Fundamentals of the GBT and Single-Dish Radio Telescopes

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National Radio Astronomy Observatory
Green Bank, WV

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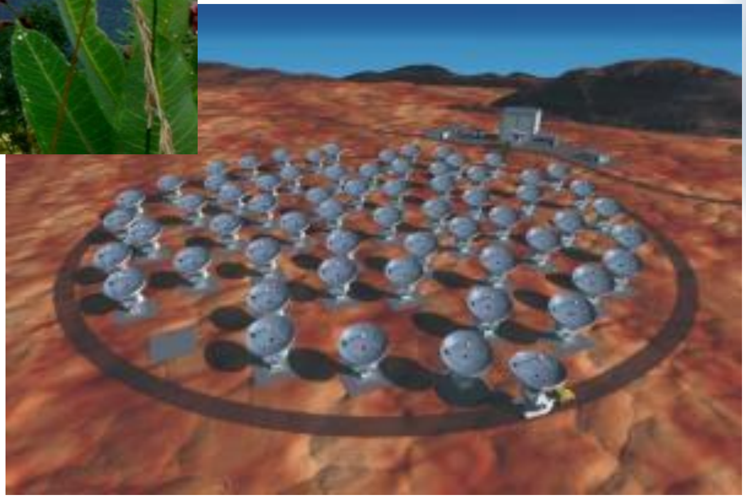
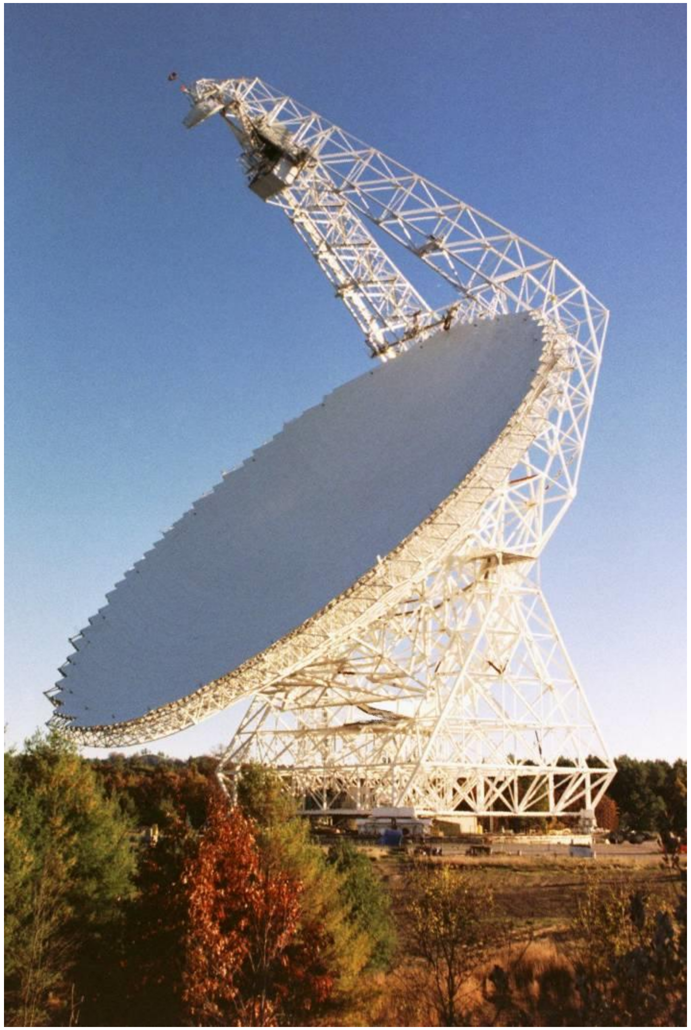
National Radio Astronomy Observatory

- National Laboratory
- Founded in 1954
- Funded by the National Science Foundation



Telescope Structure and Optics



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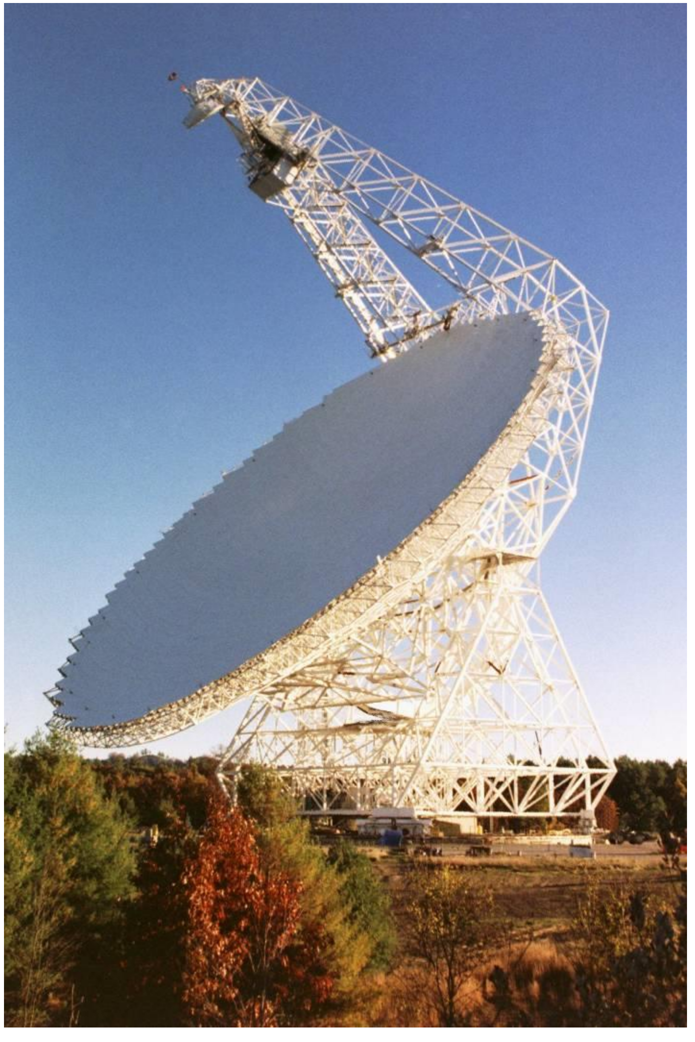
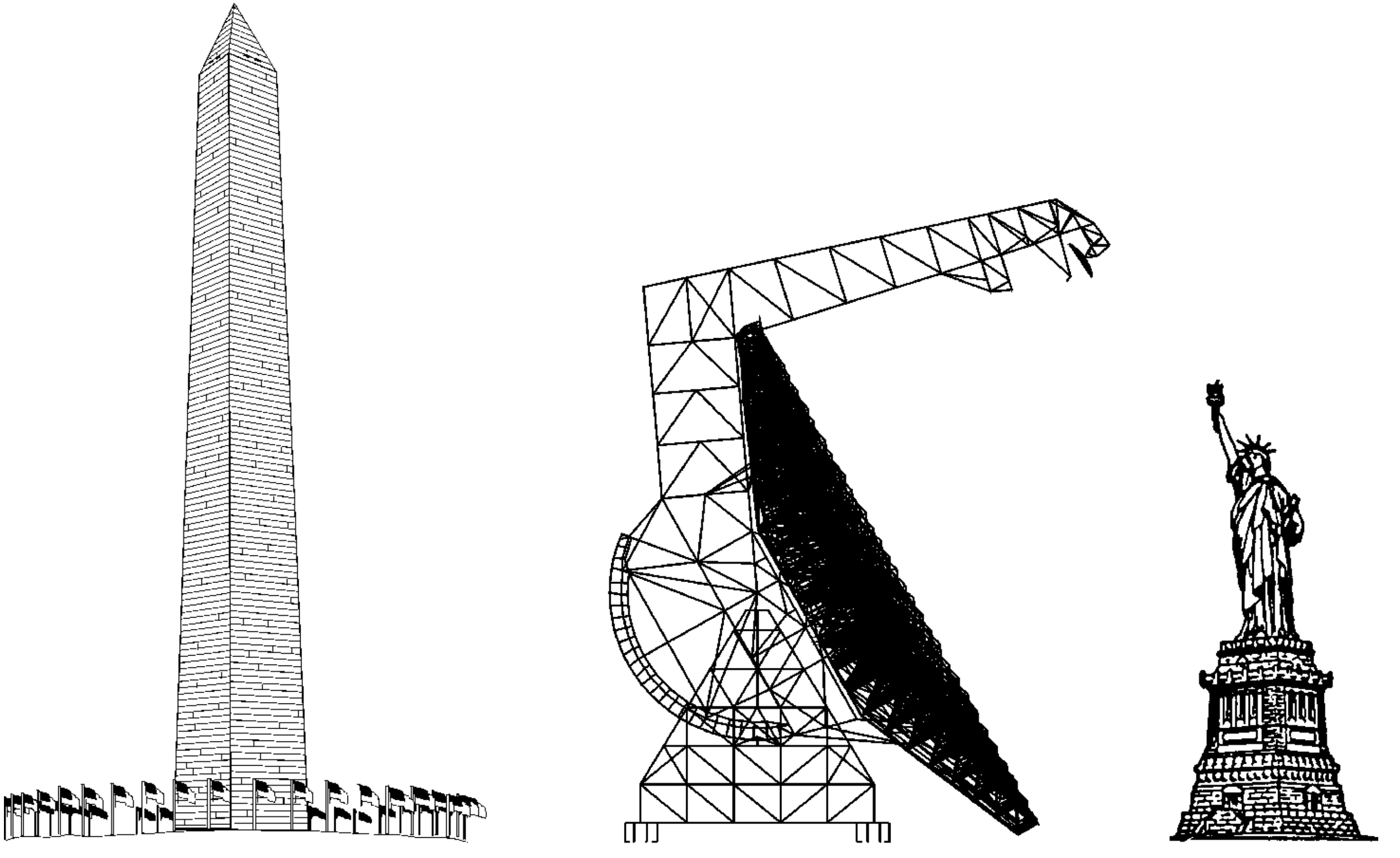
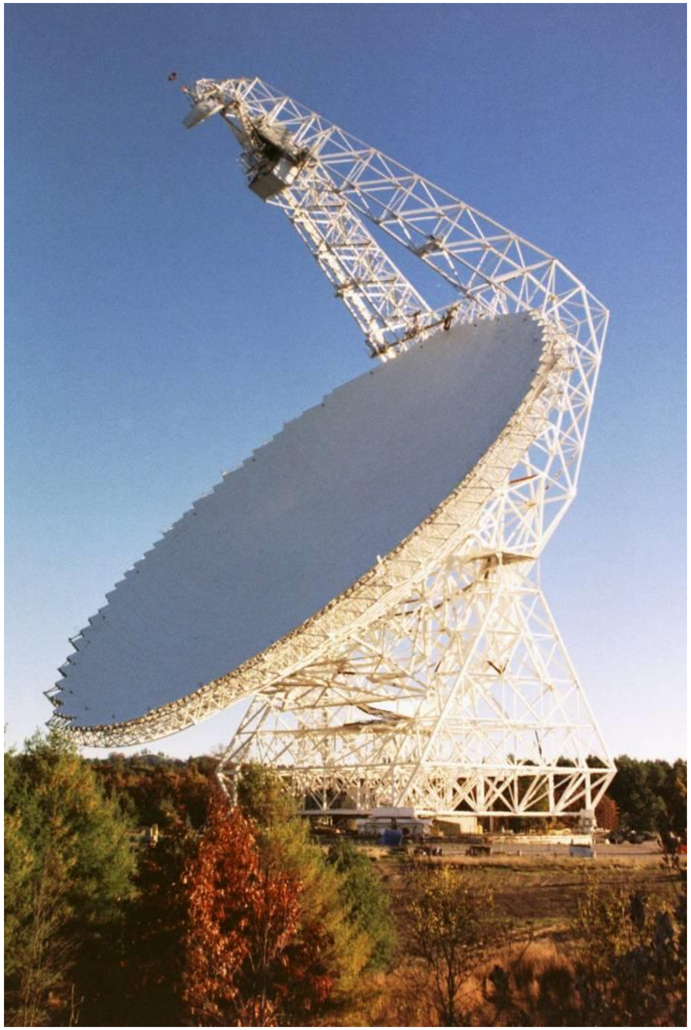


Telescope Structure and Optics



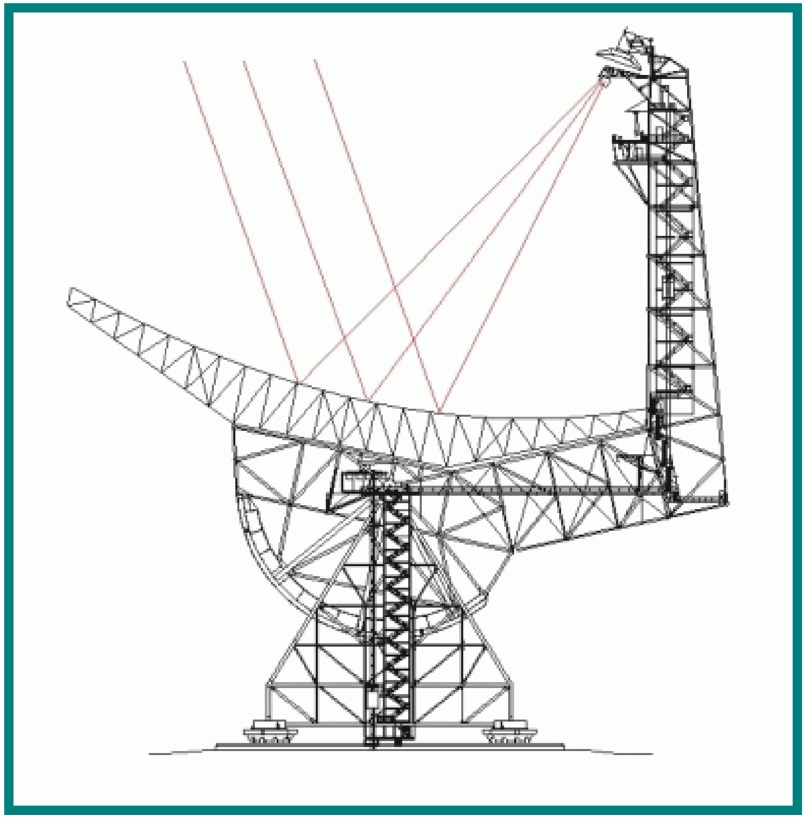
- Large 100-m Diameter:
  - High Sensitivity
  - High Angular Resolution – wavelength / Diameter

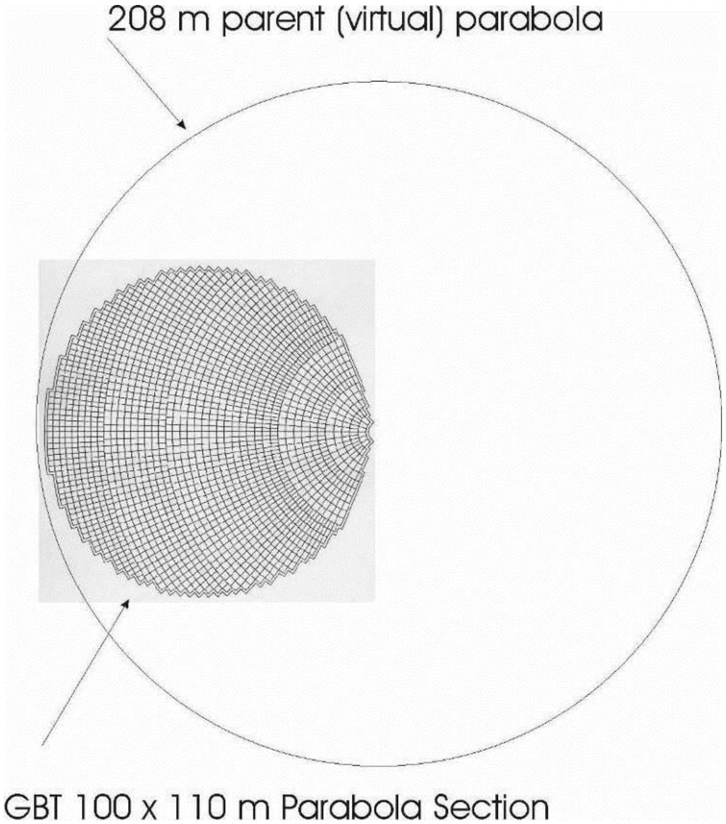
Telescope Structure and Optics



GBT Telescope Optics

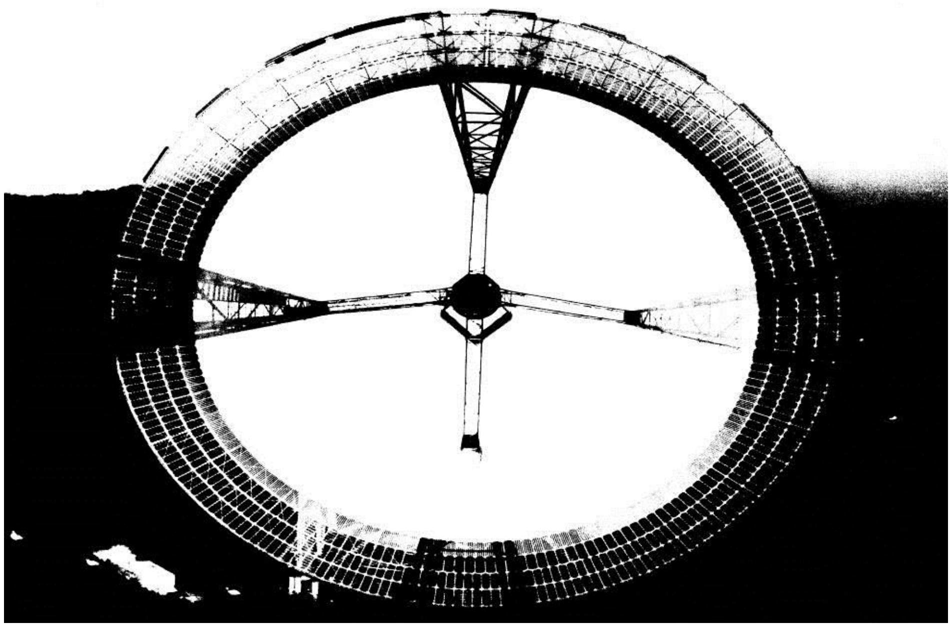
- 110 m x 100 m of a 208 m parent paraboloid
  - Effective diameter: 100 m
  - Off axis - Clear/Unblocked Aperture



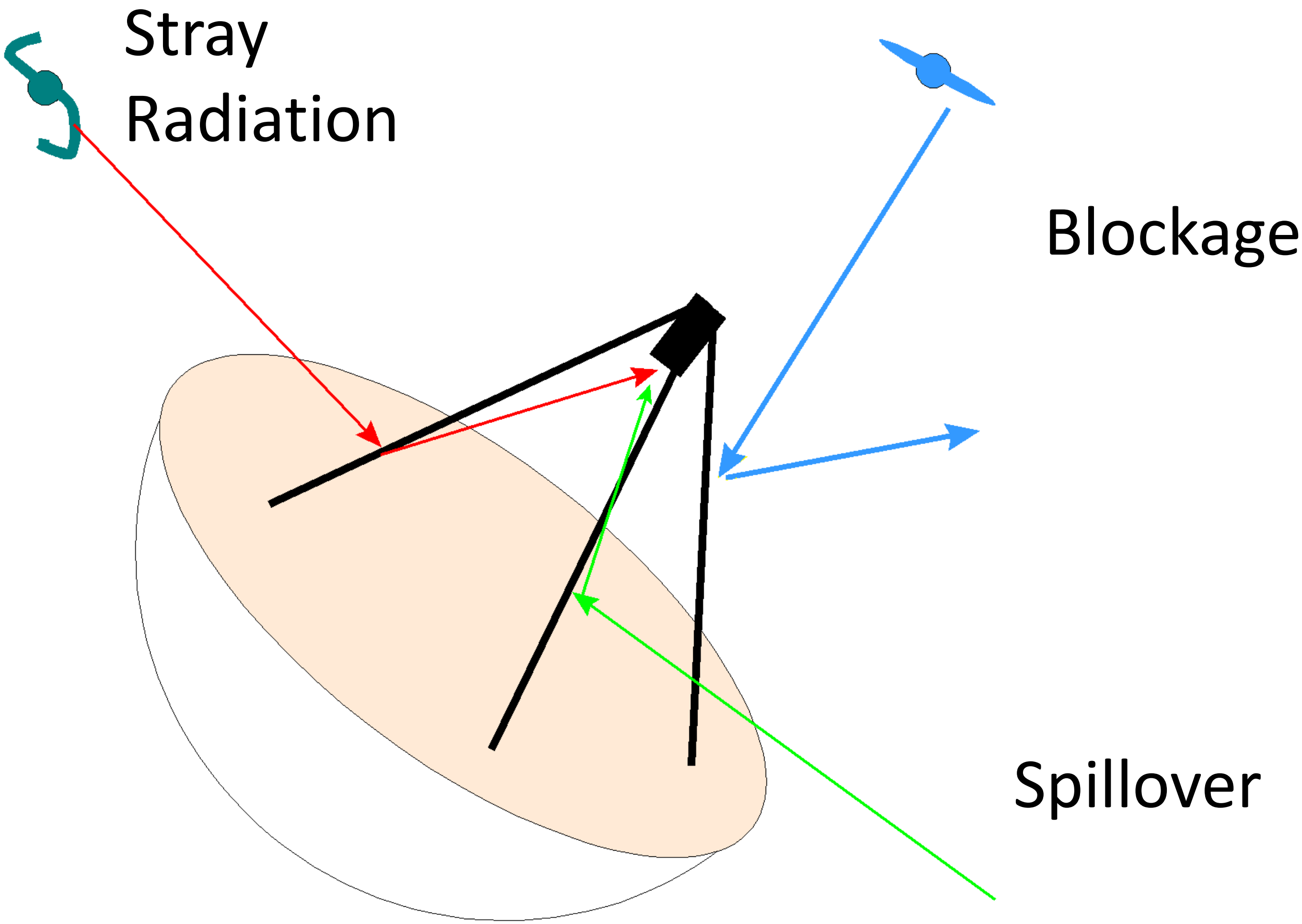


Telescope Optics

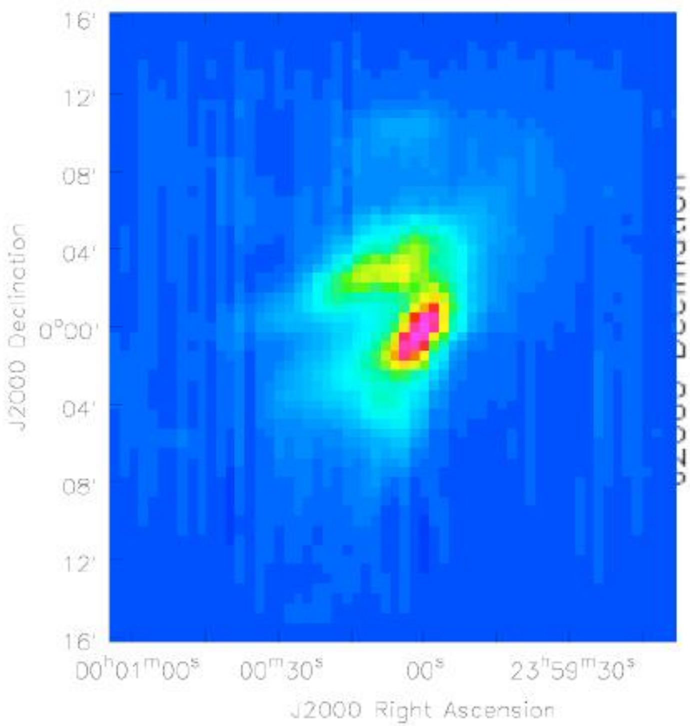
- High Dynamic Range
- High Fidelity Images

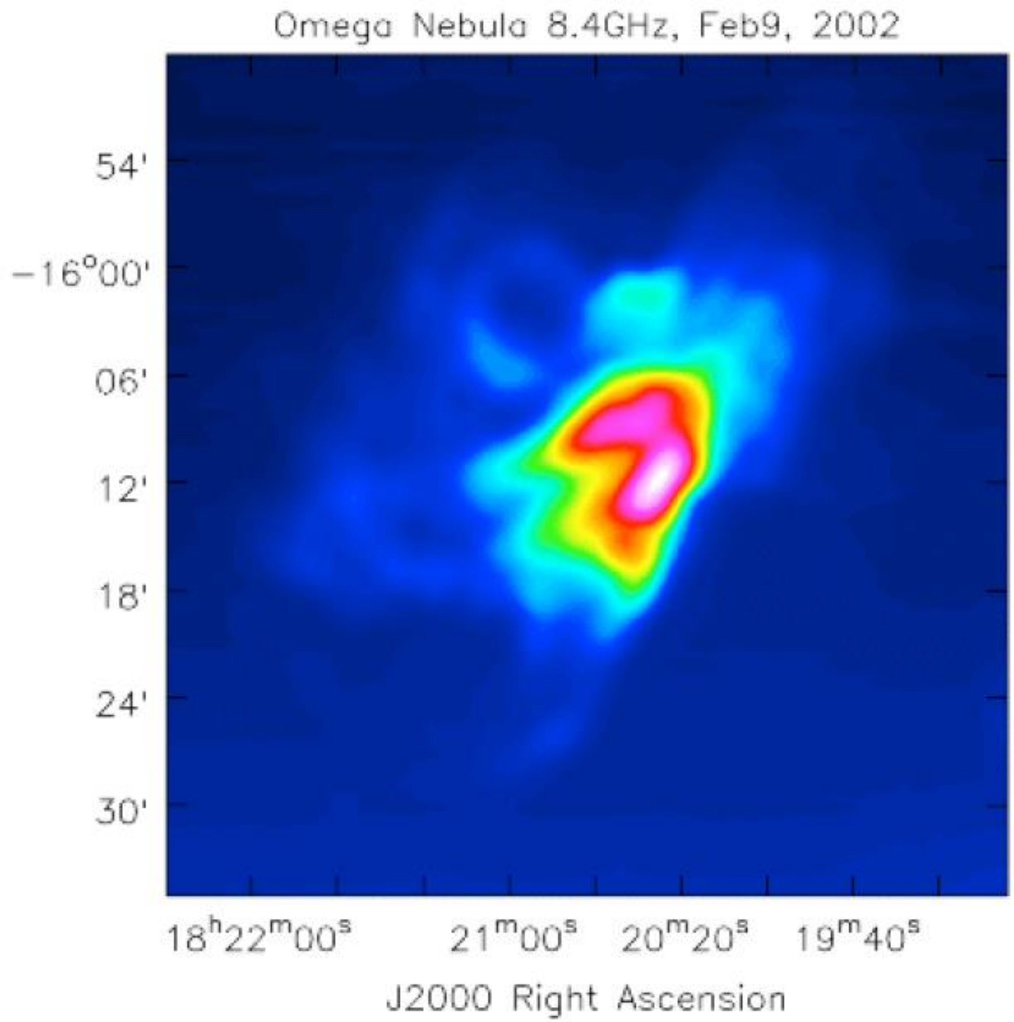


Telescope Optics



Telescope Optics





Telescope Optics

Prime Focus: Retractable boom

Gregorian Focus: 8-m subreflector - 6-degrees of freedom

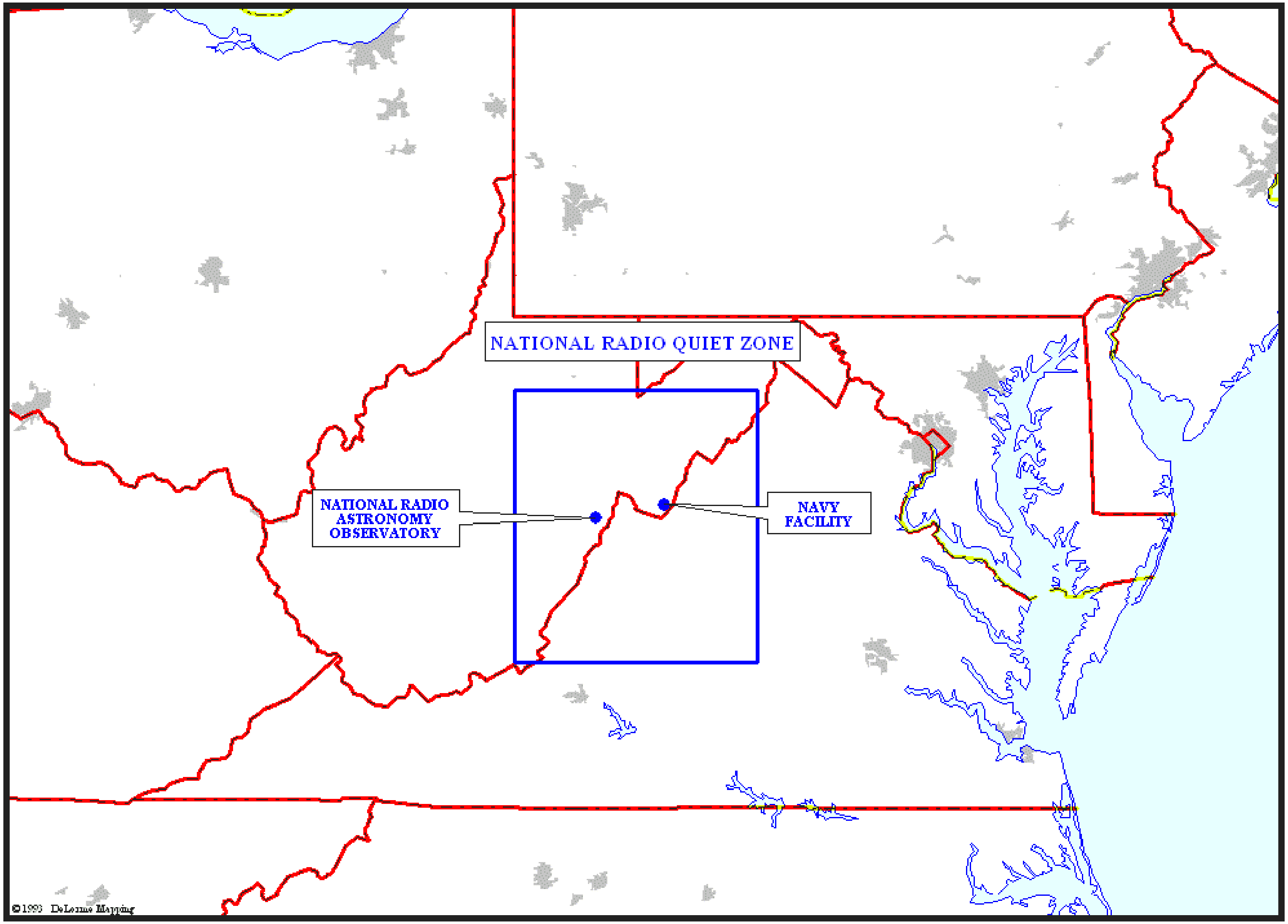
Telescope Optics

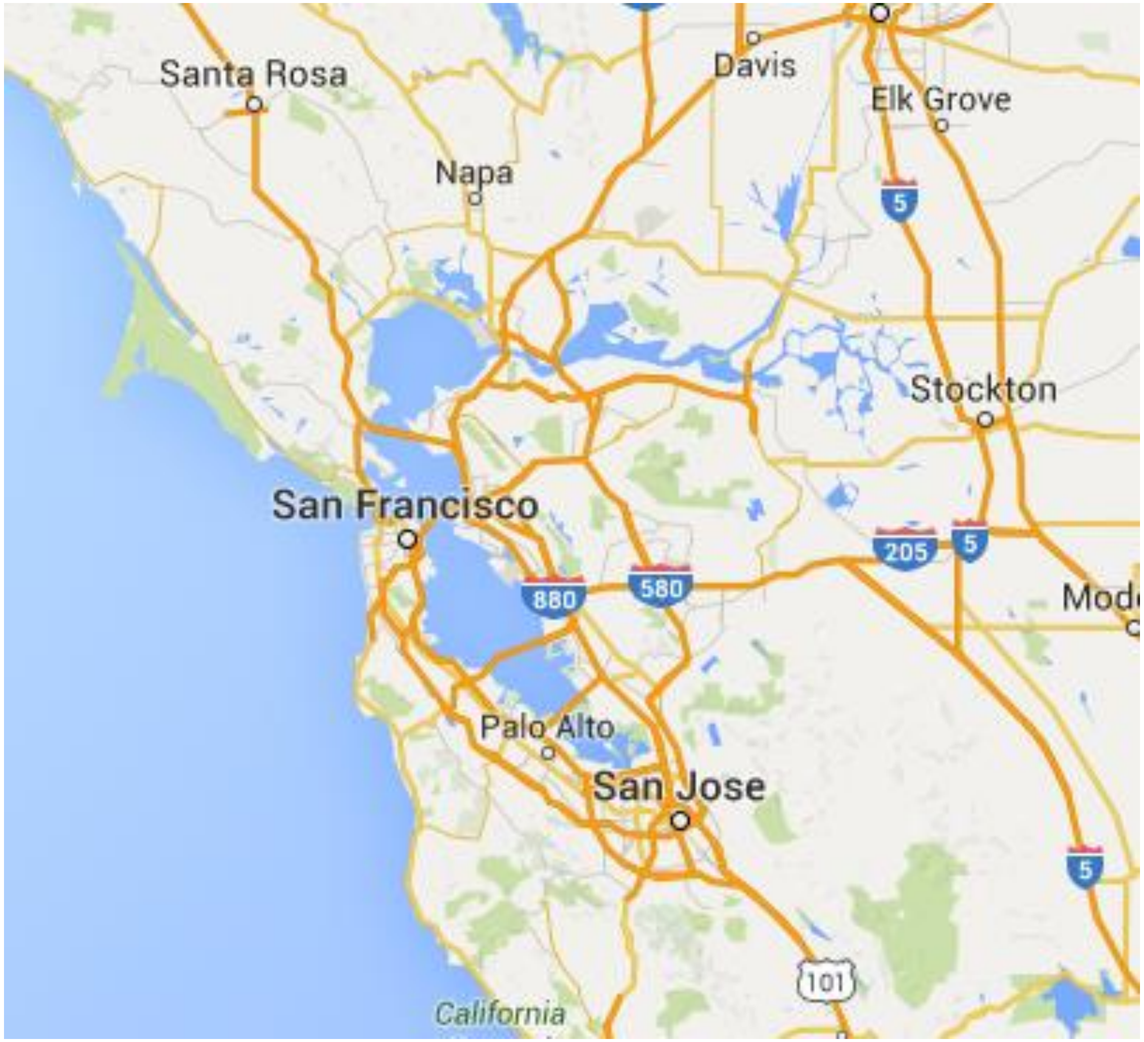
Rotating Turret with 8 receiver bays

Telescope Structure

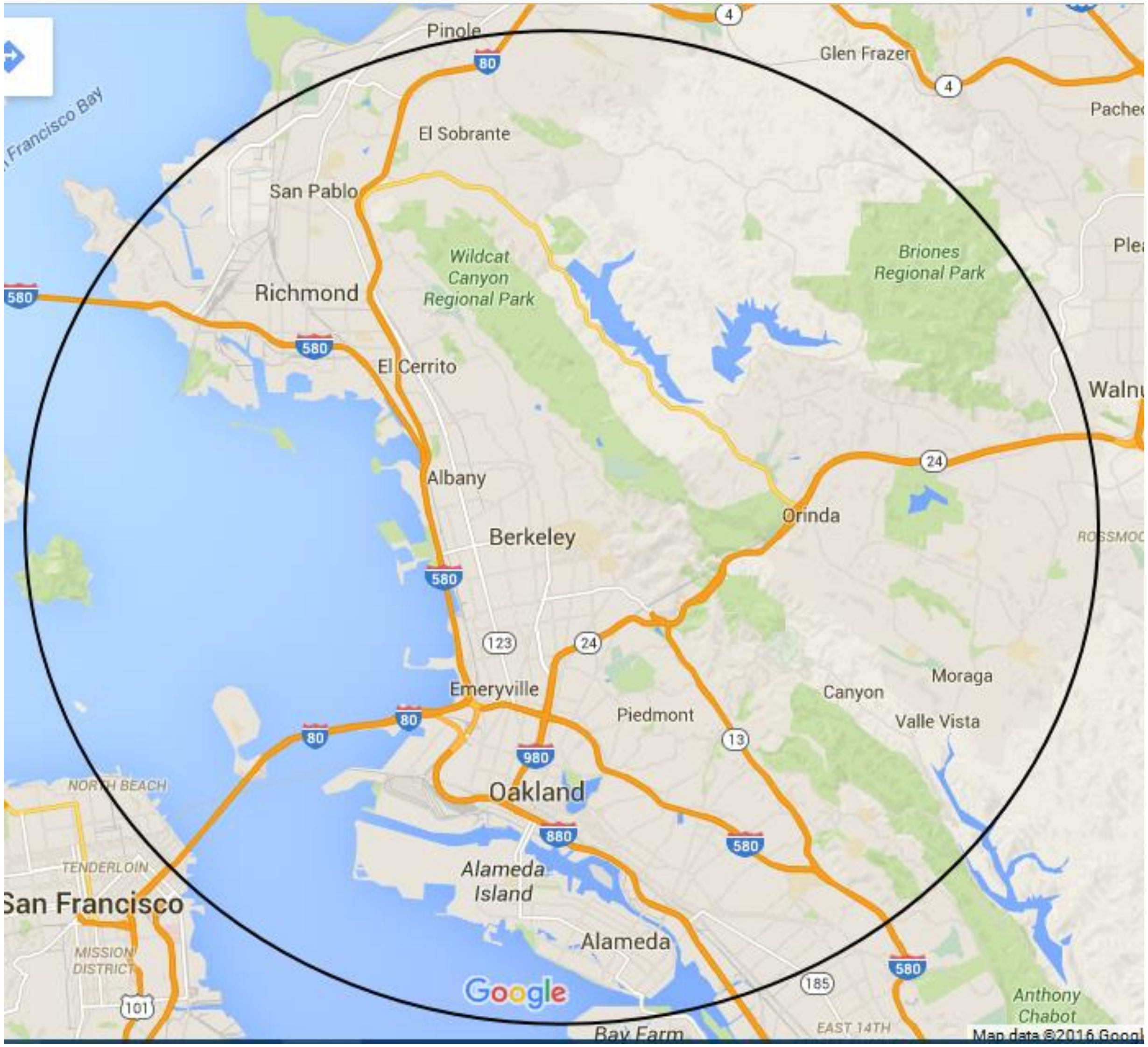
- Fully Steerable
  - Elevation Limit: 5°
  - Can observe 85% of the entire Celestial Sphere
- Slew Rates: Azimuth - 40°/min; Elevation - 20°/min

National Radio Quiet Zone



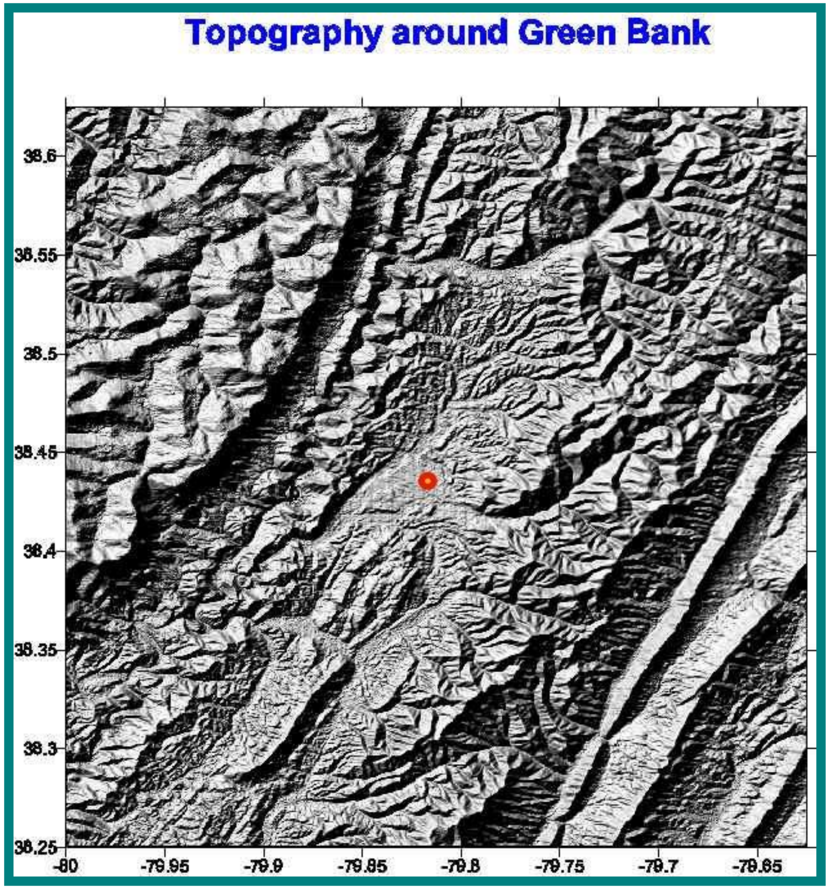


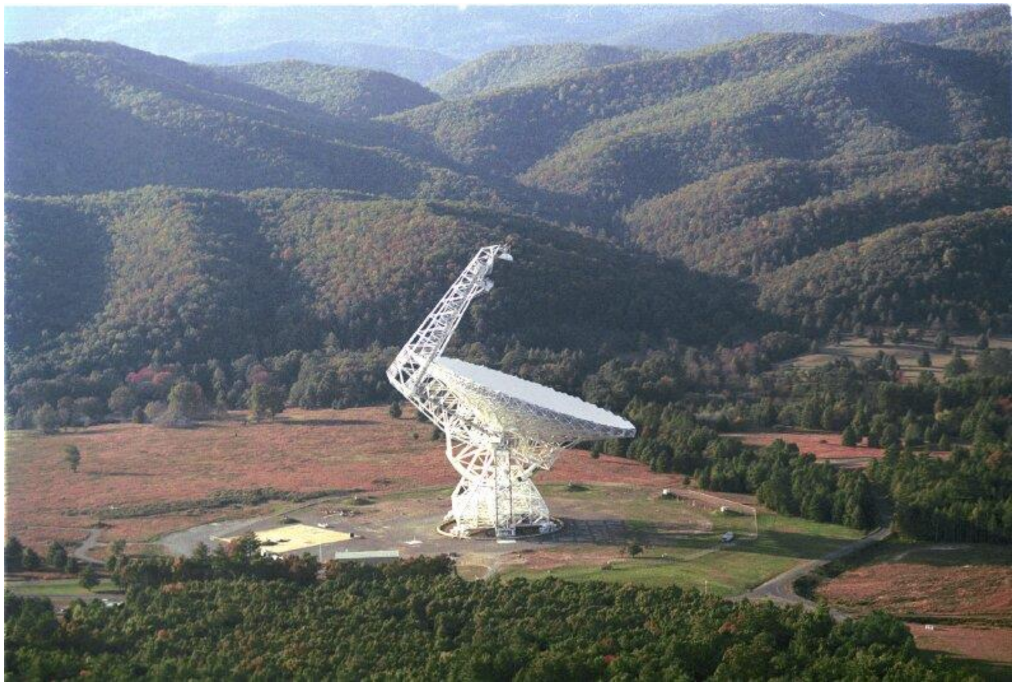
Santa Rosa
Davis
Elk Grove
Napa
5
Stockton
San Francisco
205
5
880
580
Palo Alto
San Jose
5
101
California



Pinole
Glen Frazer
El Sobrante
San Pablo
Richmond
Wildcat Canyon Regional Park
Briones Regional Park
El Cerrito
Albany
Berkeley
Orinda
Emeryville
Piedmont
Canyon
Moraga
Valle Vista
Oakland
Alameda Island
Alameda
San Francisco
NORTH BEACH
TENDERLOIN
MISSION DISTRICT
Anthony Chabot
EAST 14TH
Bay Farm
Map data ©2016 Google

National Radio Quiet Zone





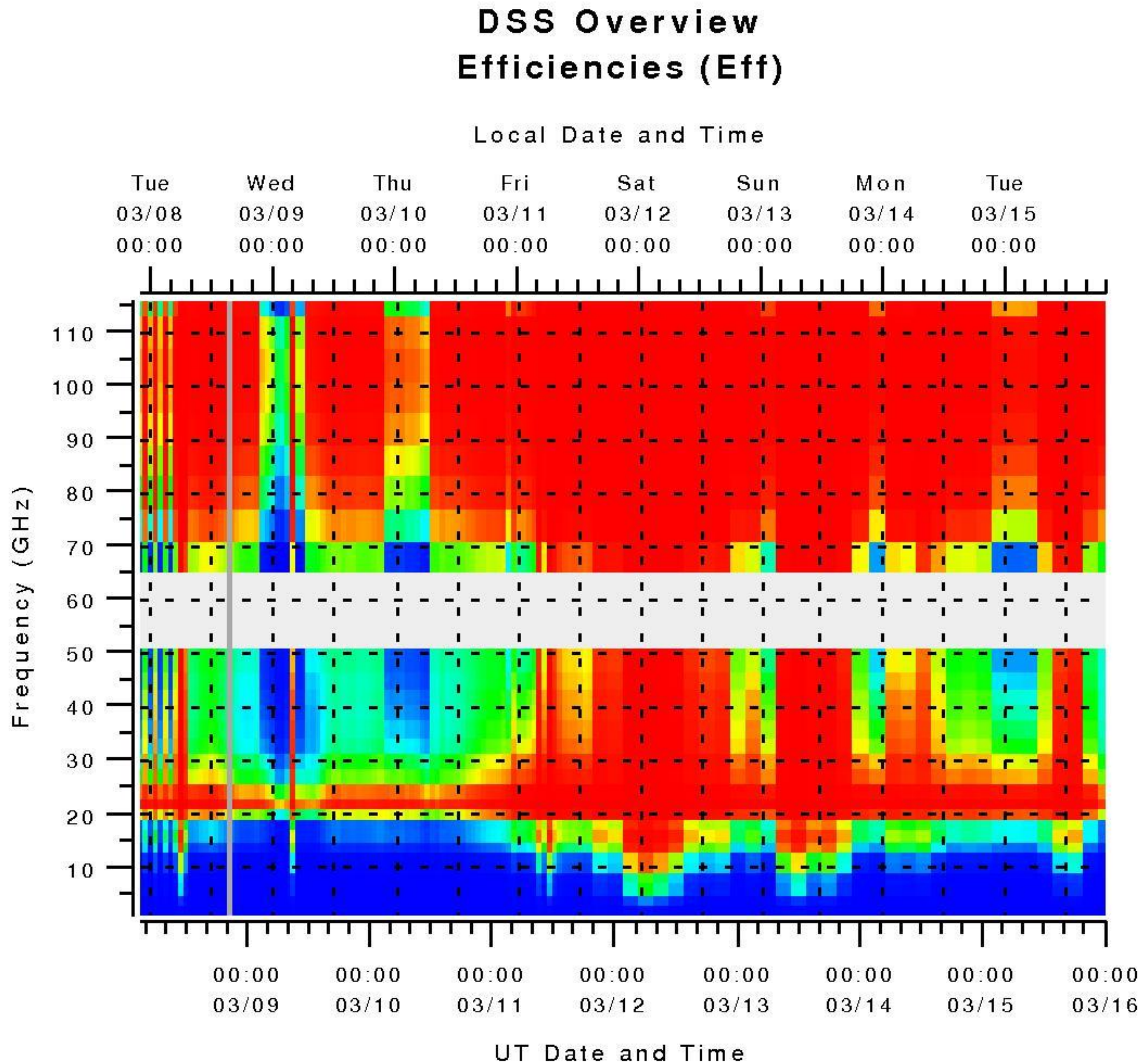
Atmosphere

- Index of Refraction
  - Weather (i.e., time) and frequency dependent
  - Real Part: Bends the light path
  - Imaginary part: Opacity
    - http://www.gb.nrao.edu/~rmaddale/Weather/
- Winds
  - Wind-induced pointing errors
  - Safety

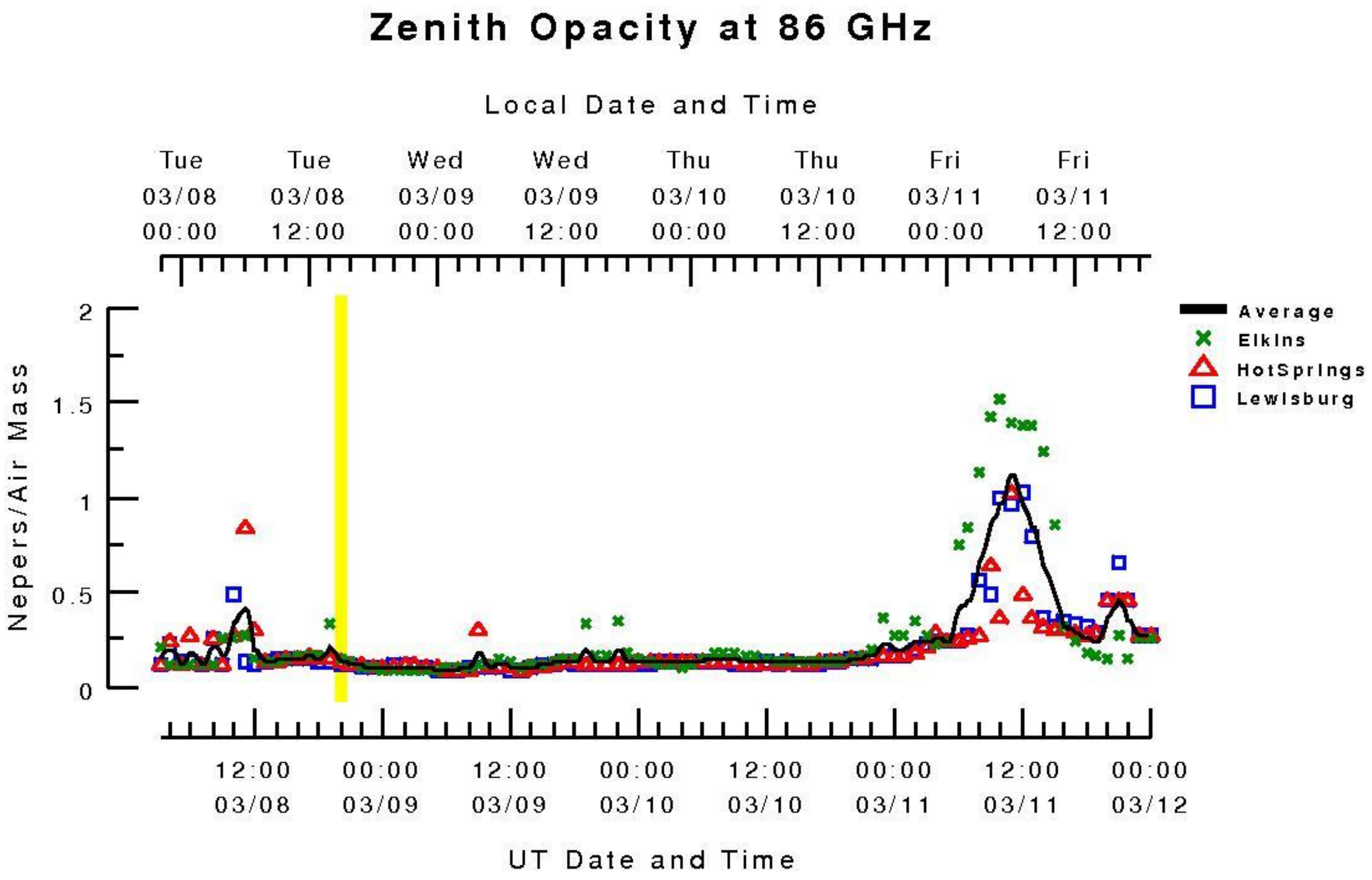
The Influence of the Atmosphere and Weather at cm- and mm-wavelengths

- Opacity
  - Calibration
  - System performance – Tsys
  - Observing techniques
  - Hardware design
- Refraction
  - Pointing
  - Air Mass
    - Calibration
    - Interferometer & VLB phase errors
  - Aperture phase errors
- Cloud Cover
  - Continuum performance
  - Calibration
- Winds
  - Pointing
  - Safety
- Telescope Scheduling
  - Proportion of proposals that should be accepted
  - Telescope productivity

Weather Forecasts for Radio Astronomy



Weather Forecasts for Radio Astronomy

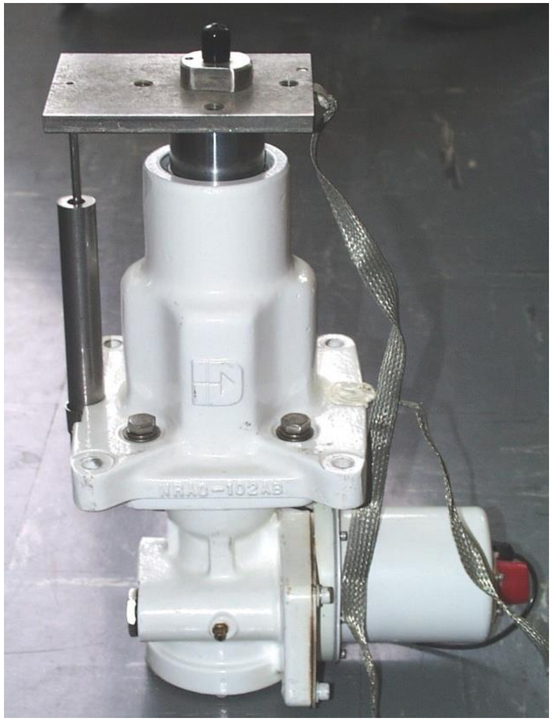


Telescope Structure

GBT active surface system

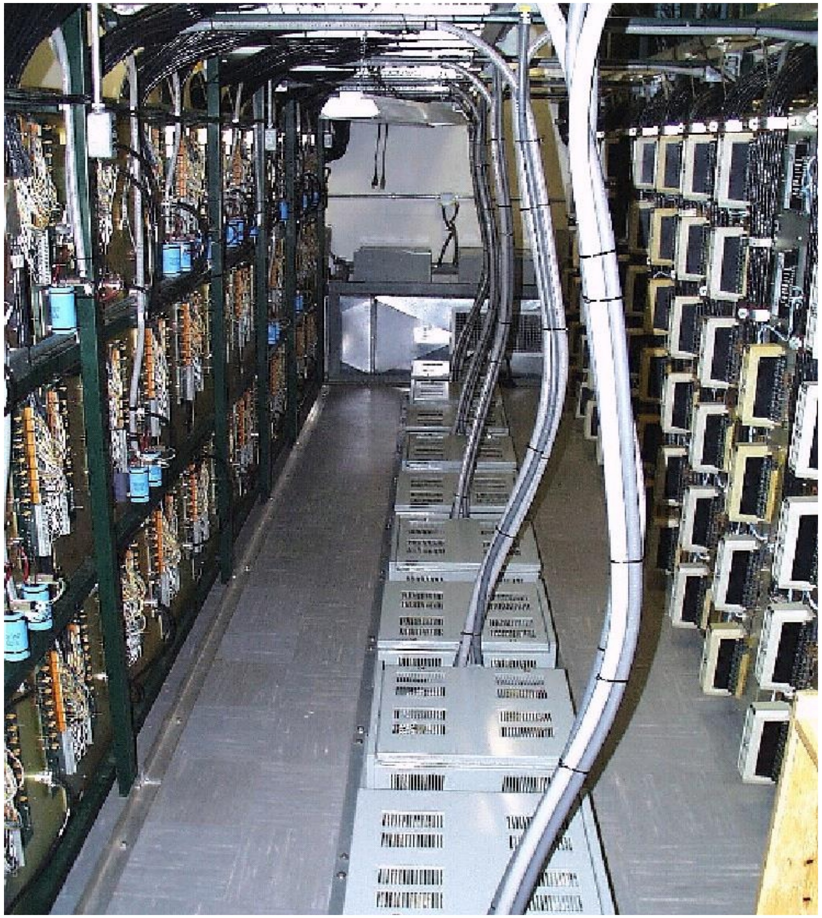
- Surface has 2004 panels
  - average panel rms: 68 µm
- 2209 precision actuators

Surface Panel Actuators



One of 2209 actuators.

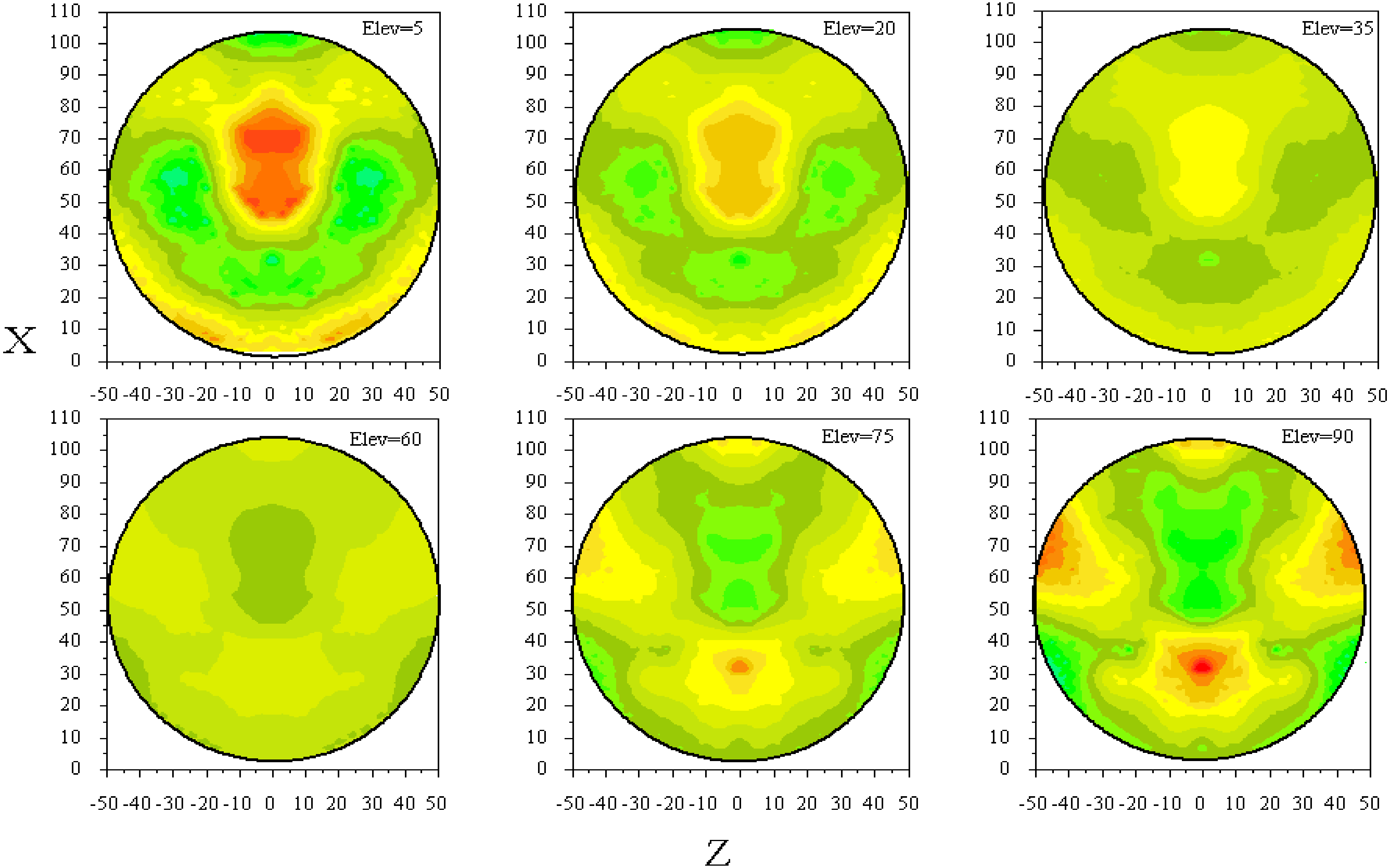
- Actuators are located under each set of surface panel corners



Actuator Control Room

- 26,508 control and supply wires terminated in this room

Finite Element Model Predictions



Mechanical adjustment of the panels

Image quality and efficiency

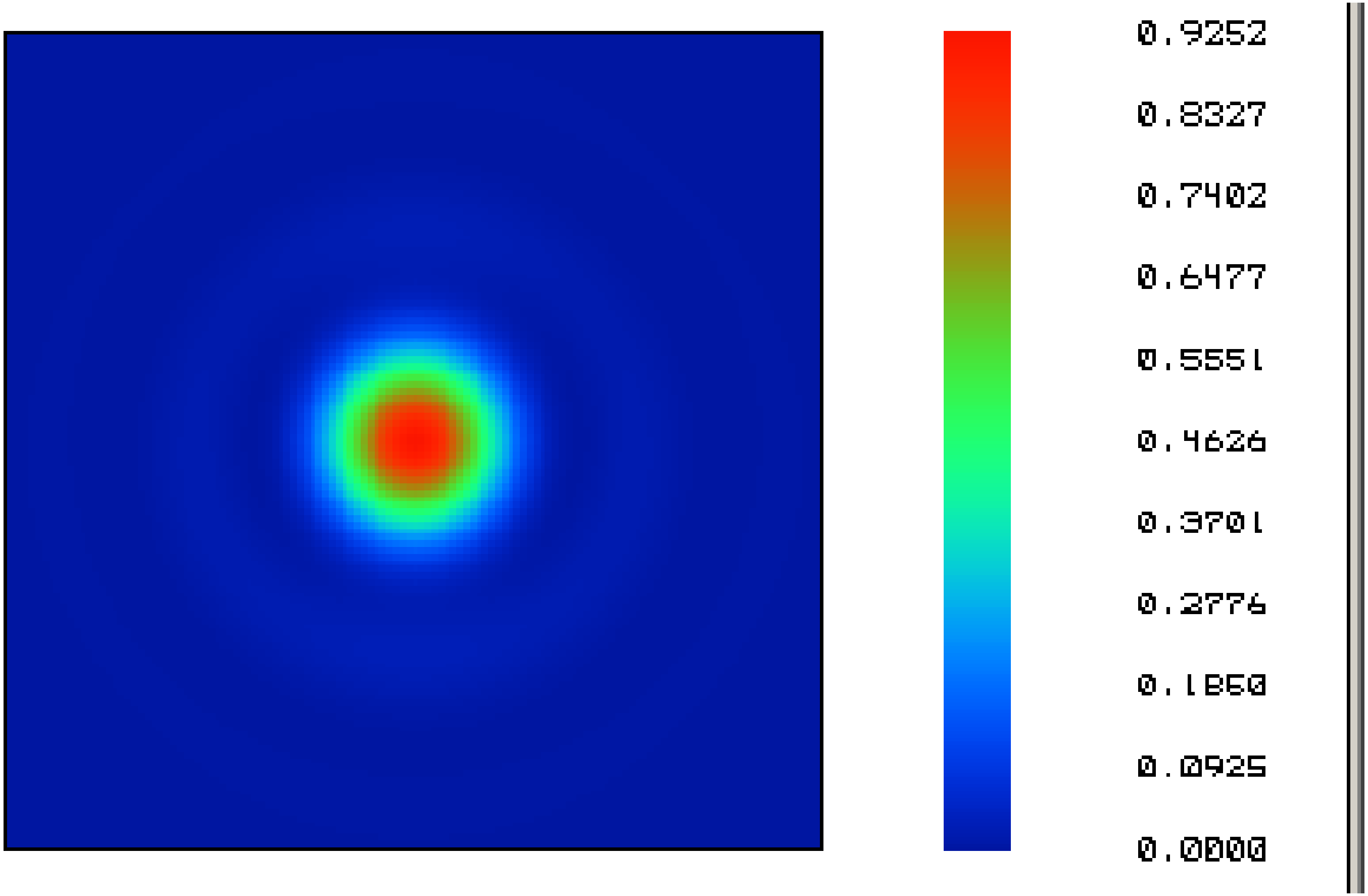
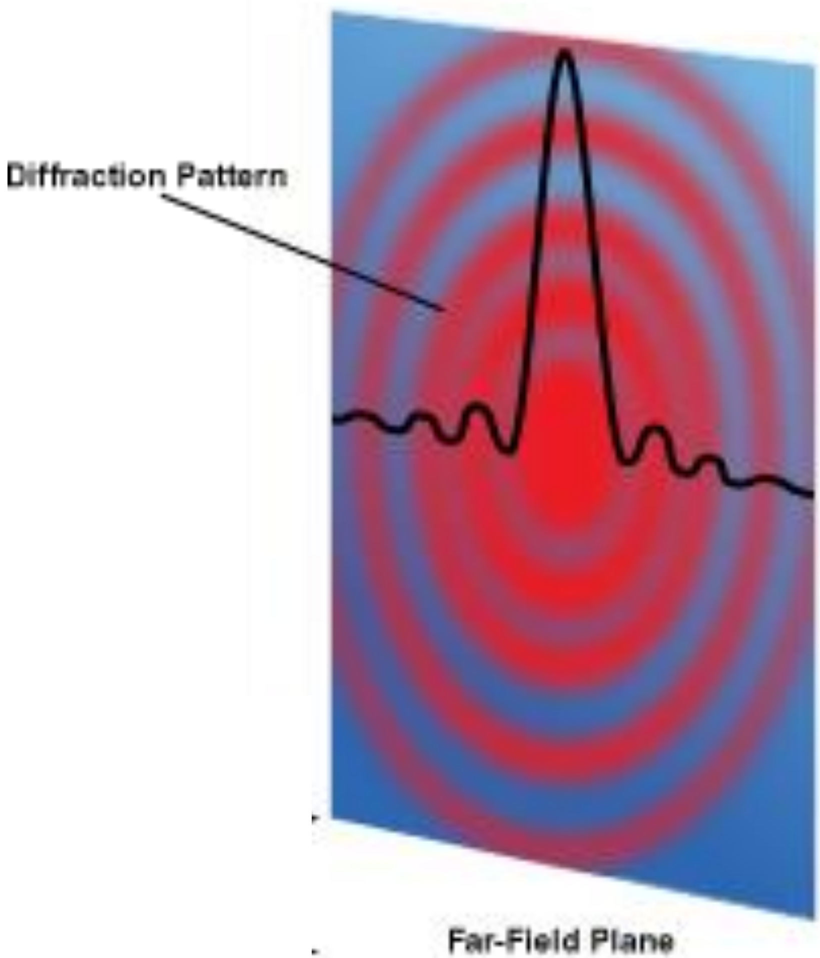


Image quality, efficiency, resolution



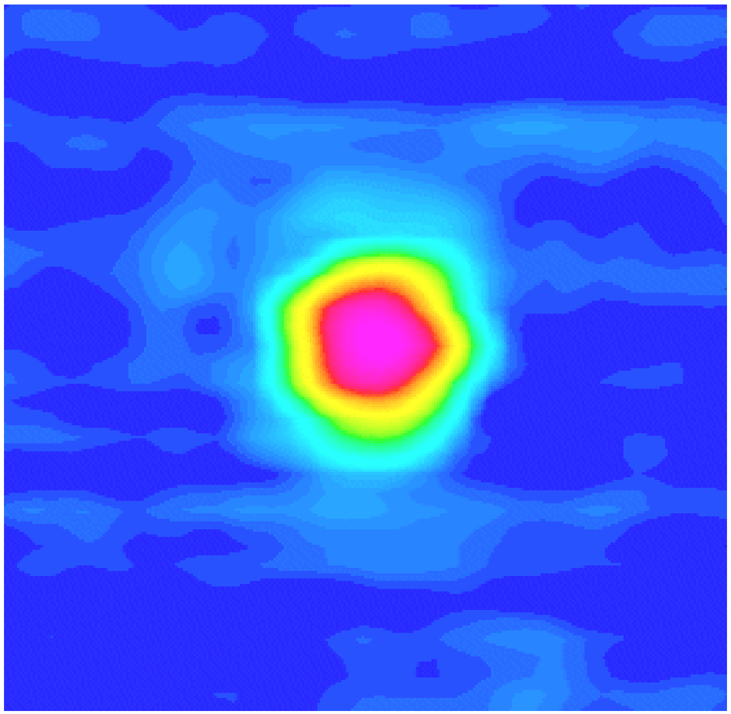
$$\theta_{HPBW} = {}^{1.2\lambda}\!/_{D}$$

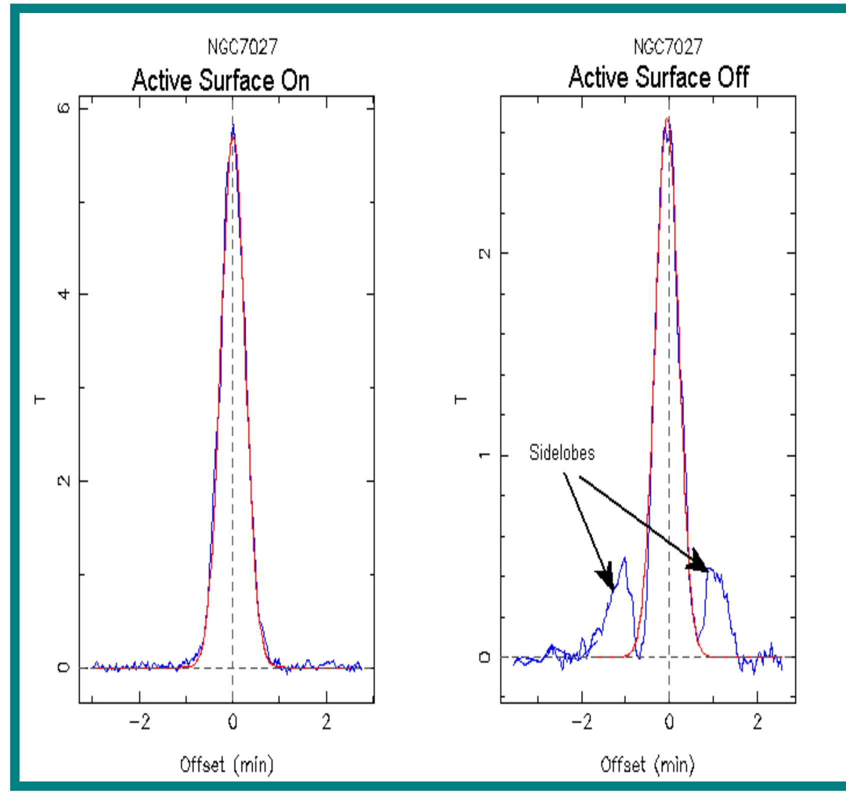
$$= 40' \text{ at } 300\,\text{MHz}\,(1\,\text{m})$$

$$= 9' \text{ at } 1420\,\text{MHz}\,(21\,\text{cm})$$

$$= 6.5'' \text{ at } 115\,\text{GHz}\,(3\,\text{mm})$$

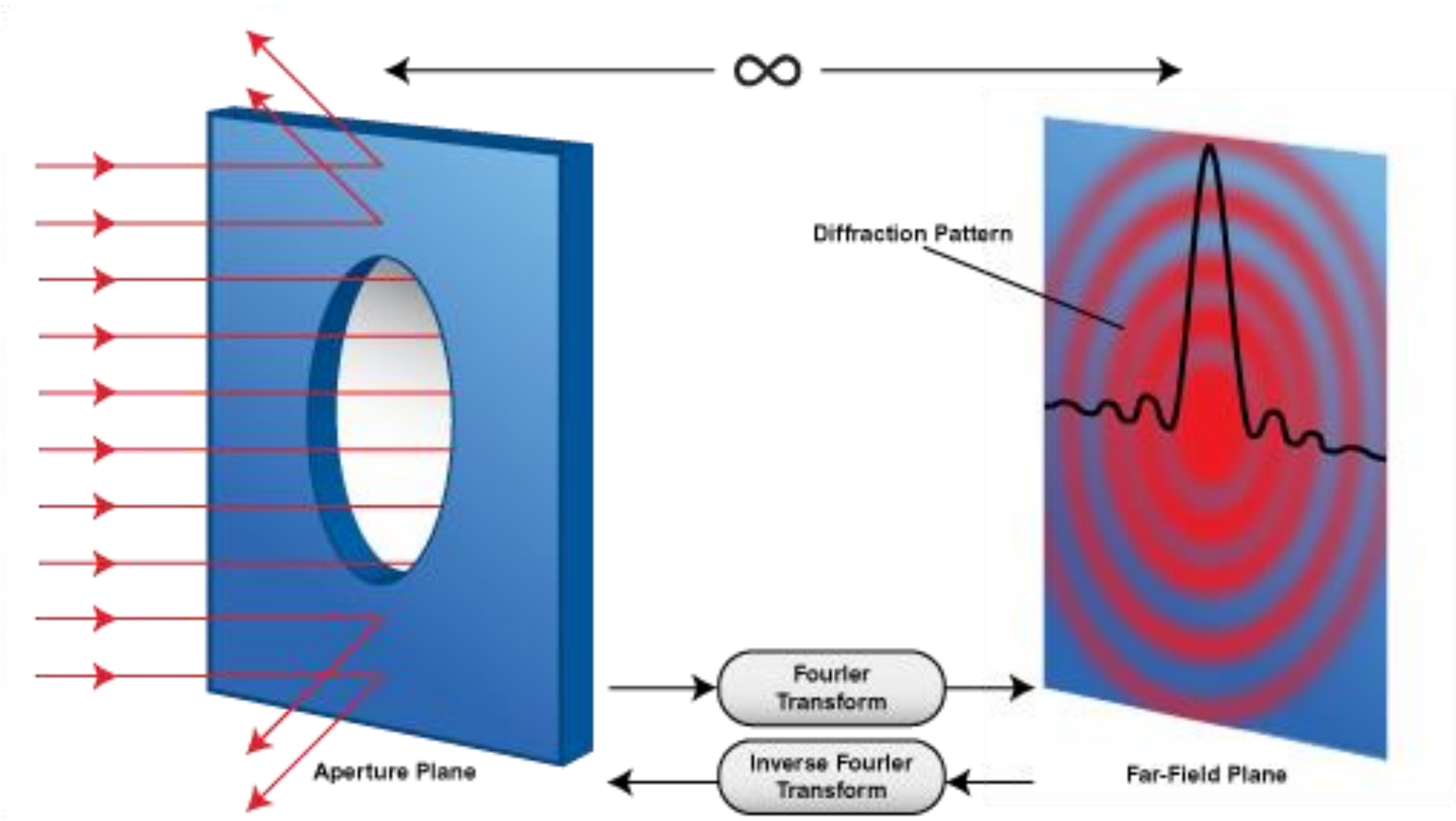
Image quality and efficiency



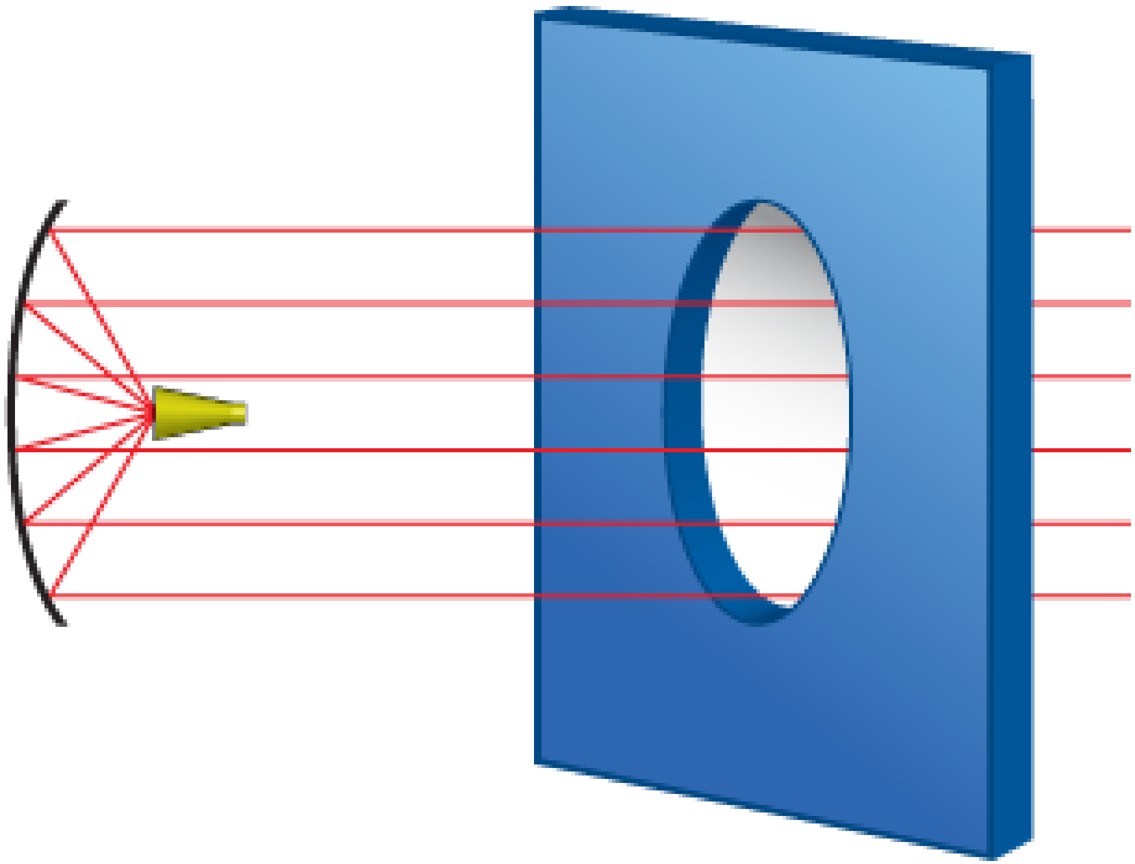


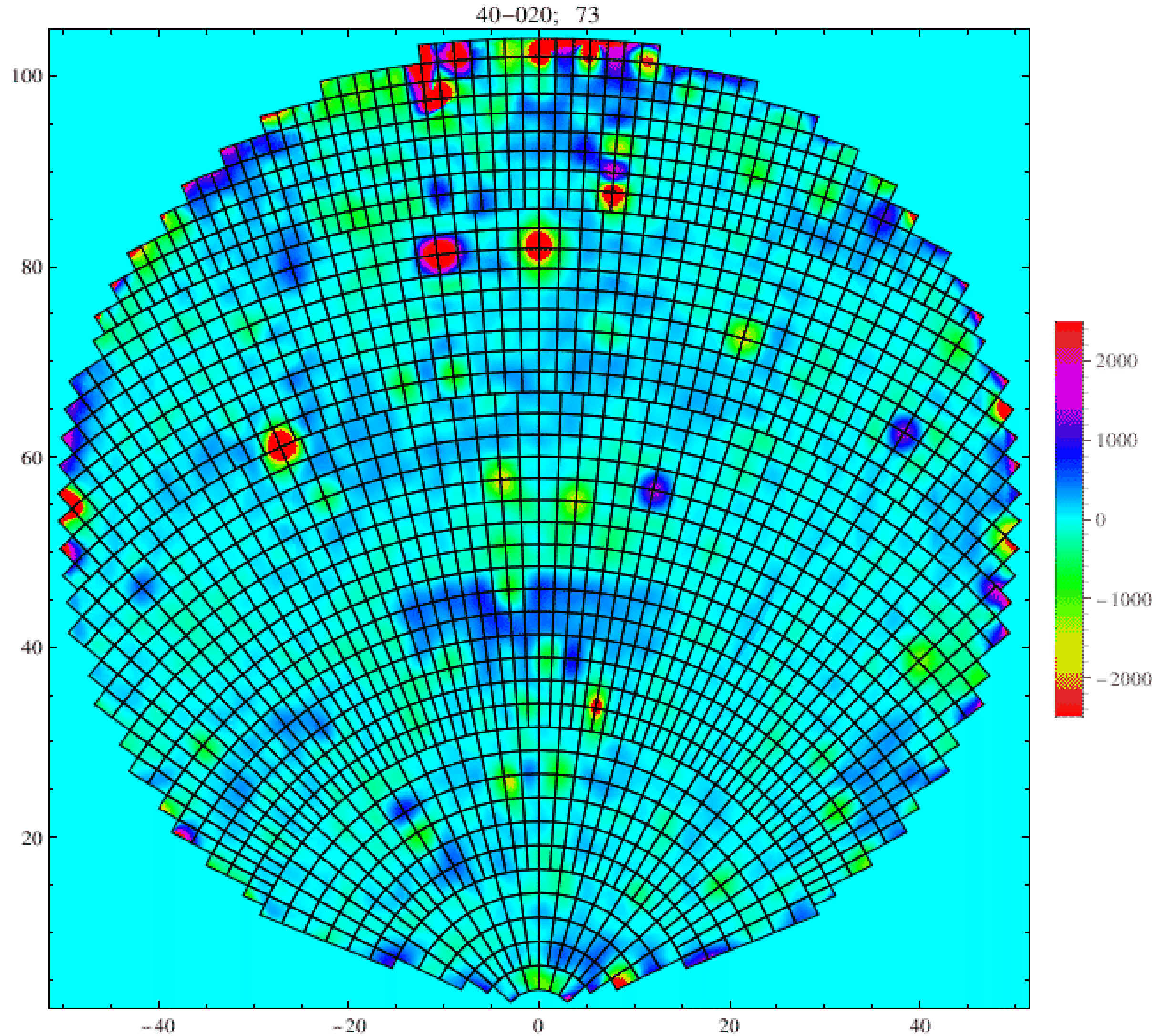
$$\text{Aperture Efficiency} = \eta_A = \frac{\text{Detected Power}}{\text{Incident Power}} \leq 0.71$$

Holography


∞
Diffraction Pattern
Fourier Transform
Inverse Fourier Transform
Aperture Plane
Far-Field Plane

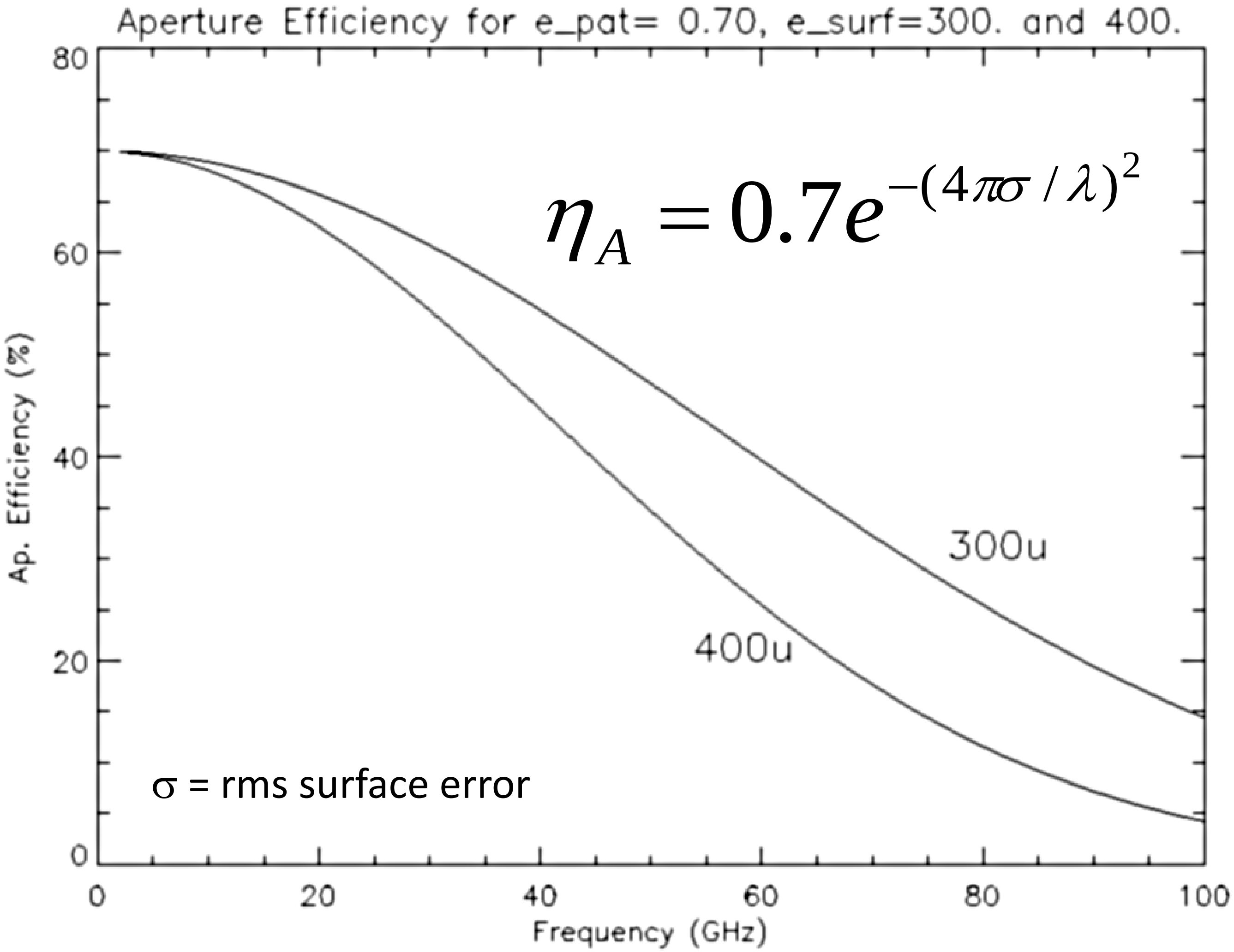
Holography





Surface accuracy (rms) = 240 µm

Aperture Efficiency



$$\eta_A = 0.7 e^{-(4\pi\sigma/\lambda)^2}$$

σ = rms surface error

Telescope Structure

Blind Pointing:
(1 point/focus)

$$\sigma_2 \approx 5 \;\; arc\sec$$
$$\sigma(focus) \approx 2.5 \;\; mm$$

Offset Pointing:
(90 min)

$$\sigma_2 \approx 2.7 \;\; arc\sec$$
$$\sigma(focus) \approx 1.5 \;\; mm$$

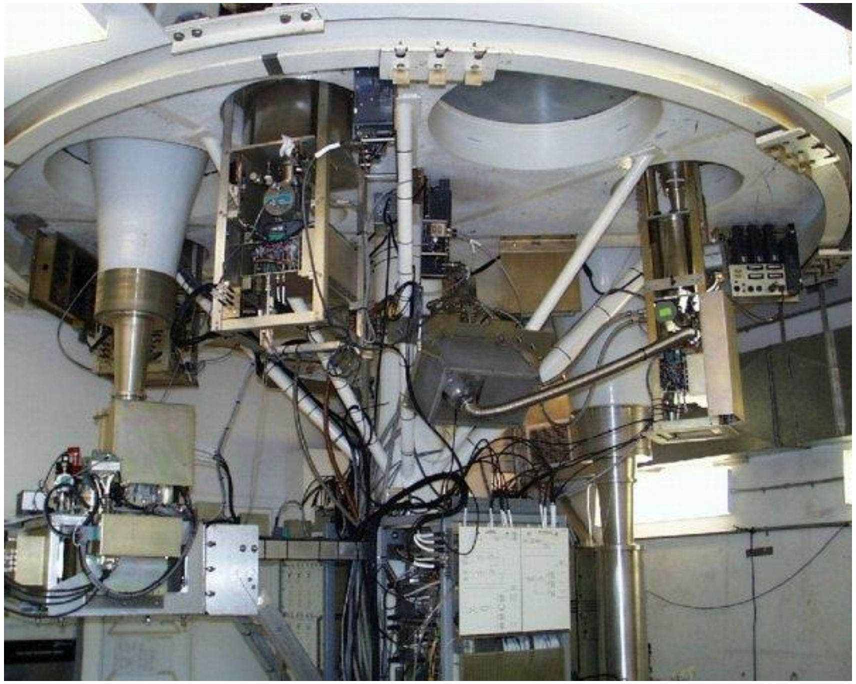
Continuous Tracking:
(30 min)

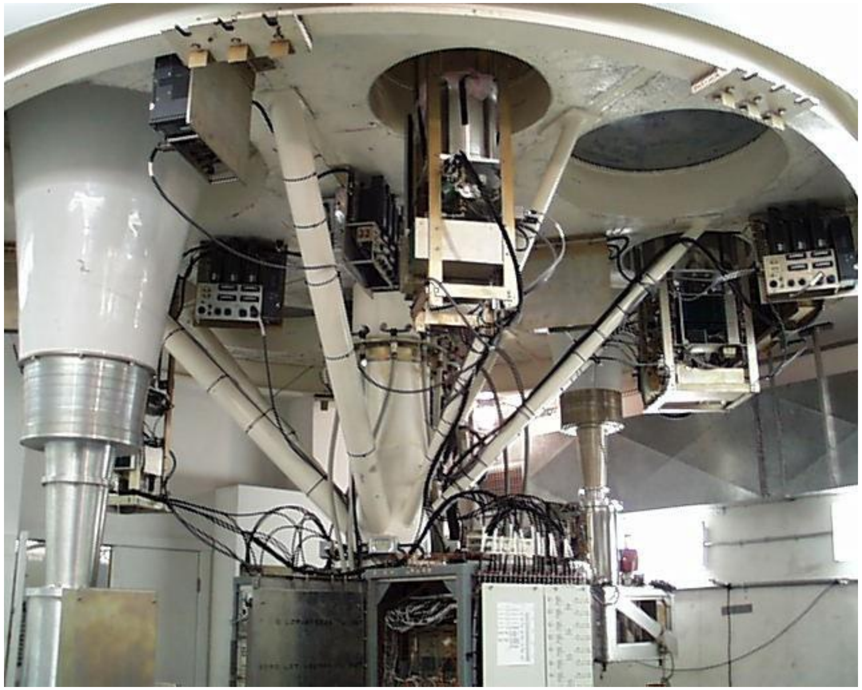
$$\sigma_2 \approx 1 \;\; arc\sec$$

Receivers

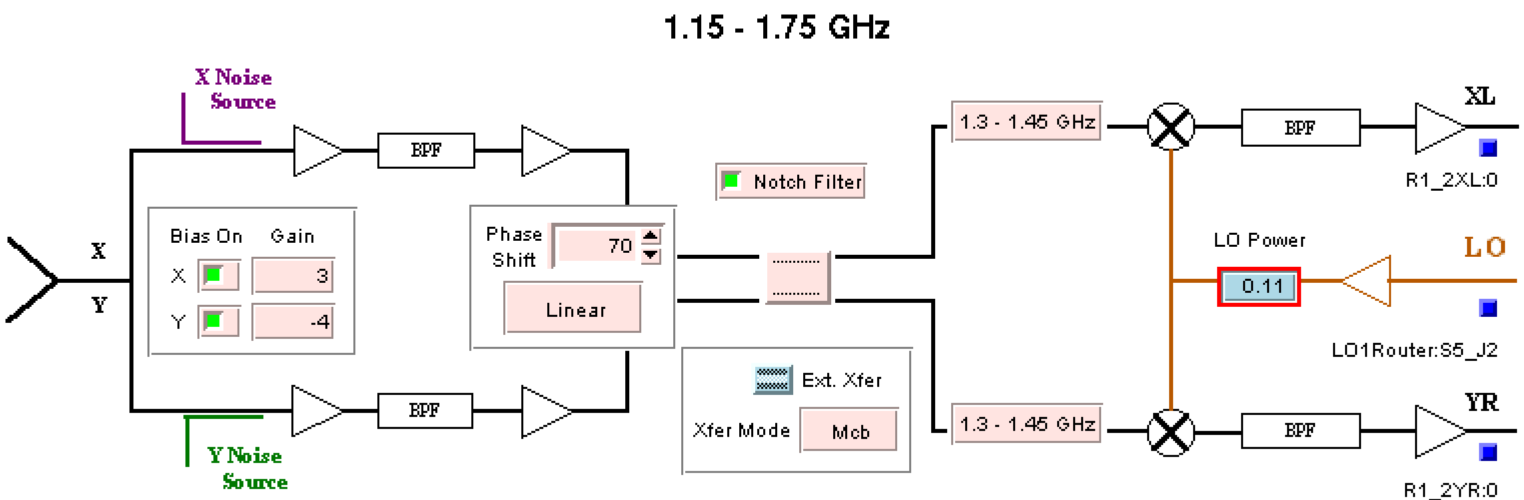
Receiver	Operating Range	Status
Prime Focus 1	0.29—0.92 GHz	Commissioned
Prime Focus 2	0.910—1.23 GHz	Commissioned
L Band	1.15—1.73 GHz	Commissioned
S Band	1.73—2.60 GHz	Commissioned
C Band	4—8.0 GHz	Recently upgraded
X Band	8—12.0 GHz	Commissioned
Ku Band	12—15 GHz	Commissioned
K Band Array	18—27 GHz	Commissioned
Ka Band	26—40 GHz	Commissioned
Q Band	40—50 GHz	Commissioned
W Band	68—92 GHz	Commissioned
Mustang Bolometer	86—94 GHz	Being upgraded
ARGUS	80—115 GHz	Being commissioned

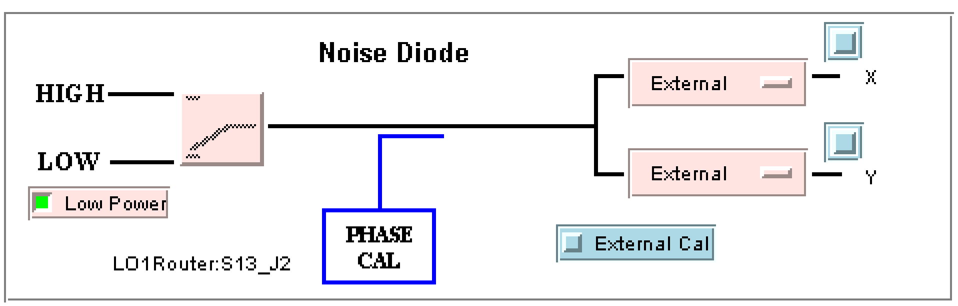
Receiver Room



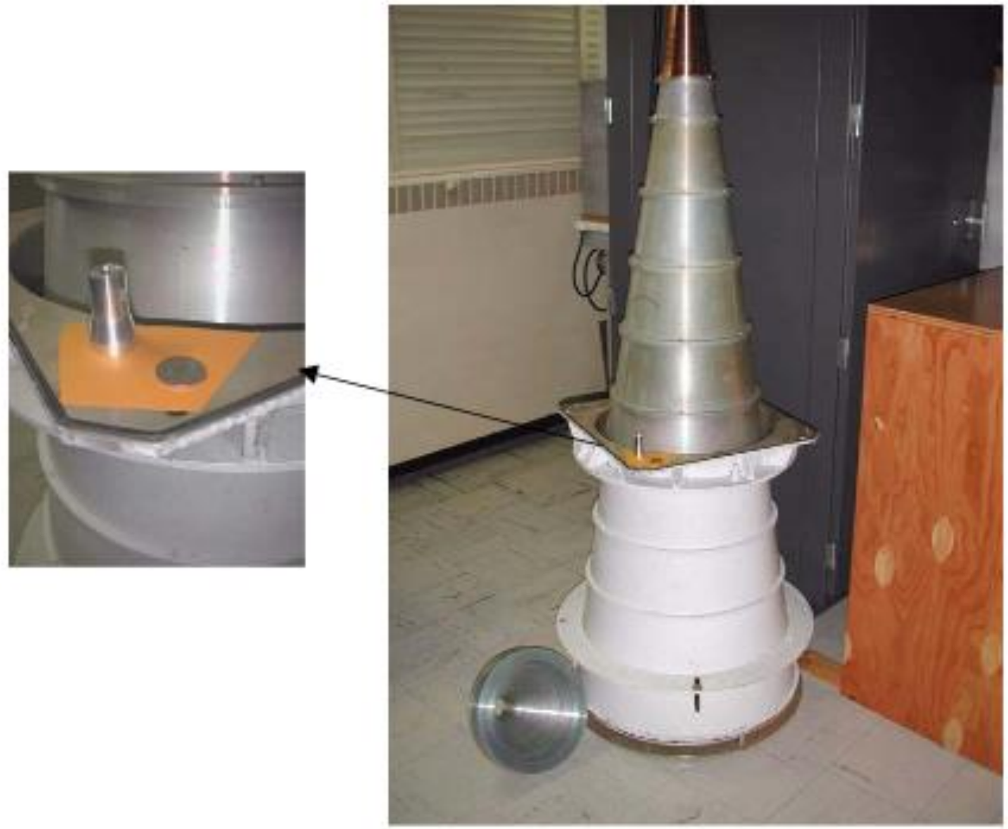


Typical Receiver

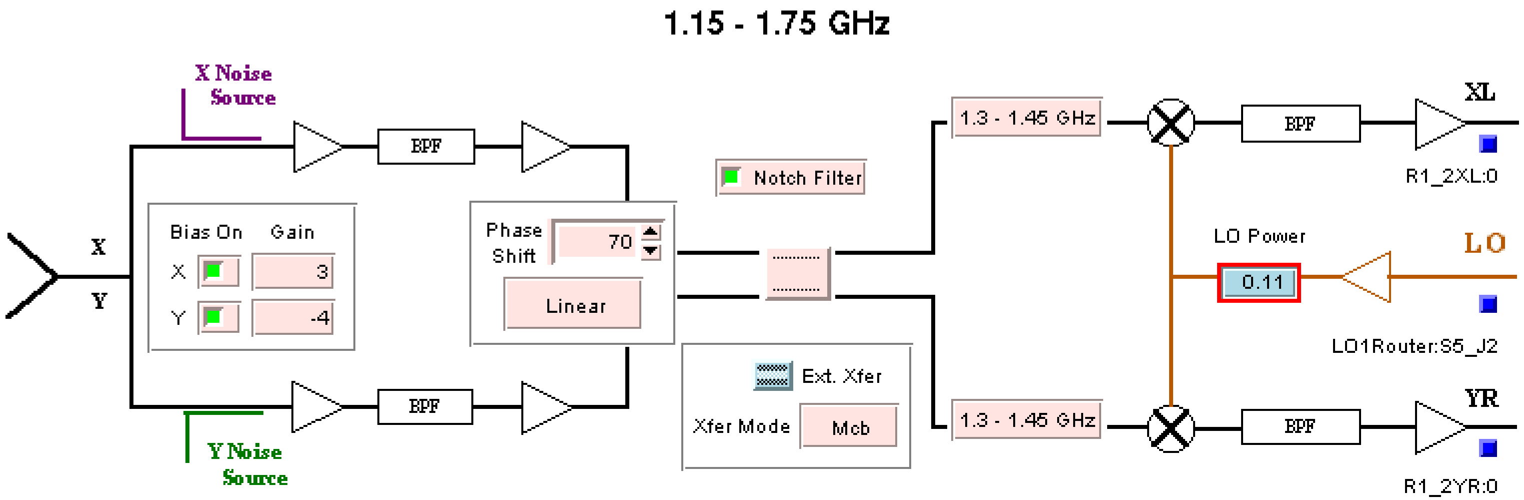


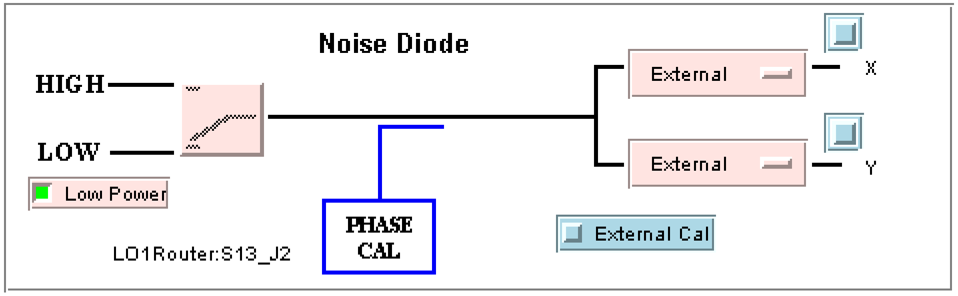


Receiver Feeds

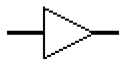


Typical Receiver

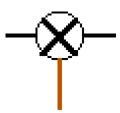




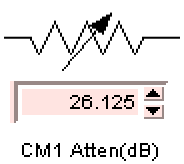
Typical Components



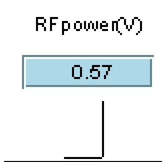
Amplifiers



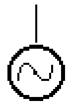
Mixers



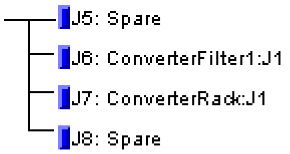
Attenuators



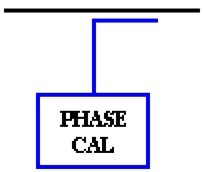
Power Detectors



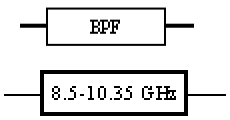
Synthesizers



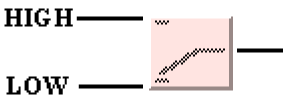
Splitters



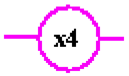
Couplers



Filters

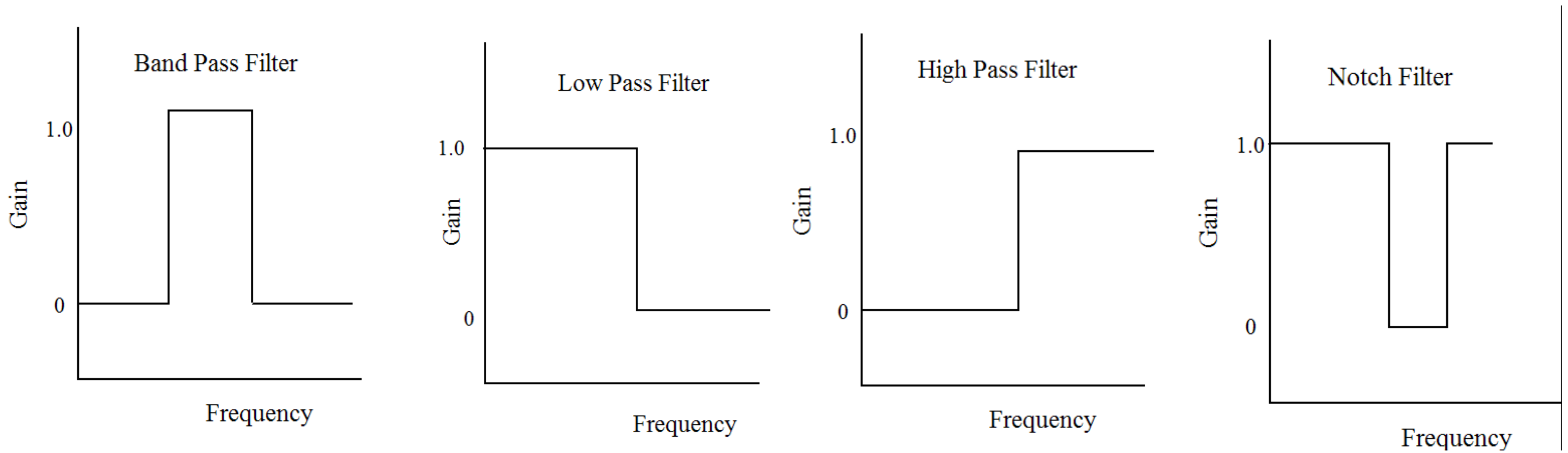


Switches



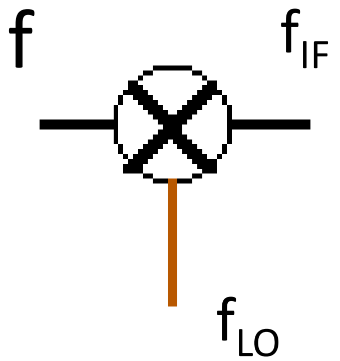
Multipliers

Types of Filters



Edges are smoother than illustrated

Types of Mixers



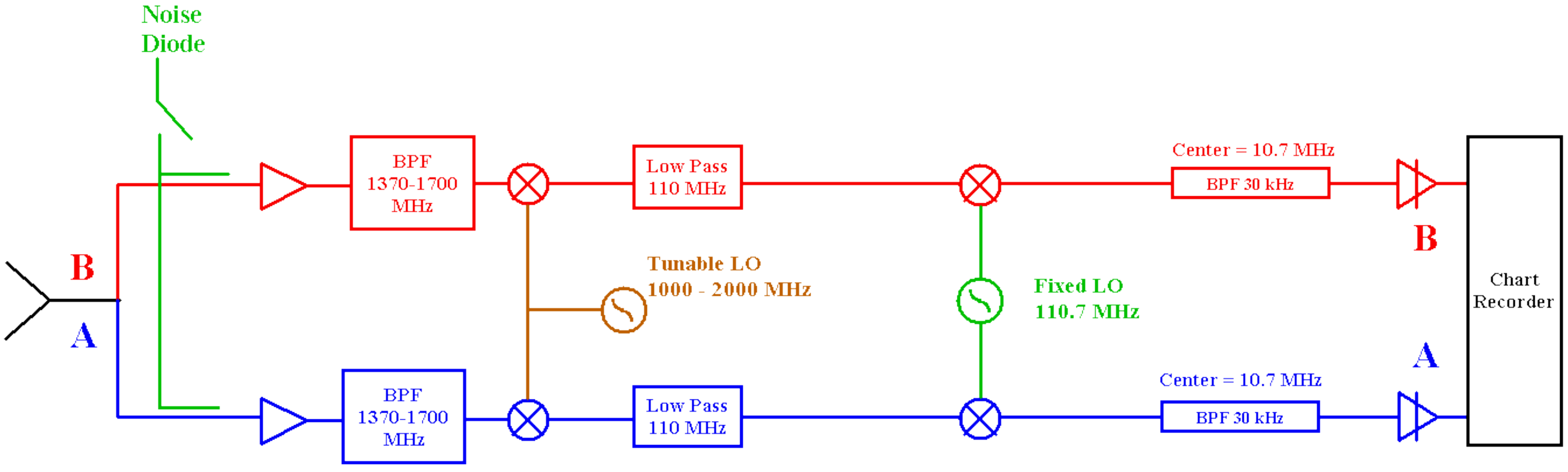
$f_{IF} = n*f_{LO} + m*f$

- n and m are positive or negative integers, usually 1 or -1

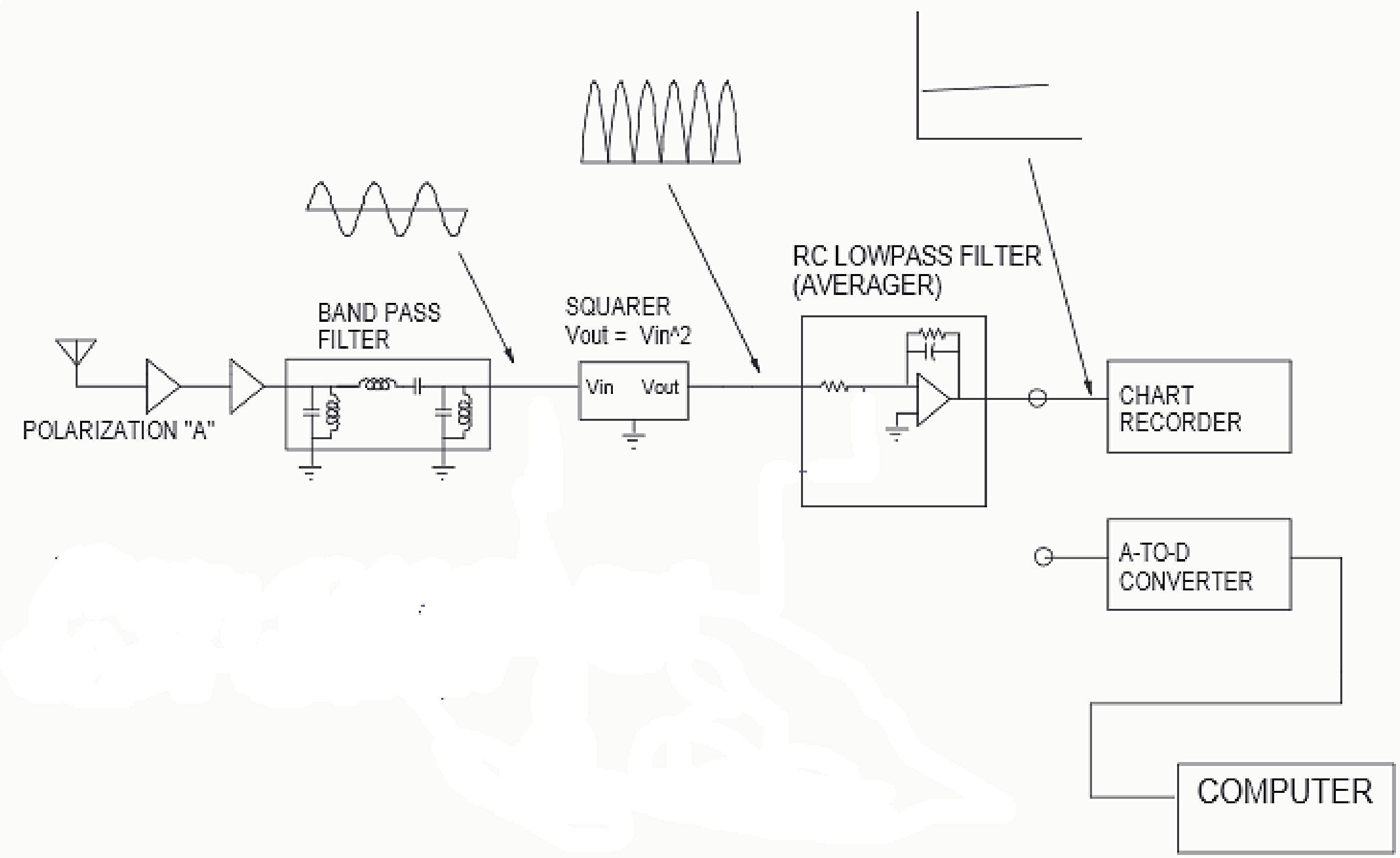
- Up Conversion : $f_{IF} > f$
- Down Conversion : $f_{IF} < f$

- Lower Side Band : $f_{LO} > f$
  - Sense of frequency flips
- Upper Side Band : $f_{LO} < f$

40-Ft System

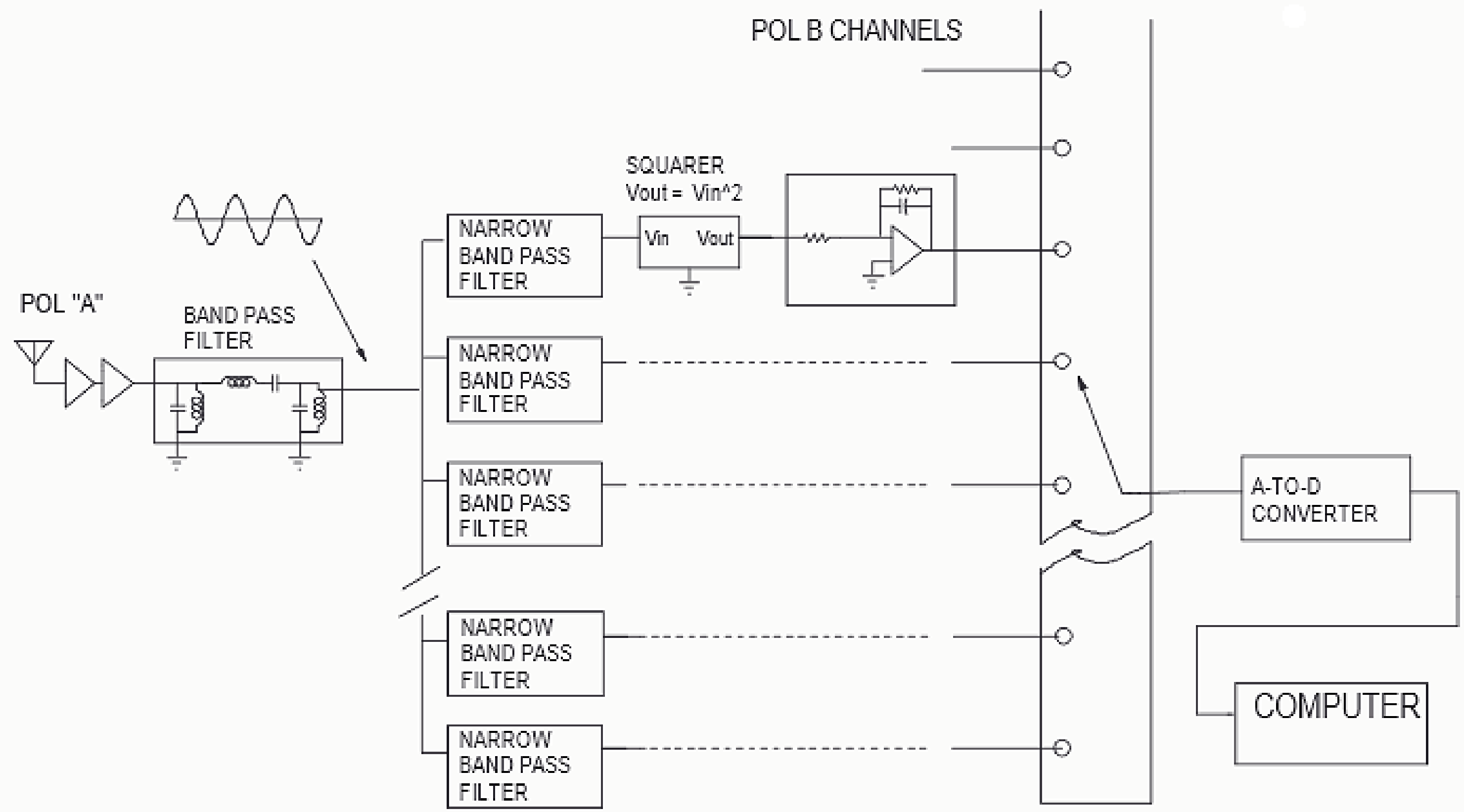


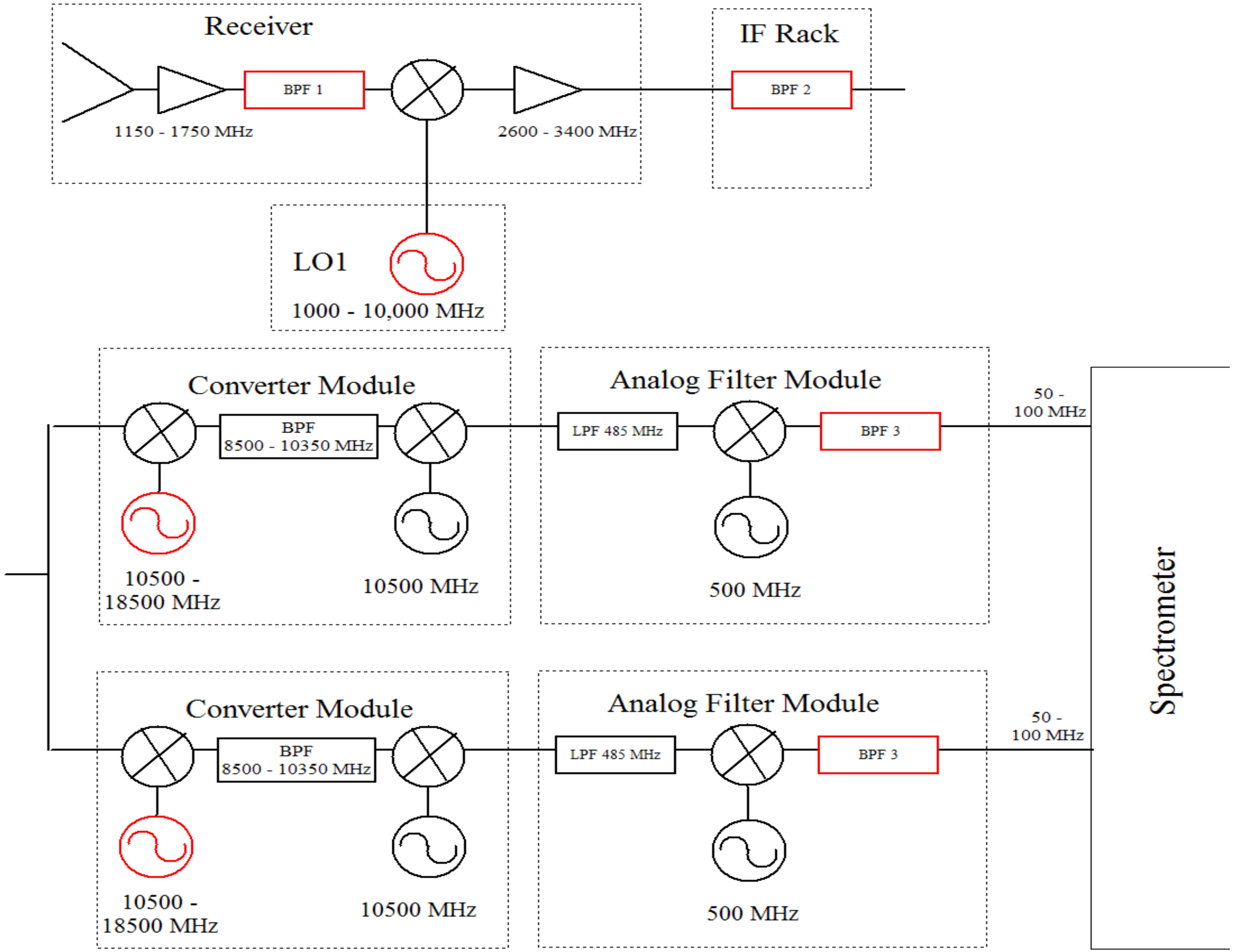
Determine values for the first LO for the 40-ft when Observing HI at 1420 MHz



FRONT END + BACK END

FILTER BANK SPECTROMETER

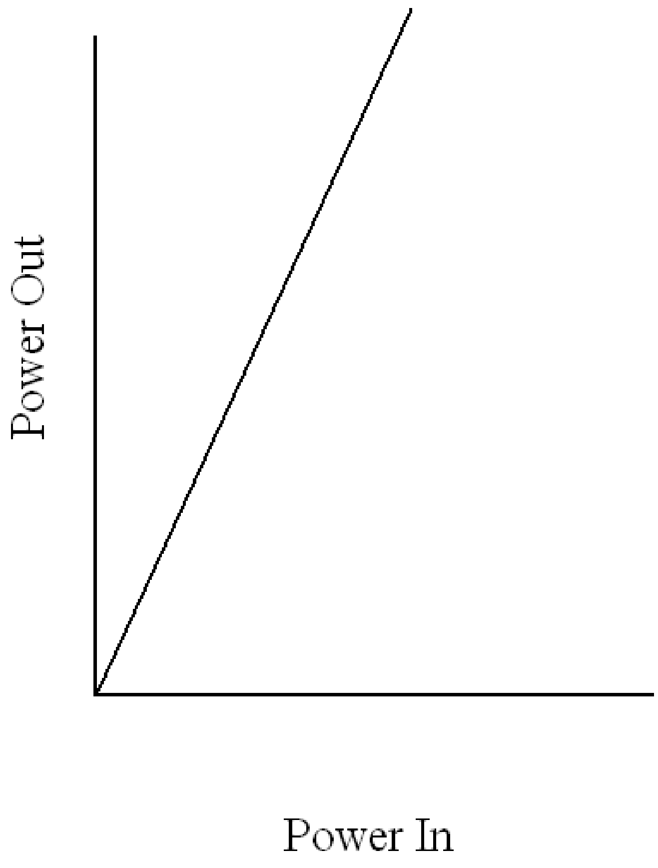


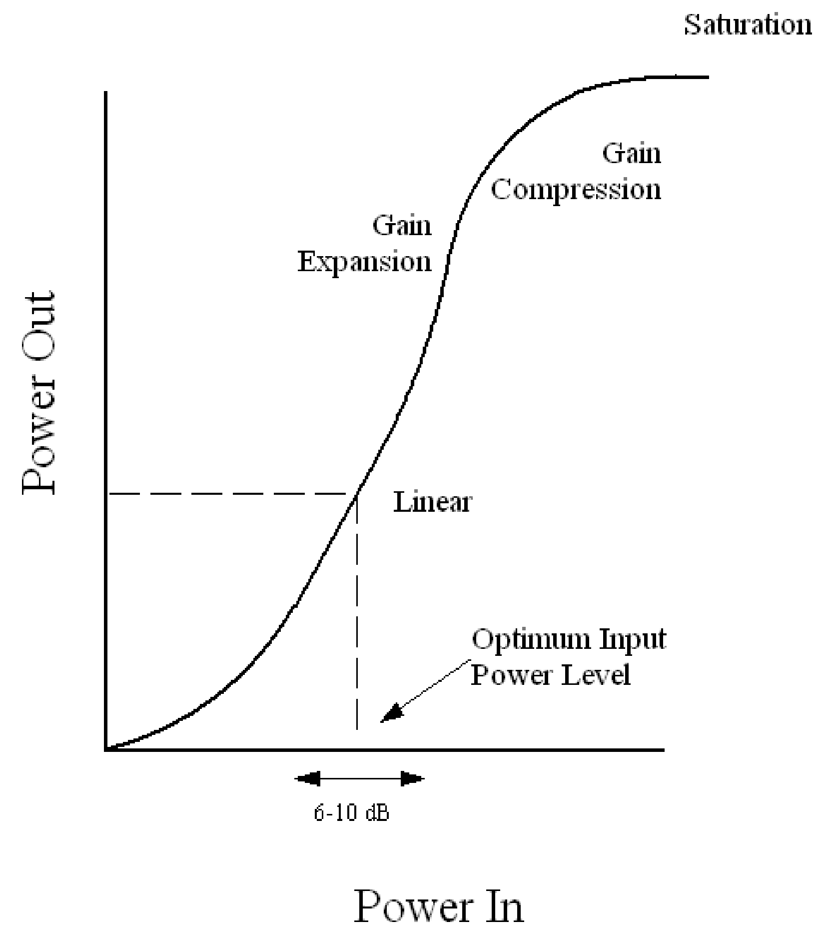

Receiver
BPF 1
1150 - 1750 MHz
2600 - 3400 MHz
IF Rack
BPF 2
LO1
1000 - 10,000 MHz
Converter Module
BPF
8500 - 10350 MHz
10500 -
18500 MHz
10500 MHz
Analog Filter Module
LPF 485 MHz
BPF 3
500 MHz
50 -
100 MHz
Converter Module
BPF
8500 - 10350 MHz
10500 -
18500 MHz
10500 MHz
Analog Filter Module
LPF 485 MHz
BPF 3
500 MHz
50 -
100 MHz
Spectrometer

GBT – Astrid program does all the hard work for you.....

```
configLine = """
receiver  = "Rcvr1_2"
beam      = “B1"
obstype   = "Spectroscopy"
backend   = "Spectrometer"
nwin      = 1
restfreq  = 1420.4058
deltafreq = 0
bandwidth = 12.5
swmode    = "tp"
swtype    = "none"
swper     = 1.0
swfreq    = 0.0, 0.0
tint      = 30
vlow      = 0
vhigh     = 0
vframe    = "lsrk"
vdef      = "Radio"
noisecal  =  "lo"
pol       = "Linear"
nchan  =  "low"
spect.levels = 3
"""
```

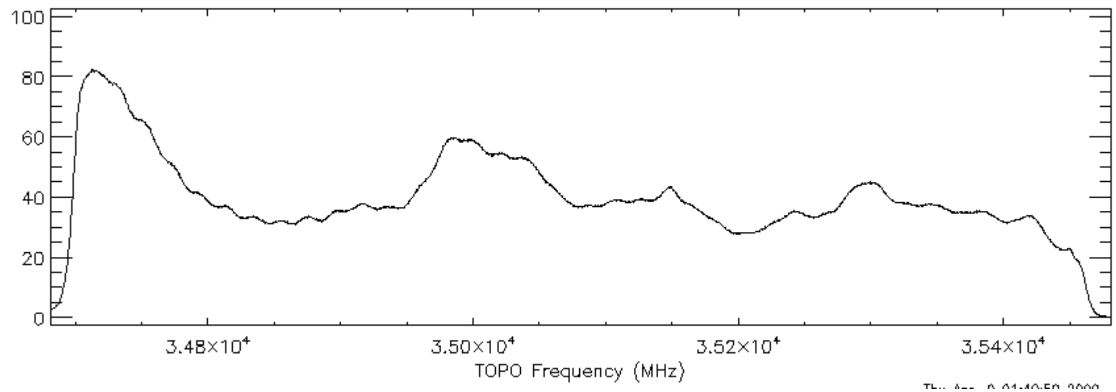
Power Balancing/Leveling and Non-Linearity



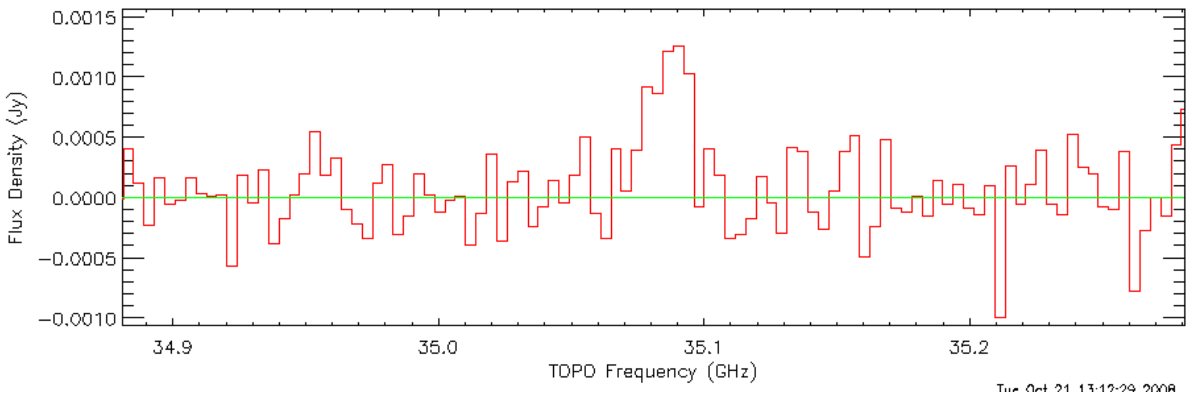


Spectral-line observations

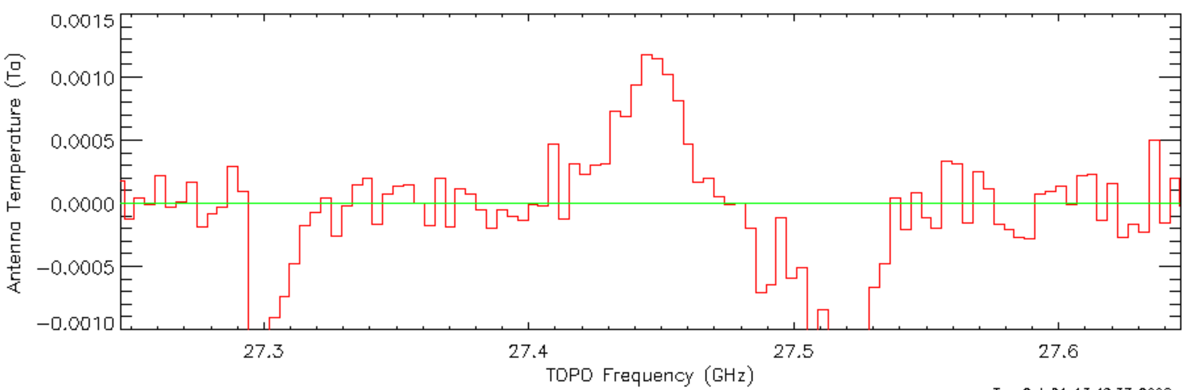
Raw Data



Reduced Data – High Quality



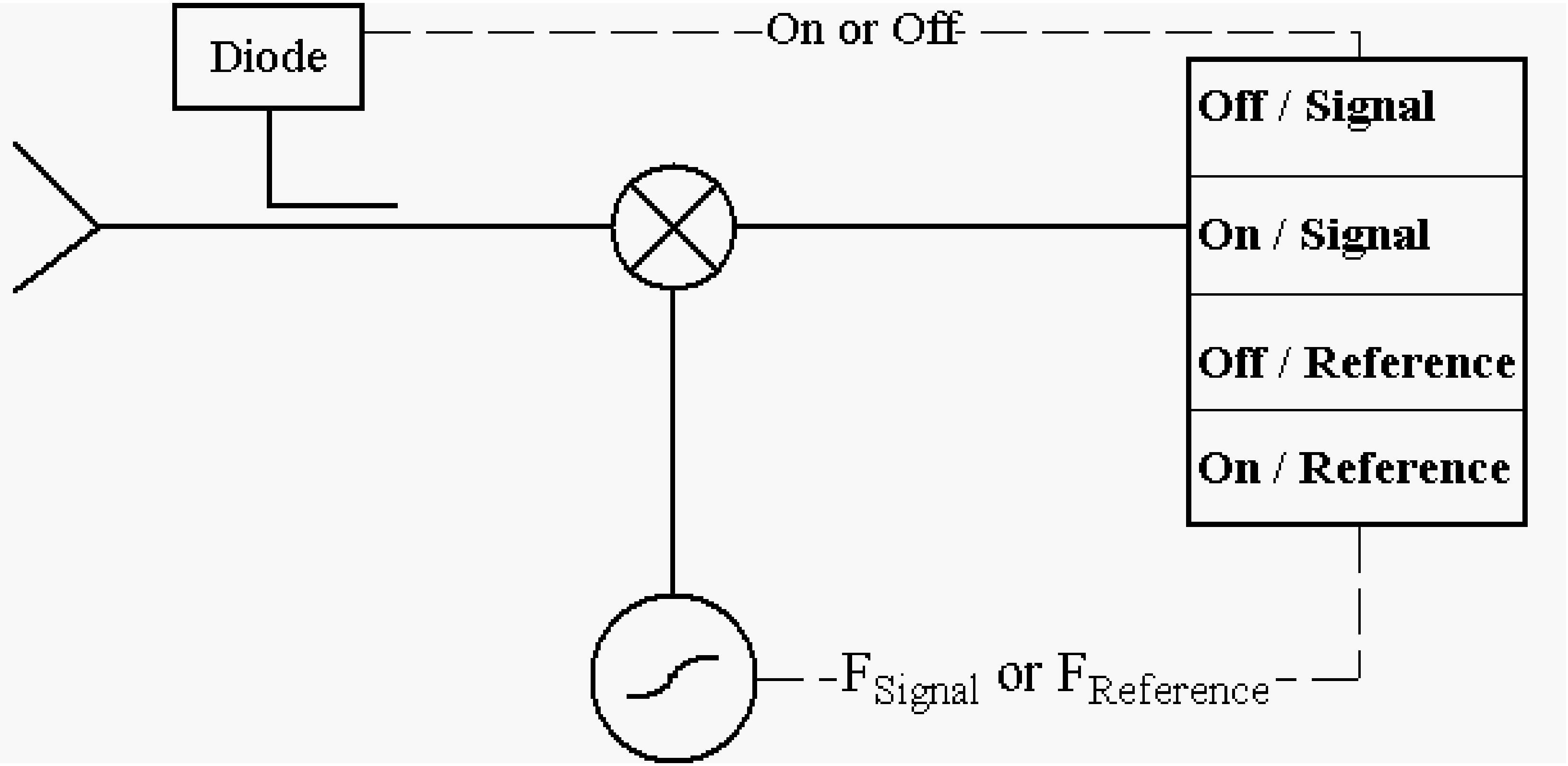
Reduced Data – Problematic



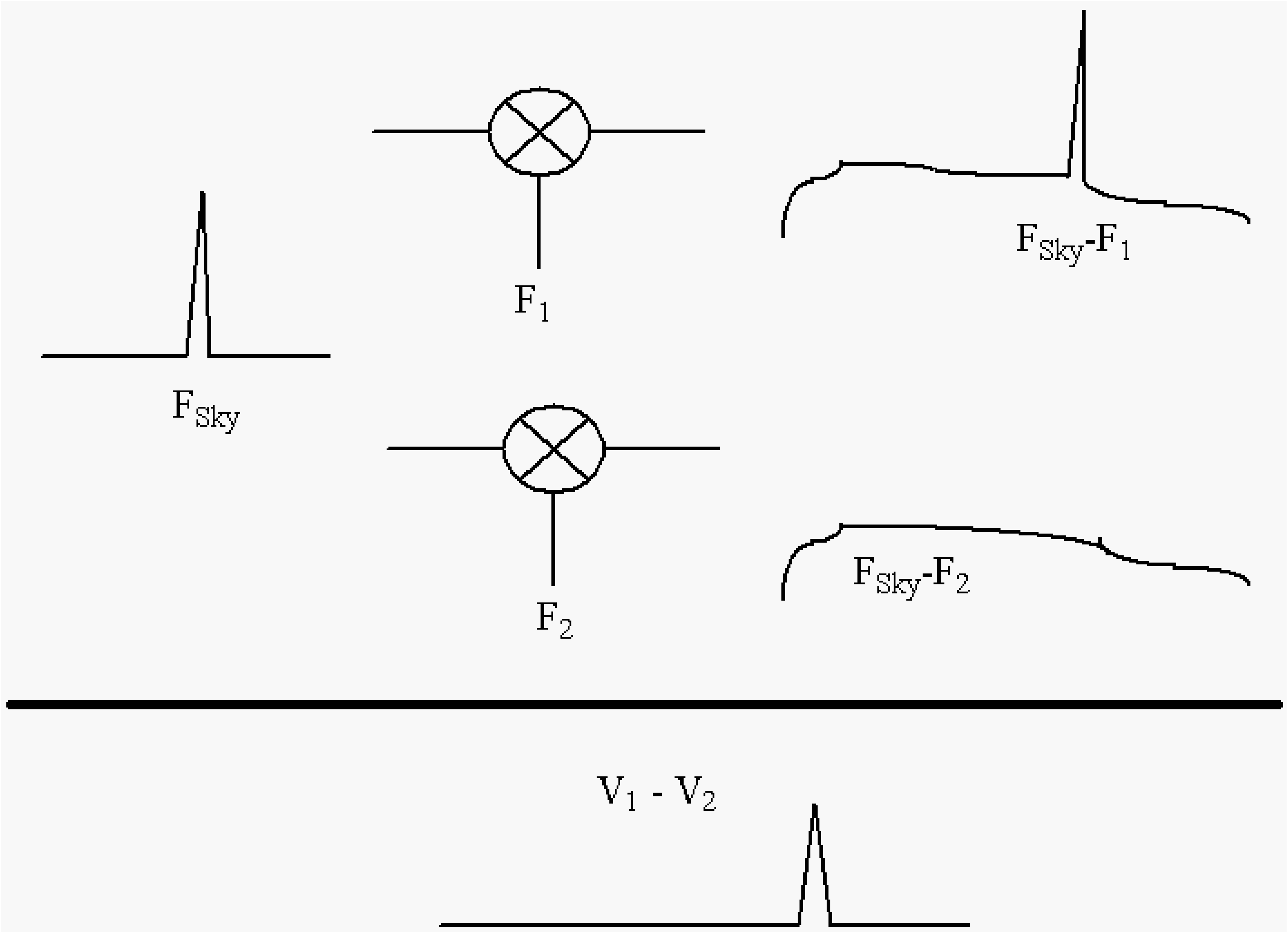
Reference observations

- Difference a signal observation with a reference observation
- Types of reference observations
  - Frequency Switching
    - In or Out-of-band
  - Position Switching
  - Beam Switching
    - Move Subreflector
    - Receiver beam-switch
  - Dual-Beam Nodding
    - Move telescope
    - Move Subreflector

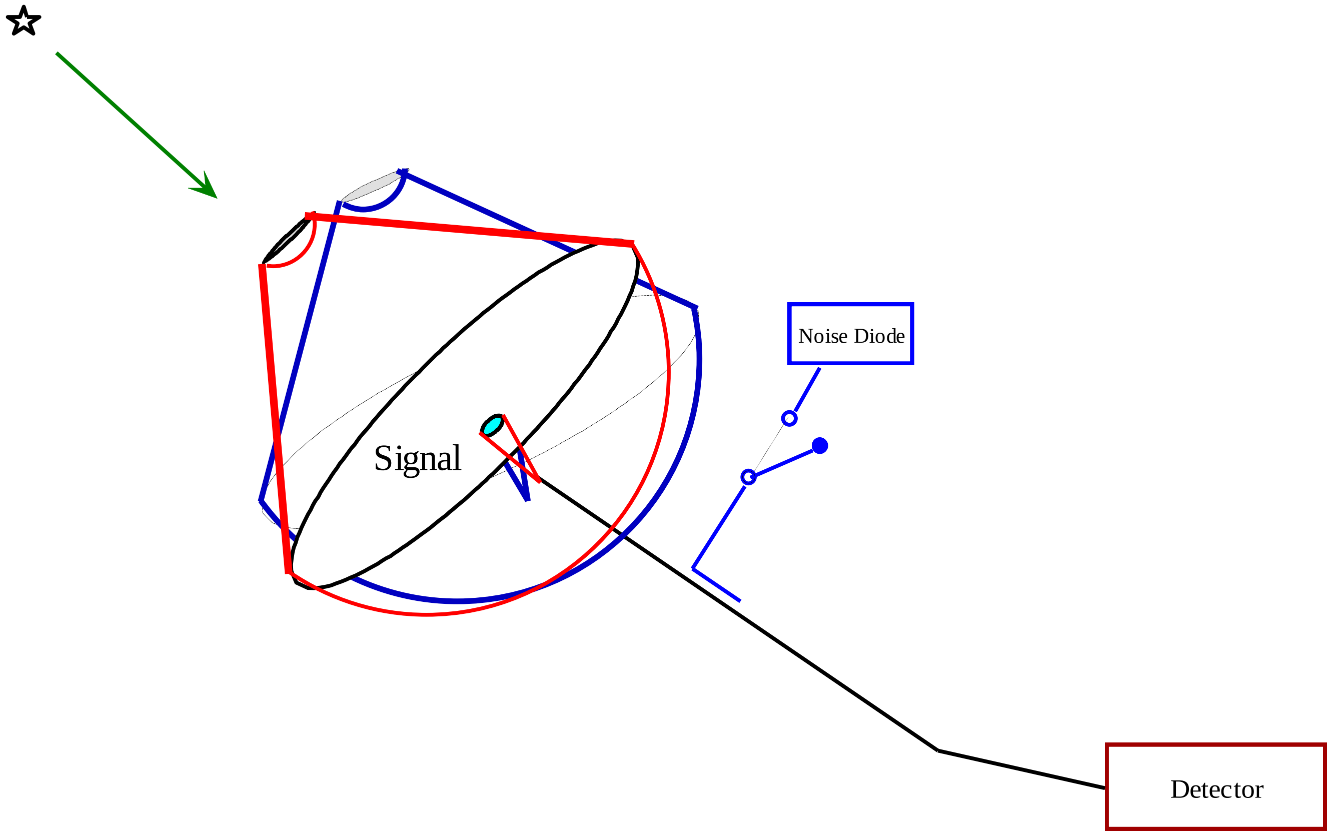
Model Receiver



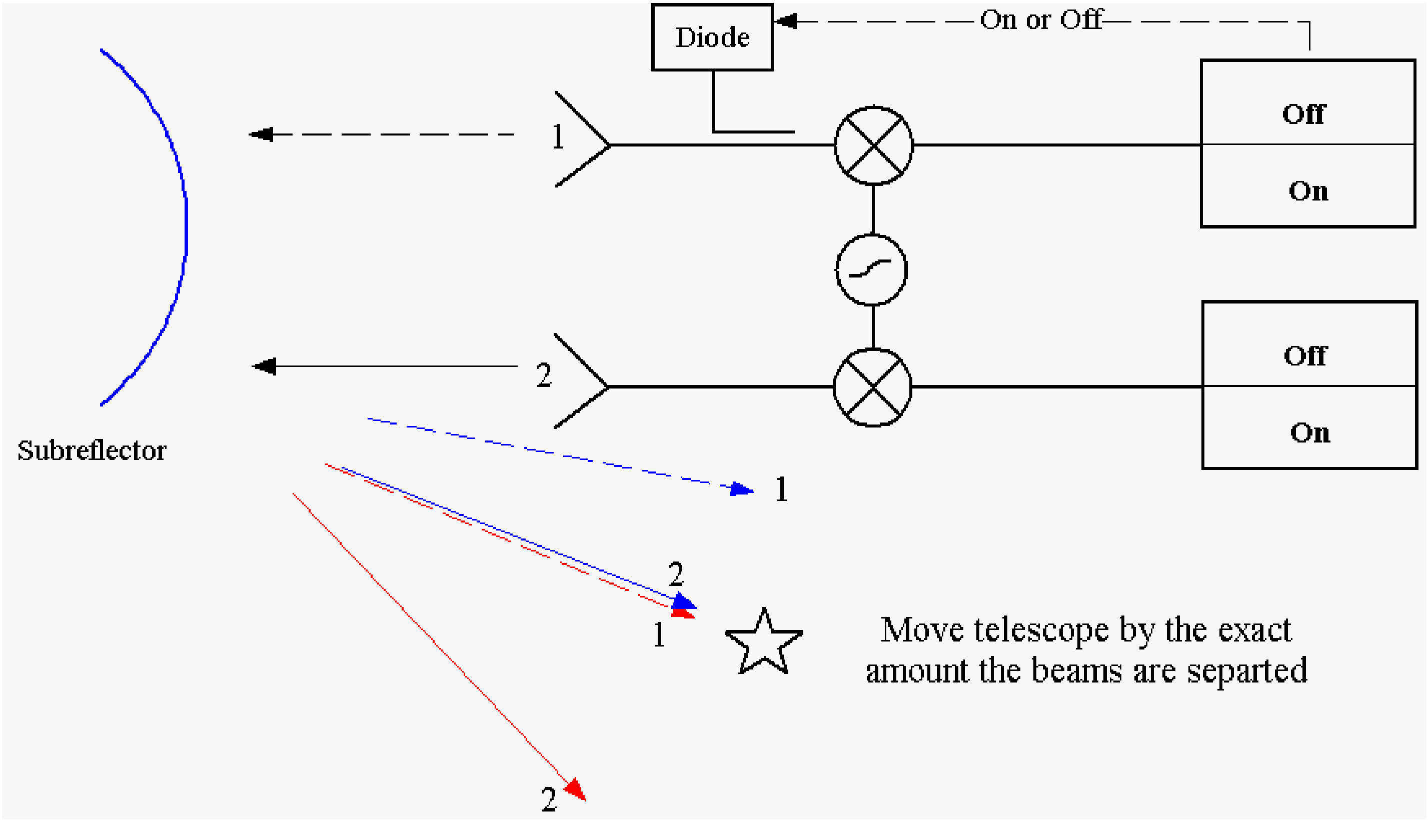
Out-Of-Band Frequency Switching



On-Off Observing

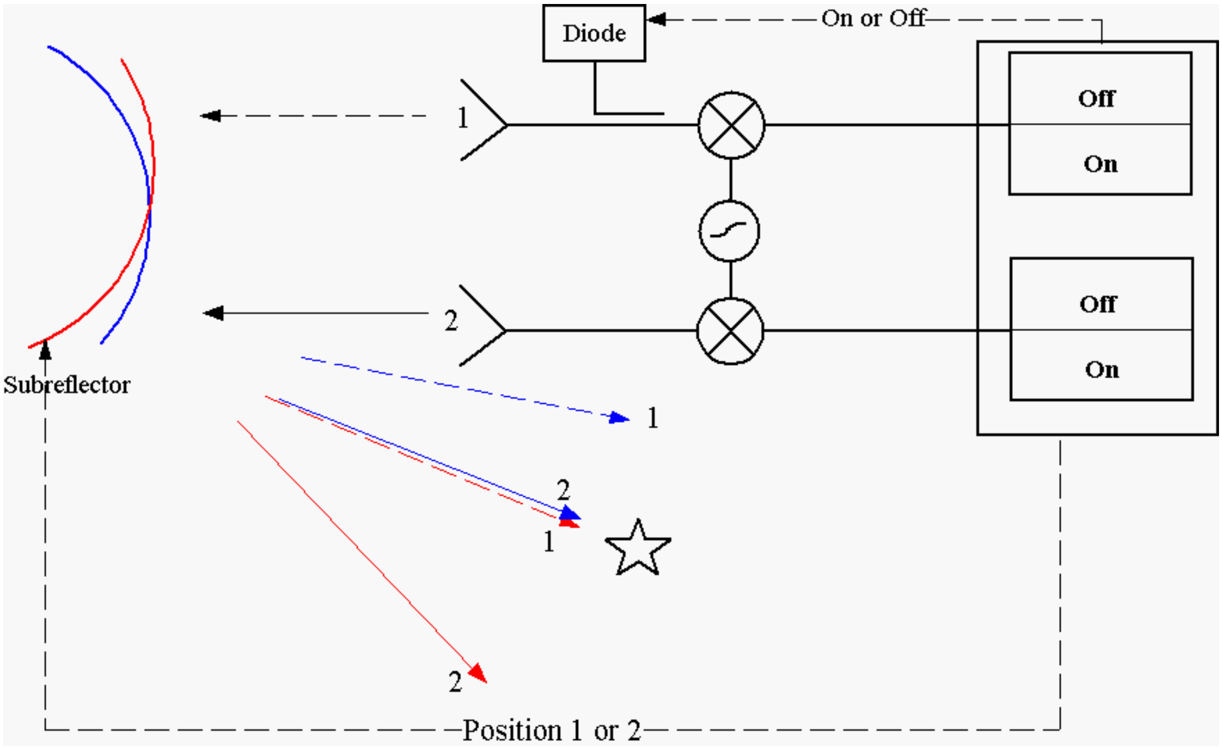


Nodding with dual-beam receivers - Telescope motion



- Optical aberrations
- Difference in spillover/ground pickup
- Removes any ‘fast’ gain/bandpass changes
- Overhead from moving the telescope. All the time is spent on source

Nodding with dual-beam receivers - Subreflector motion



- Optical aberrations
- Difference in spillover/ground pickup
- Removes any ‘fast’ gain/bandpass changes
- Low overhead. All the time is spent on source

Intrinsic Power P (Watts)
Distance R (meters)
Aperture A (sq.m.)

Flux = Power Received/Area
Flux Density (S) = Power Received/Area/bandwidth
Bandwidth (BW)

A "Jansky" is a unit of flux density

$$10^{-26} Watts / m^2 / Hz$$

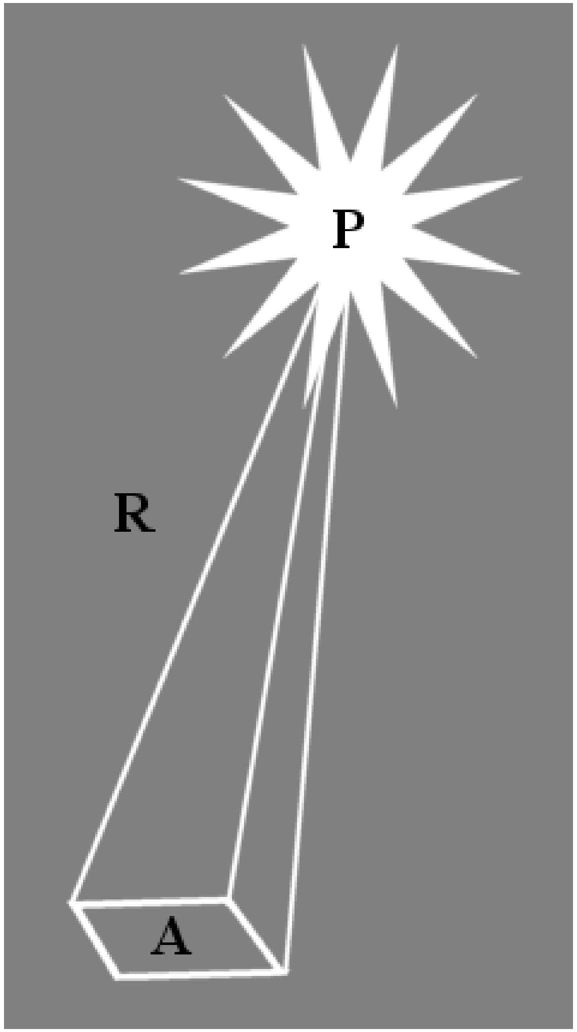
$$S = \frac{10^{26} P}{4\pi R^2 \cdot BW}$$

$$2kT_A = S \cdot \eta_A \cdot A_g \cdot e^{-\tau \cdot AirMass}$$

$$Gain = T_A / S = \eta_A \cdot A_g / 2761$$

$$Gain = 2.84 \cdot \eta_A \text{ for GBT}$$

$$Gain = 2.0 \text{ for GBT at low frequencies}$$



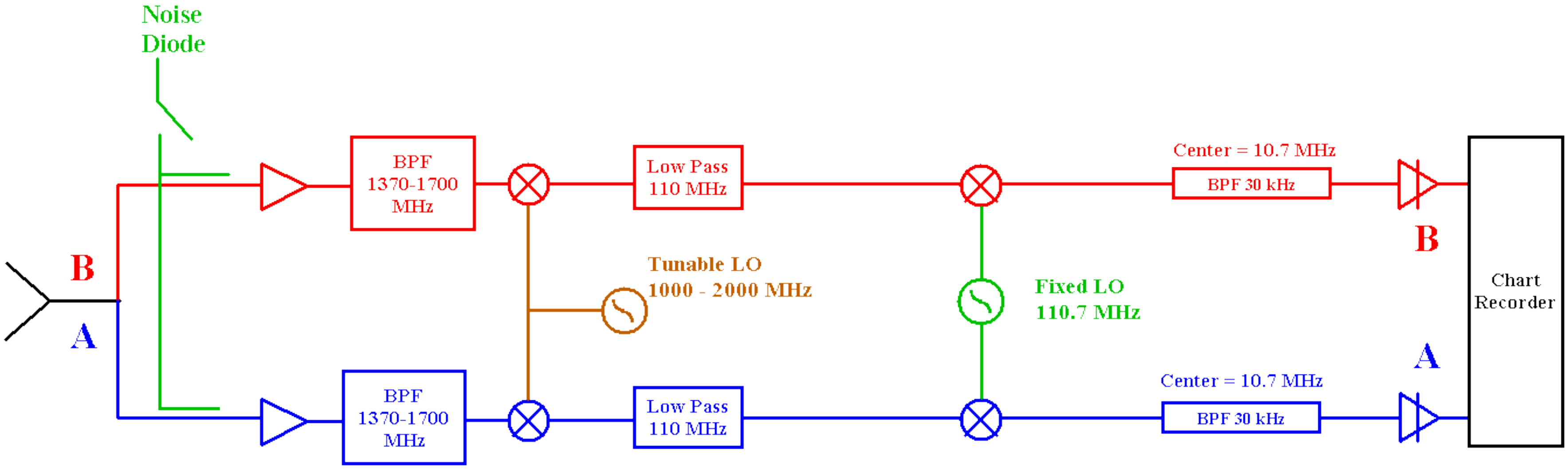
System Temperature

$$T_{SYS} = T_{Rcvr} + (1-\eta_l)\cdot T_{Spill} + \eta_l \cdot \left[\left(T_{CMB} + T_A + T_{Background} \right) \cdot e^{-\tau \cdot Airmass} + T_{ATM} \cdot (1 - e^{-\tau \cdot Airmass}) \right]$$

Radiometer Equation

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

40-Ft System

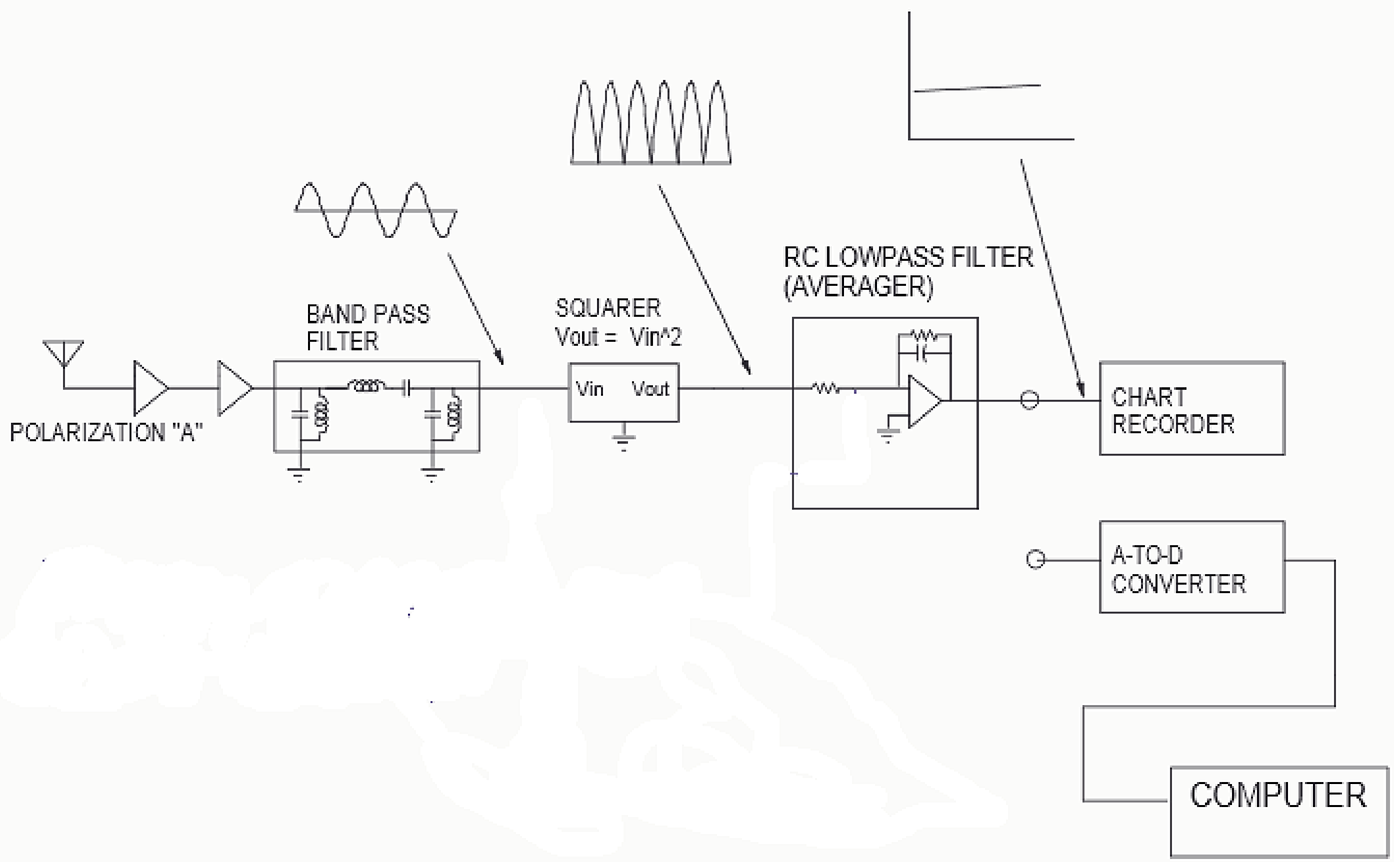


Noise
Diode
B
A
BPF
1370-1700
MHz
Low Pass
110 MHz
Tunable LO
1000 - 2000 MHz
Fixed LO
110.7 MHz
Center = 10.7 MHz
BPF 30 kHz
BPF
1370-1700
MHz
Low Pass
110 MHz
Center = 10.7 MHz
BPF 30 kHz
B
A
Chart
Recorder

System Temperature

$$T_{SYS} = T_{Rcvr} + (1-\eta_l) \cdot T_{Spill} + \eta_l \cdot \left[\left(T_{CMB} + T_A + T_{Background} \right) \cdot e^{-\tau \cdot Airmass} + T_{ATM} \cdot (1 - e^{-\tau \cdot Airmass}) \right]$$

$$T_{SYS} = T_{Rcvr} + T_{NoiseDiode} + (1-\eta_l) \cdot T_{Spill} + \eta_l \cdot \left[\left(T_{CMB} + T_A + T_{Background} \right) \cdot e^{-\tau \cdot Airmass} + T_{ATM} \cdot (1 - e^{-\tau \cdot Airmass}) \right]$$



FRONT END + BACK END

System Temperature

$$V = G_{Electronics} \cdot T_{SYS}$$

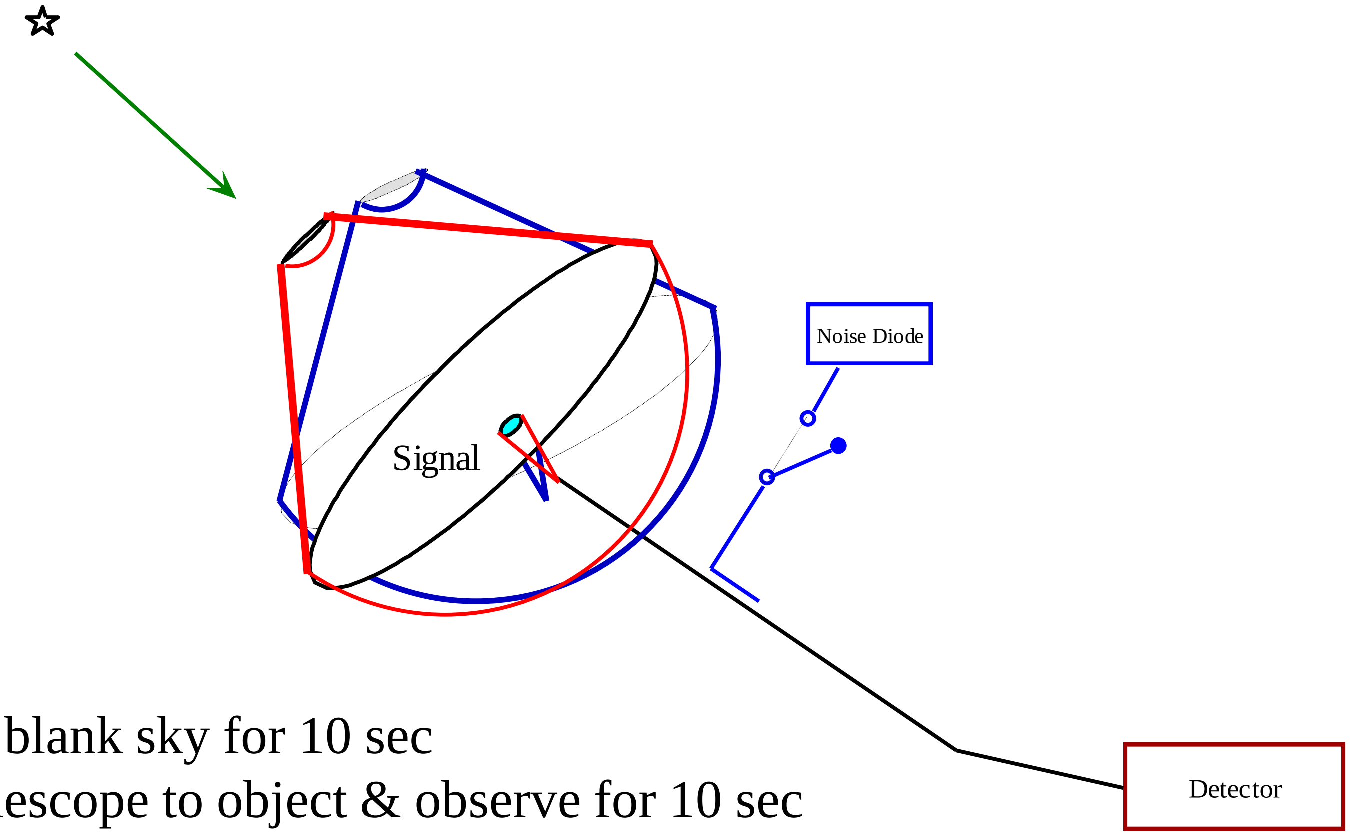
$$T_{SYS}^{DiodeOff} = T_{Rcvr} + (1-\eta_l) \cdot T_{Spill} +$$
$$\eta_l \cdot \left[\left(T_{CMB} + T_A + T_{Background} \right) \cdot e^{-\tau \cdot Airmass} + T_{ATM} \cdot (1 - e^{-\tau \cdot Airmass}) \right]$$

$$T_{SYS}^{DiodeOn} = T_{Rcvr} + T_{NoiseDiode} + (1-\eta_l) \cdot T_{Spill} +$$
$$\eta_l \cdot \left[\left(T_{CMB} + T_A + T_{Background} \right) \cdot e^{-\tau \cdot Airmass} + T_{ATM} \cdot (1 - e^{-\tau \cdot Airmass}) \right]$$

$$\Delta V_{CalOnOff} = G_{Electronics} \cdot \Delta T_{SYS} = G_{Electronics} \cdot T_{NoiseDiode}$$

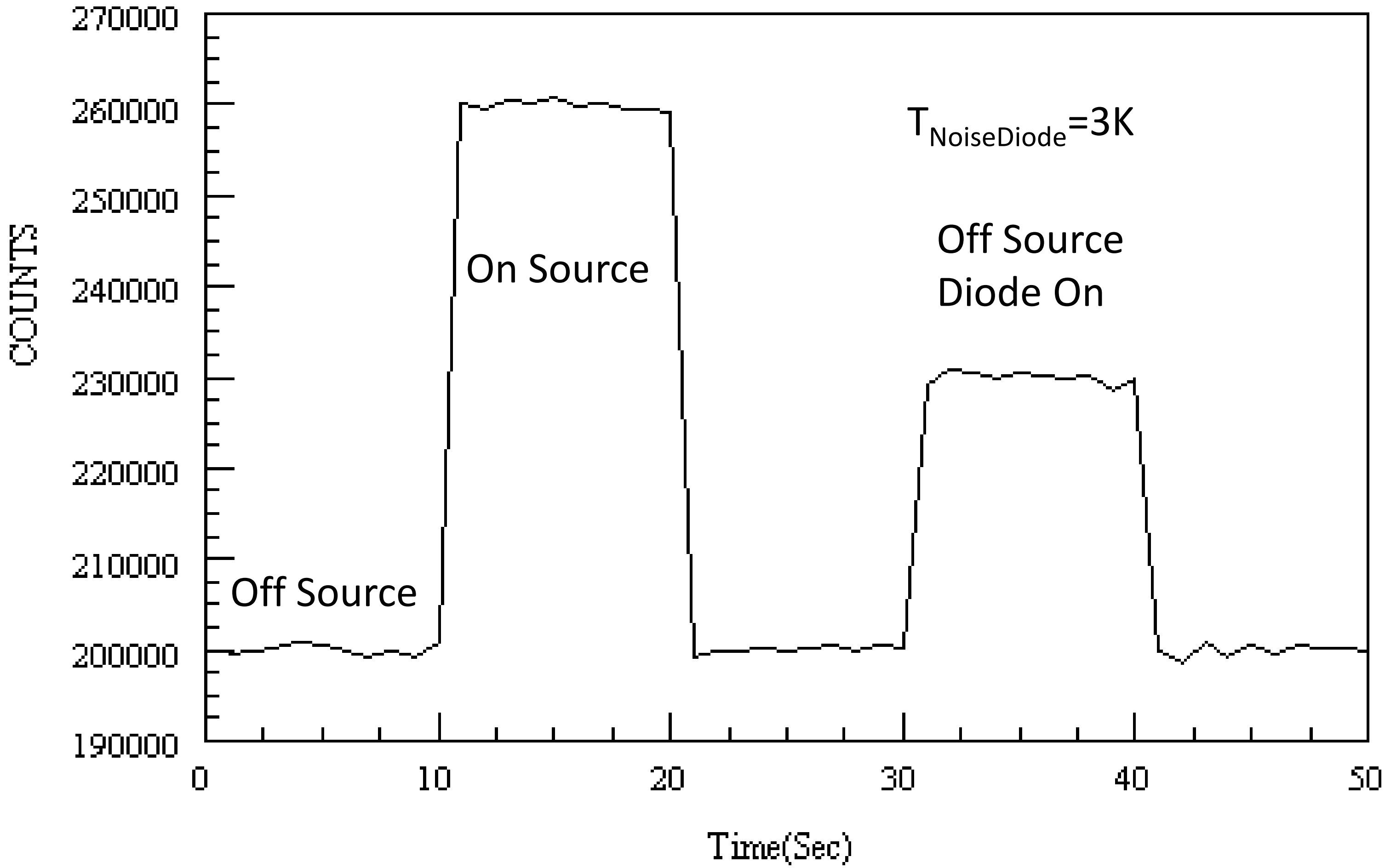
$$\therefore G_{Electronics} = \frac{\Delta V_{CalOnOff}}{T_{NoiseDiode}}$$

On-Off Observing



- Observe blank sky for 10 sec
- Move telescope to object & observe for 10 sec
- Move to blank sky & observe for 10 sec
- Fire noise diode & observe for 10 sec
- Observe blank sky for 10 sec

Continuum - Point Sources
On-Off Observing



Source Antenna Temperature

$$\Delta V_{SigRef} = G_{Electronics} \cdot \Delta T_{SYS} = G_{Electronics} \cdot T_A$$

$$\Delta V_{CalOnOff} = G_{Electronics} \cdot \Delta T_{SYS} = G_{Electronics} \cdot T_{NoiseDiode}$$

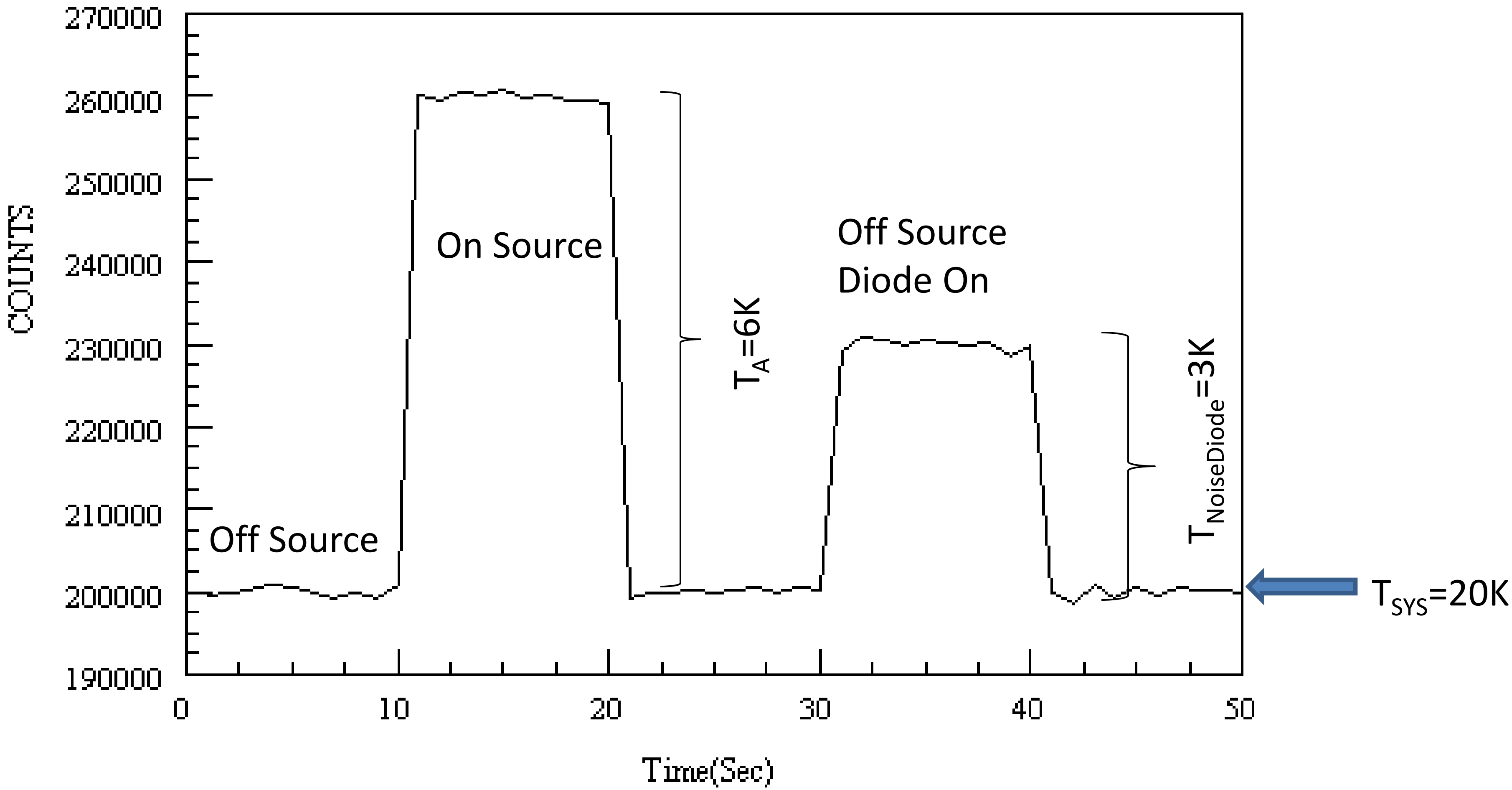
$$\therefore G_{Electronics} = \frac{\Delta V_{CalOnOff}}{T_{NoiseDiode}}$$

$$T_A = \Delta V_{SigRef} \cdot T_{NoiseDiode} \big/ \Delta V_{CalOnOff}$$

$$T_{SYS} = V_{RefCalOff} \cdot T_{NoiseDiode} \big/ \Delta V_{CalOnOff}$$

Continuum - Point Sources

On-Off Observing



Converting T_A to Scientifically Useful Values

$$T_A(K) = \frac{\eta_A \cdot Area \cdot e^{-\tau \cdot Airmass}}{2k} S(W \cdot m^{-2} Hz^{-1})$$ Point Source

$$= \eta_{Src} \cdot e^{-\tau \cdot Airmass} \cdot T_B(K)$$ Extended source; η_{Src} depends upon source size

$$\approx e^{-\tau \cdot Airmass} \cdot T_B(K)$$ Source $>> \theta_{\mathrm{HPBW}}$

$$\approx \left(\frac{\theta_{Src}}{\theta_{HPBW}}\right)^2 e^{-\tau \cdot Airmass} \cdot T_B(K)$$ Source $<< \theta_{\mathrm{HPBW}}$ but not point source

$$= \eta_{MB} \cdot e^{-\tau \cdot Airmass} \cdot T_{MB}(K)$$ Equivalent to a uniform source that fills just the main beam