Spectral Line Calibration Techniques with Single Dish Telescopes

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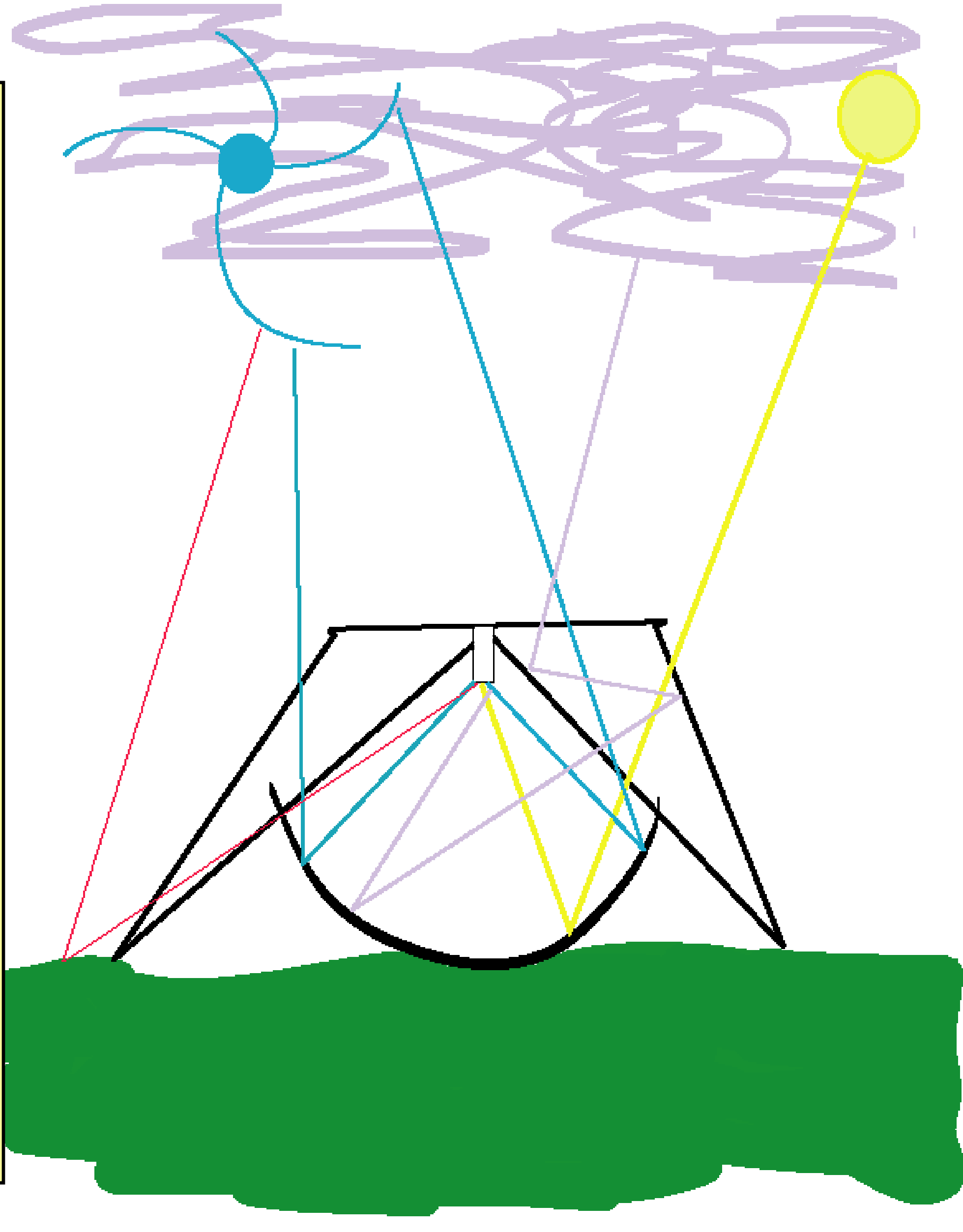


A Quick Review

Review:
The Rayleigh-Jeans Approximation

- Planck Law for Blackbody radiation:

$$B = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$$

- If ν~GHz, often $h\nu << kT$. Taylor series gives:

$$B = \frac{2kT\nu^2}{c^2} = \frac{2kT}{\lambda^2}$$

- Source flux in Rayleigh Jeans limit:

$$S = \frac{2k}{\lambda^2} \int_{\Omega_S} T(\theta,\phi) d\Omega$$

- If brightness temperature is constant across source:

$$S = \frac{2kT}{\lambda^2} \Omega_S$$

B=Brightness, n = frequency; h = 6.626 x 10^{-16} J s; k = 1.380 x 10^{-23} J K^{-1} ;T = temperature

Review:
Antenna Temperature

- Telescope observes a point source (flux density S)
- Telescope feed replaced with matched load (resistor)
- Load temperature adjusted until power received equals power of the source
- This is equal to the Antenna Temperature

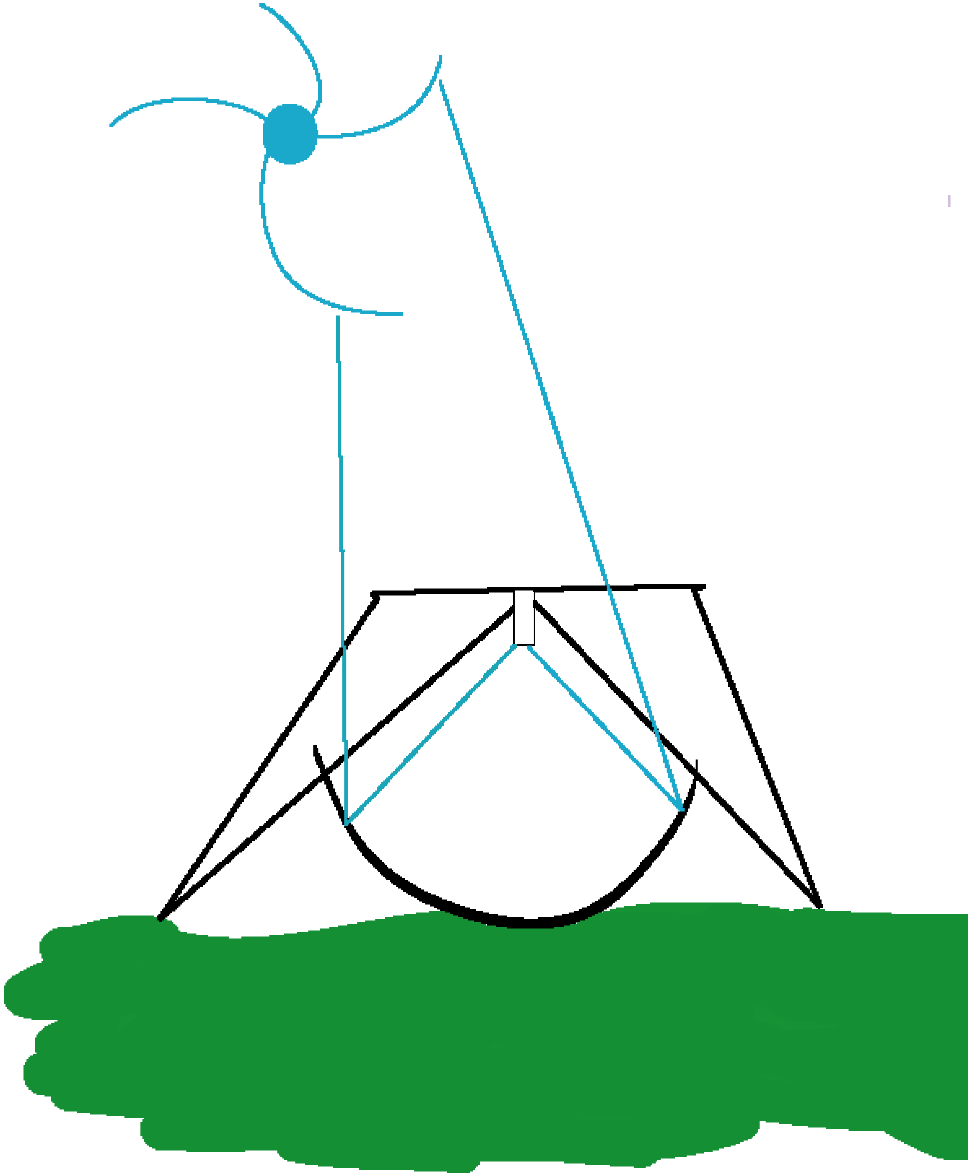
Determining the Source Temperature

Determining T_{source}

- $T_{meas}\,(\alpha,\delta,az,za) =$

  $T_{src}(\alpha,\delta,az,za)$

  $+\ T_{system}$



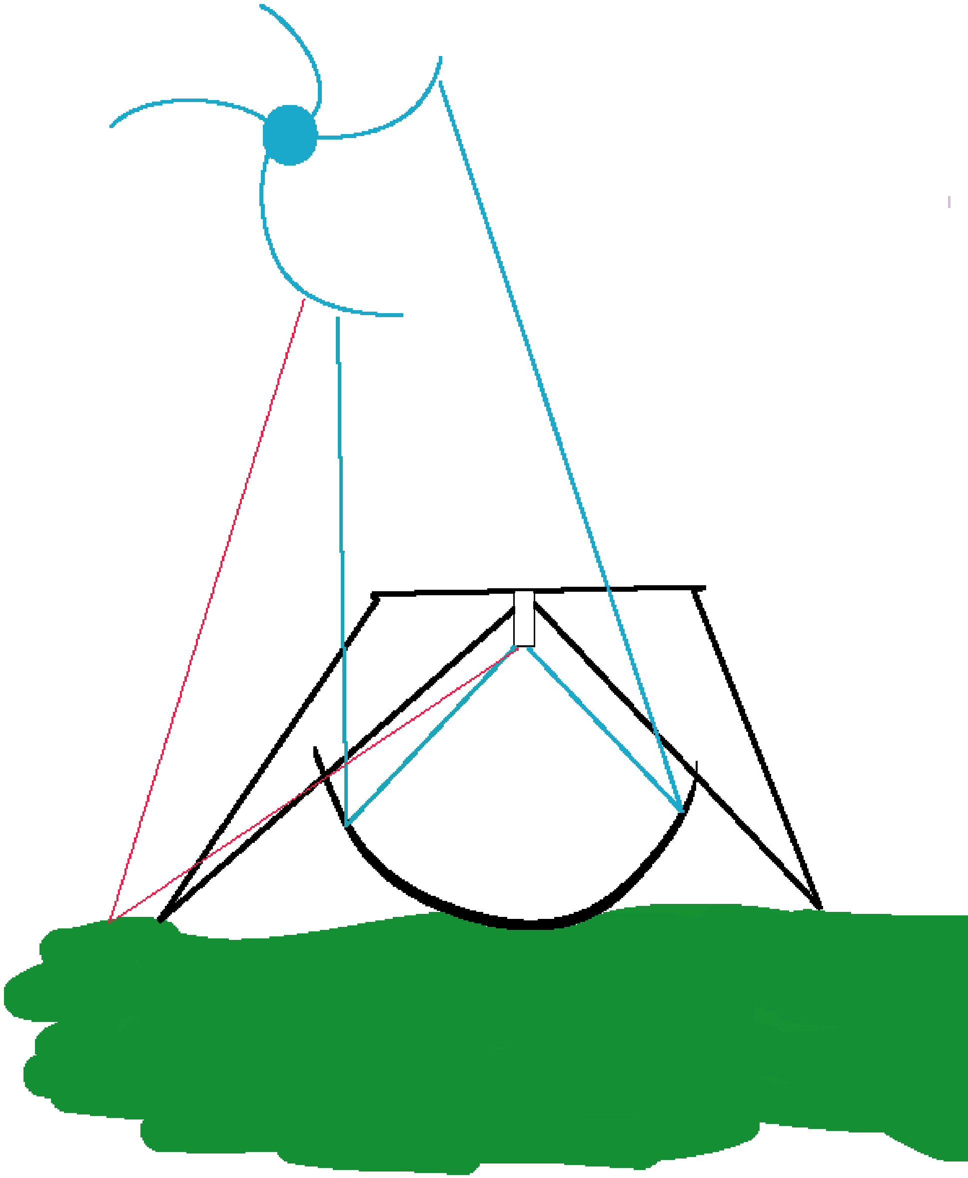
Determining T_{source}

- $T_{meas}(\alpha,\delta,az,za) =$

  $T_{src}(\alpha,\delta,az,za)$

  $+ T_{RX}$

  $+ T_{gr}(za,az)$



Determining T_{source}

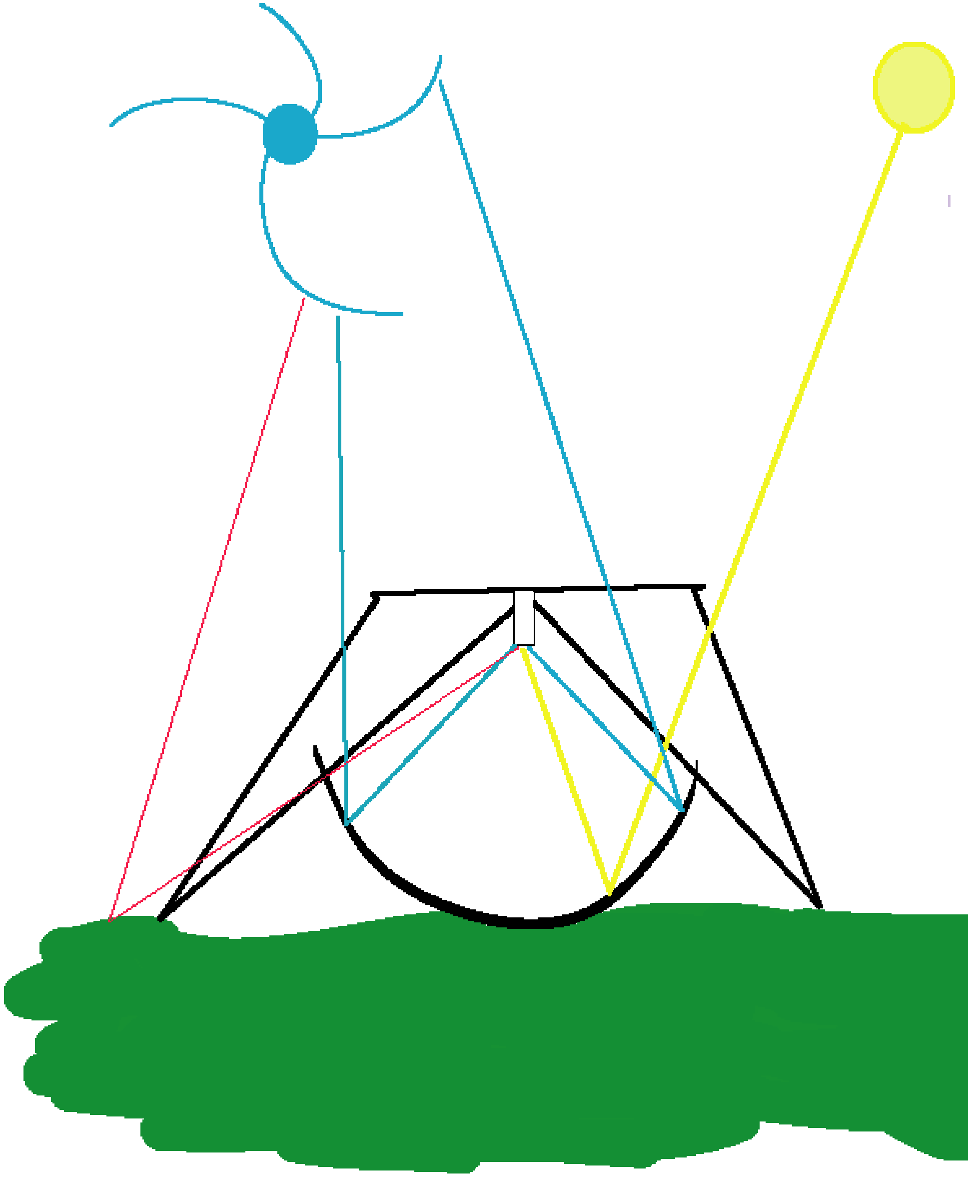
- $T_{meas}(\alpha,\delta,az,za) =$

  $T_{src}(\alpha,\delta,az,za)$

  $+\ T_{RX}$

  $+\ T_{gr}(za,az)$

  $+\ T_{cel}(\alpha,\delta,t)$

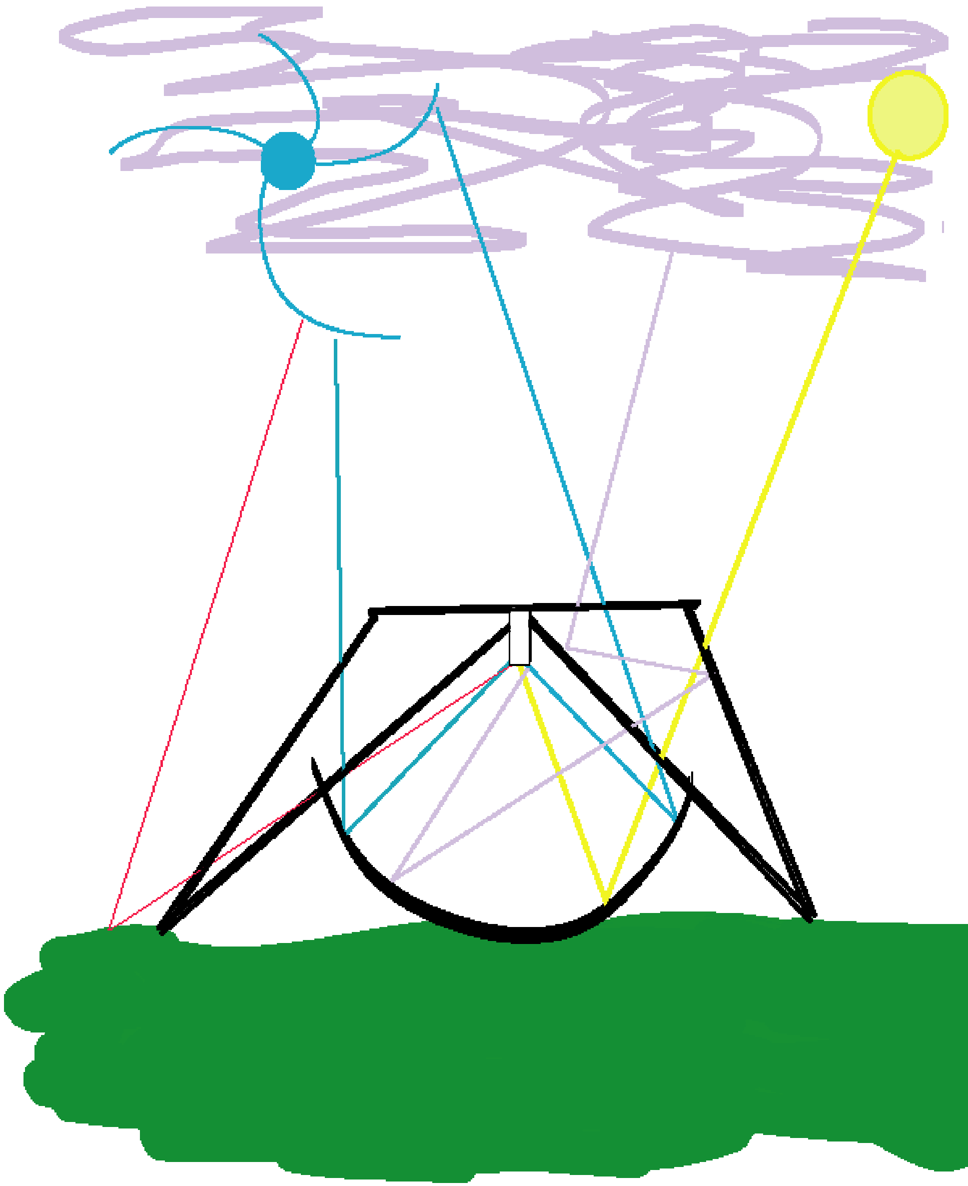


Determining T_{source}

- $T_{meas}(\alpha,\delta,az,za) =$

$$T_{src}(\alpha,\delta,az,za)$$
$$+ T_{RX}$$
$$+ T_{gr}(za,az)$$
$$+ T_{cel}(\alpha,\delta,t)$$
$$+ T_{CMB}$$
$$+ T_{atm}(za)$$

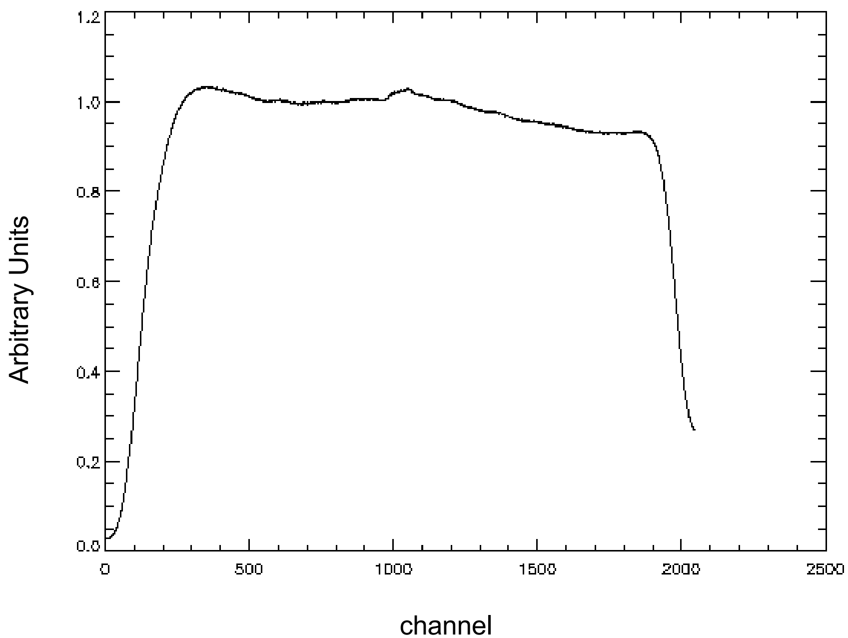
$$T_{meas} = T_{source} + T_{everything\ else}$$



Determining T_{source}

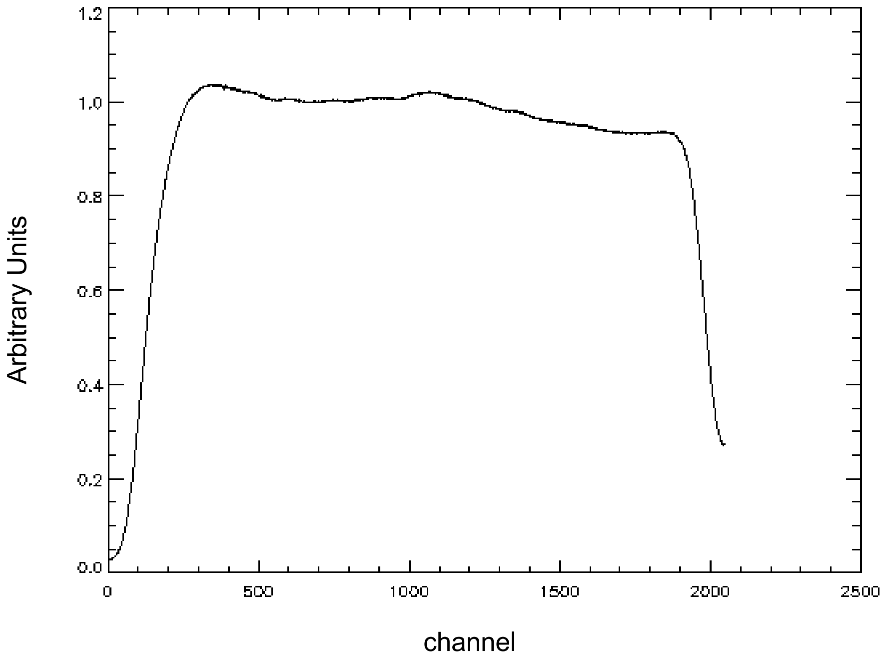
ON

$T_{source} + T_{everything\ else}$



OFF

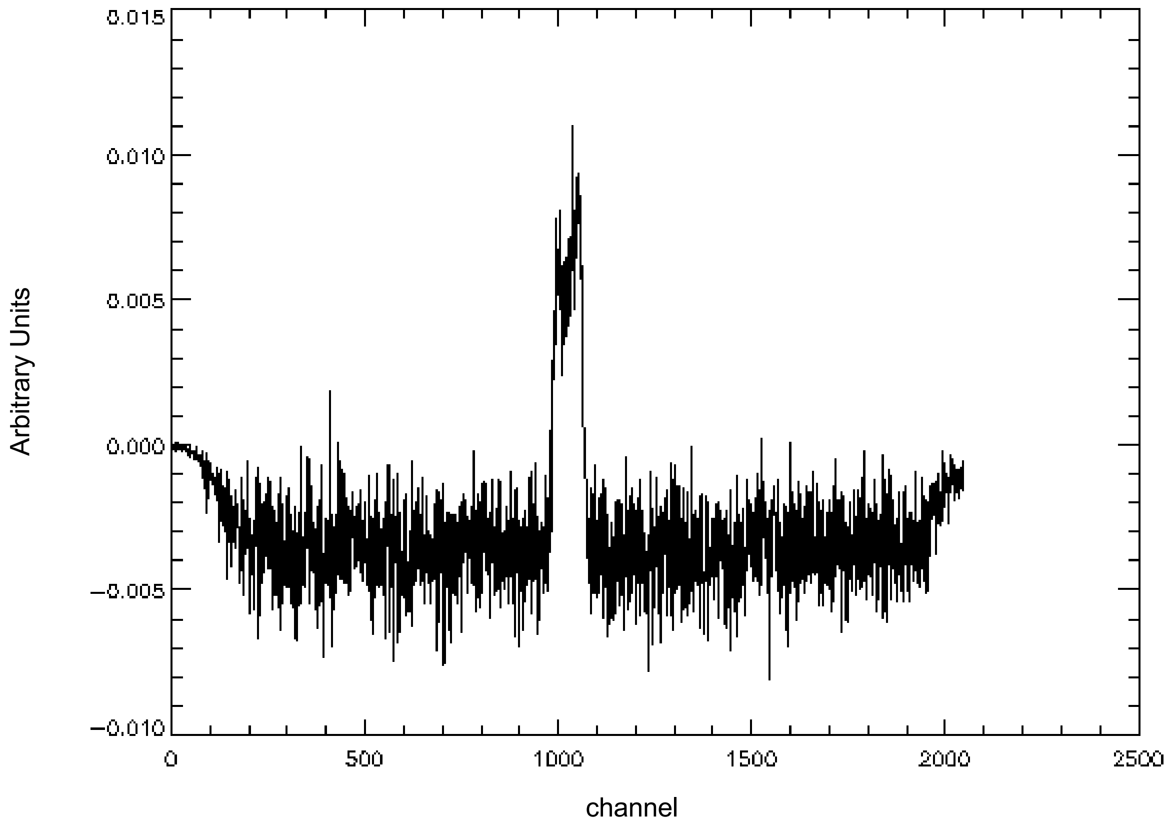
$T_{everything\ else}$



Determining T_{source}

ON - OFF

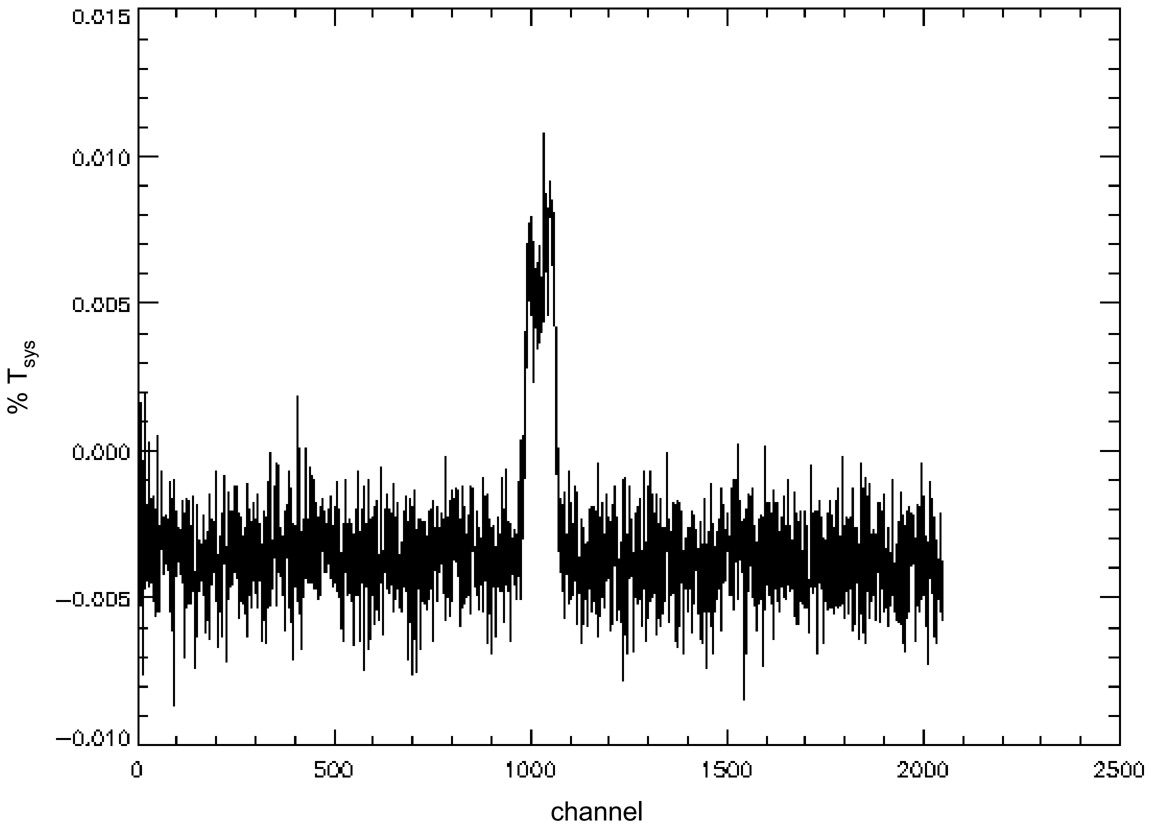
$(T_{source} + T_{everything\ else}) - (T_{everything\ else})$



Determining T_{source}

(ON – OFF)/OFF

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



Determining T_{src}

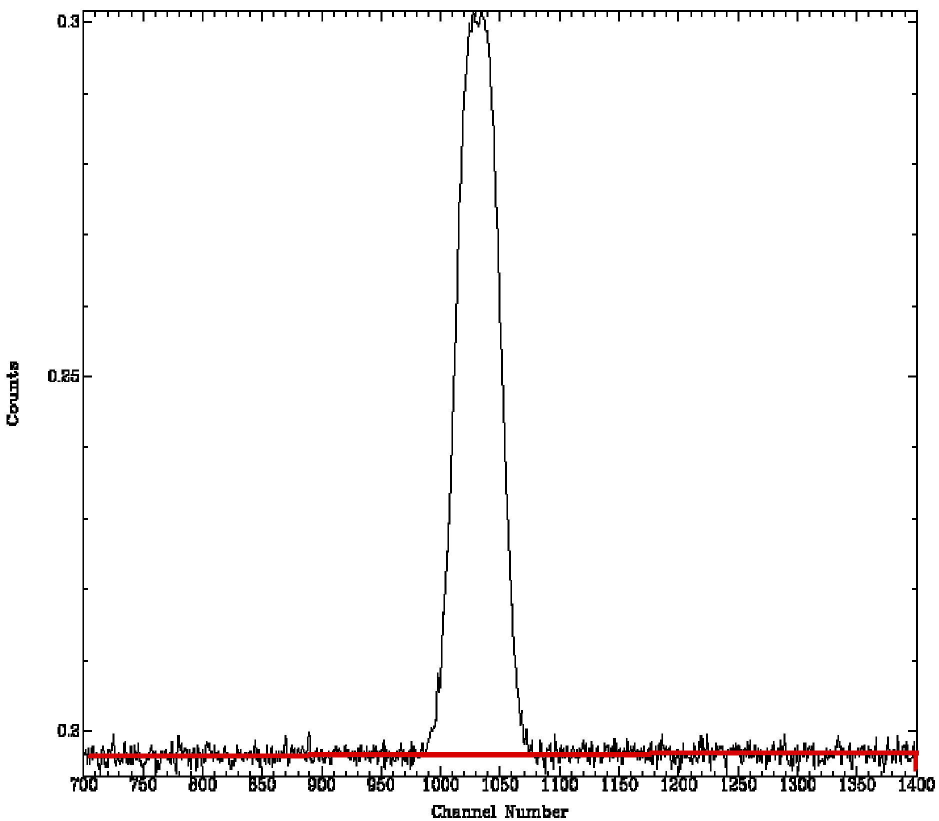
$$T_{source} = \frac{(\mathrm{ON} - \mathrm{OFF})}{\mathrm{OFF}}$$

???

Choosing the Best OFF

Off—Source Observations

Baseline Fitting



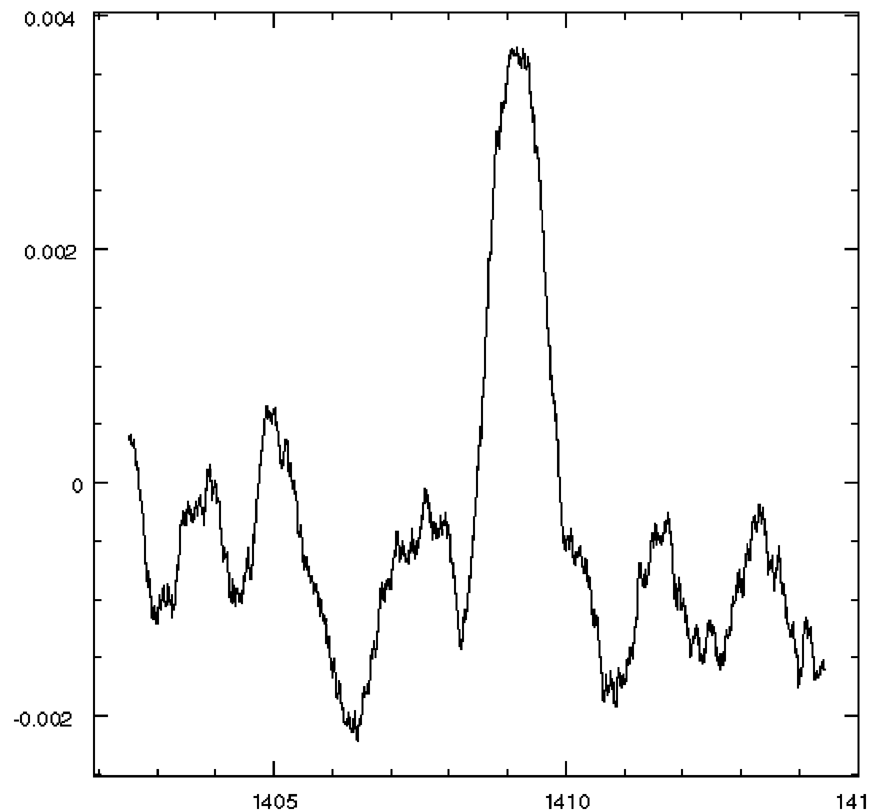


Image on right courtesy of C. Conselice

Off—Source Observations

Baseline Fitting

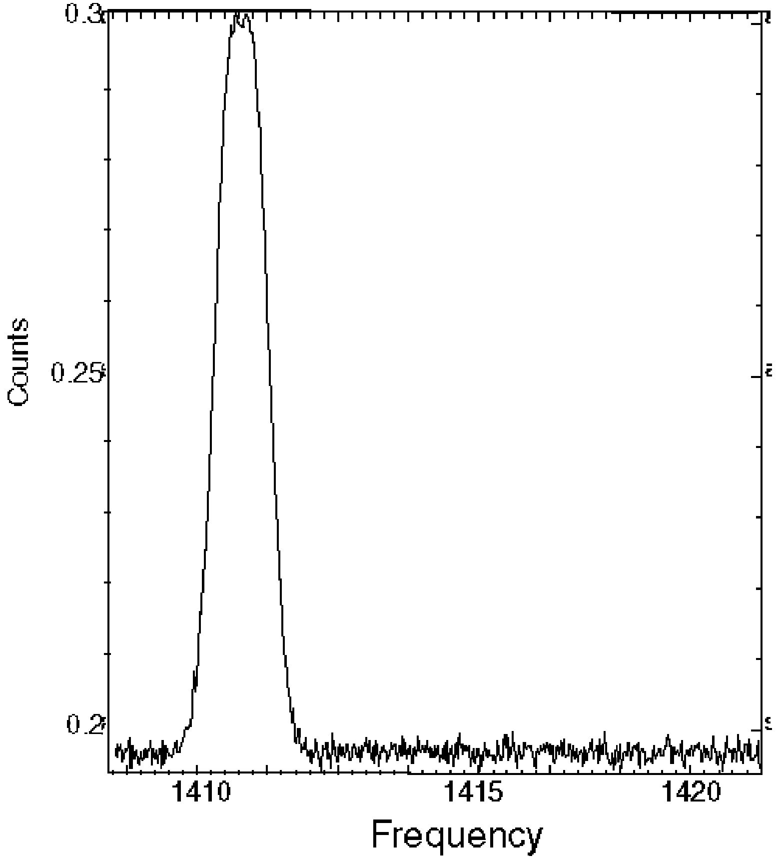
- Simplest & most efficient method

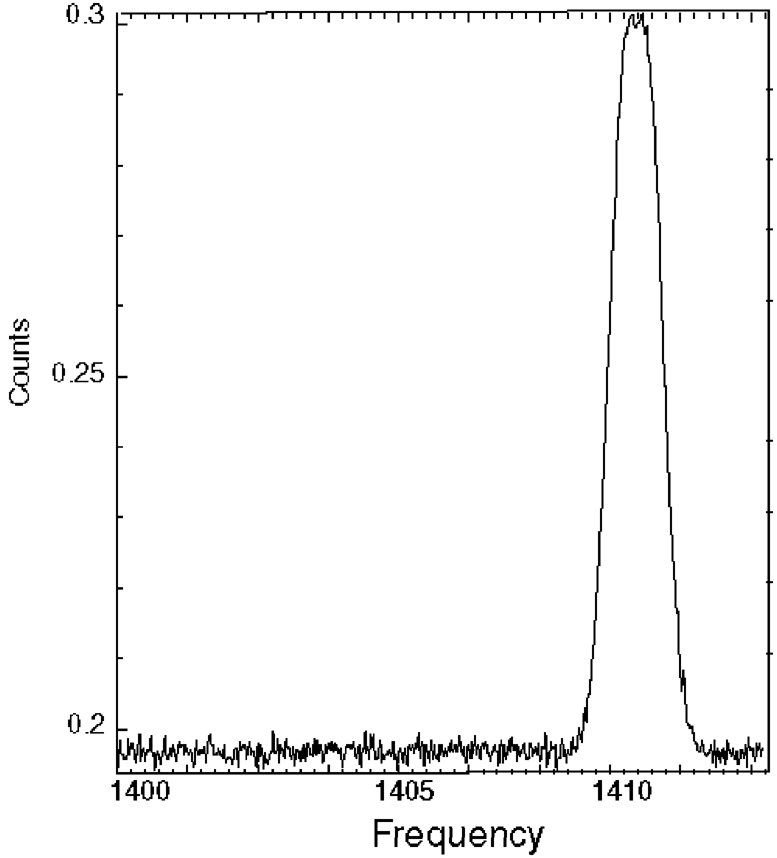
- Not feasible if:
  - Line of interest is large compared with bandpass
  - Standing waves in data
  - Cannot readily fit bandpass

- Errors are primarily from quality of fit

Off—Source Observations

Frequency Switching





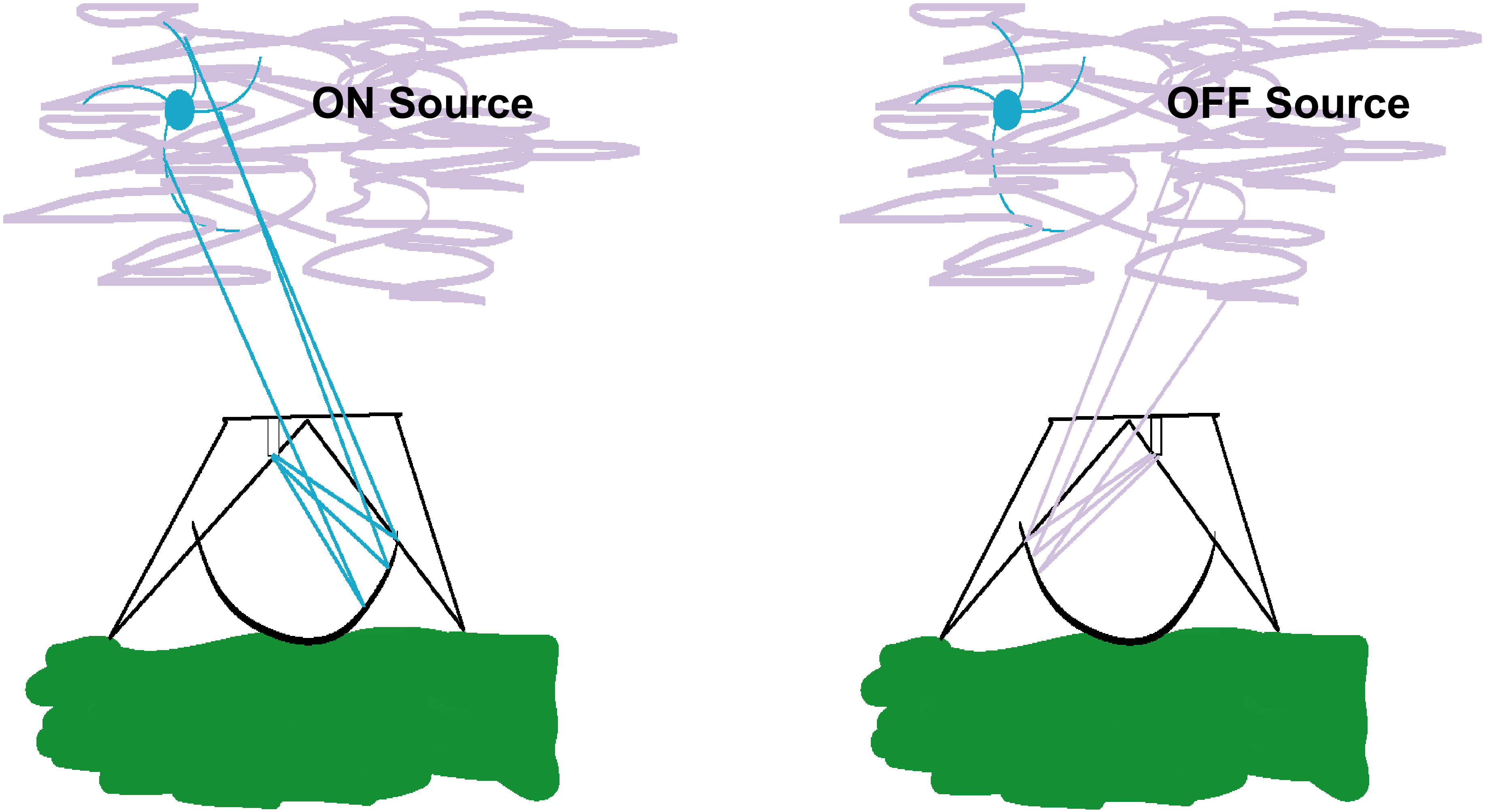
Off—Source Observations

Frequency Switching

- Allows for rapid switch between ON & OFF observations
- Does not require motion of telescope
- Can be very efficient
- Disadvantages:
  - Frequency of line of interest must be known
  - System must be stable
  - Will not work with significant (changing) standing waves

Off—Source Observations

Position Switching



Off—Source Observations

Position Switching

- Little a priori information needed
- Typically gives very good results
- Disadvantages:
    - System must be stable
    - Requires re-pointing the telescope
    - Sky position must be carefully chosen
    - Source must not be too extended

Off—Source Observations

Beam Switching

- Same idea as position switching
- Removes need to move telescope
- Source is always in one beam

- Disadvantages/Caveats:
  - Requires at least two receivers
  - Switch sources/beams periodically
  - Sky position must be carefully chosen
  - Source must not be too extended

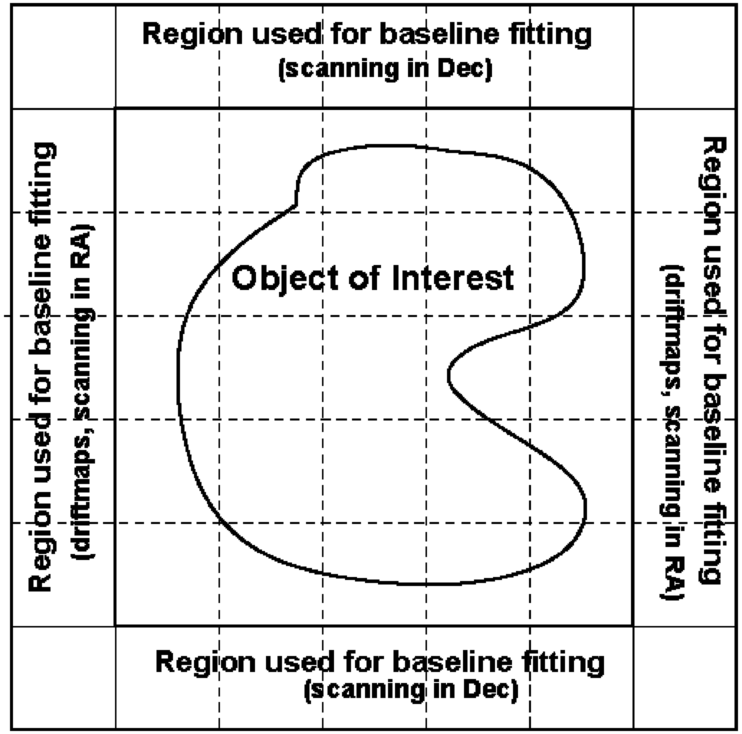
Off—Source Observations
Variations

Baseline fitting with an average fit

- Offers a very good fit
- May lose detailed information for individual fits
- System must be very stable

Off—Source Observations
Variations

‘Position Switching’ on an Extended Source

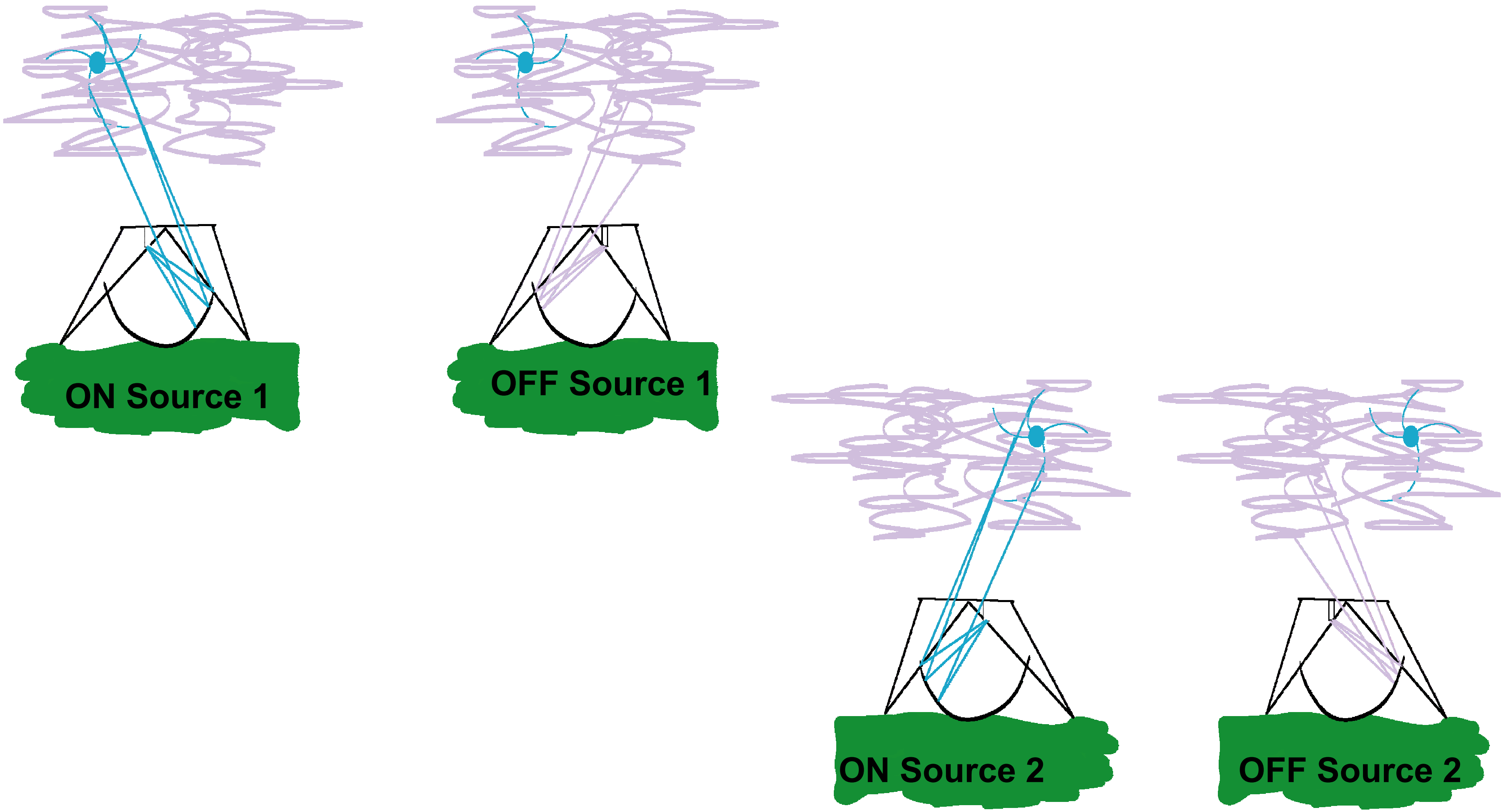


Alternative if frequency switching is not an option
May lose detailed information for individual fits
System must be very stable

Off—Source Observations

Variations

Position Switching on Strong Continuum



Off—Source Observations
Variations

Position Switching on Strong Continuum

- Possibly only alternative if T_{src} > few x T_{sys}
- Designed to remove residual standing waves
- Result:

$$R = \frac{[On(\nu) - Off(\nu)]_{source1}}{[On(\nu) - Off(\nu)]_{source2}}$$

From ATOM 2001-02 by Ghosh & Salter

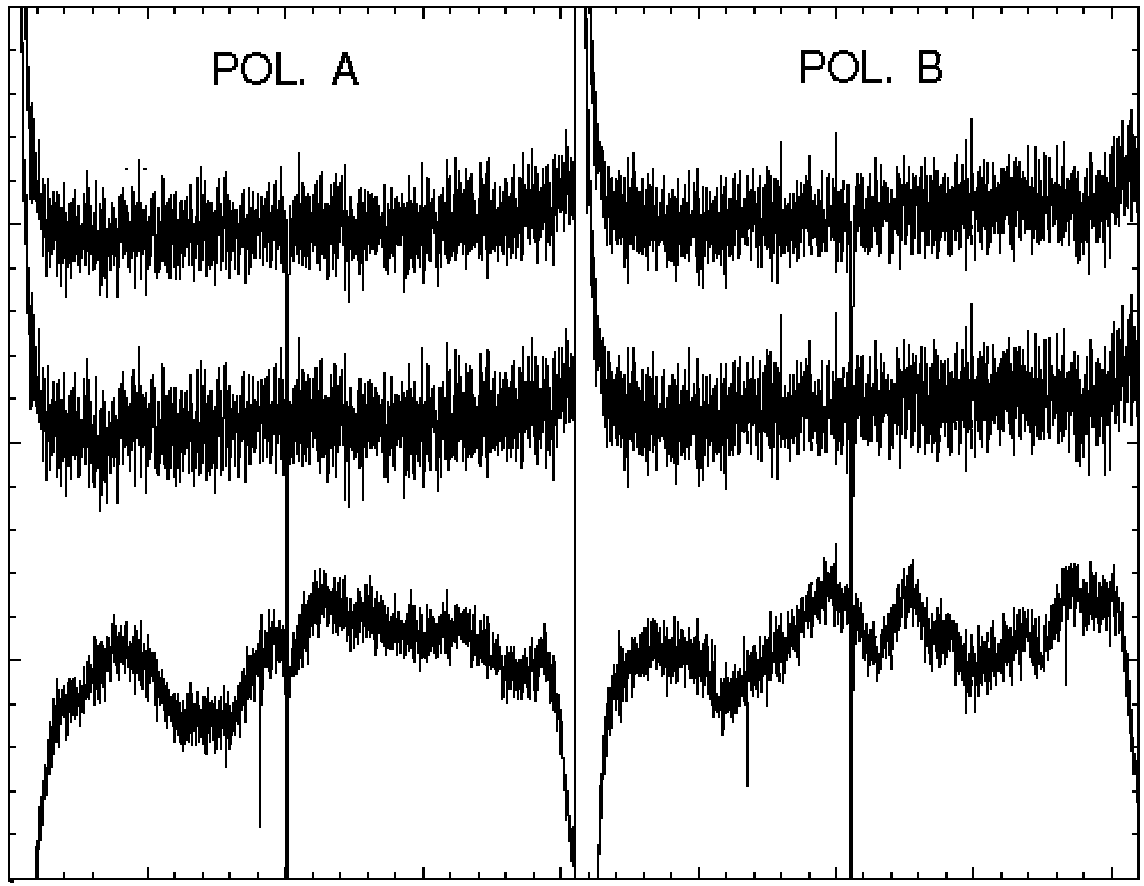
Off—Source Observations
Variations

Position Switching on Strong Continuum

$$\frac{[(On - Off)]_1}{[(on - Off)]_2}$$

$$\frac{[(On - Off)/Off]_1}{[(on - Off)/Off]_2}$$

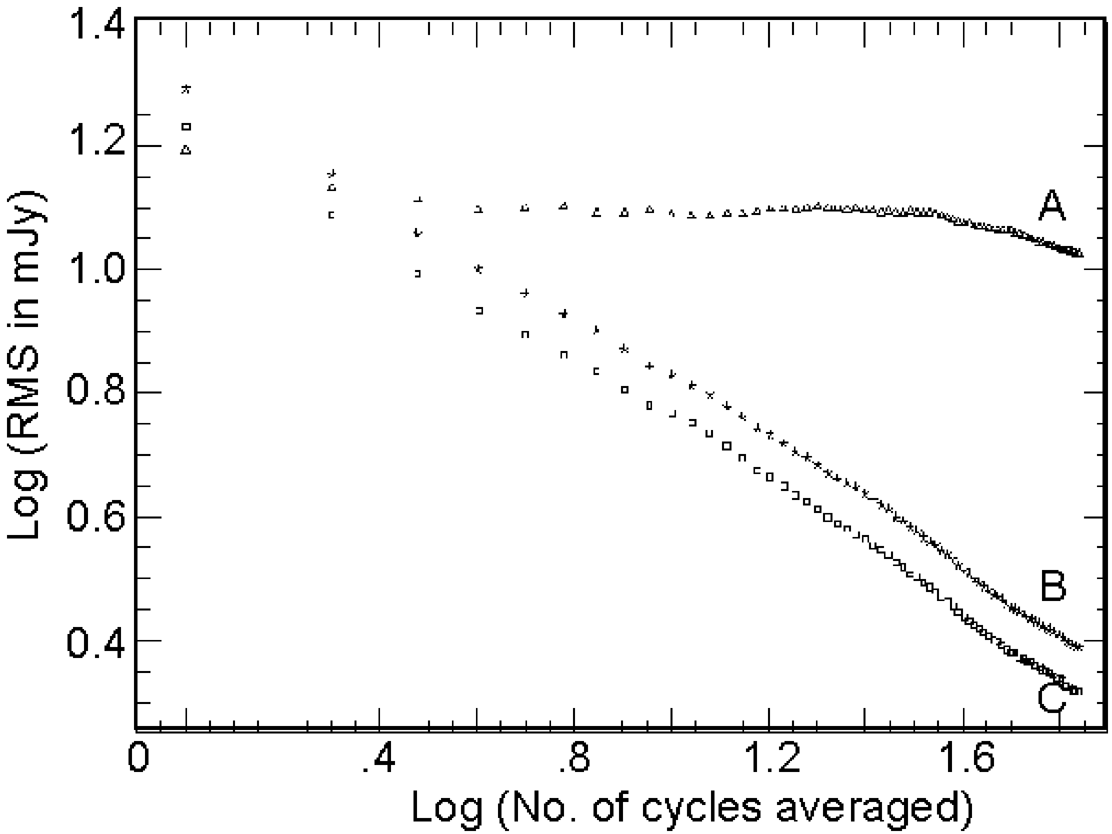
Standard (On – Off)/Off



From ATOM 2001-02 bu Ghosh & Salter

Off—Source Observations
Variations

Position Switching on Strong Continuum



Standard (On – Off)/Off

$$\frac{[(On - Off)/Off]_1}{[(on - Off)/Off]_2}$$

$$\frac{[(On - Off)]_1}{[(on - Off)]_2}$$

From ATOM 2001-02 by Ghosh & Salter

Determining T_{source}

(ON – OFF)/OFF

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

$$\text{Result} = \frac{T_{source}}{T_{system}}$$

Units are % * System Temperature

Need to determine system temperature to calibrate data

Determining System Temperature

Determining T_{sys}

Theory

Measure various components of T_{sys}:

Decreasing Confidence

T_{RX} — Can be readily measured/monitored

T_{CMB} — Well known (2.7 K)

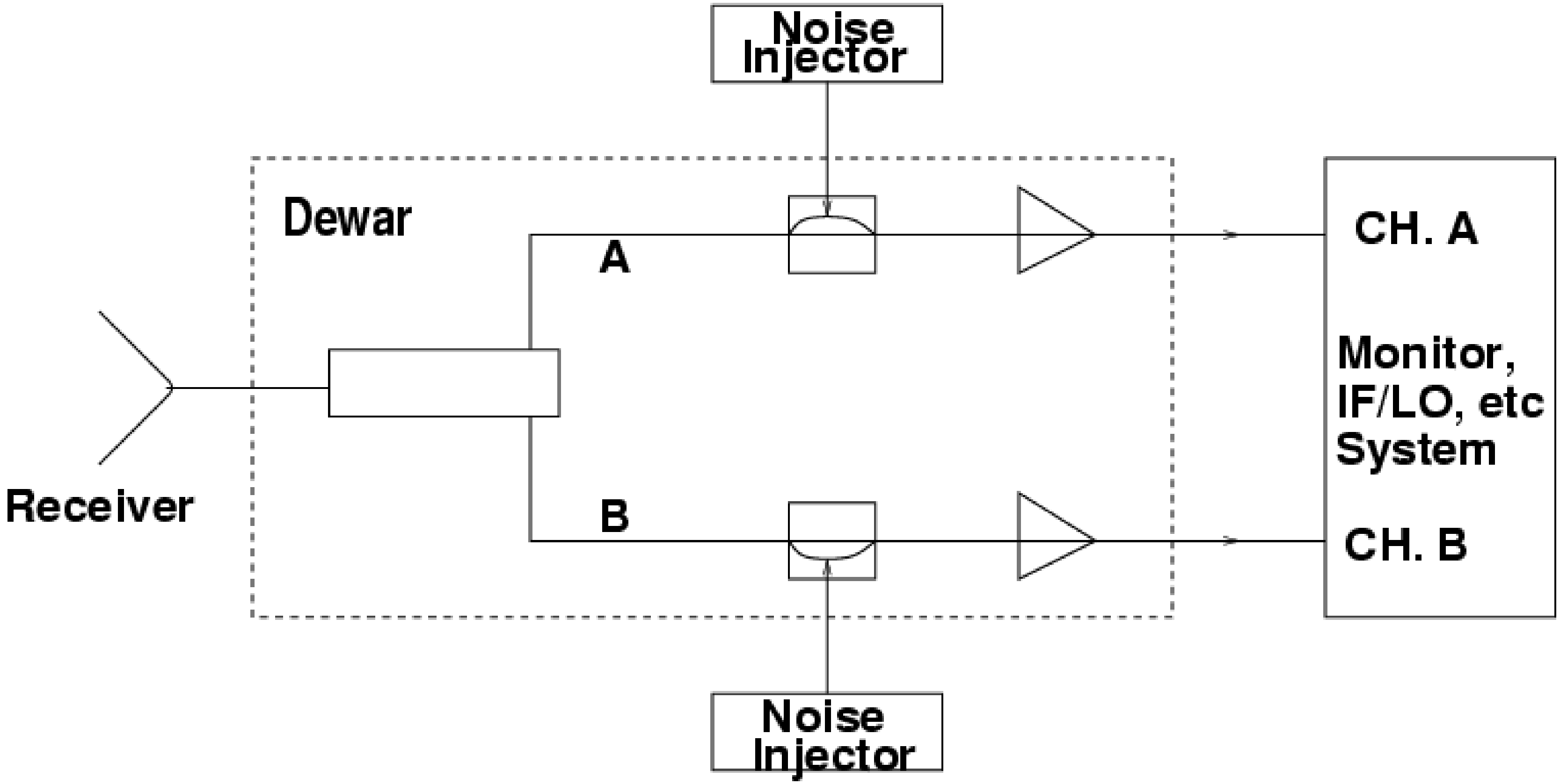
$T_{cel}(\alpha,\delta,t)$ — Can be determined from other (tel.) measurements

$T_{atm}(za)$ — Can be determined from other (tel.) measurements

$T_{gr}(za,az)$ — Can be calculated

Determining T_{sys}

Noise Diodes



Determining T_{sys}

Noise Diodes

$$T_{src}/T_{sys} = (ON - OFF)/OFF$$

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.

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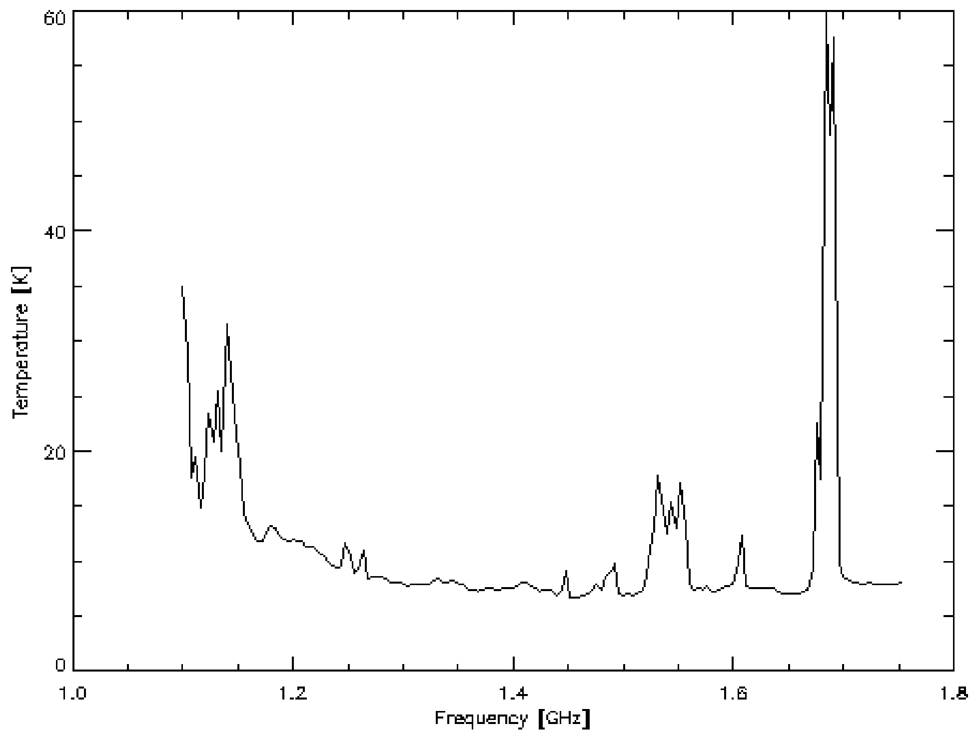
$$T_{diode}/ T_{sys} = (On - Off) / Off$$

$$T_{sys} = T_{diode} * Off/(On - Off)$$

Determining T_{sys}

Noise Diodes - Considerations

- Frequency dependence



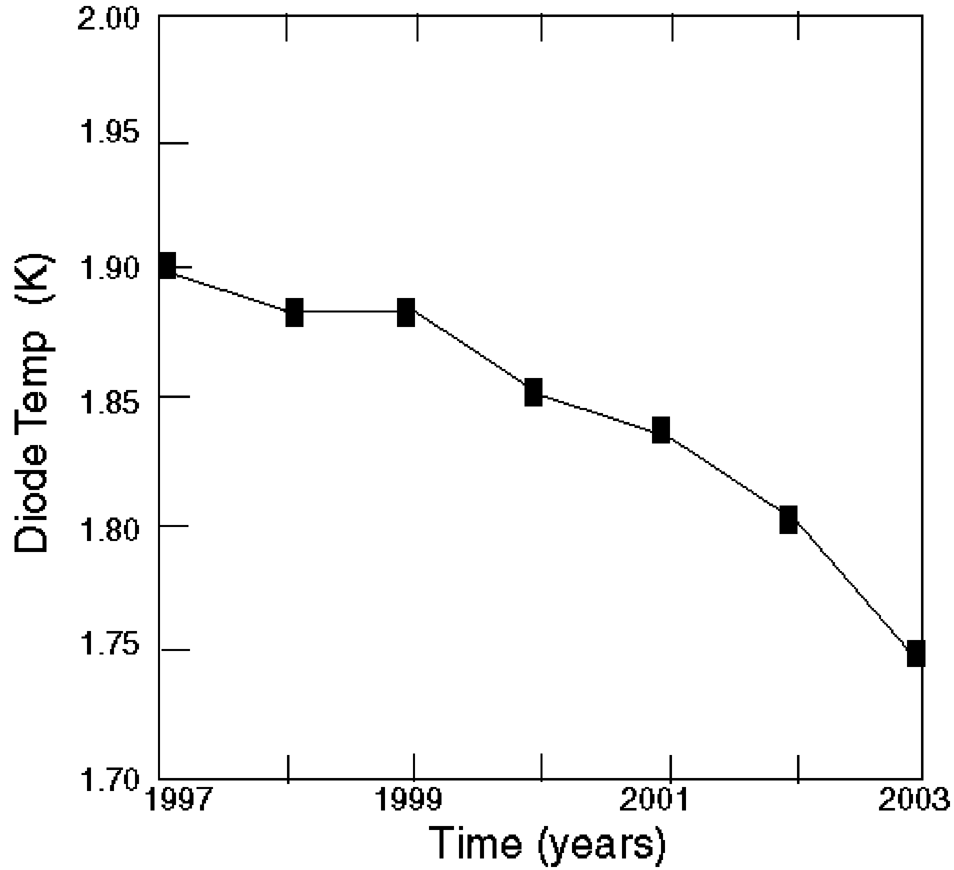
Lab measurements of the GBT L-Band calibration diode, taken from work of M. Stennes & T. Dunbrack - February 14, 2002

Determining T_{sys}

Noise Diodes - Considerations

- Frequency dependence

- Time stability



Determining T_{sys}

Noise Diodes - Considerations

- Frequency dependence
- Time stability
- Accuracy of measurements

Determining T_{sys}

Noise Diodes - Considerations

Accuracy of measurements

Typically measured against another diode or other calibrator

Errors inherent in instruments used to measure both diodes

Measurements often done in lab. Have numerous losses through path from diode injection to back ends

$$\sigma^2_{\text{measured value}} = \sigma^2_{\text{standard cal}} + \sigma^2_{\text{instrumental error}} + \sigma^2_{\text{loss uncertainties}}$$

Determining T_{sys}

Noise Diodes - Considerations

- Frequency dependence
- Time stability
- Accuracy of measurements

$$\sigma^2_{\text{measured value}} = \sigma^2_{\text{standard cal}} + \sigma^2_{\text{instrumental error}} + \sigma^2_{\text{loss uncertainties}}$$

$$\sigma^2_{\text{total}} = \sigma^2_{\text{freq. dependence}} + \sigma^2_{\text{stability}} + \sigma^2_{\text{measured value}} + \sigma^2_{\text{conversion error}}$$

Determining T_{sys}

Two Diodes

(the Y-Factor)

$$Y = \frac{T_1 + T_{off}}{T_2 + T_{off}} \qquad T_{off} = \frac{T_1 - YT_2}{Y - 1}$$

- Can be more accurate than just one diode
- Ignores effects of the antenna

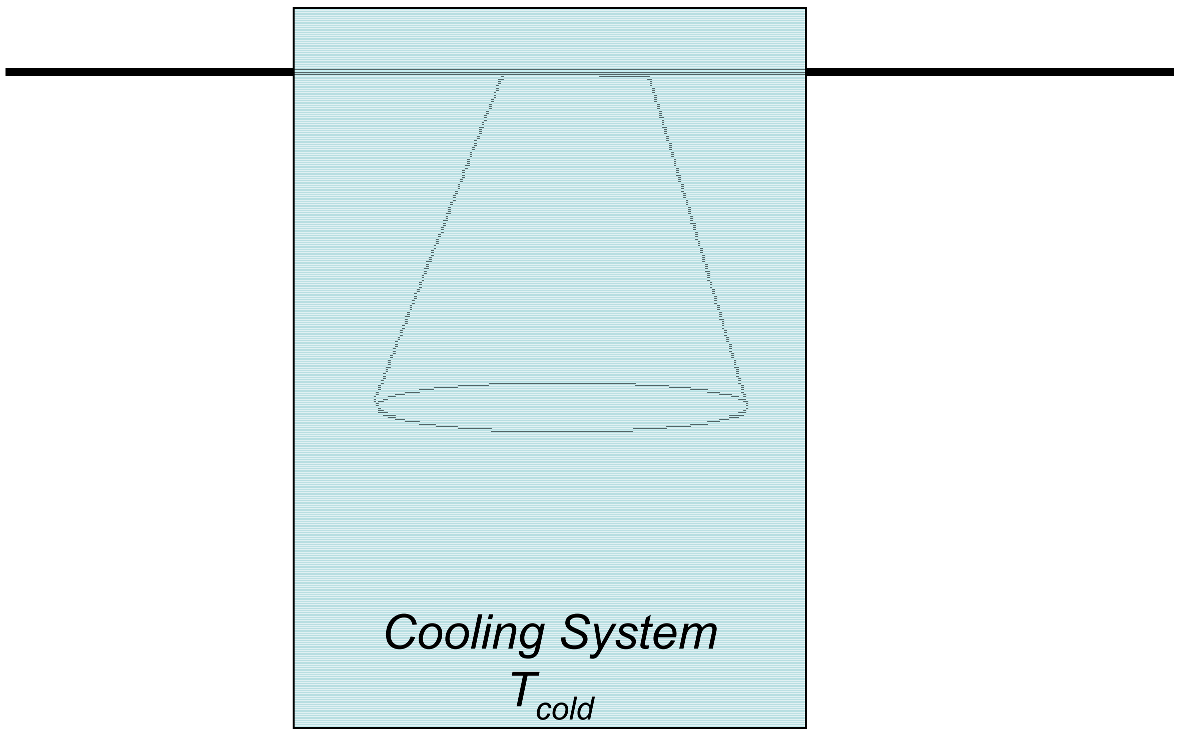
Determining T_{sys}

Hot & Cold Loads

- Same idea as two diodes
- Takes antenna into account
- True temperature measurement (no conversions)

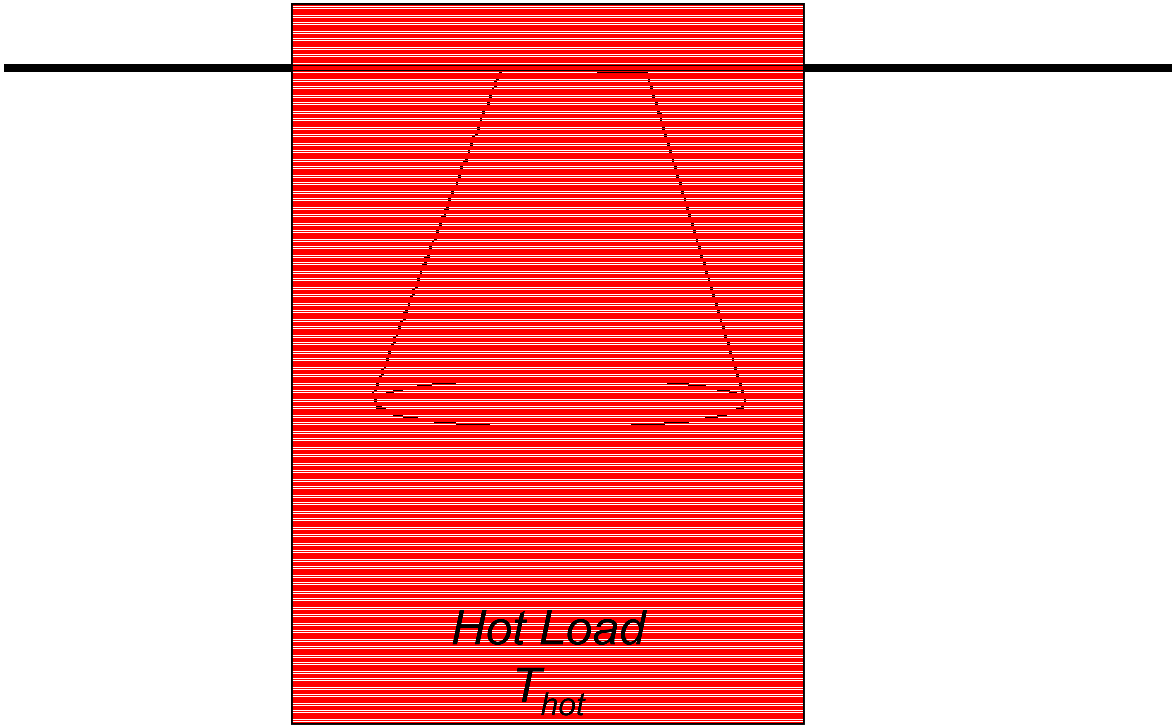
Determining T_{sys}

Hot & Cold Loads



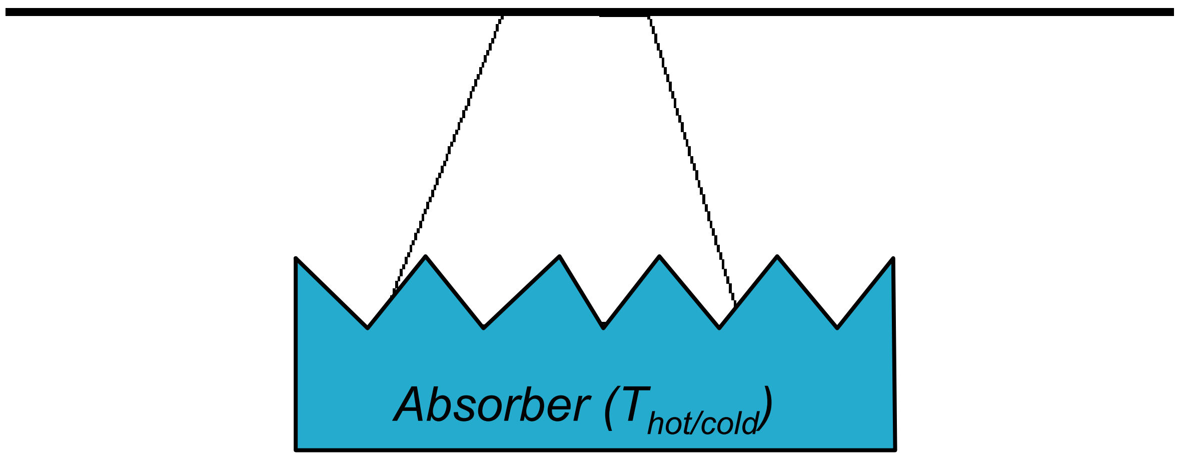
Determining T_{sys}

Hot & Cold Loads



Determining T_{sys}

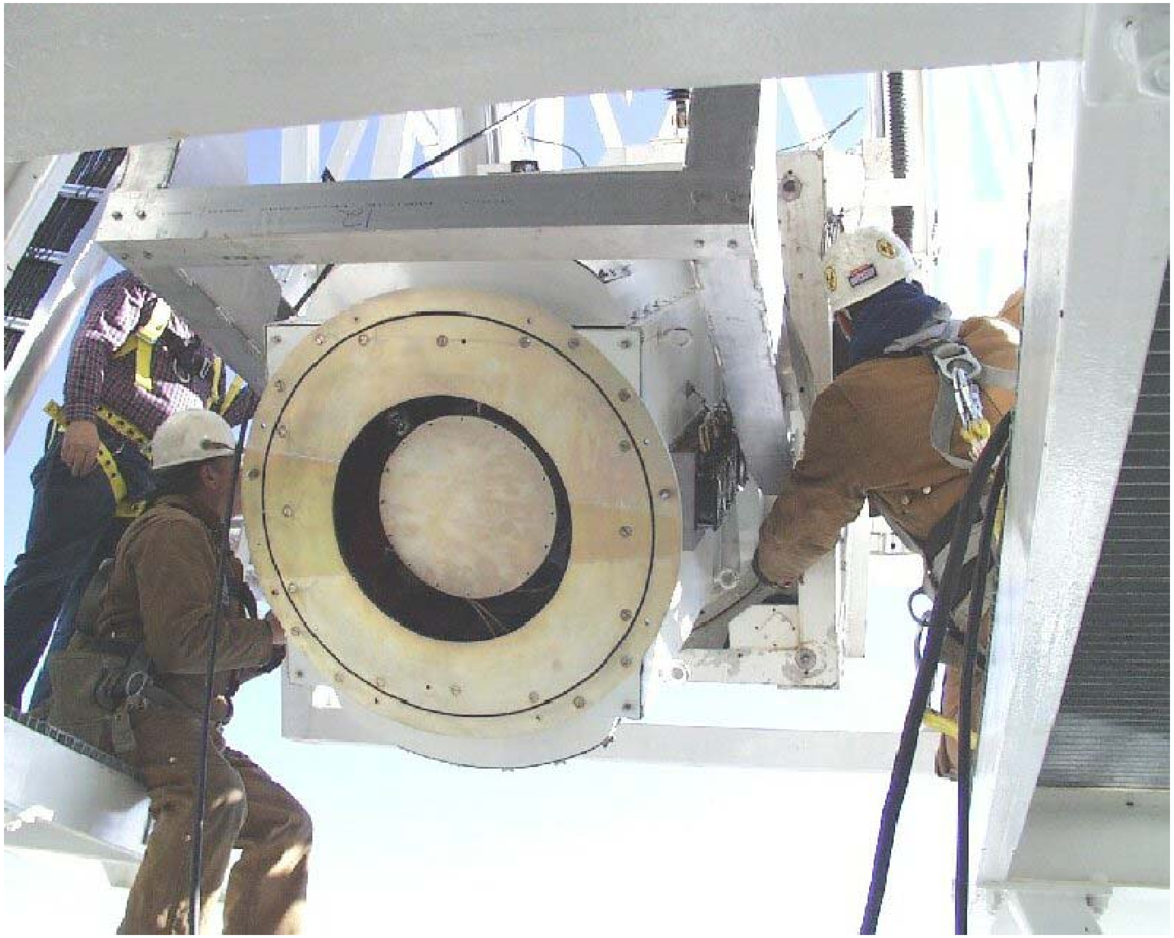
Hot & Cold Loads



$$\mathbf{T_{off}} = \frac{T_1 - YT_2}{Y - 1}$$

Determining T_{sys}

Hot & Cold Loads



Determining T_{sys}

Hot & Cold Loads

- Same idea as two diodes
- Takes antenna into account
- True temperature measurement (no conversions)

Requires a reliable load able to encompass the receiver,

with response fast enough for on-the-fly measurements

Determining T_{sys}

Theory:

Needs detailed understanding of telescope & structure

Atmosphere & ground scatter must be stable and understood

Noise Diodes:

Can be fired rapidly to monitor temperature

Requires no 'lost' time

Depends on accurate measurements of diodes

Hot/Cold Loads:

Can be very accurate

Observations not possible when load on

Must be in mm range for on-the-fly measurements

Determining T_{source}

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

Blank Sky or other

From diodes, Hot/Cold loads, etc.

Telescope response has not been accounted for!

Determining Telescope Response

Telescope Response

- Main Beam Brightness:

$$T_{MB} = \eta_{beam}\, T_{measured}$$

- Flux Density:

$$S = \frac{2k}{\lambda^2} \iint T(\theta,\phi)\, P_n\,(\theta,\phi)\,d\Omega$$

Units: W m^{-2} Hz^{-1} or Jy (1 Jy = 10^{-22} W m^{-2} Hz^{-1})

Ω = Solid angle of tel. pattern; η_{beam} = telescope efficiency; λ = wavelength; S=Flux, k = constants, T = temperature; P = antenna power pattern

Telescope Response

- Ideal Telescope:

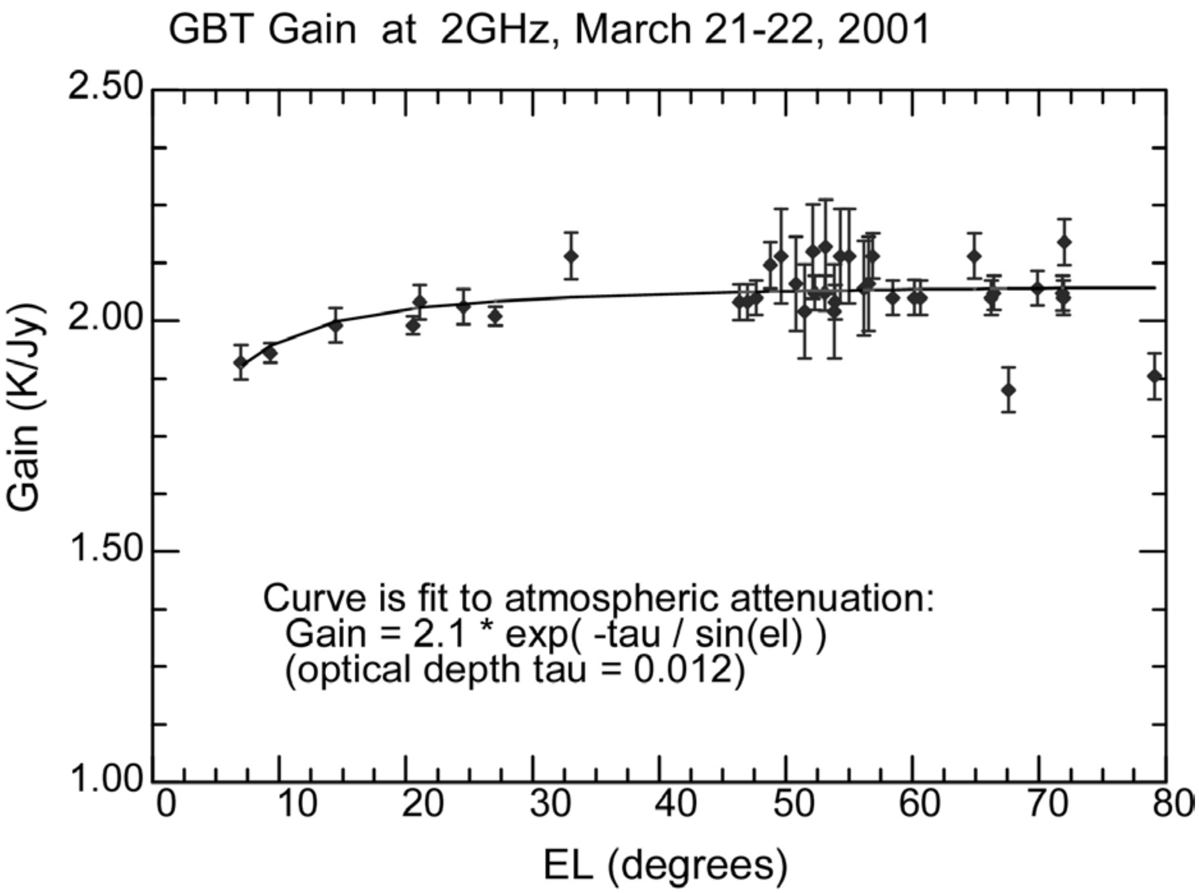
  Accurate gain, telescope response can be modeled

  Can be used to determine the flux density of 'standard' continuum sources

  Not practical in cases where telescope is non-ideal (blocked aperture, cabling/electronics losses, ground reflection, etc)

Telescope Response

- Ideal Telescope:



Telescope Response

- 'Bootstrapping':

  Observe source with pre-determined fluxes

  Determine telescope gain

$$T_{source} = \frac{(ON - OFF)}{OFF} \; T_{system} \; \frac{1}{GAIN}$$

$$GAIN = \frac{OFF}{(ON - OFF)} \; \frac{T_{system}}{T_{source}}$$

Telescope Response

- ‘Bootstrapping’:

  Useful when gain is not readily modeled

  Offers ready means for determining telescope gain

  Requires flux of calibrator sources be known in advance

  Not practical if gain changes rapidly with position

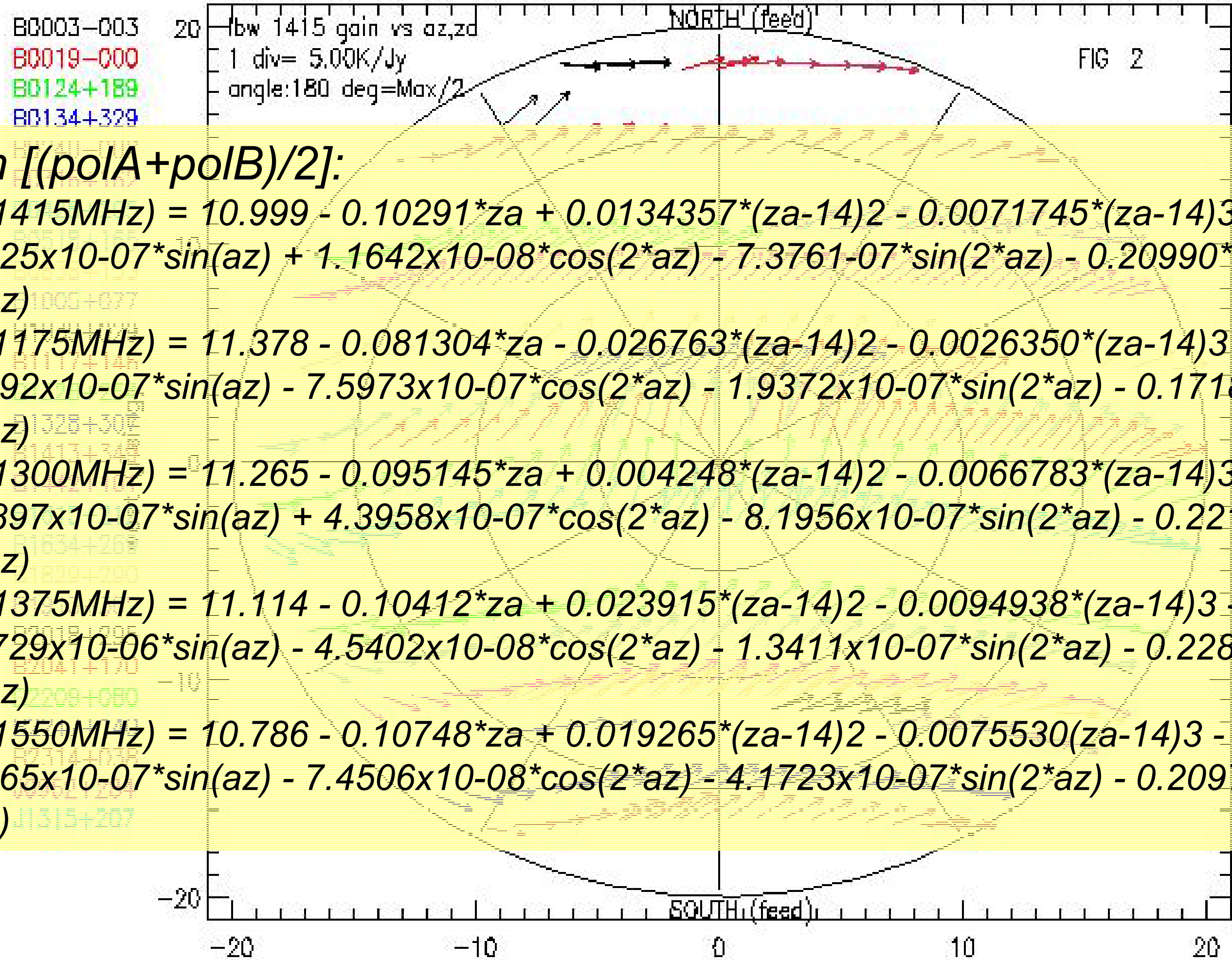
Telescope Response

Pre-determined Gain curves:

- Allows for accurate representation of gain at all positions
- Saves observing time
- Can be only practical solution

Telescope Response

Pre-determined Gain curves:



Average Gain [(polA+polB)/2]:

*gainavg(az,za,f=1415MHz) = 10.999 - 0.10291*za + 0.0134357*(za-14)2 - 0.0071745*(za-14)3 - 5.2154x10-08*cos(az) - 1.3225x10-07*sin(az) + 1.1642x10-08*cos(2*az) - 7.3761-07*sin(2*az) - 0.20990*cos(3*az) - 0.098026*sin(3*az)*

*gainavg(az,za,f=1175MHz) = 11.378 - 0.081304*za - 0.026763*(za-14)2 - 0.0026350*(za-14)3 + 1.0319x10-06*cos(az) - 3.1292x10-07*sin(az) - 7.5973x10-07*cos(2*az) - 1.9372x10-07*sin(2*az) - 0.17180*cos(3*az) - 0.046071*sin(3*az)*

*gainavg(az,za,f=1300MHz) = 11.265 - 0.095145*za + 0.004248*(za-14)2 - 0.0066783*(za-14)3 + 7.2271x10-07*cos(az) + 9.0897x10-07*sin(az) + 4.3958x10-07*cos(2*az) - 8.1956x10-07*sin(2*az) - 0.22135*cos(3*az) - 0.074295*sin(3*az)*

*gainavg(az,za,f=1375MHz) = 11.114 - 0.10412*za + 0.023915*(za-14)2 - 0.0094938*(za-14)3 - 8.3447x10-07*cos(az) + 1.0729x10-06*sin(az) - 4.5402x10-08*cos(2*az) - 1.3411x10-07*sin(2*az) - 0.22827*cos(3*az) - 0.080216*sin(3*az)*

*gainavg(az,za,f=1550MHz) = 10.786 - 0.10748*za + 0.019265*(za-14)2 - 0.0075530(za-14)3 - 7.8976x10-07*cos(az) - 6.5565x10-07*sin(az) - 7.4506x10-08*cos(2*az) - 4.1723x10-07*sin(2*az) - 0.20972*cos(3*az) - 0.14330*sin(3*az)*

Telescope Response

Pre-determined Gain curves:

Allows for accurate representation of gain at all positions

Saves observing time

Can be only practical solution

Caveat:

Observers should *always* check the predicted gain during observations against a number of calibrators!

Determining T_{source}

$$T_{source} = \frac{(ON - OFF)}{OFF} \quad T_{system} \quad \frac{1}{GAIN}$$

Blank Sky or other

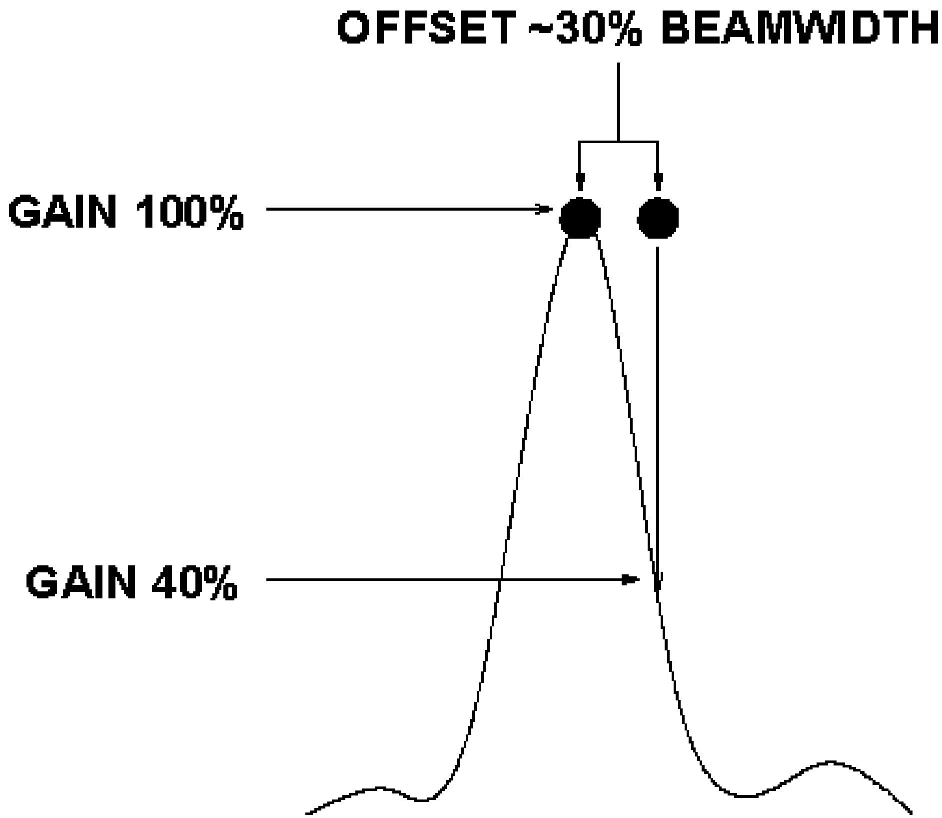
From diodes, Hot/Cold loads, etc.

Theoretical, or Observational

Great, you're done?

A Few Other Issues

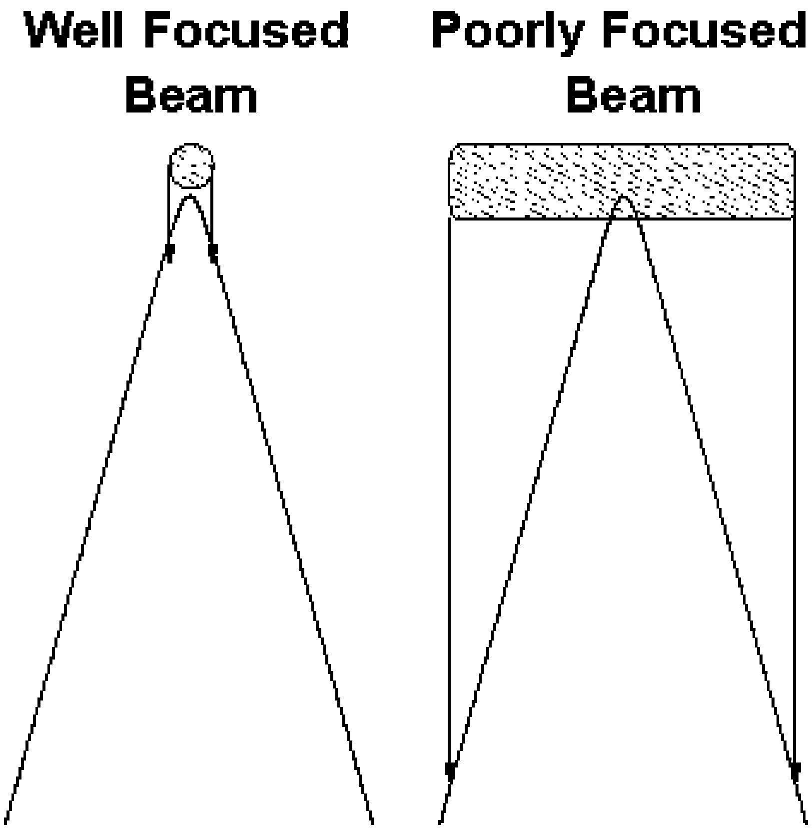
Other Issues: Pointing



Results in reduction of telescope gain

Typically can be corrected in software

Other Issues: Focus

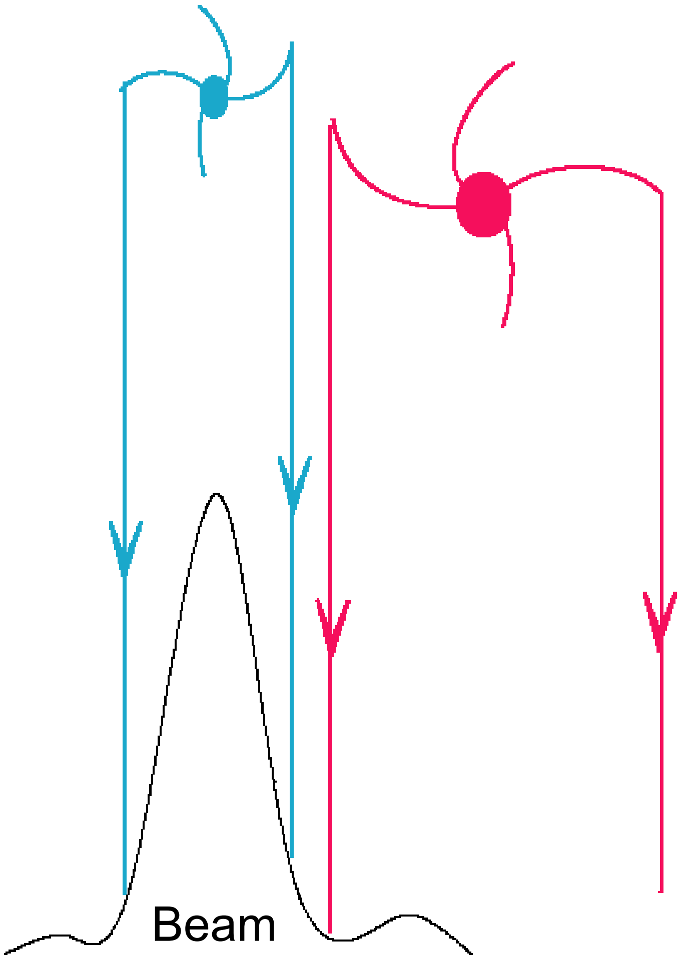


Results in reduction of telescope gain

Corrected mechanically

Other Issues: Side Lobes*

- Allows in extraneous or unexpected radiation
- Can result in false detections, over-estimates of flux, incorrect gain determination
- Solution is to fully understand side lobes



*Covered more fully in talk by Lockman

Other Issues: Coma & Astigmatism

Comatic Error:

– sub-reflector shifted perpendicular from main beam
– results in an offset between the beam and sky pointing

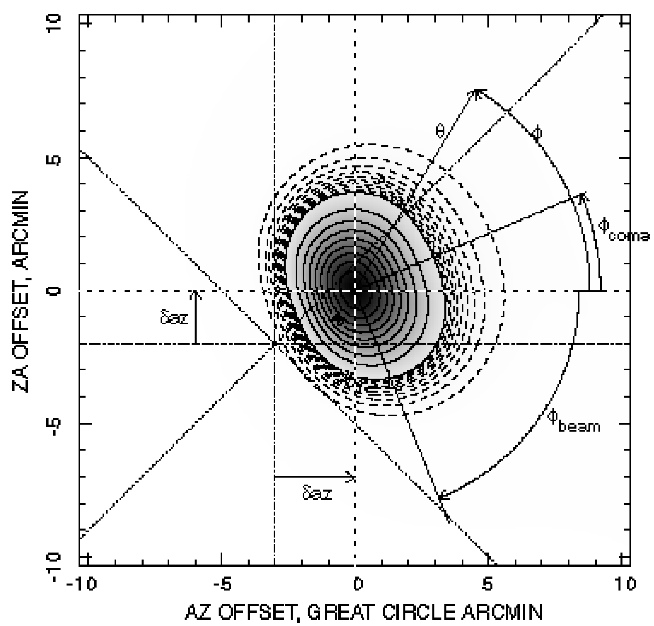
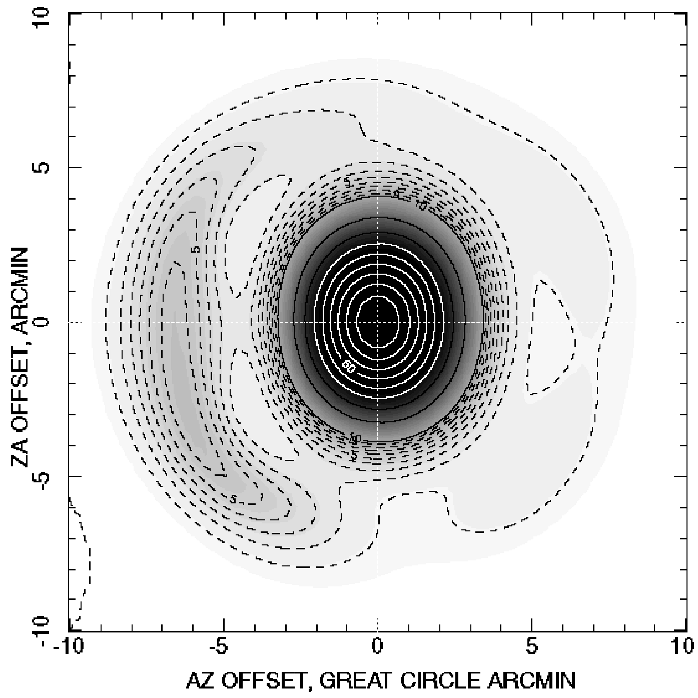


Image from ATOM 99-02, Heiles

Image from ATOM 99-02, Heiles

Other Issues:
Coma & Astigmatism

Astigmatism: deformities in the reflectors



Can result in false detections, over-estimates of flux, incorrect gain determination

Solution is to fully understand beam shape

The End

List of useful references pp 310-311 in book