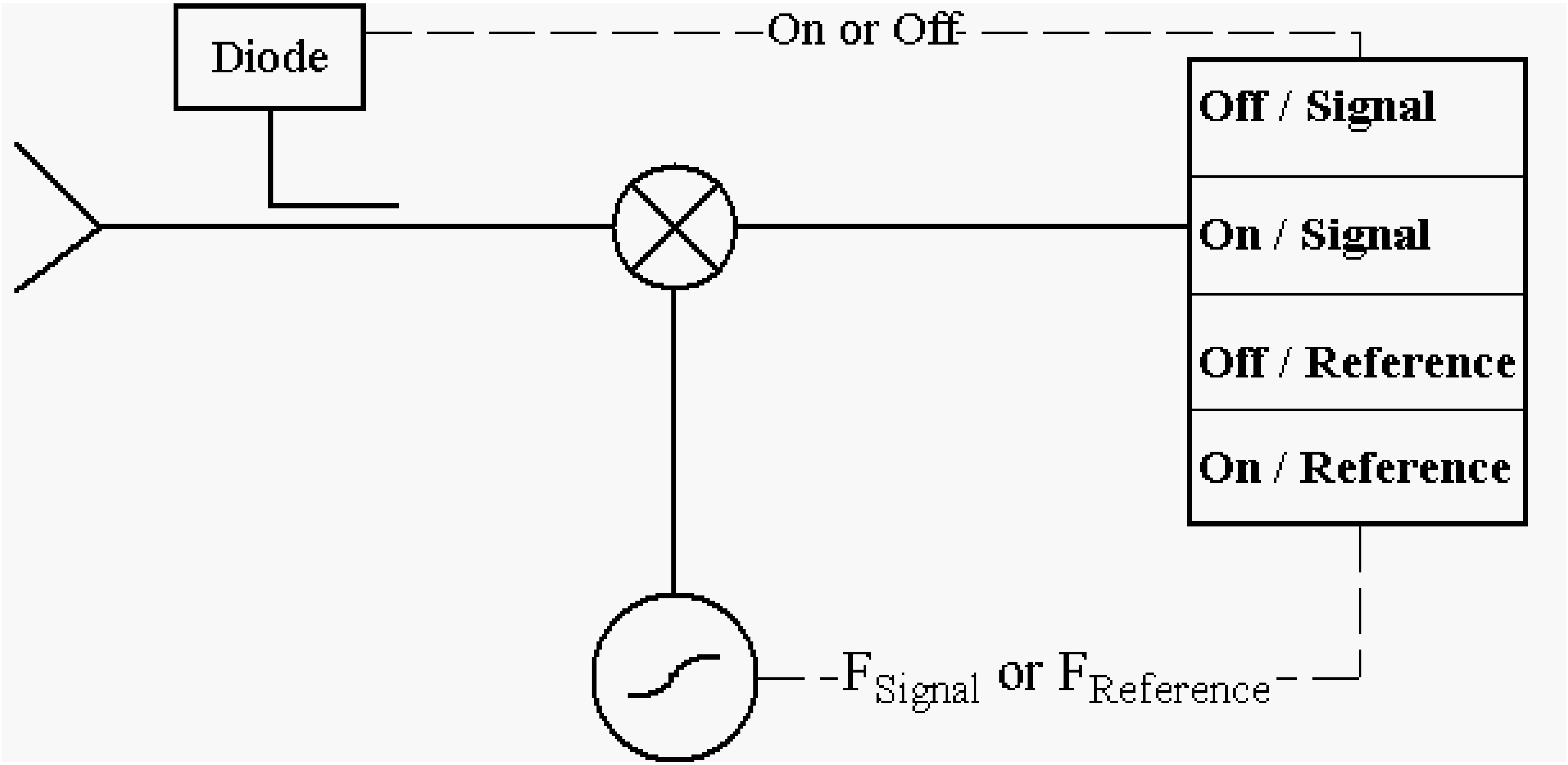
Calibration

Ron Maddalena
NRAO – Green Bank
November 2012

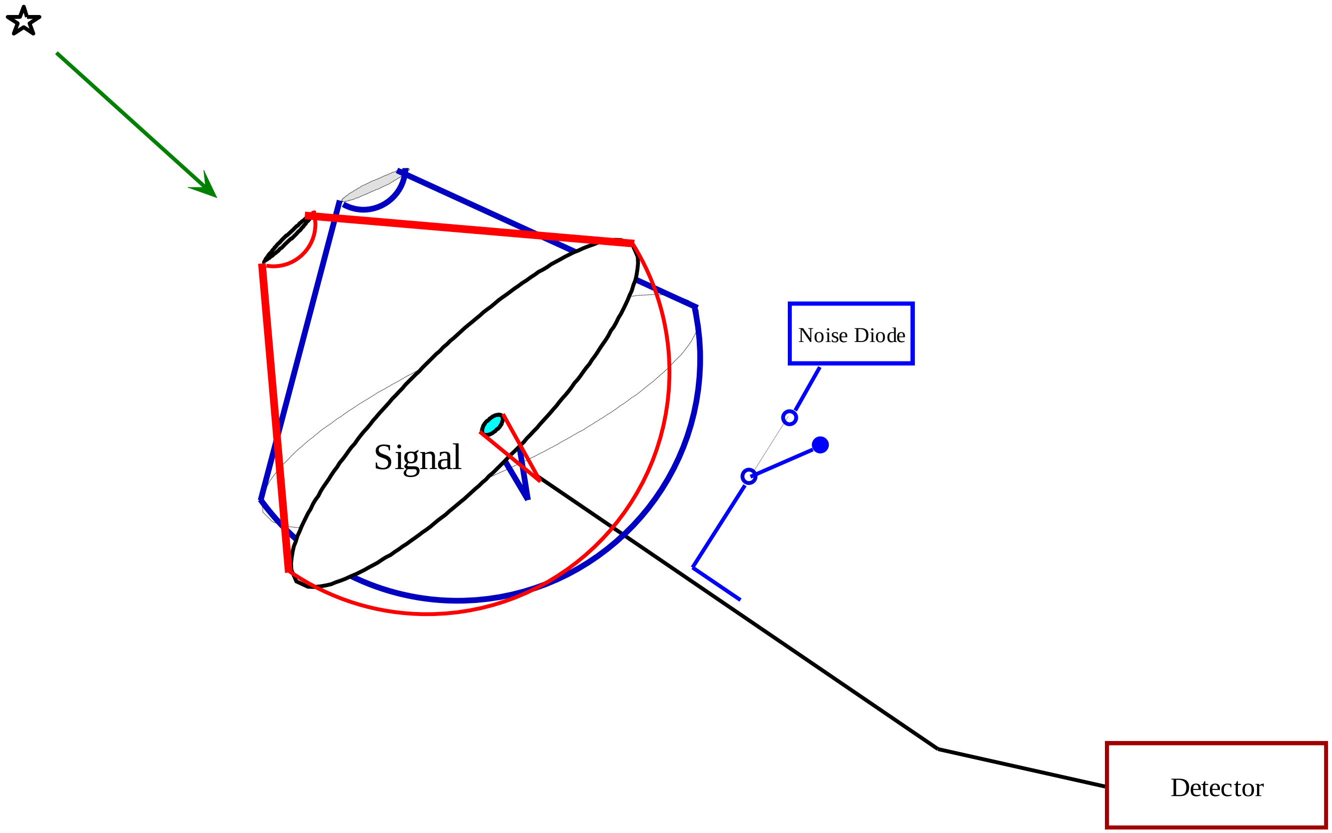


Receiver calibration sources allow us to convert the backend's detected voltages to the intensity the signal had at the point in the system where the calibration signal is injected.

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

Position-Switched (On-Off) Observing



Typical Position-Switched Calibration Equation for a Point Source

$$S(\nu) = \left(\frac{2k}{\eta_A(\nu, Elev) \cdot Area_p} \right) \cdot T_A(\nu) \cdot e^{\tau(\nu,t) \cdot A(Elev,t)}$$

$$T_A(\nu) = \left(\frac{Sig(\nu) - Ref(\nu)}{Ref(\nu)} \right) \cdot T_{Sys}^{Ref}$$

$$T_{Sys}^{Ref} = \left\langle \frac{Ref(\nu)}{Ref_{On}(\nu) - Ref_{Off}(\nu)} T_{Cal}(\nu) \right\rangle_{BW}$$

A(Elev,t) = Air Mass

$\tau(\nu,t)$ = Atmospheric Zenith Opacity

T_{cal} = Noise Diode Temperature

Area = Physical area of the telescope

$\eta_A(\nu,Elev)$ =Aperture efficiency (point sources)

$T_A(\nu)$ = Source Antenna Temperature

$S(\nu)$ = Source Flux Density

$Sig(\nu)$, $Ref(\nu)$ = Data taken on source and on blank sky (in units backend counts)

On,Off = Data taken with the noise diode on and off

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Position-Switched Calibration Equation

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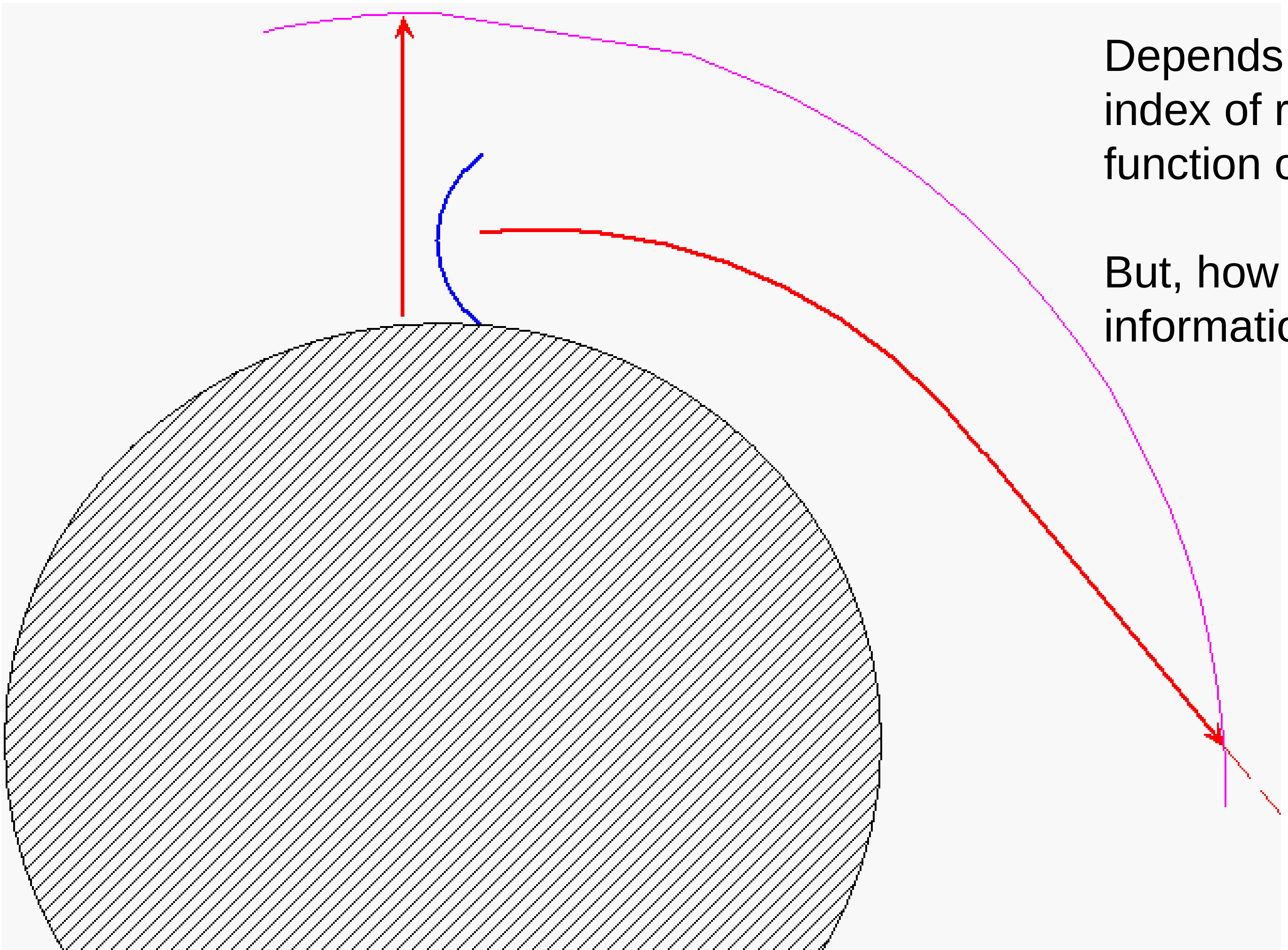
Sources of uncertainties

$$\left(\frac{\Delta S}{S} \right)^2 = (\tau \cdot \Delta A)^2 + (A \cdot \Delta \tau)^2 + \left(\frac{\Delta T_{cal}}{T_{Cal}} \right)^2 + \left(\frac{\Delta \eta}{\eta} \right)^2$$

- 10-15% accuracy have been the ‘standard’
- Usually, errors in T_{cal} dominate
- Goal: To achieve 5% calibration accuracy without a significant observing overhead.

Air Mass Estimates

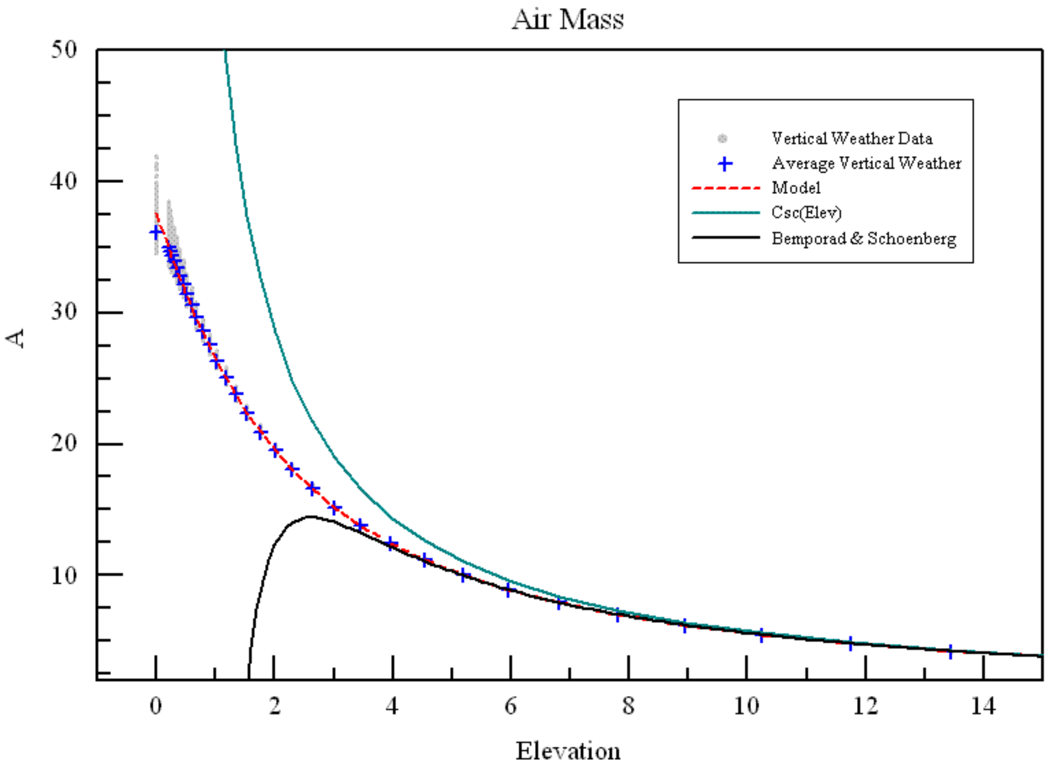


Depends upon density and index of refraction as a function of height

But, how can one get this information?

Air Mass Estimate

- Air Mass traditionally modeled as 1/sin(Elev)
- For 1% calibration accuracy, must use a better model below 15 deg.



$$A = -0.0234 + \frac{1.014}{\sin\left(Elev + \frac{5.18}{Elev + 3.35}\right)}$$

- Good to 1 deg
- Use 1/sin(Elev) above 60 deg
- Coefficients are site specific, at some low level

Typical Position-Switched Calibration Equation

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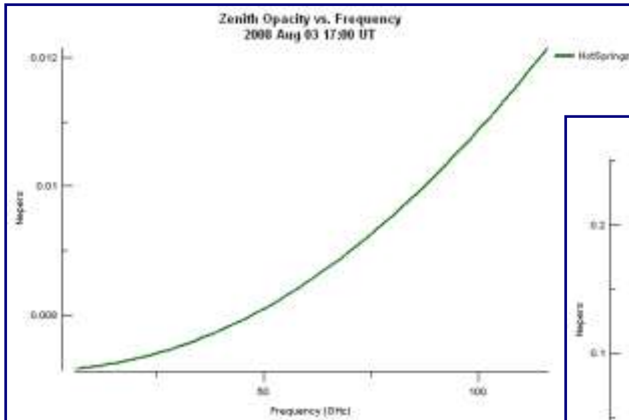
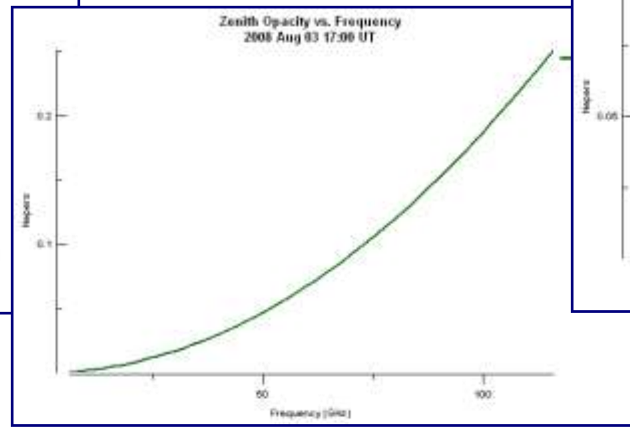
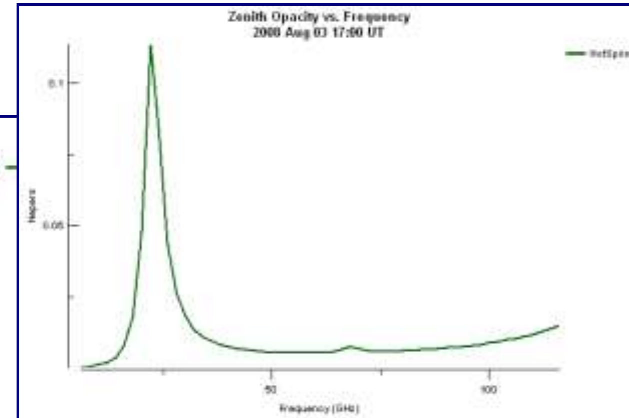
Opacities from the various components



Dry Air Continuum

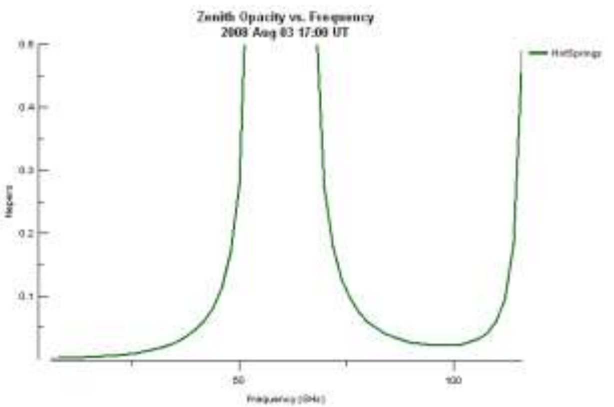
Water Continuum



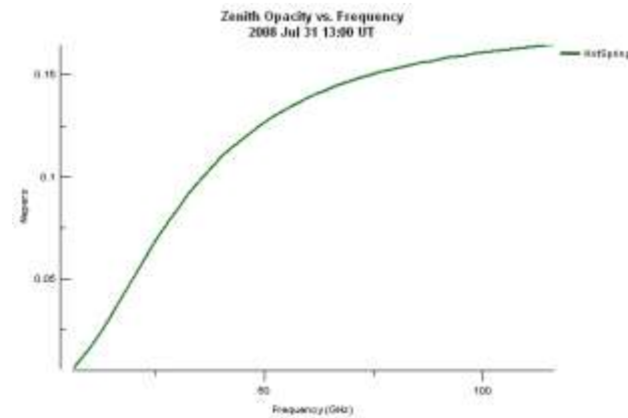


Water Line

Oxygen Line



Hydrosols



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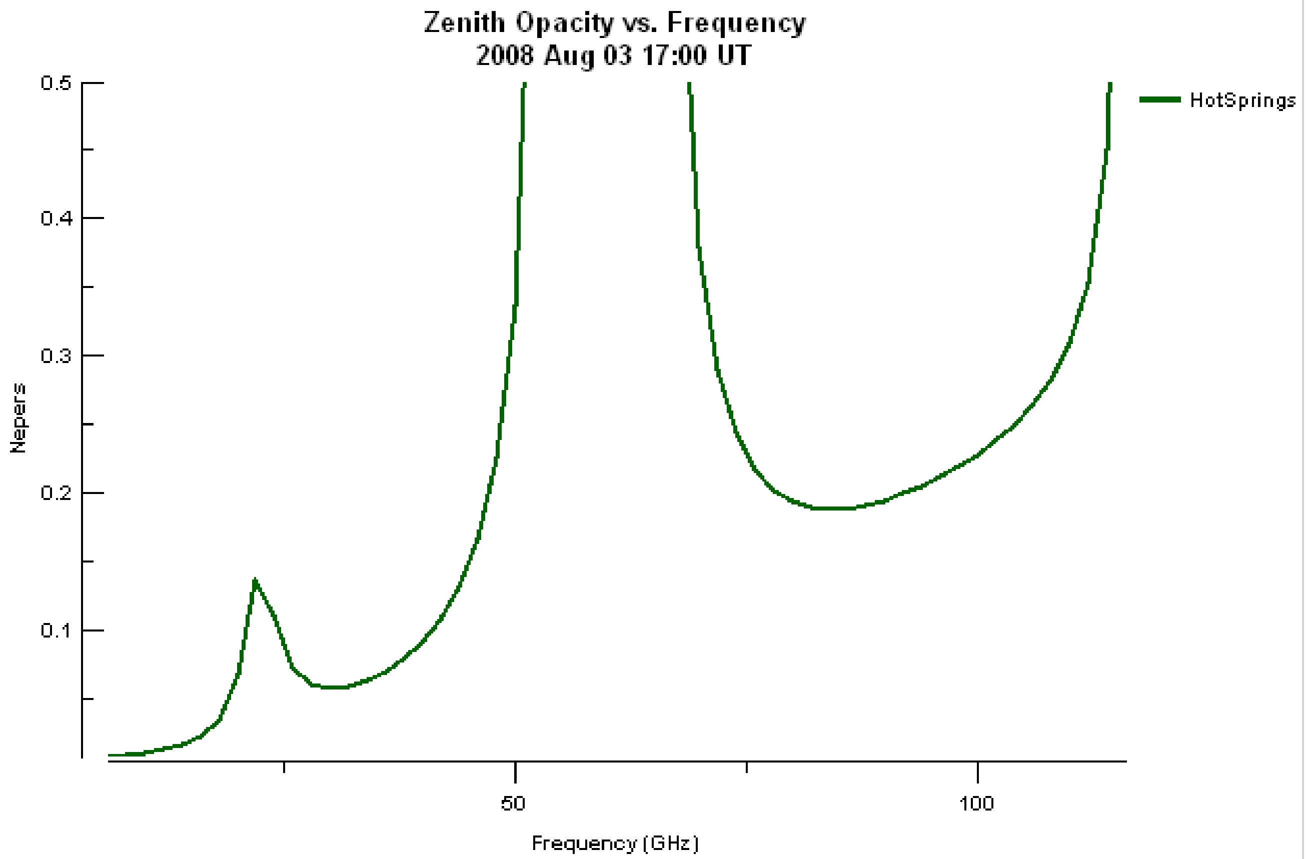
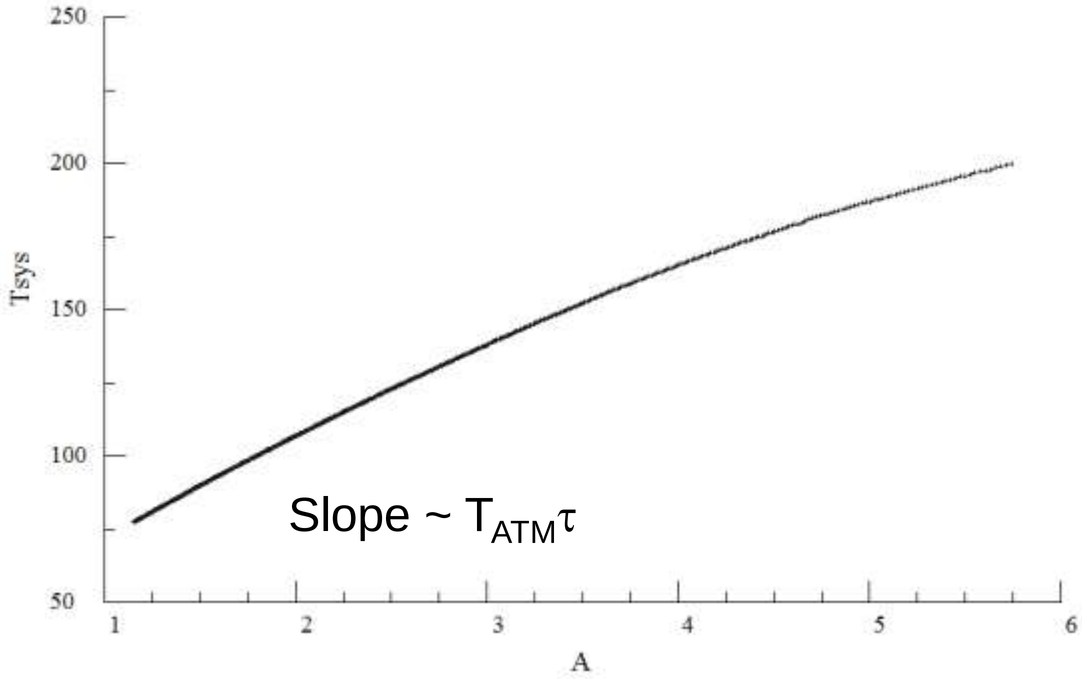


Total Opacity

Determining Opacities

$$T_{SYS} = T_{Rcvr} + T_{Spillover} + T_{CMB} e^{-\tau \cdot A} + T_{ATM} \cdot (1 - e^{-\tau \cdot A})$$



Typical Position-Switched Calibration Equation

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Determining T_{Cal} from hot-cold load measurements in the lab

- Place black bodies (absorbers) of two known temperatures in front of the feed and record detected voltages.
  - $V_{Hot\_Off} = g * T_{Hot}$
  - $V_{Cold\_Off} = g * T_{Cold}$
  - $V_{Cold\_On} = g * (T_{Cold} + T_{Cal})$
- g and T_{Cal} are unknown

Determining T_{Cal} from hot-cold load measurements in the lab

$$T_{Cal} = \frac{V_{Cold\_On} - V_{Cold\_Off}}{V_{Hot\_Off} - V_{Cold\_Off}} \cdot \left(T_{Hot} - T_{Cold}\right)$$

- Course frequency resolution
- Uncertainties in load temperatures
- Are the absorbers black bodies?
- Detector linearities (300 & 75 K)
- Lab T_{Cal} may be off by 10%
- So… all good observers perform their own astronomical calibration observation

Noise Diode Estimates

- Instead, we recommend an On-Off observation
  - Use a point source with known flux -- polarization should be low or understood
  - Use the same exact hardware, exact setup as your observation. (i.e., don’t use your continuum pointing data to calibrate your line observations.)
  - Observations take ~5 minutes per observing run
  - Staff take about 2 hrs to measure the complete band of a high-frequency, multi-beam receiver.
  - Resolution sufficient: 1 MHz, sometimes better
  - Accuracy of ~ 1%, mostly systematics.

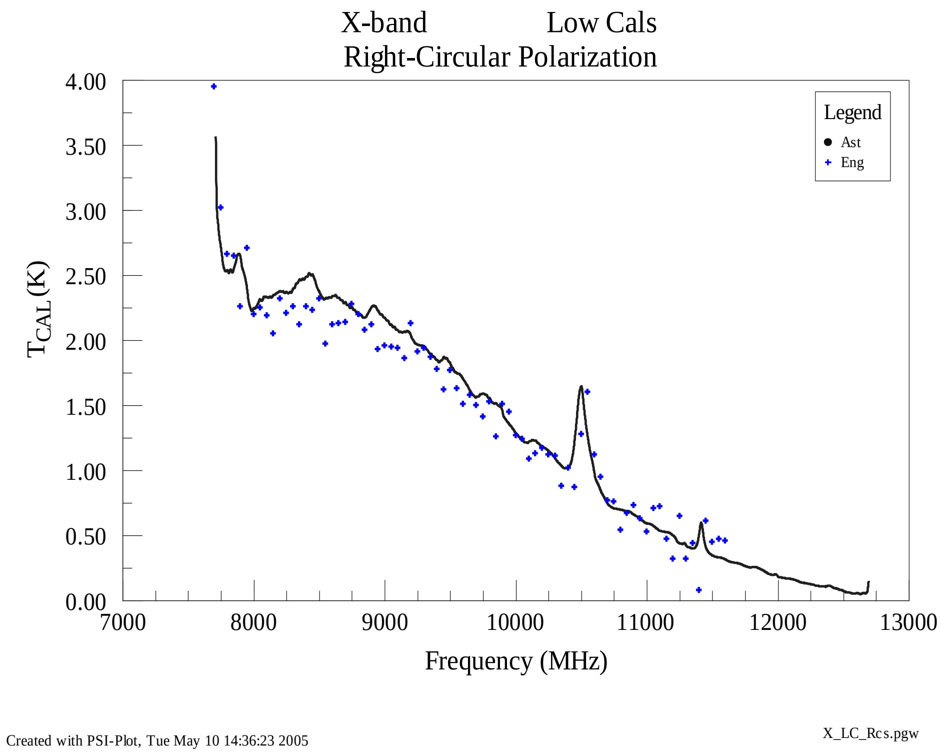
Noise Diode Estimates

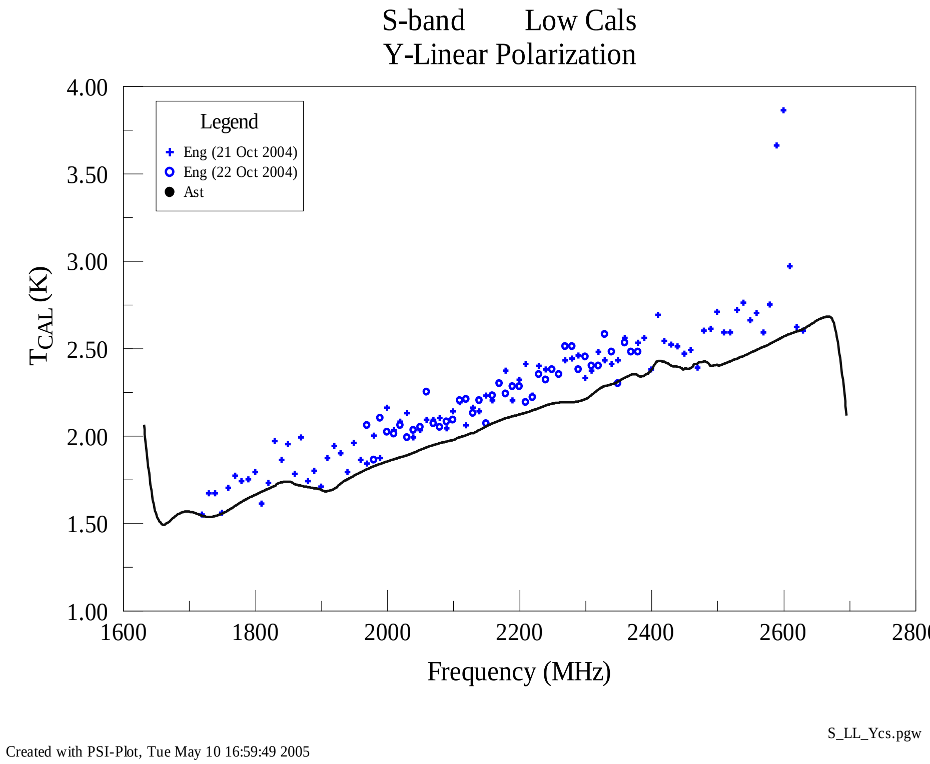
$$S(\nu) = \left(\frac{2k}{\eta_A(\nu, Elev) \cdot A_p} \right) \cdot \left(\frac{Sig(\nu) - Ref(\nu)}{Ref(\nu)} \right) \left\langle \frac{Ref(\nu)}{Ref_{On}(\nu) - Ref_{Off}(\nu)} T_{Cal}(\nu) \right\rangle \cdot e^{\tau(\nu)A}$$

Remove Averaging, Solve for Tcal

$$T_{Cal}(\nu) = \frac{\eta_A(\nu, Elev) \cdot Area_p}{2k \cdot e^{\tau(\nu) \cdot A}} \left(\frac{Ref_{On}(\nu) - Ref_{Off}(\nu)}{Sig(\nu) - Ref(\nu)} \right) \cdot S(\nu)$$

Noise Diode Estimates





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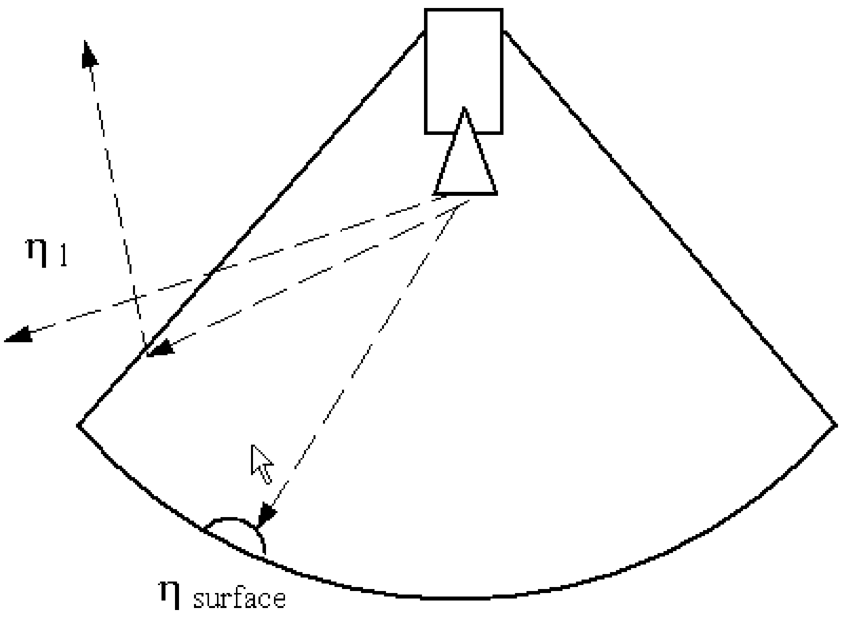
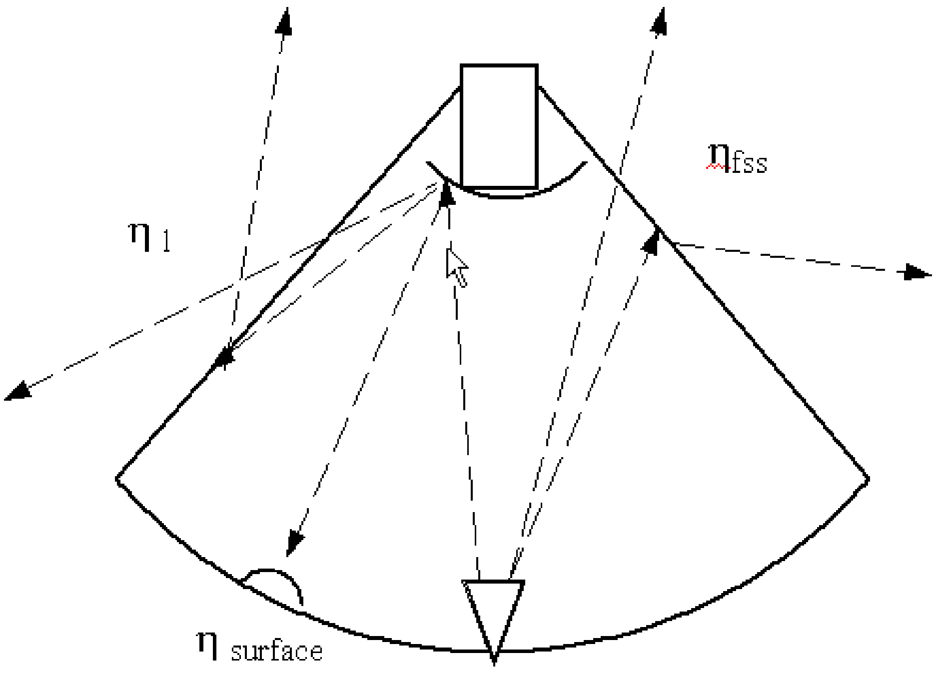
Telescope efficiencies – Part 1



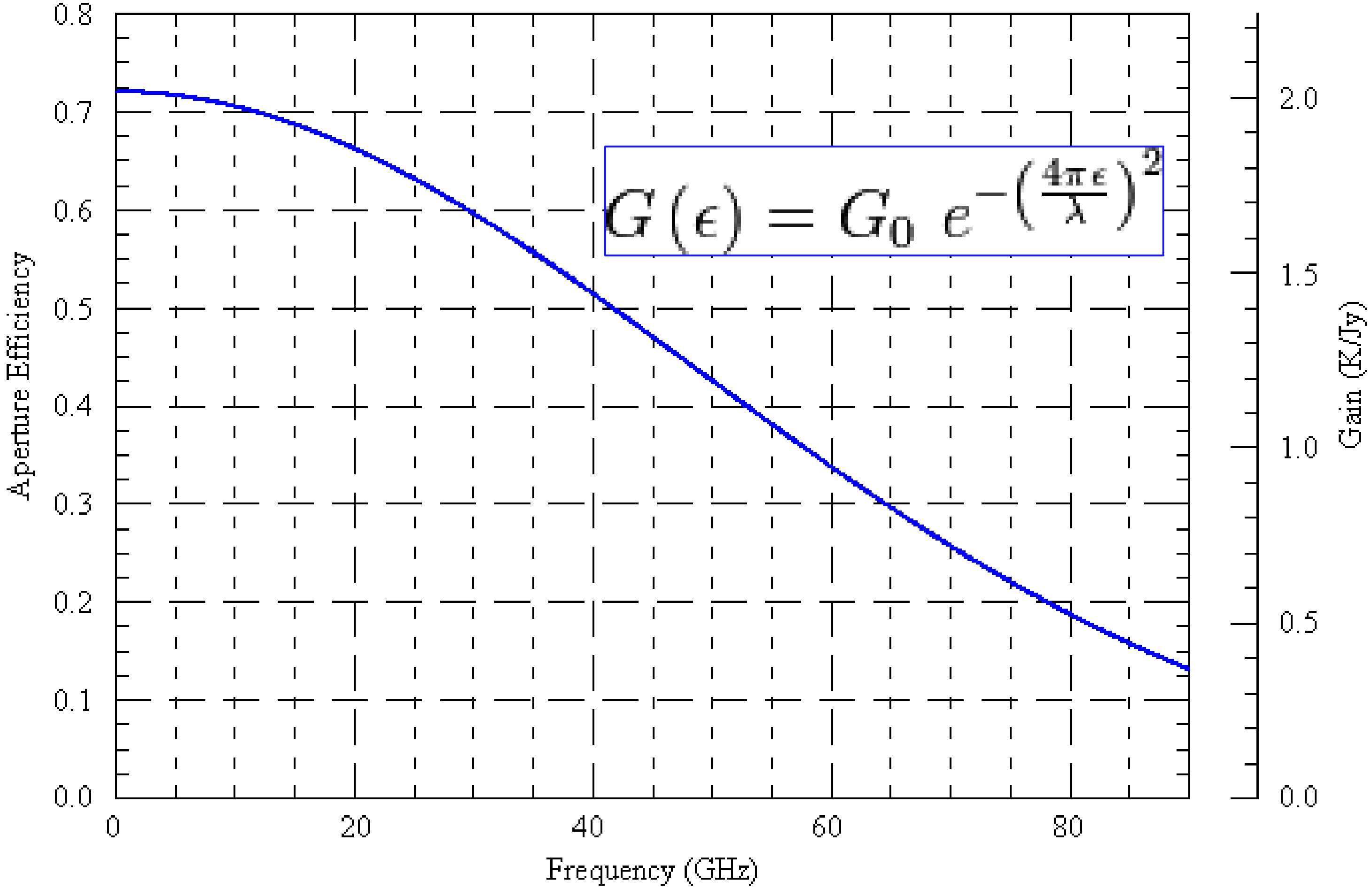
Not shown: η_r and $\eta_{illumination}$



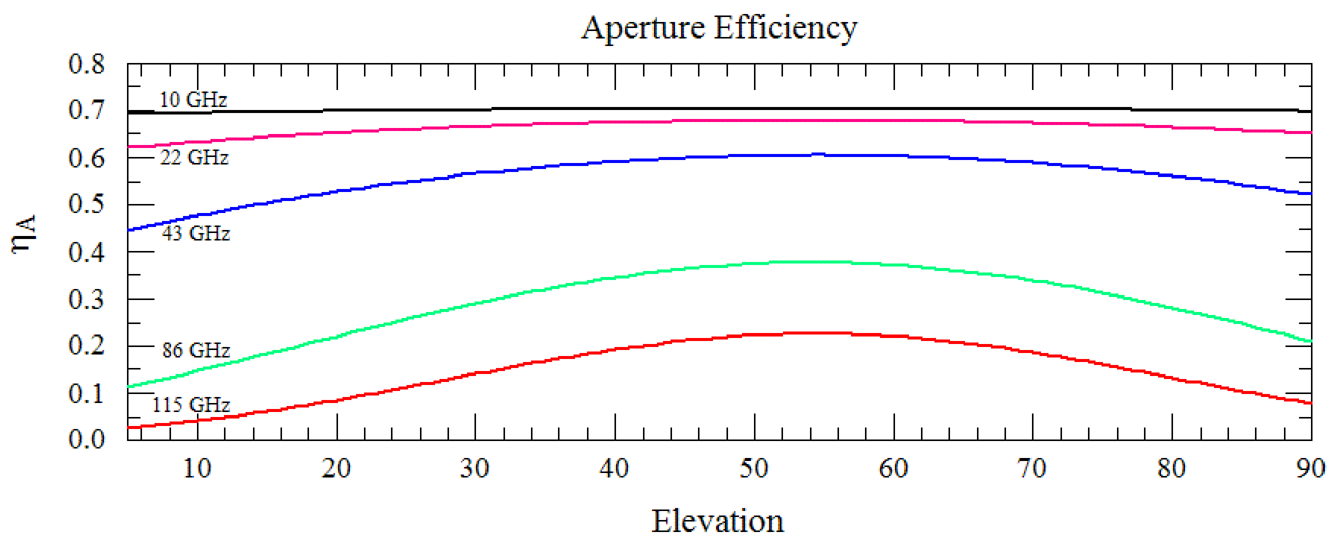
Not shown: η_r and $\eta_{illumination}$

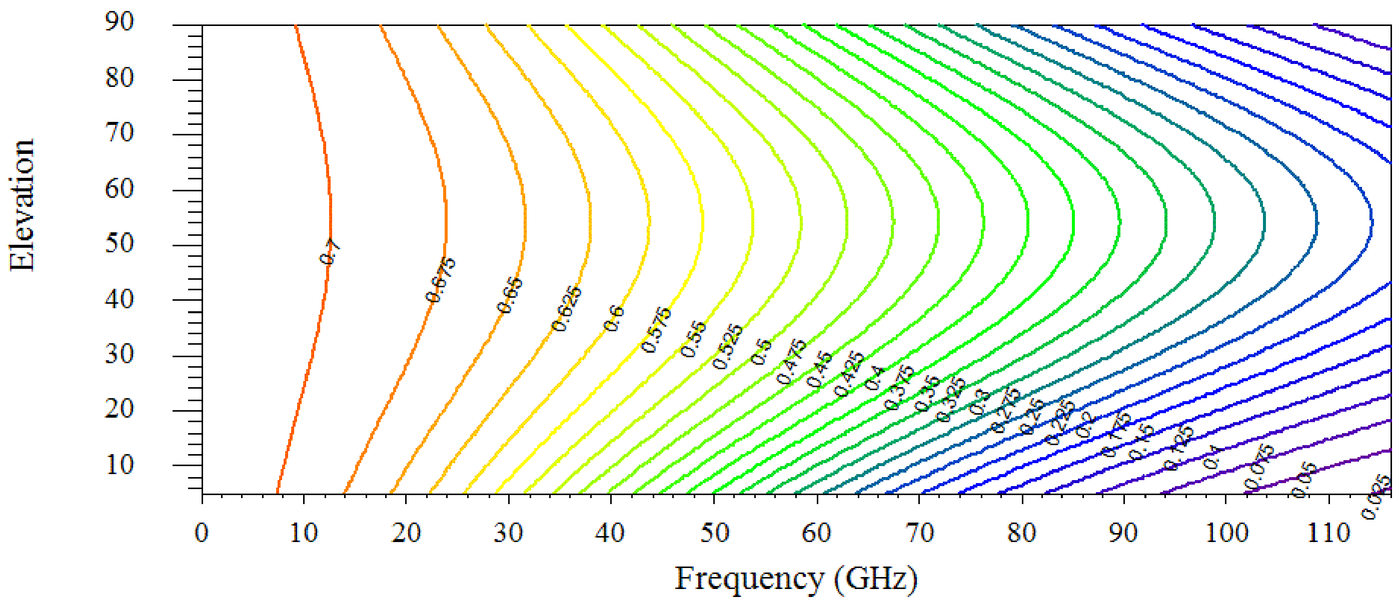
GBT Gain Curve

Ruze Equation – Surface errors

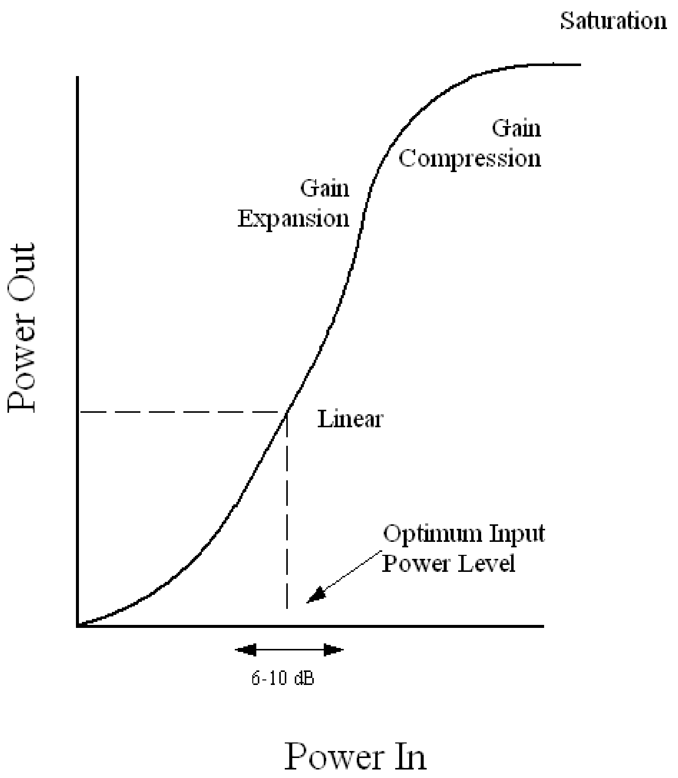


GBT Gain Curve



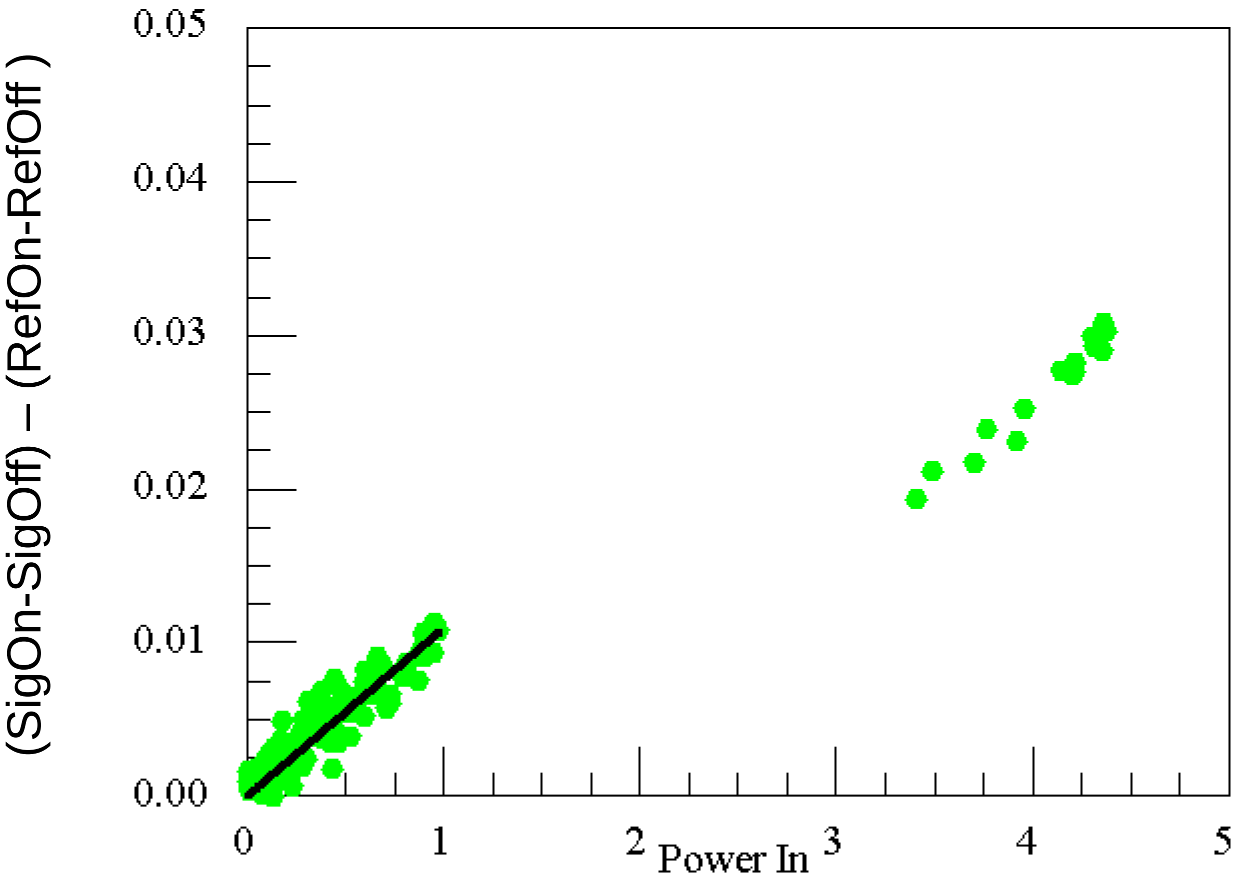


Non-linearity



- If system is linear,
  - $P_{out} = B * P_{in}$
  - $(Sig_{On}-Sig_{Off}) – (Ref_{On}-Ref_{Off}) = 0$
- Model the response curve to 2nd order:
  - $P_{out} = B * P_{in} + C * P_{in}^2$
- Our 'On-Off' observations of a calibrator provide:
  - Four measured quantities: $Ref_{off,}$ $Ref_{on,}$ $Sig_{off,}$ Sig_{on}
  - T_A From catalog
  - Four desired quantities: B, C, Tcal, Tsys
- It's easy to show that:
  - $C = [(Sig_{on}- Sig_{off})-(Ref_{on}- Ref_{off})]/(2T_AT_{cal})$
- Thus:
  - Can determine if system is sufficiently linear
  - Can correct to 2nd order if it is not

Non-linearity



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
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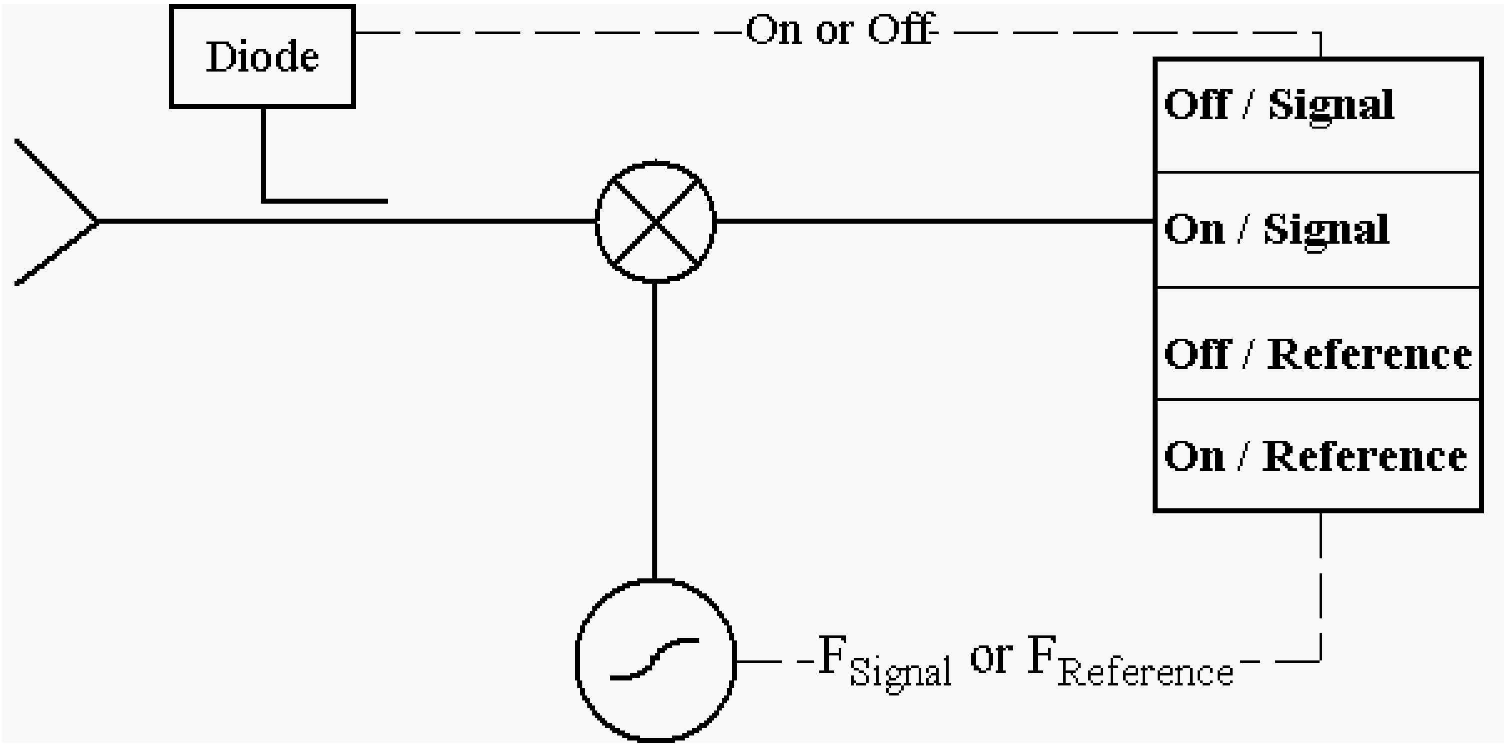
Position switching

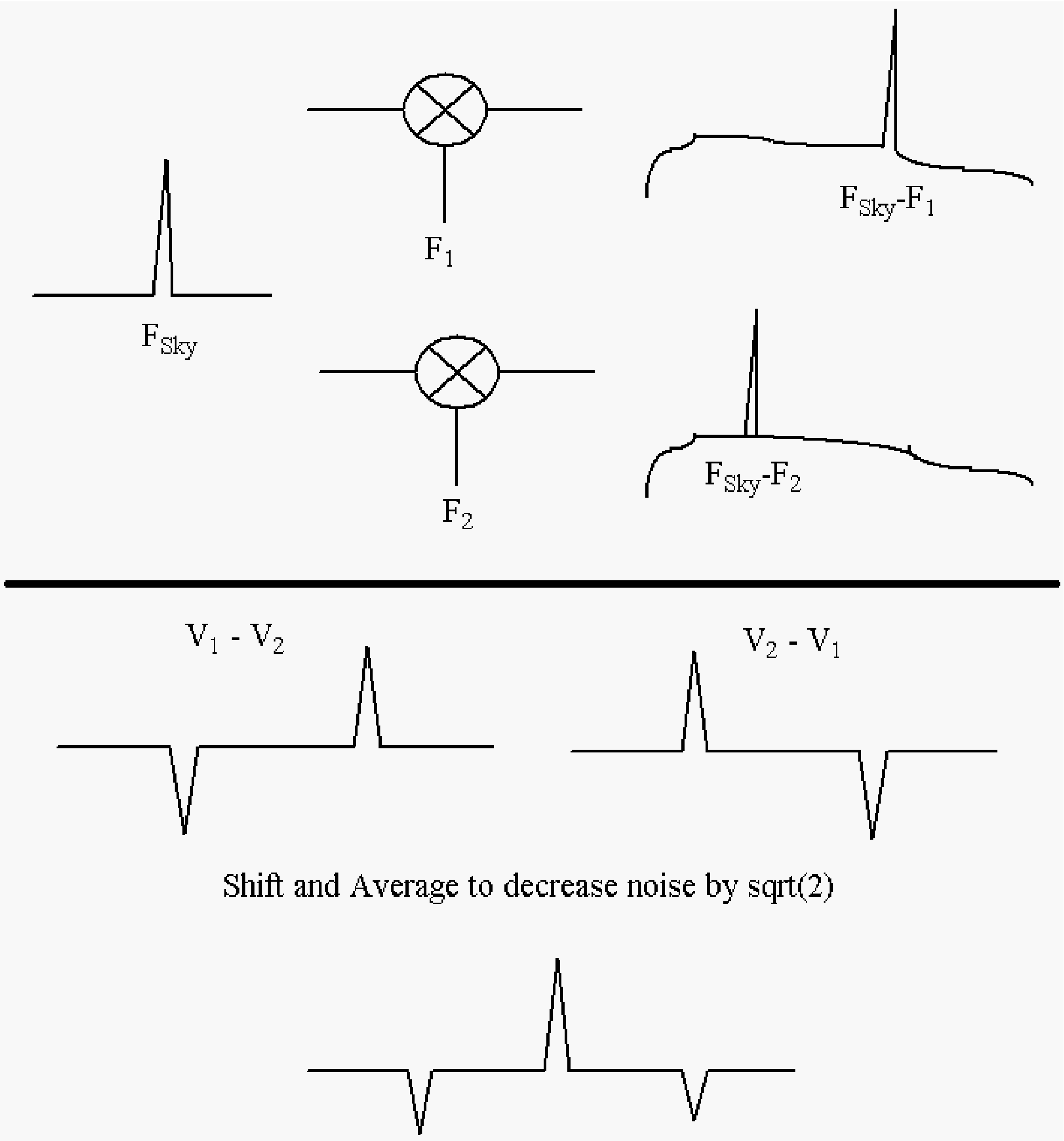
- Move the telescope between a signal and reference position
  - Overhead
  - ½ time spent off source
- Difference the two spectra
- Assumes shape of gain/bandpass doesn’t change between the two observations.
- For strong sources, must contend with dynamic range and linearity restrictions.

Frequency switching

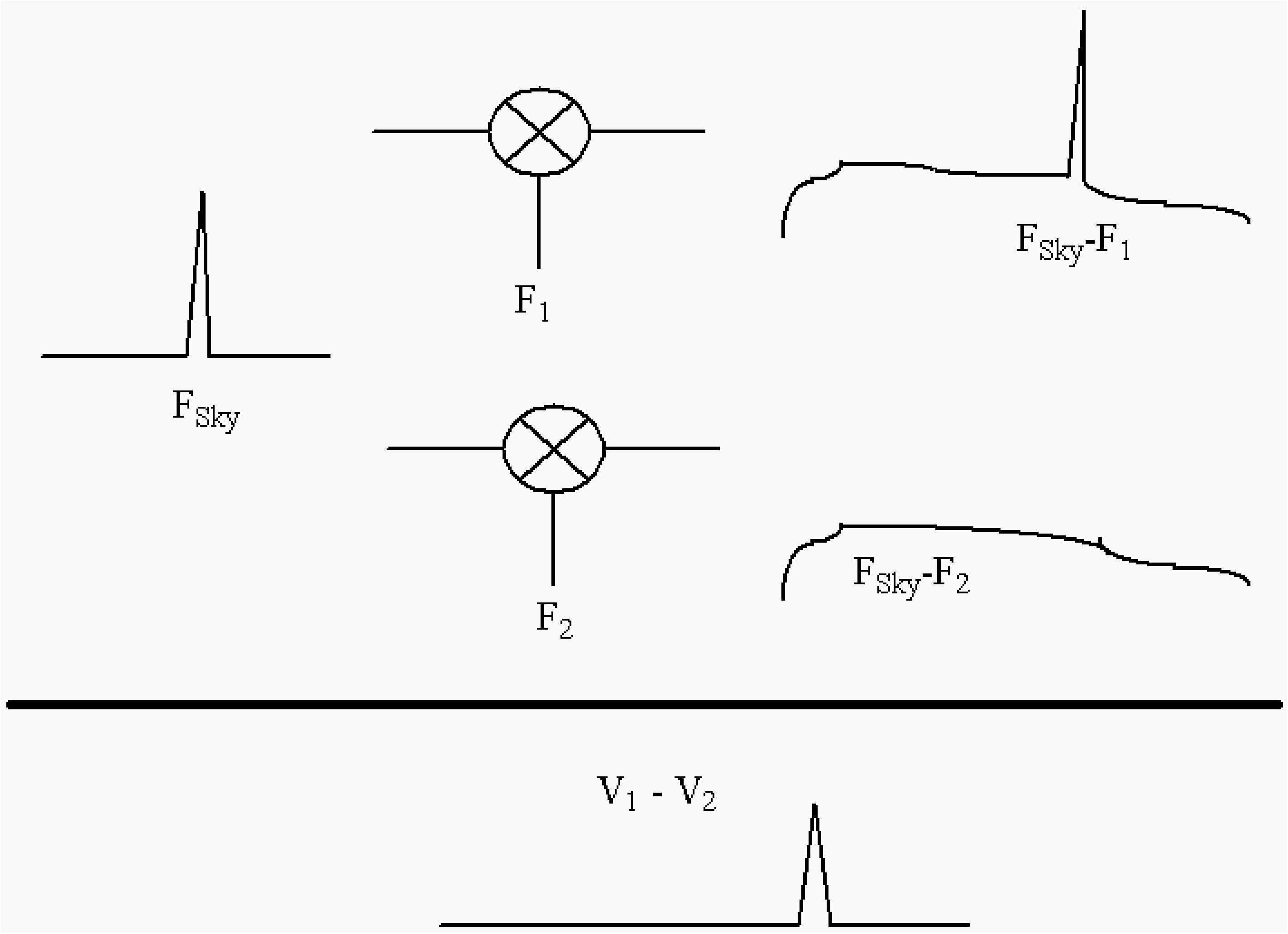


- Eliminates bandpass shape from components after the mixer
- Leaves the derivative of the bandpass shape from components before the mixer.

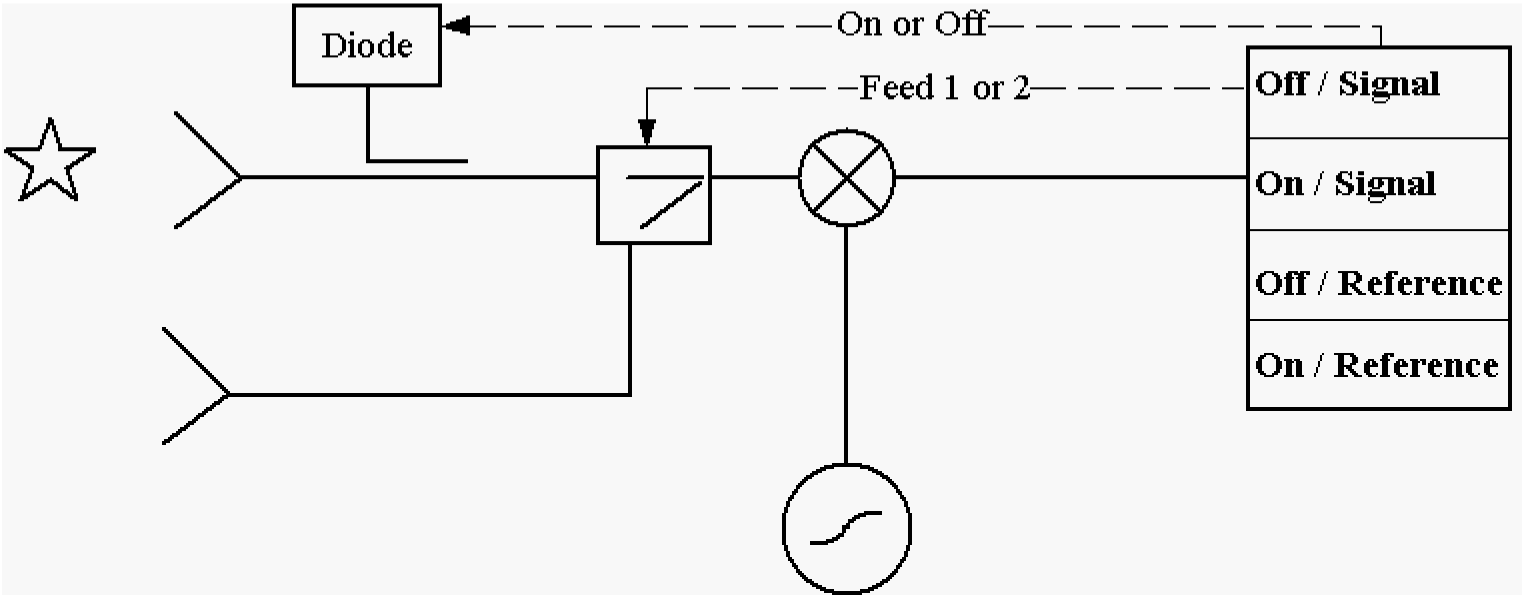
In-Band Frequency Switching



Out-Of-Band Frequency Switching



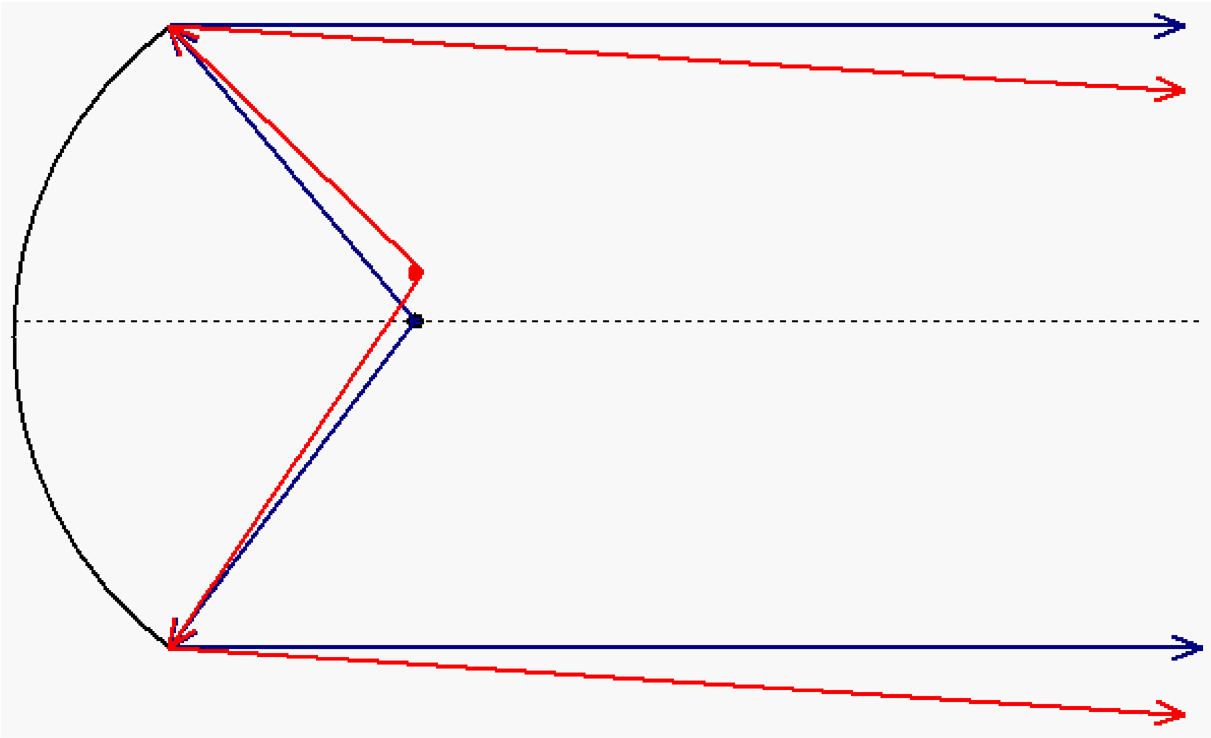
Beam switching – Internal switch



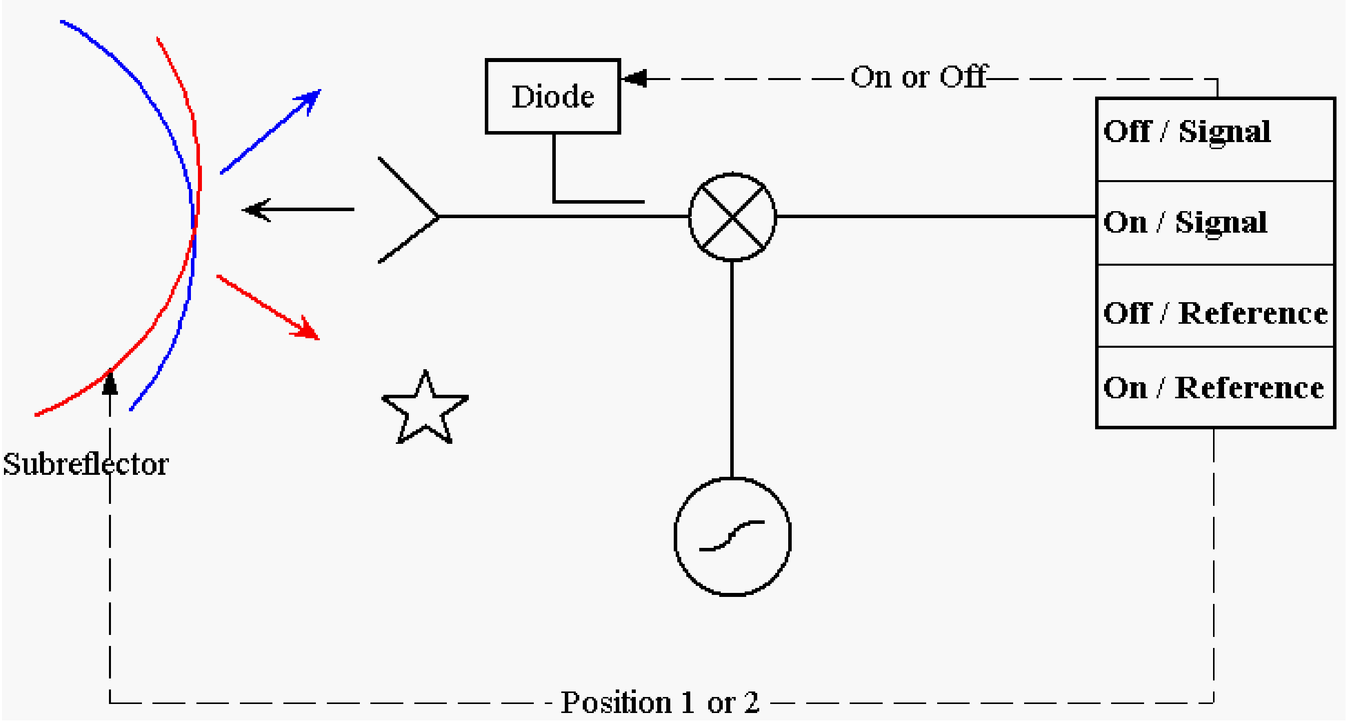
- Difference spectra eliminates any contributions to the bandpass from after the switch
- Residual will be the difference in bandpass shapes from all hardware in front of the switch.
- Low overhead but ½ time spent off source

Atmosphere is in the near field

- Common to all feeds in a multi-feed receiver

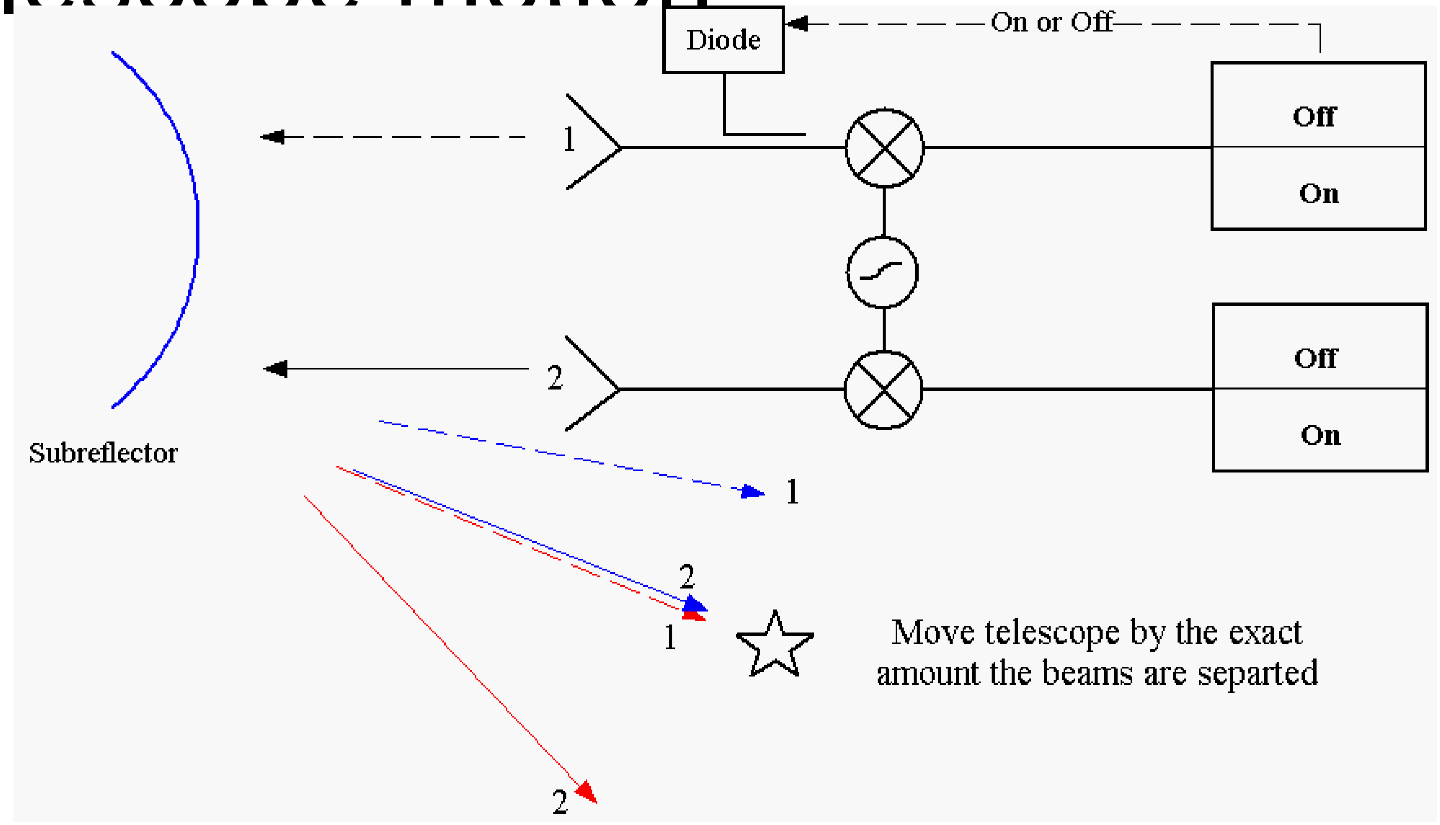


Beam Switching – Subreflector or tertiary mirror



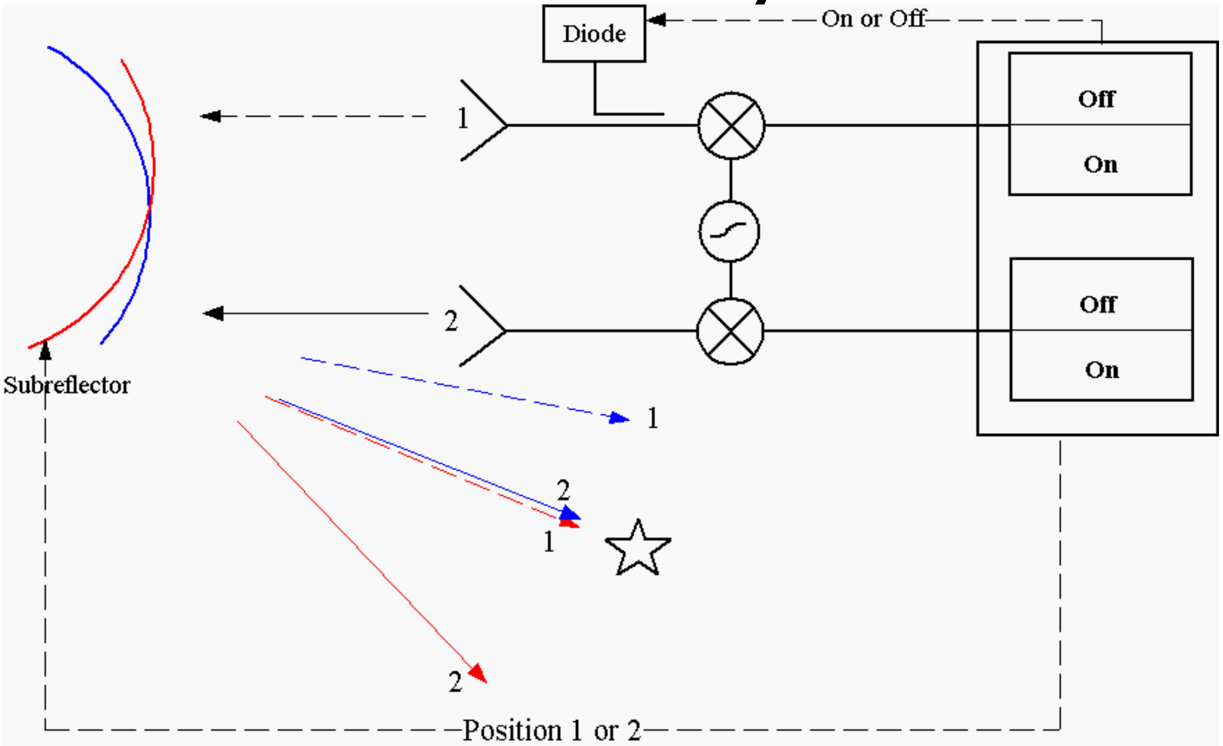
- Optical aberrations
- Difference in spillover/ground pickup
- Removes any 'fast' gain/bandpass changes
- Low overhead. ½ time spent off source

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 or tertiary mirror



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References

- Rohlfs & Wilson, “Tools of Radio Astronomy”
- Stanimrovis et al, “Single-Dish Radio Astronomy: Techniques and Practices”
- Baars, 1973, IEEE Trans Antennas Propagat, Vol AP-21, no. 4, pp 461-474
- Kutner & Ulich, 1981, Astronomica Journal, Vol 250,pp 341-348
- Winkel, Kraus, & Bach, 2012, Astronomy & Astrophysics, vol. 540.