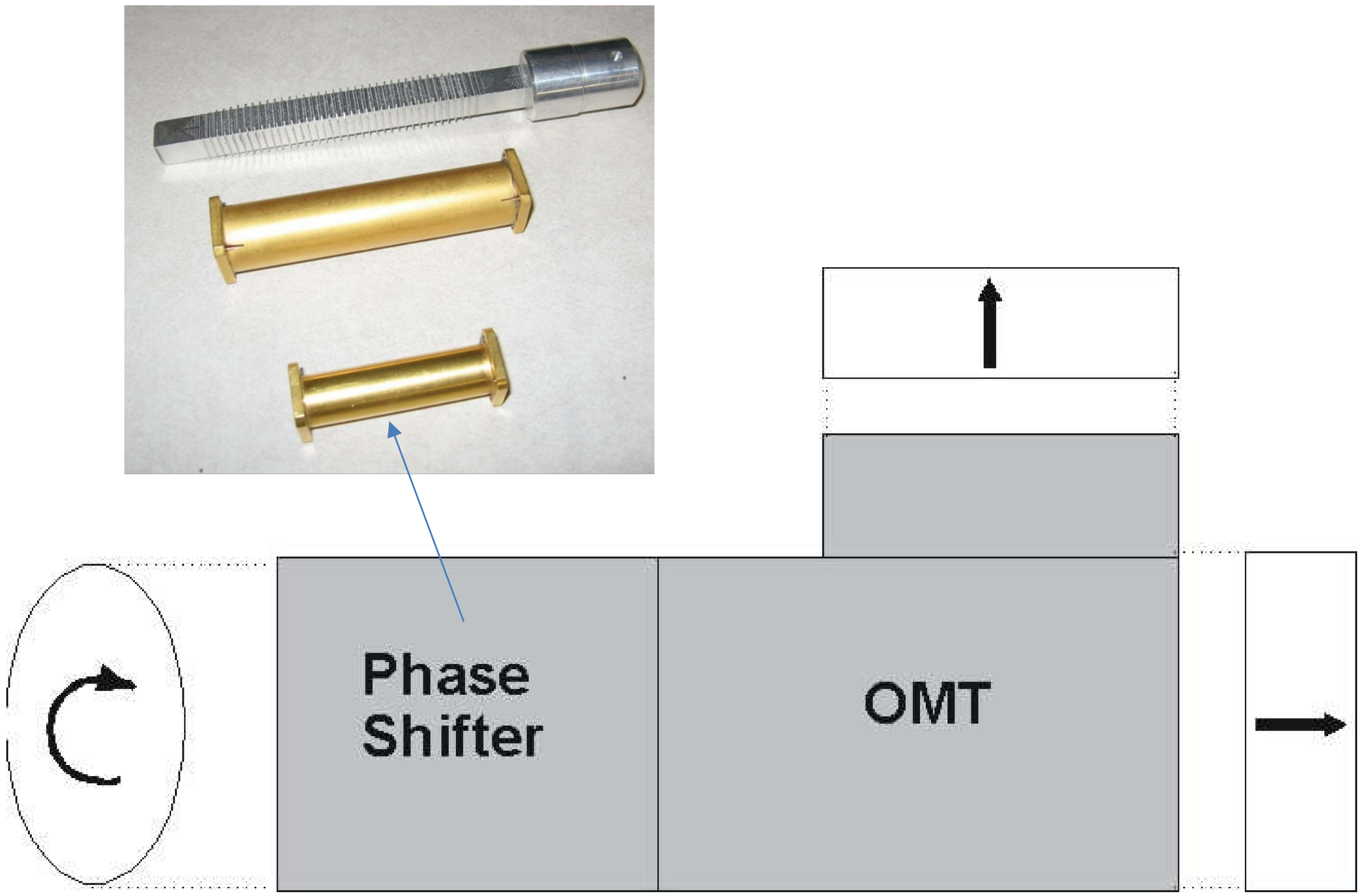
Linear Polarization



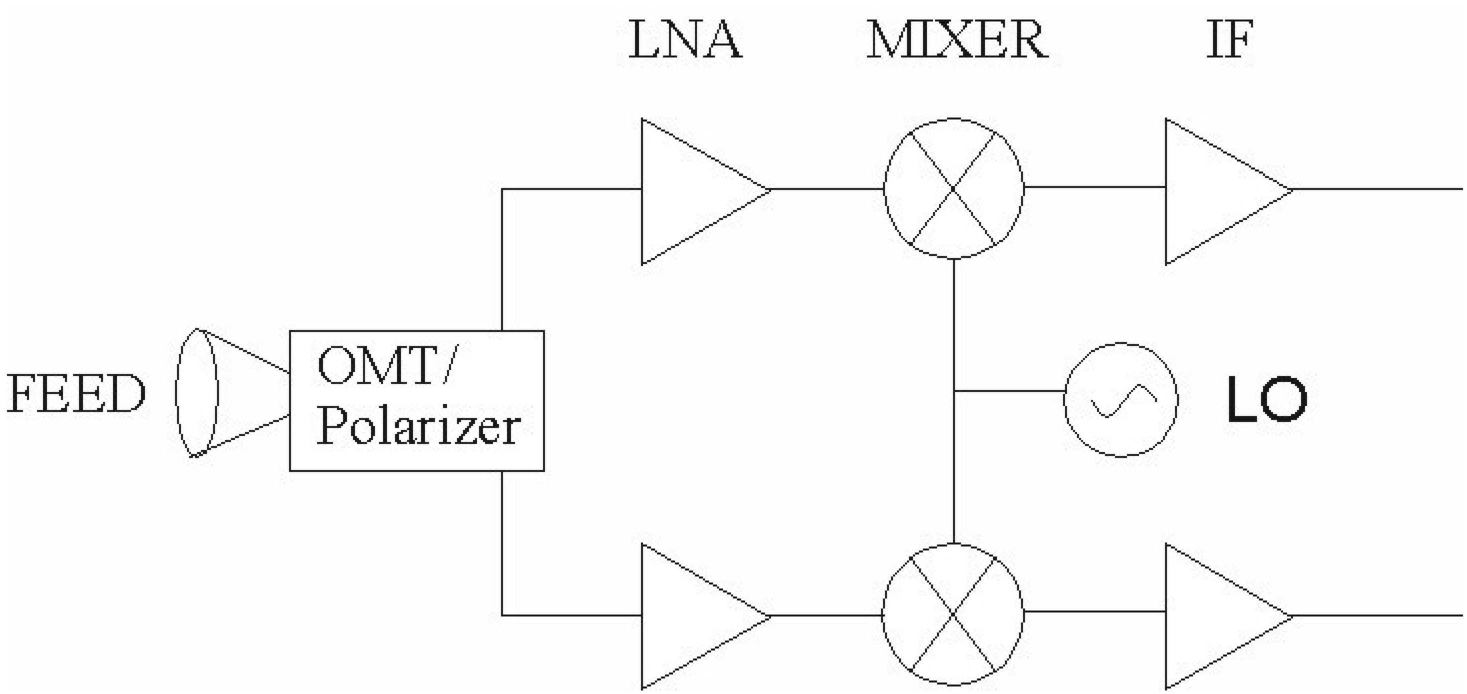


Orthomode Transducer

Circular Polarization



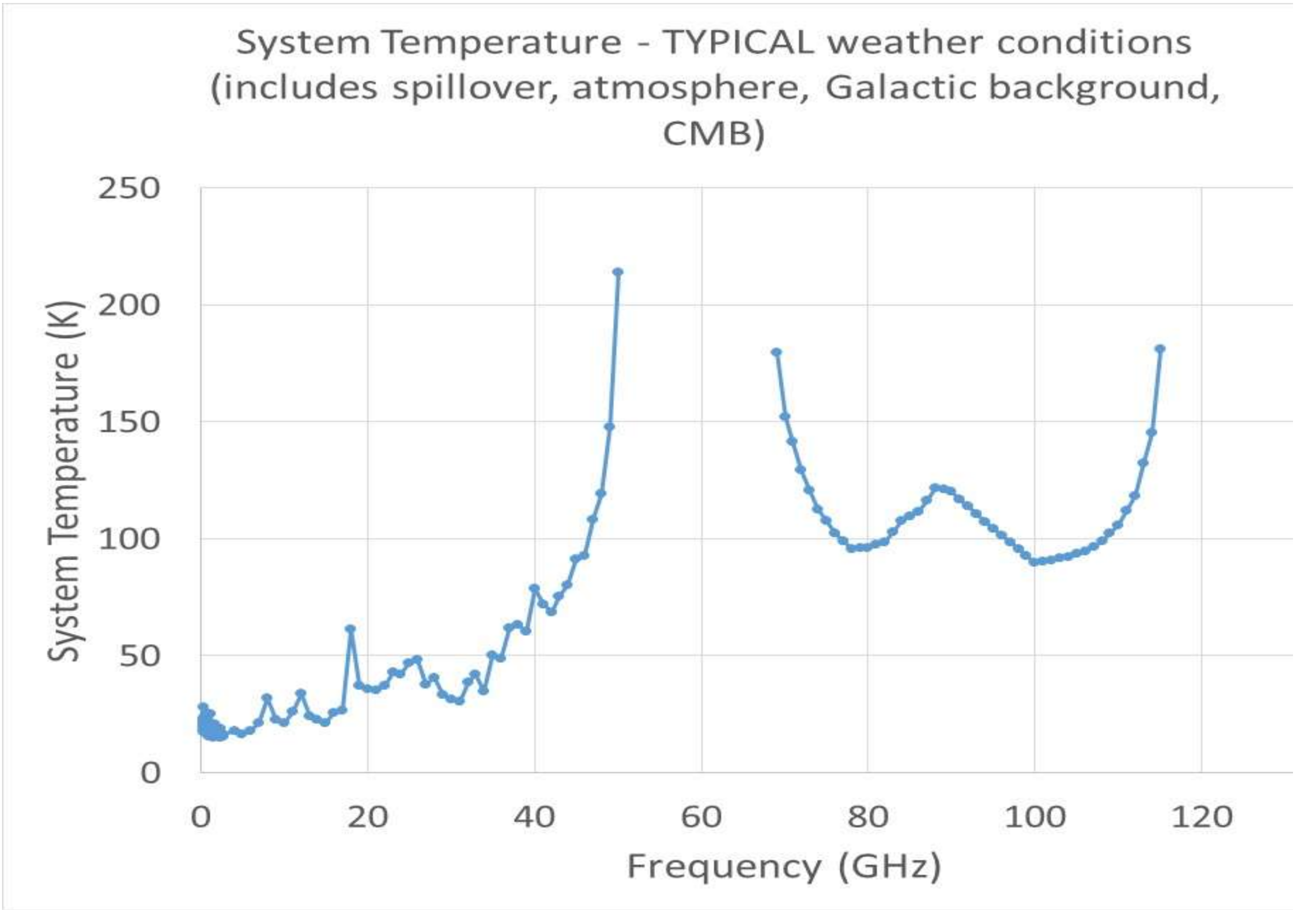
Typical Heterodyne Receiver



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)
250
200
150
100
50
0
System Temperature (K)
0
20
40
60
80
100
120
Frequency (GHz)

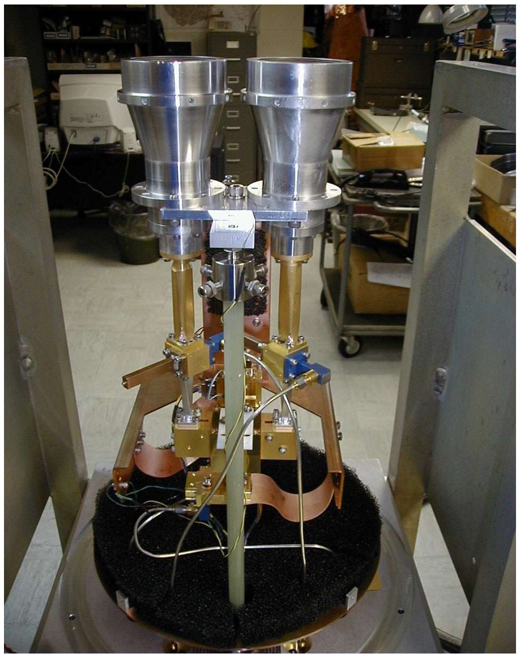
Prime Focus Receivers

Receiver	Frequency	T_{sys}
• PF1.1	0.290 - 0.395	46 K
• PF1.2	0.385 - 0.520	43 K
• PF1.3	0.510 - 0.690	30 K
• PF1.4	0.680 - 0.920	22 K
• PF2	0.910 - 1.230	20 K

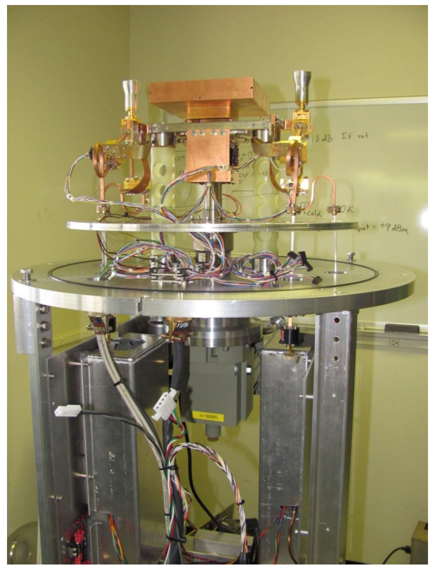
Frequency [GHz]	WG Band	Temperature [º K]
1.3-1.8	L	20
2-3	S	22
4-6	C	23
8-10	X	27
12-15	Ku	30
18-26.5	K	30-40
26-40	Ka	35-45
40-52	Q	67-134
68- 92	~E	30-90
75-115	W	>100
80-100	W	NEP: ~ 10^{-31} [W^2/Hz]

GBT Receivers

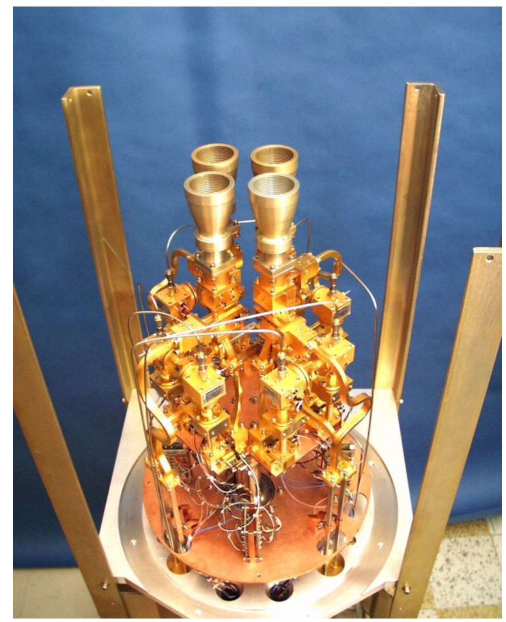
Ka Band



W Band (2 Pixel)



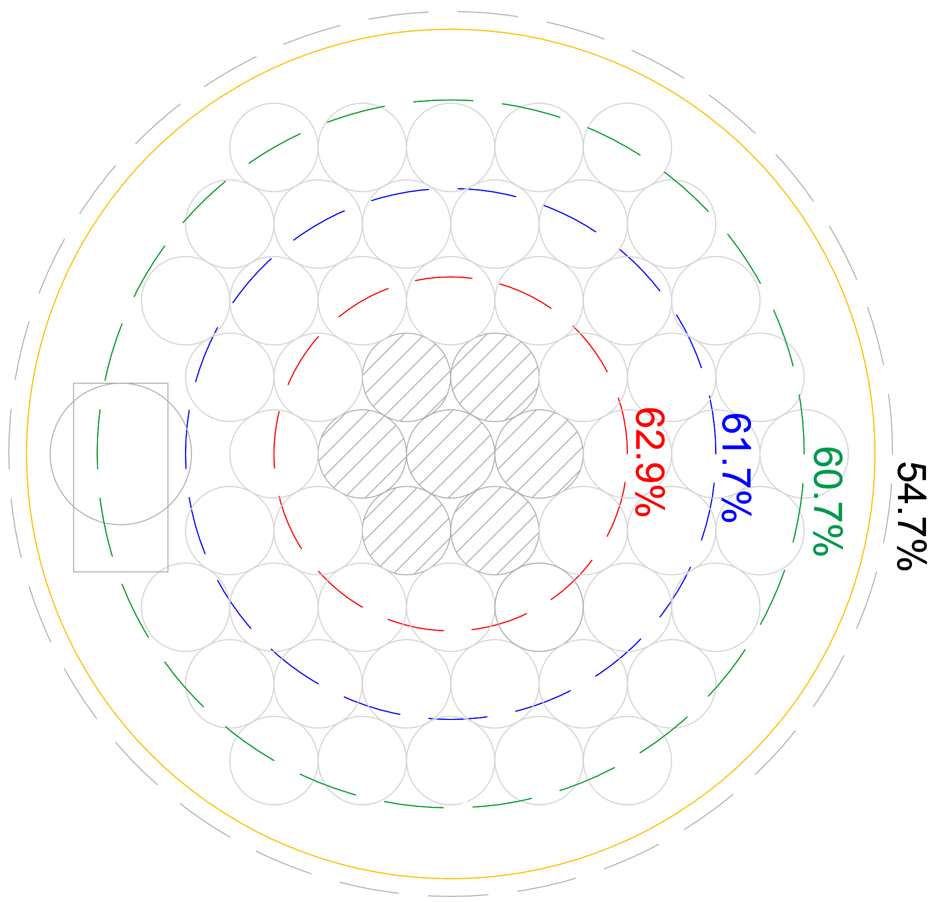
Q band



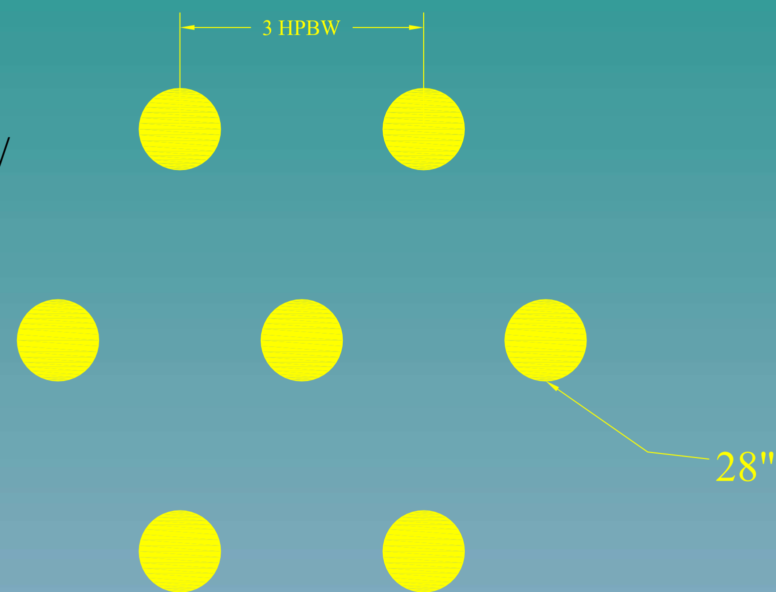
Inside Receiver Room

Focal Plane Arrays

K Band Focal Plane Array

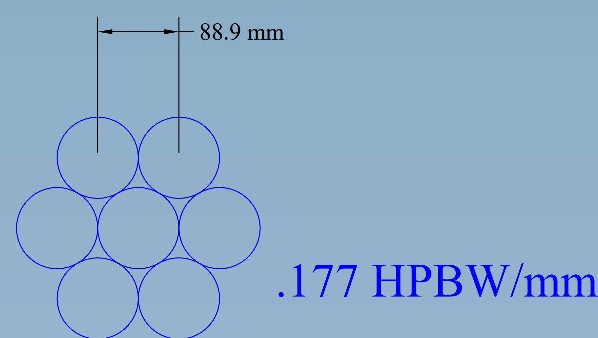


GBT Beam Spatial Coverage/ Resolution



K Band f = 22 GHz λ = 13.36 mm

GBT Aperture Spacing



K Band Single Pixel

Feed

Thermal Transition

Phase Shifter

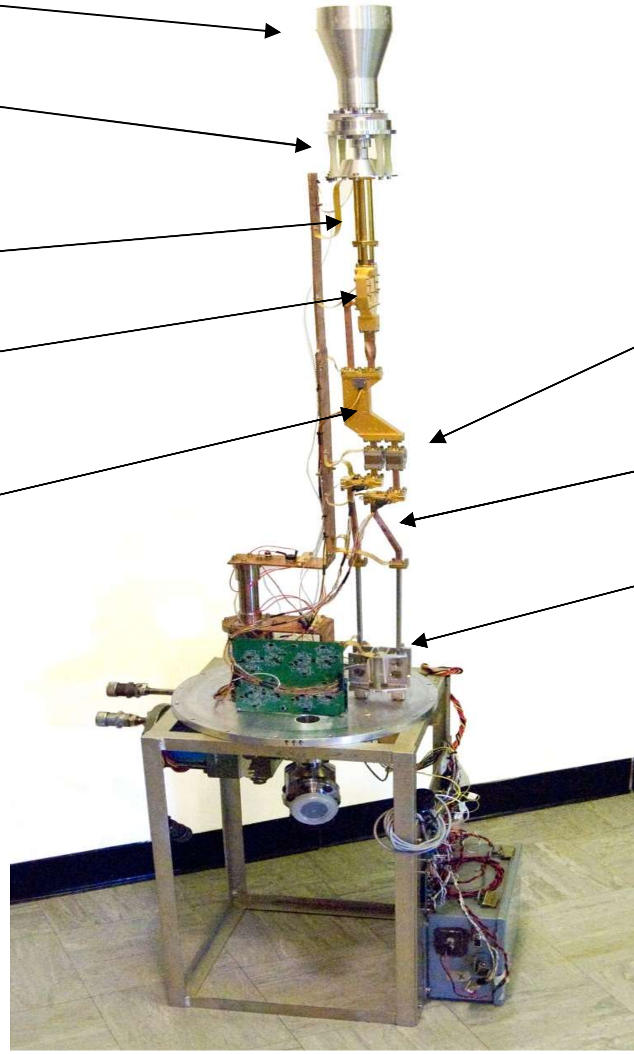
OMT

Noise Module

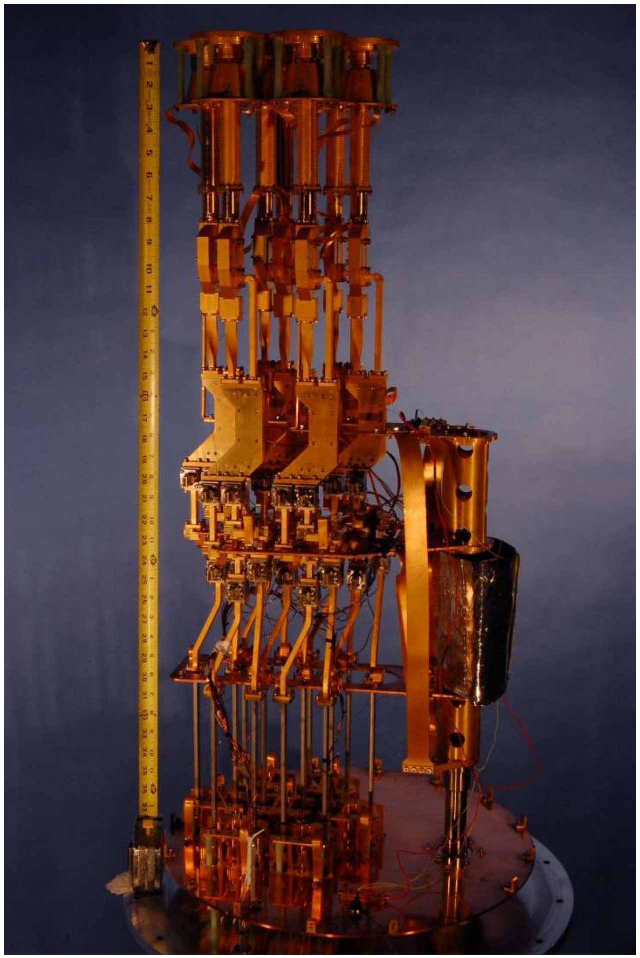
Isolators

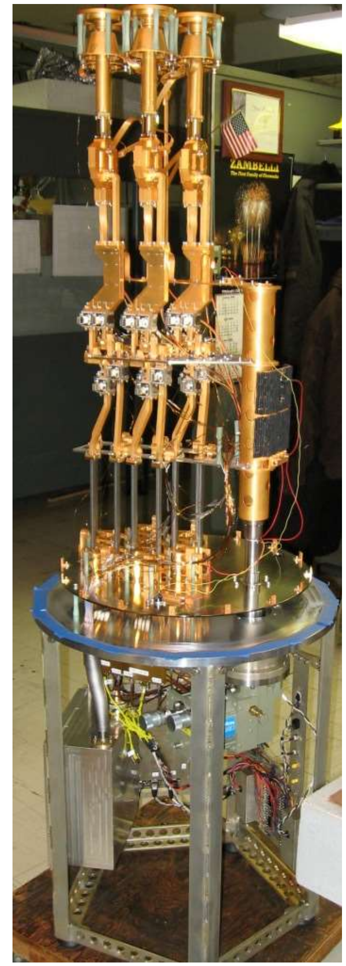
LNA

Sliding Transition

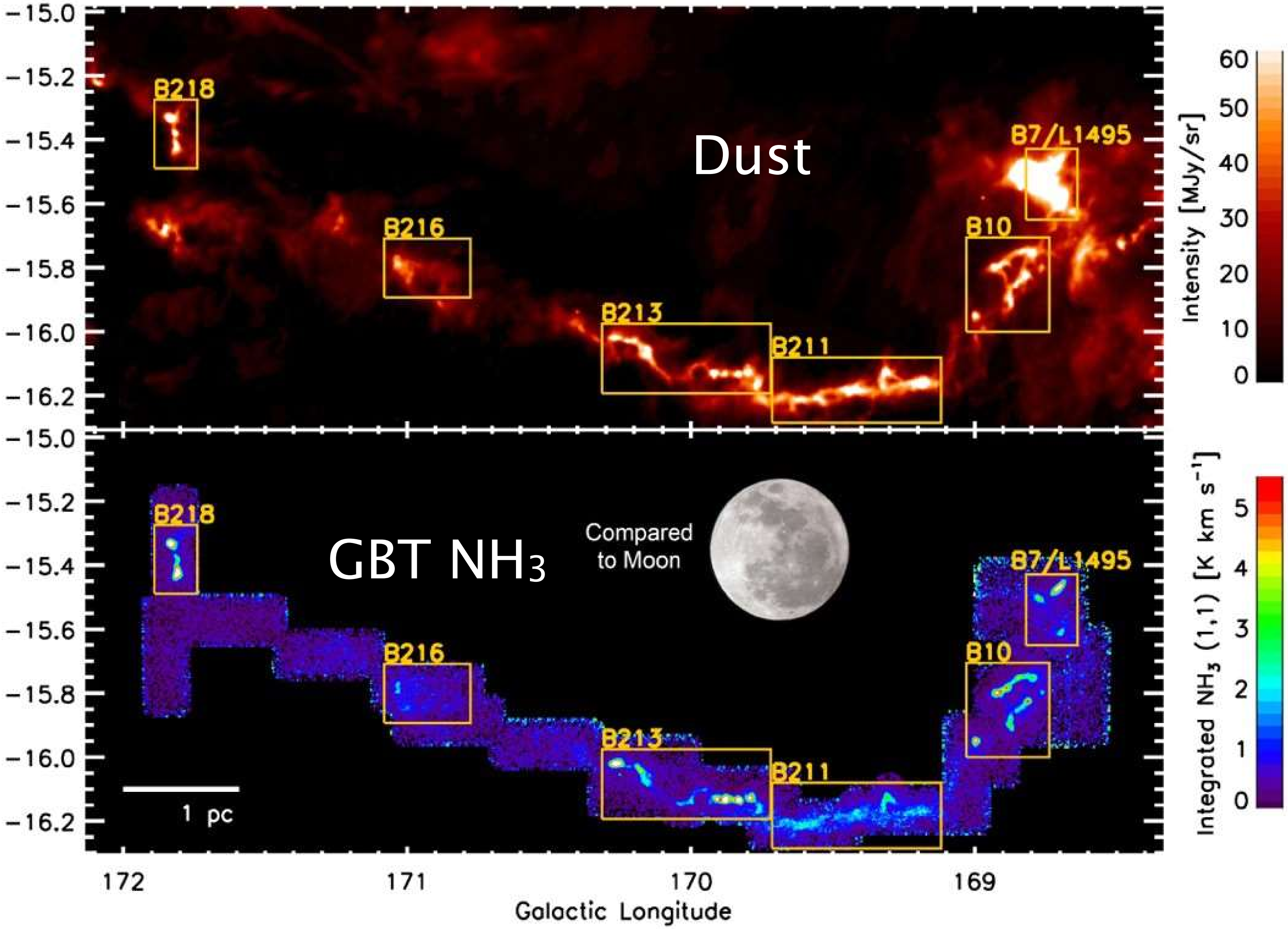


7 Pixel K band Receiver



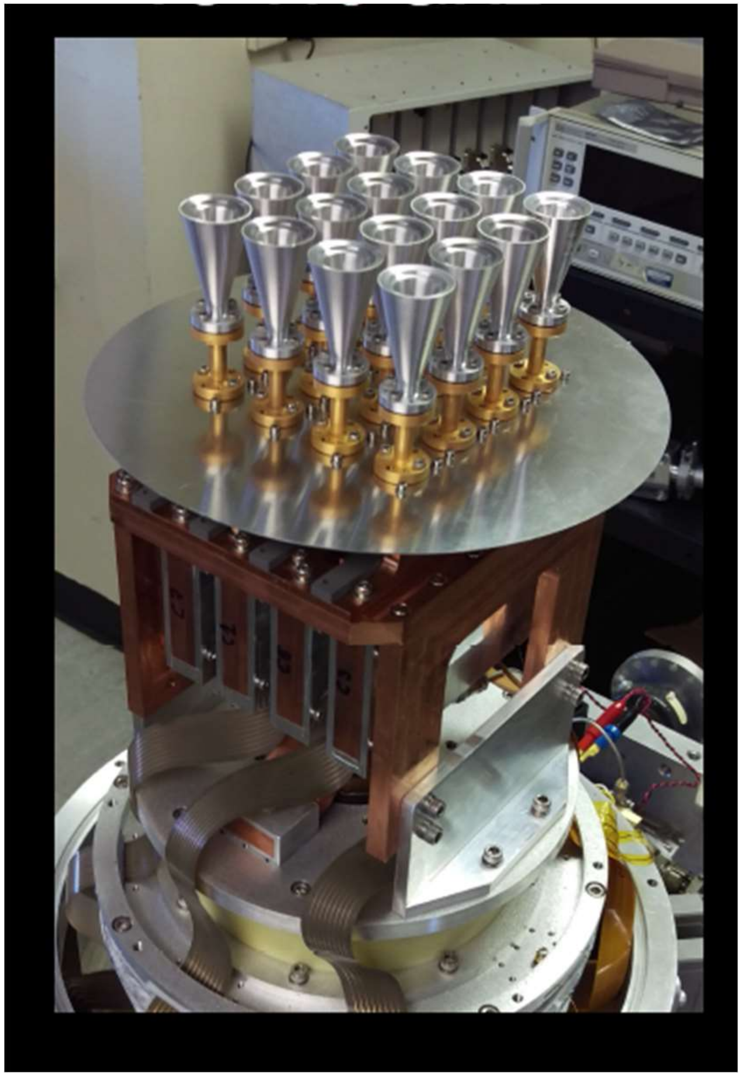


Star Formation in a Filament in Taurus



ARGUS

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

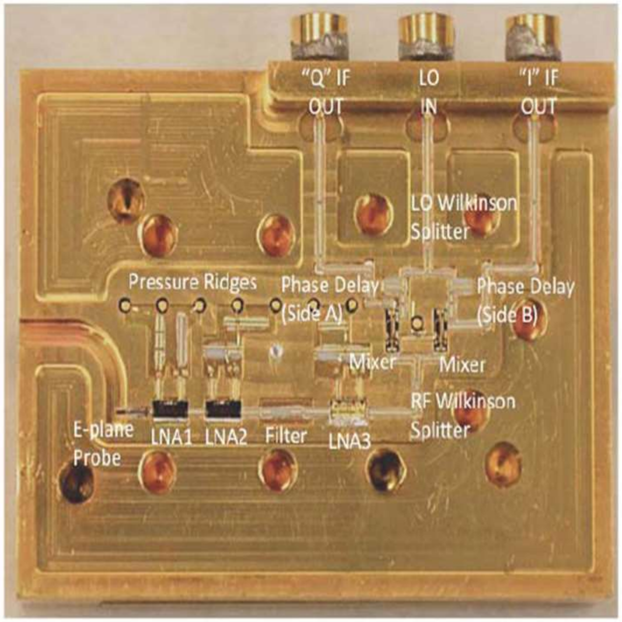


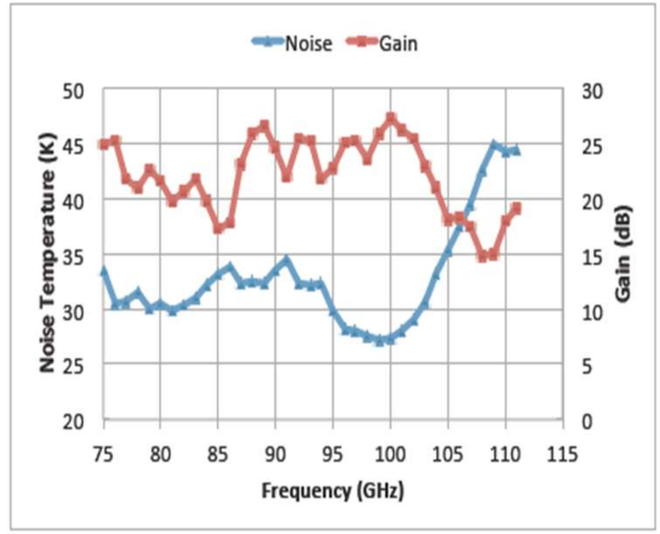
- 16 InP MMIC RF amplifiers cooled to 15 K
- Noise temperature < 50-60 K
- Open for general use

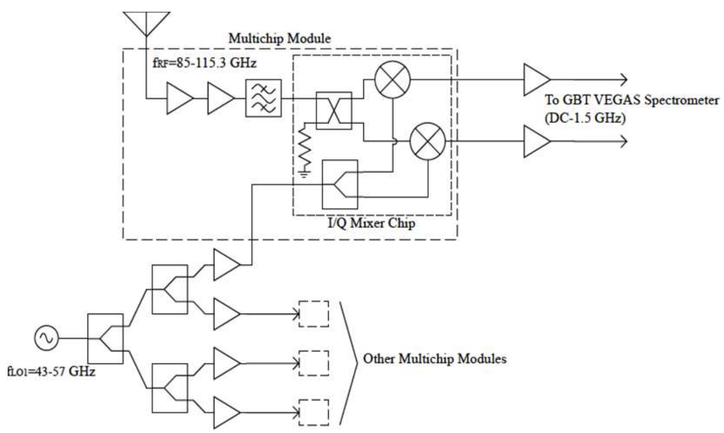
- A collaborative effort: S. Church [PI], M. Sieth, K. Devaraj, P. Voll (Stanford); A. Readhead, K. Cleary, R. Gawande (Caltech); L. Samoska, P. Kangaslahti, T. Gaier, P. Goldsmith (JPL), A. Harris (U. Maryland); J. Gunderson (U. Florida)

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

ARGUS



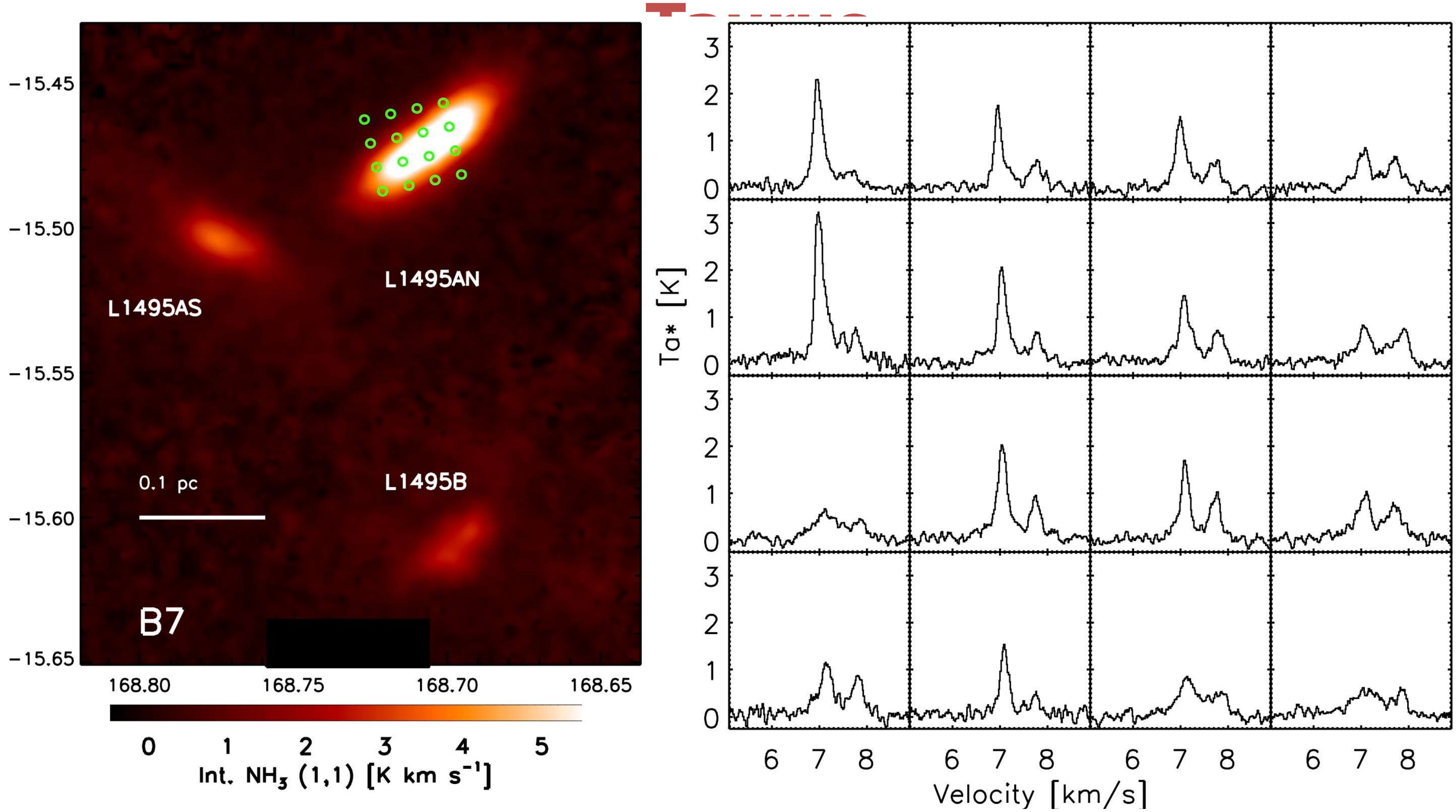




Component	Physical Temp. (K)	Gain (dB)	Contrib. to Rec. Noise Temp (K)
Cryostat window	300	-0.07	4.9
Entrance feedhorns	20	-0.04	0.2
MMIC module	20	25.0	33.9
Module to 20K board	20	-1.0	< 0.1
20 K board	20	-3.3	< 0.1
IF flex line	20-77	-1.4	0.1
77 K Board	77	-1.8	0.4
IF Amplifier	77	15	1.8
77 K Board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

ARGUS

HCO+ 10 min snapshot; 8" <-> 0.005 pc at Taurus



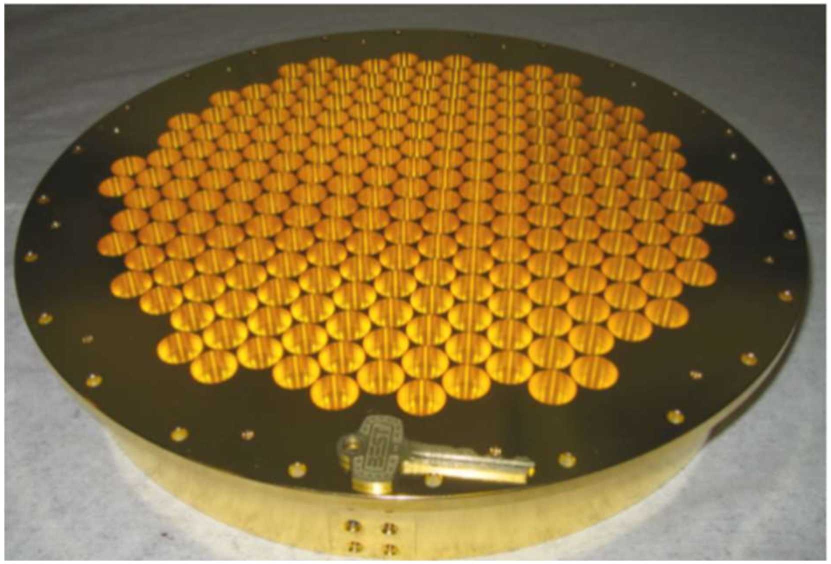
MUSTANG-2

223 Feedhorn Bolometer Array

4′ FoV; 10″ beam

63 μJy; 0.062 mK (T_A^*) across a 5′× 5 ′ field in 1 hour

Sunyaev–Zel'dovich effect



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

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

Phased Array Feed

Cryogenic PAF

$$SurveySpeed \propto N \left(\frac{\eta}{T_{sys}} \right)^2$$

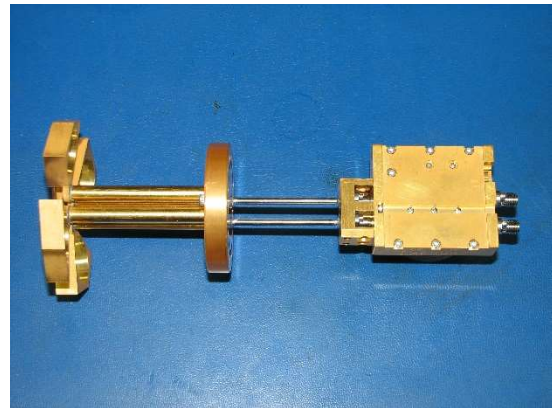
Sample aperture: $\frac{f\,\lambda}{D}$

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

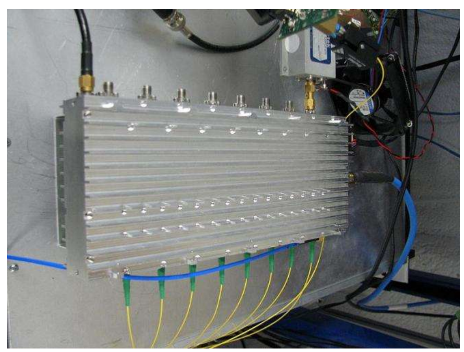
Authors:
Anish Roshi, D.; Shillue, W.; Simon, B.; Warnick, K. F.; Jeffs, B.; Pisano, D. J.; Prestage, R.; White, S.; Fisher, J. R.; Morgan, M.; Black, R.; Burnett, M.; Diao, J.; Ruzindana, M.; van Tonder, V.; Hawkins, L.; Marganian, P.; Chamberlin, T.; Ray, J.; Pingel, N. M.; Rajwade, K.; Lorimer, D. R.; Rane, A.; Castro, J.; Groves, W.; Jensen, L.; Nelson, J. D.; Boyd, T.; Beasley, A. J.

- 2018, AJ, 155, 202

- Formed L Band Phased Array GBT Feed



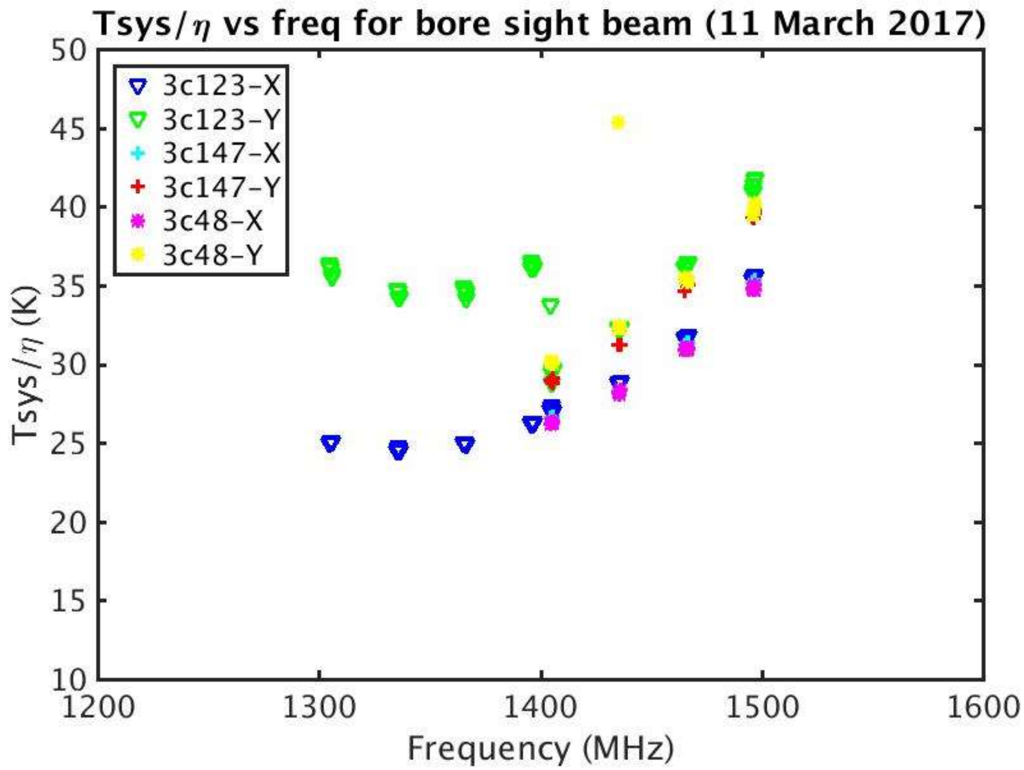
- The March 2017 GBT test was successful, demonstrating:
  - Seven low-noise beams on sky
  - Tsys/eff of central beam <30K
  - Close correspondence between measured result and model
- *Digital Data Links (DDL)*
- *BeamFormer Backend.*



FLAG

Sensitive Phased Array Feed

NRAO and Green Bank Observatory break the record for the coldest, most sensitive phased array feed system on Earth!



Ultrawideband Receiver

Ahmed Akgiray Thesis

New Technologies Driving
Decade-Bandwidth Radio Astronomy:

Quad-Ridged Flared Horn
&
Compound-Semiconductor LNAs

Thesis by

Ahmed Halid Akgiray

In Partial Fulfillment of the Requirements
for the Degree of
Doctor of Philosophy

49

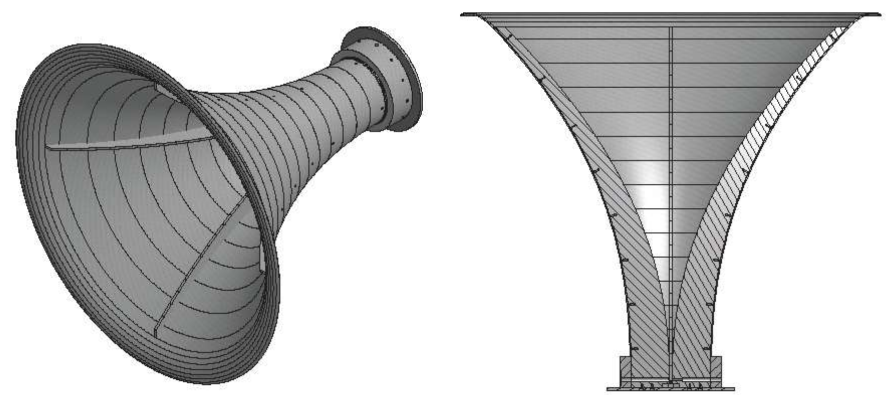
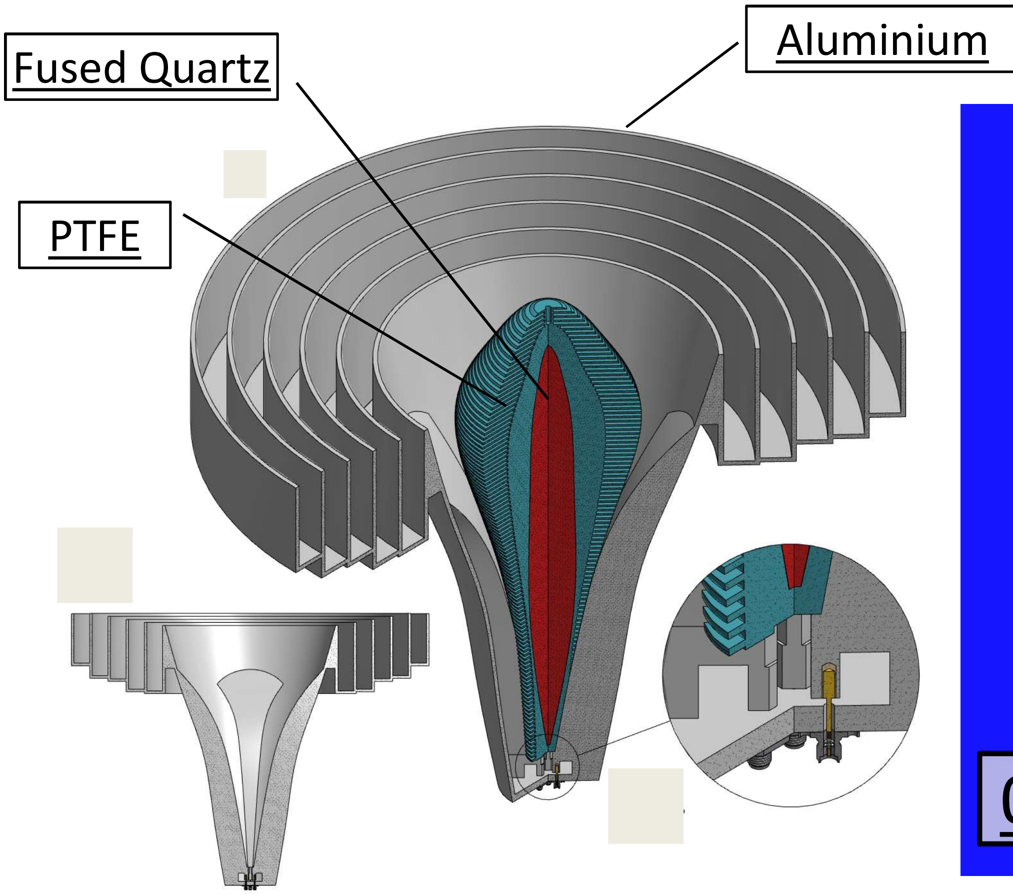
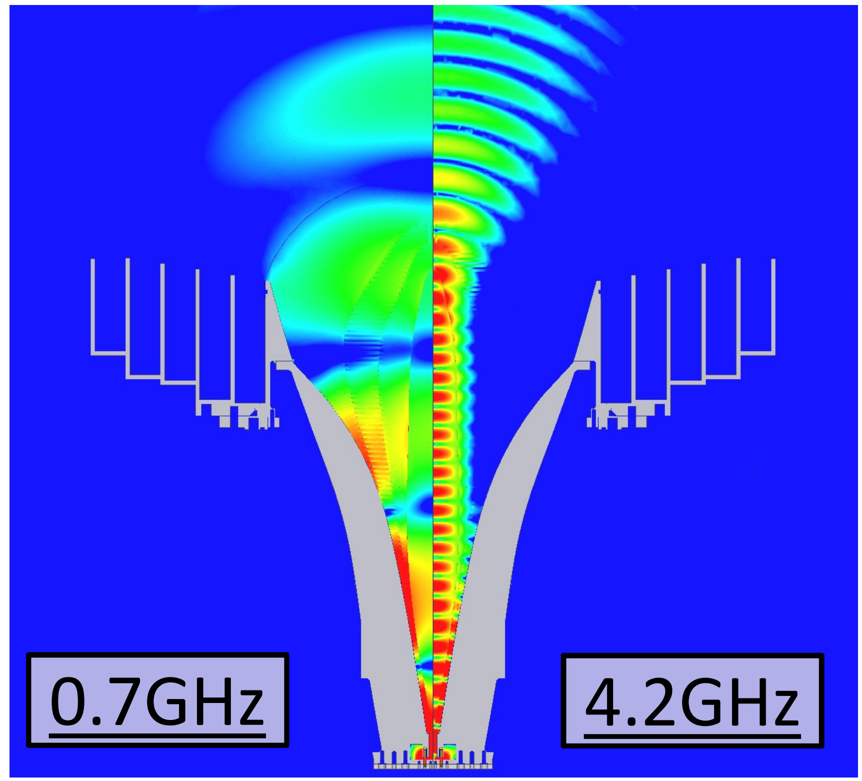


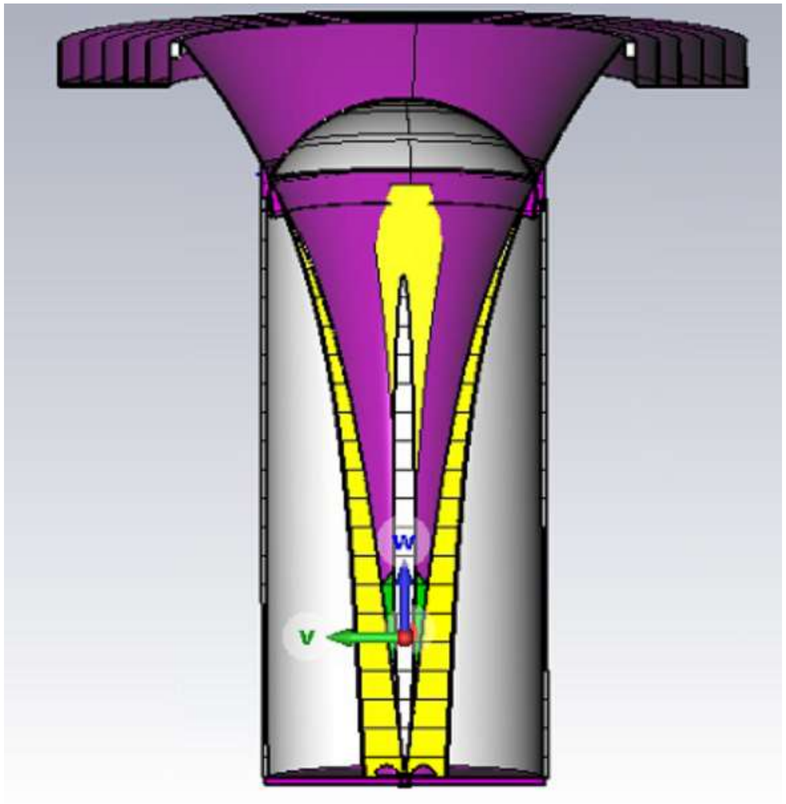
Figure 4.11: Three-dimensional CAD drawings of the high-gain quad-ridge horn. Feed diameter is 82 cm ($1.9\lambda_{lo}$) and length is 73.2 cm ($1.7\lambda_{lo}$) with $f_{lo} = 0.7$ GHz

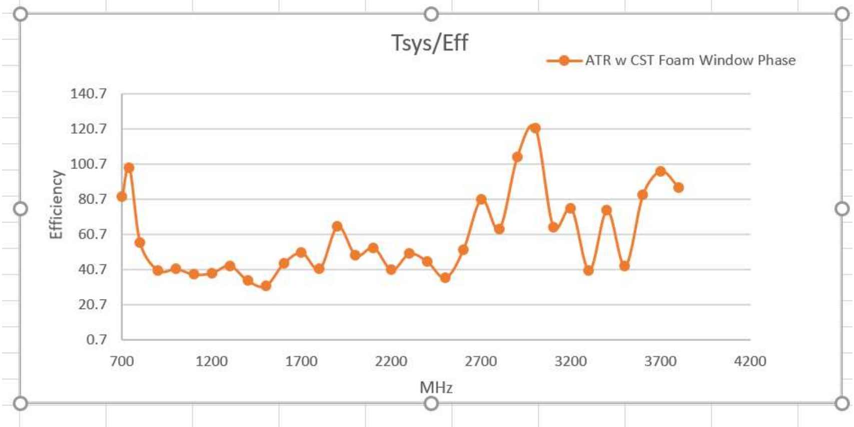
4.3 High-Gain QRFH


Fused Quartz
Aluminium
PTFE

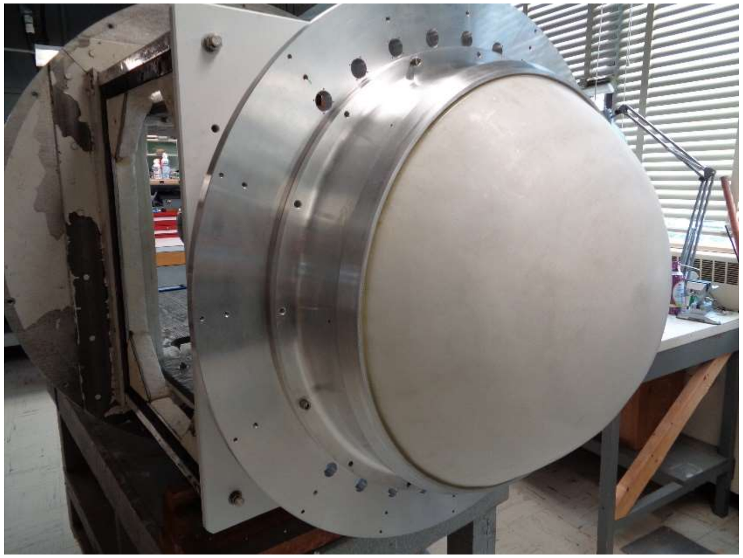

0.7GHz
4.2GHz

• Wideband Feed Development





- 0.7 to 4 GHz
- Corrugation
- Quartz Spear
- Quartz Vacuum Window



UWBR Photographs