Spectral Line Calibration Techniques with Single Dish Telescopes

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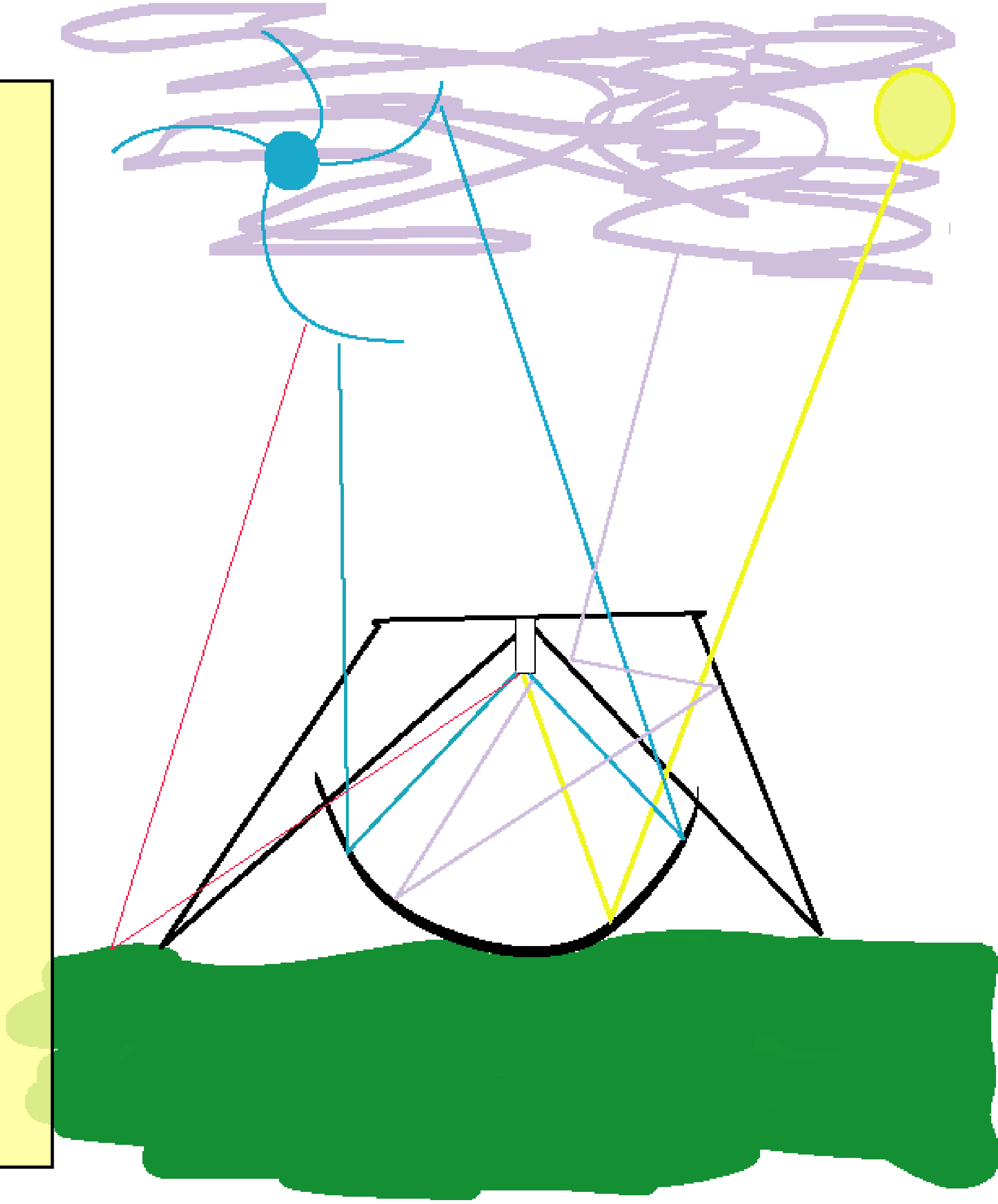


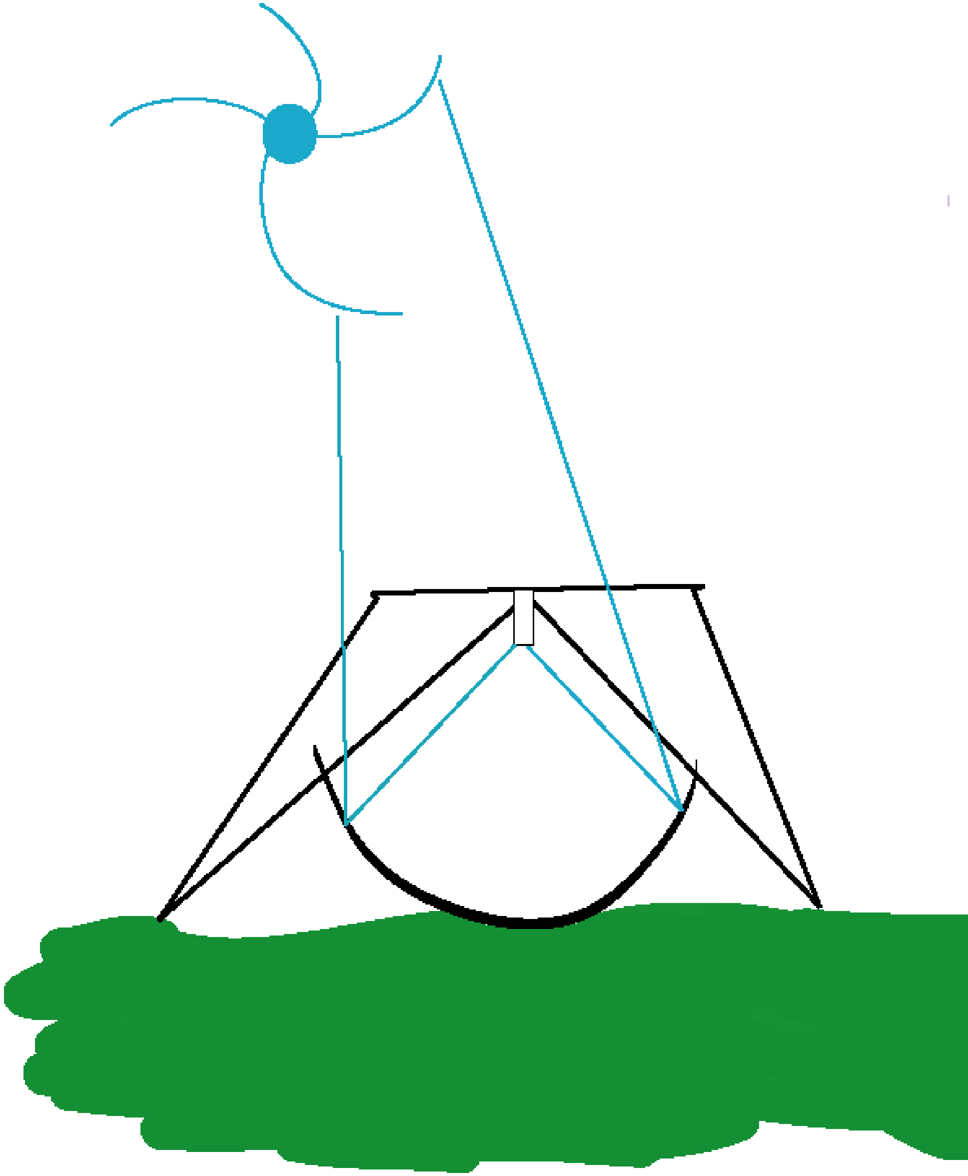
Determining the Source Temperature

Determining T_{source}

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

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

  $+ T_{system}$



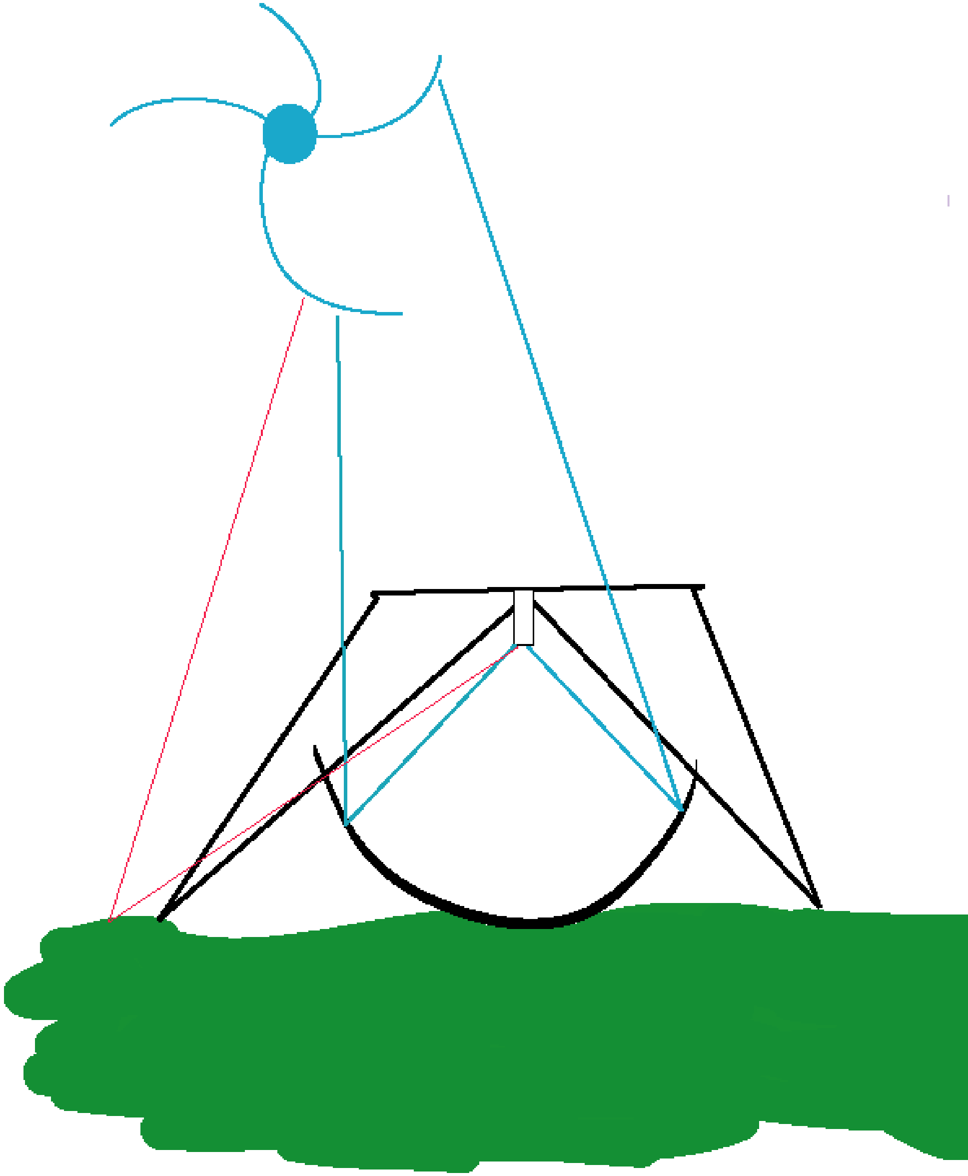
Determining T_{source}

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

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

  $+ T_{RX,\ other\ hardware}$

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



Determining T_{source}

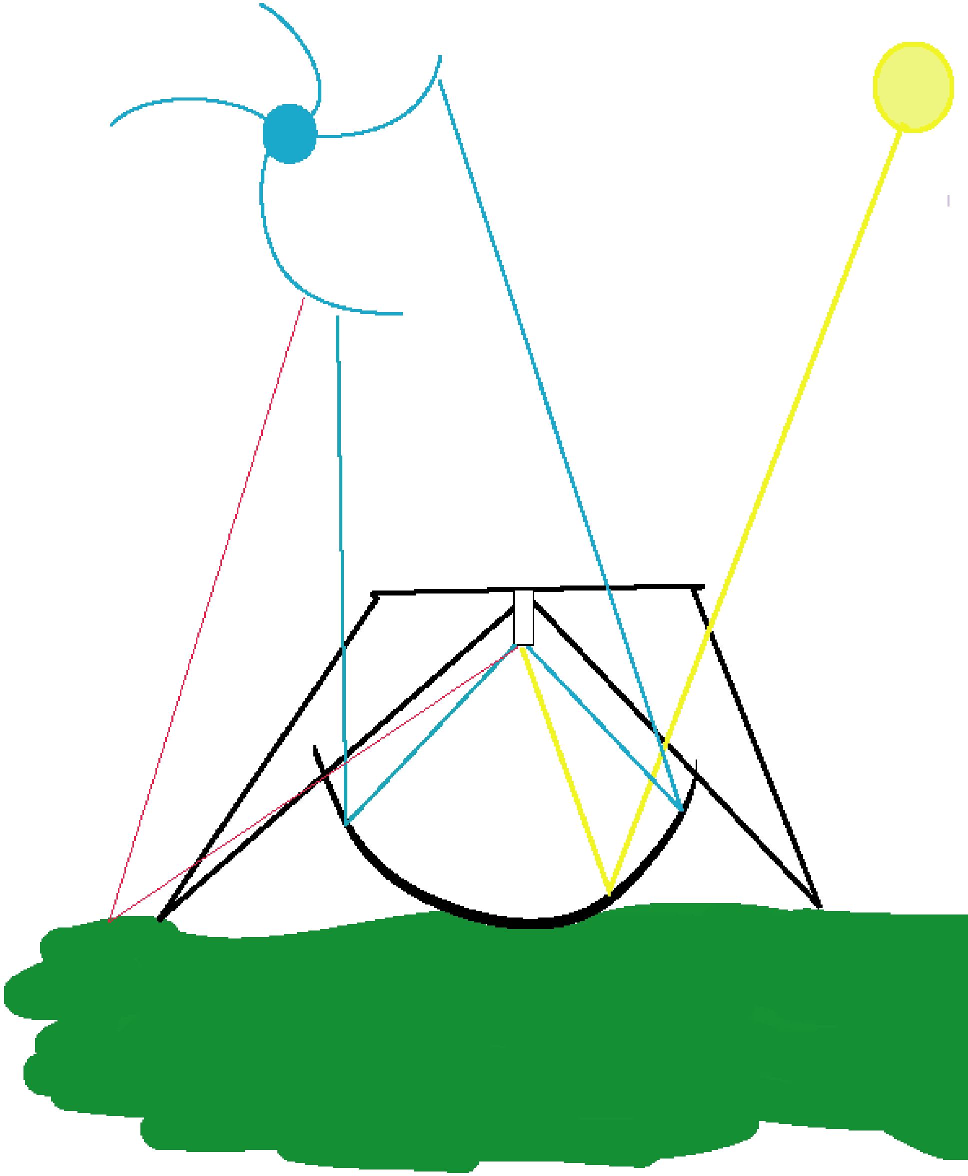
- $T_{meas}(\alpha,\delta,az,za) =$

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

  $+ \ T_{RX,\text{ other hardware}}$

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

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



Determining T_{source}

- T_{meas} (α,δ,az,za) =

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

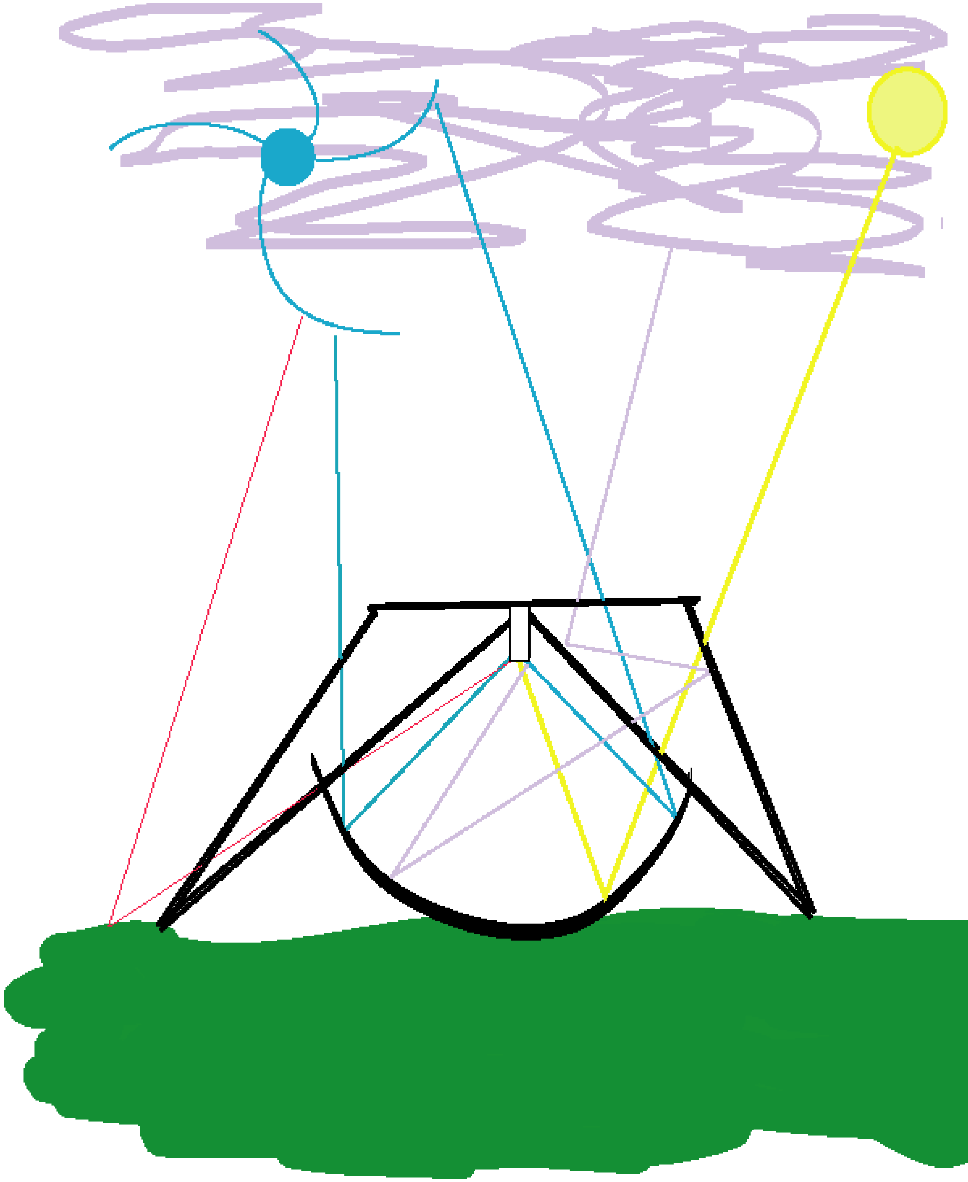
  + $T_{RX,\ other\ hardware}$

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

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

  + T_{CMB}

  + $T_{atm}(za)$

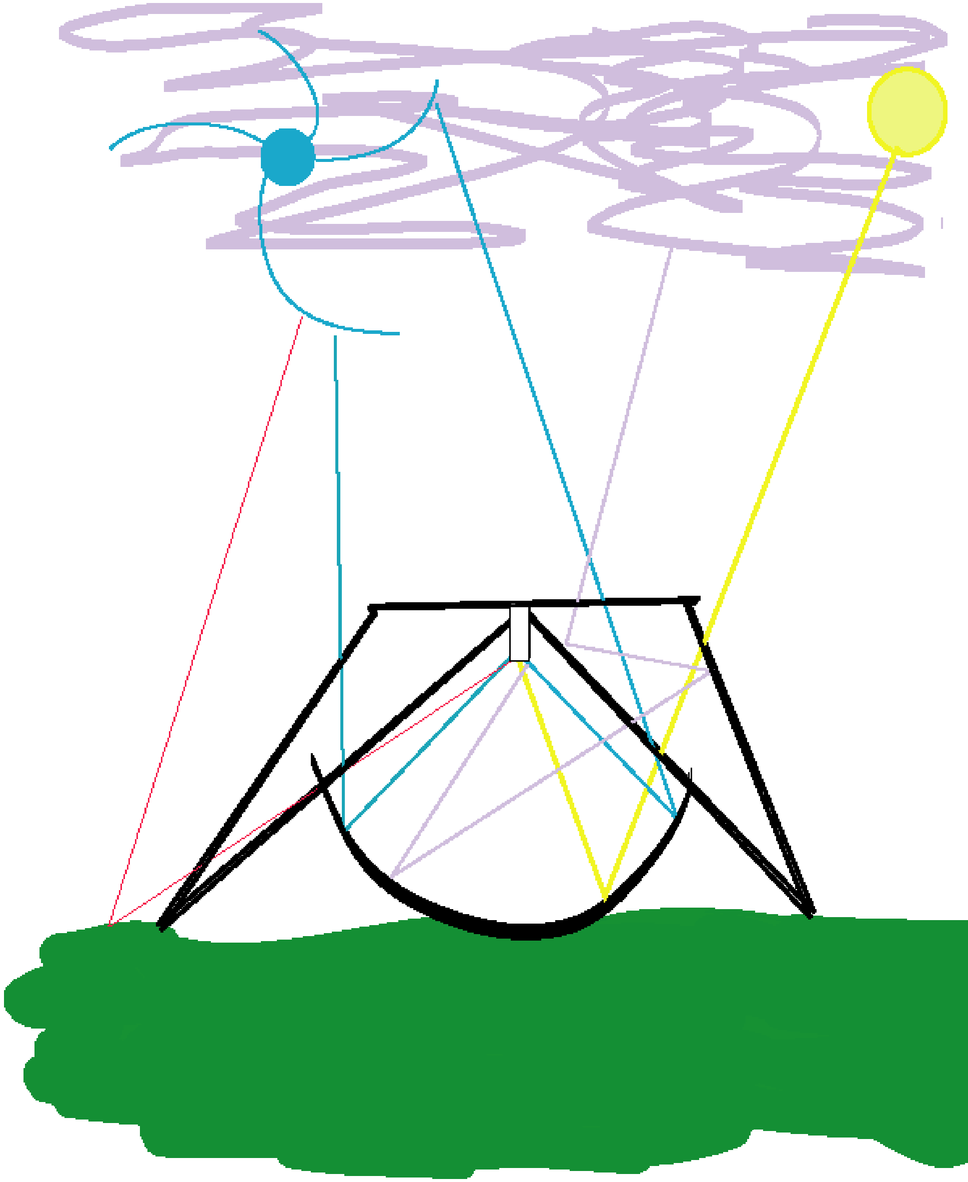


Determining T_{source}

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

  $T_{src}(\alpha,\delta,az,za)$
  $+ T_{RX,\text{ other hardware}}$
  $+ T_{spillover}(za,az)$
  $+ T_{celestial}(\alpha,\delta,t)$
  $+ T_{CMB}$
  $+ T_{atm}(za)$

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

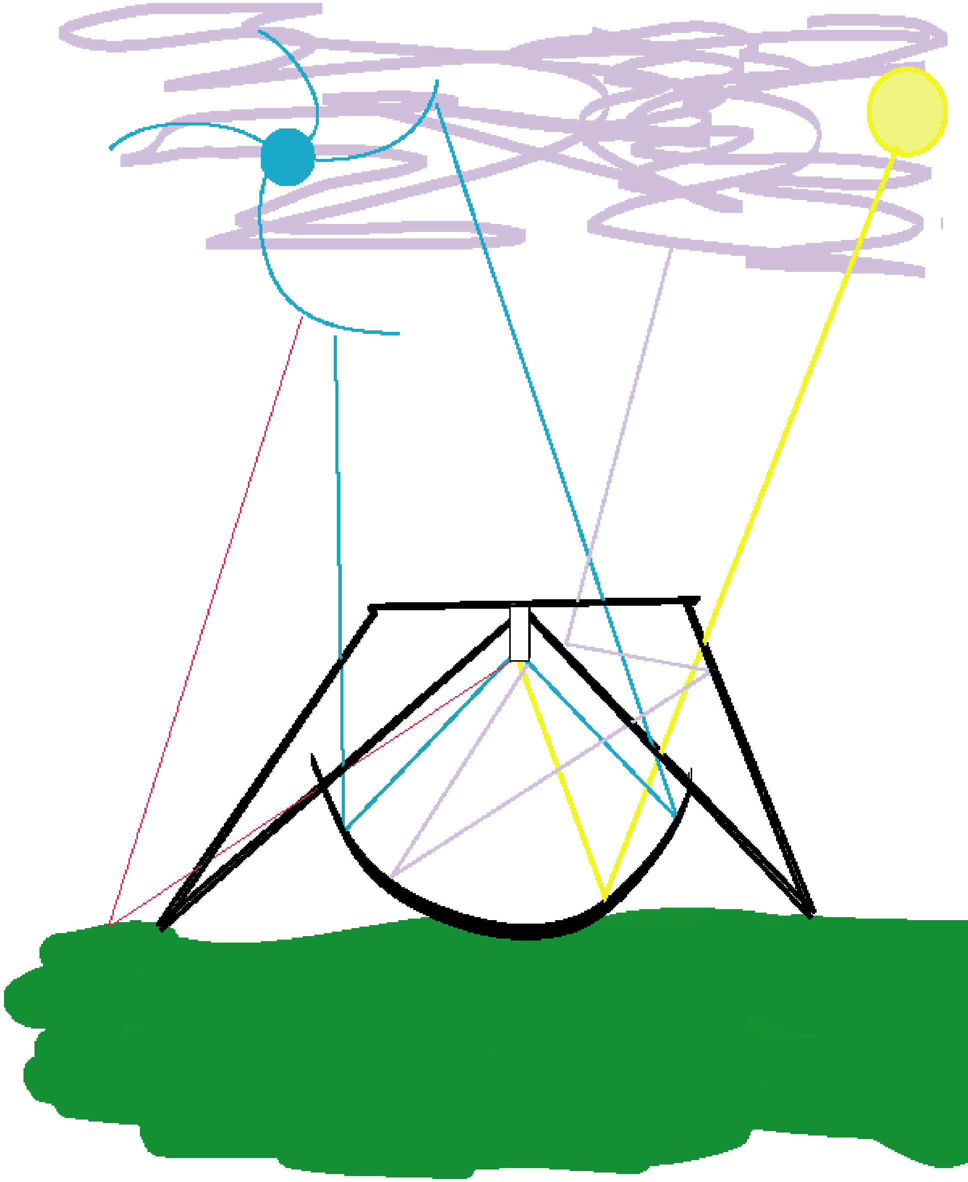


Determining T_{source}

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

$$T_{src}(\alpha,\delta,az,za)$$
$$+\ T_{RX,\ other\ hardware}$$
$$+\ T_{spillover}(za,az)$$
$$+\ T_{celestial}(\alpha,\delta,t)$$
$$+\ T_{CMB}$$
$$+\ T_{atm}(za)$$

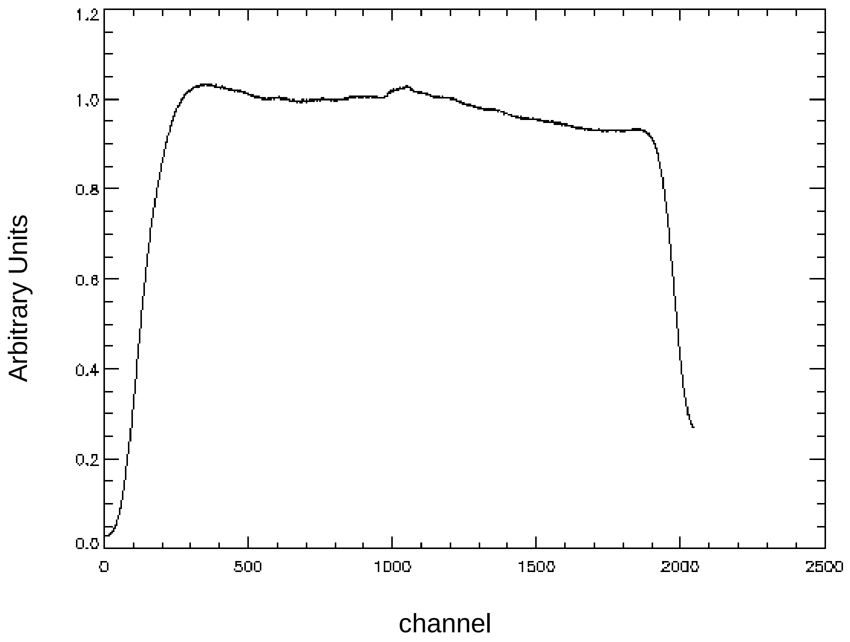
$$T_{meas} = T_{source} + T_{everything\ else}$$



Determining T_{source}

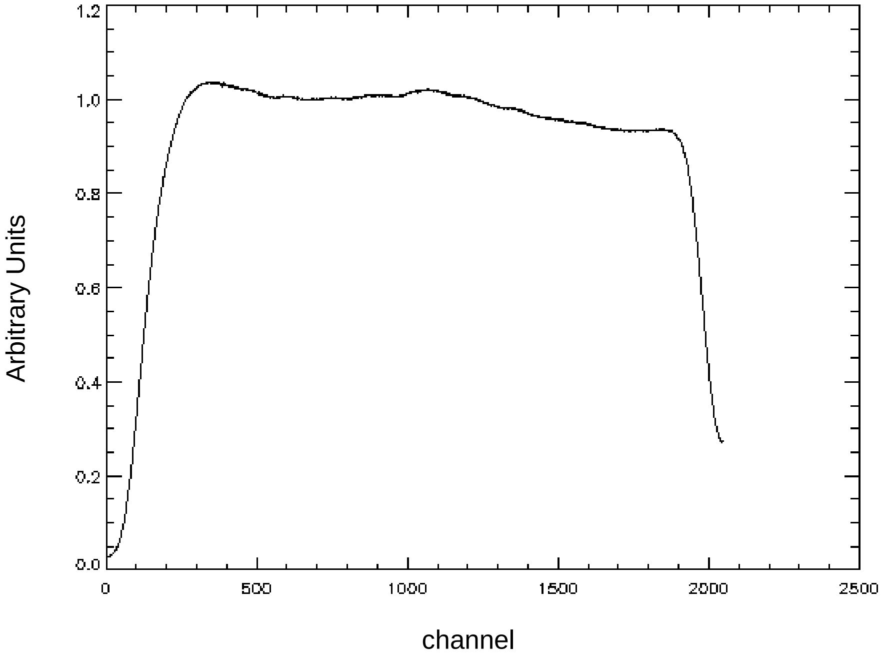
ON source

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



OFF source

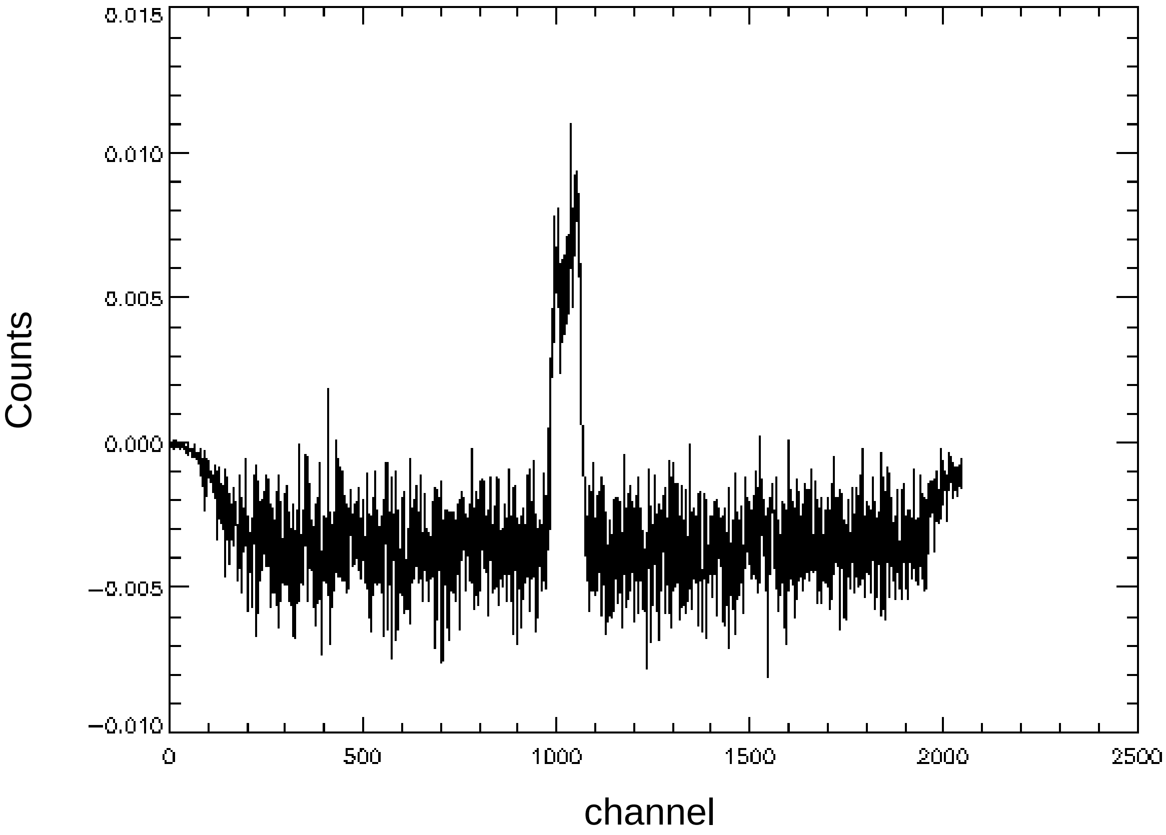
$T_{everything\ else}$



Determining T_{source}

ON - OFF

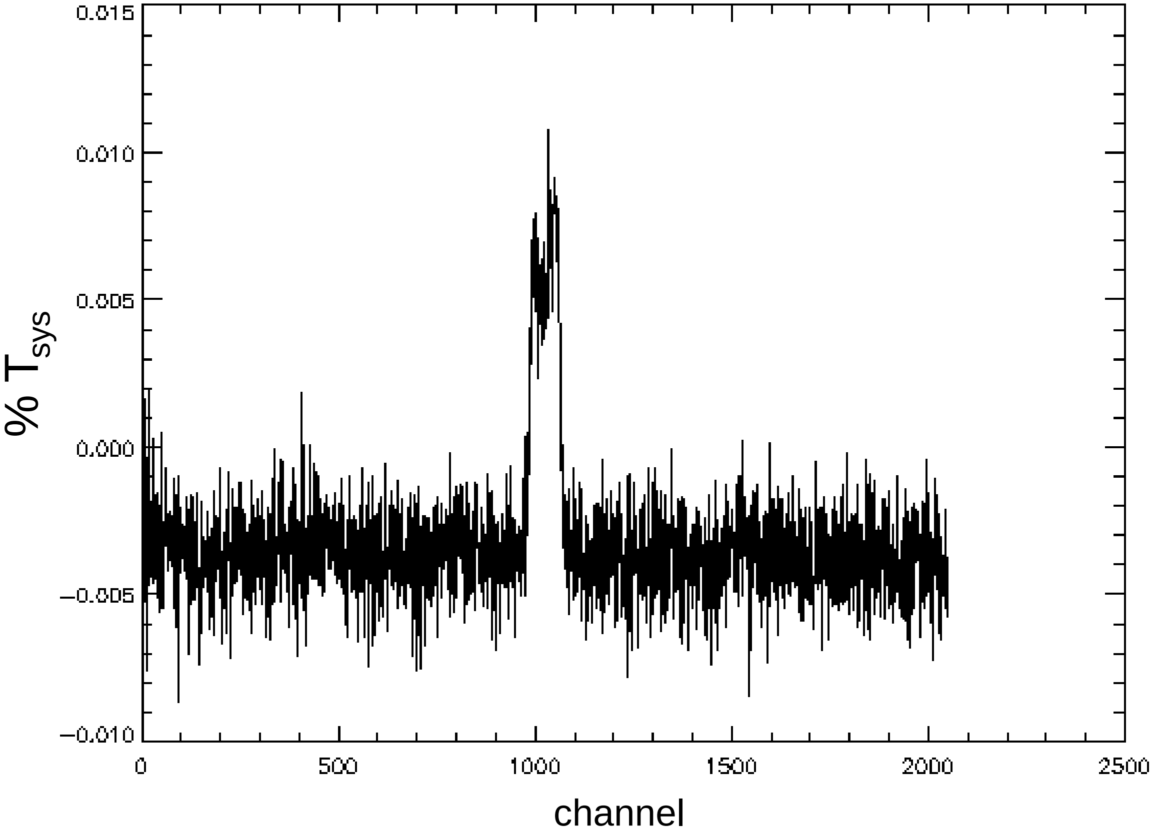
$(T_{source} + T_{everything\ else}) - (T_{everything\ else})$



Determining T_{source}

(ON - OFF)/OFF

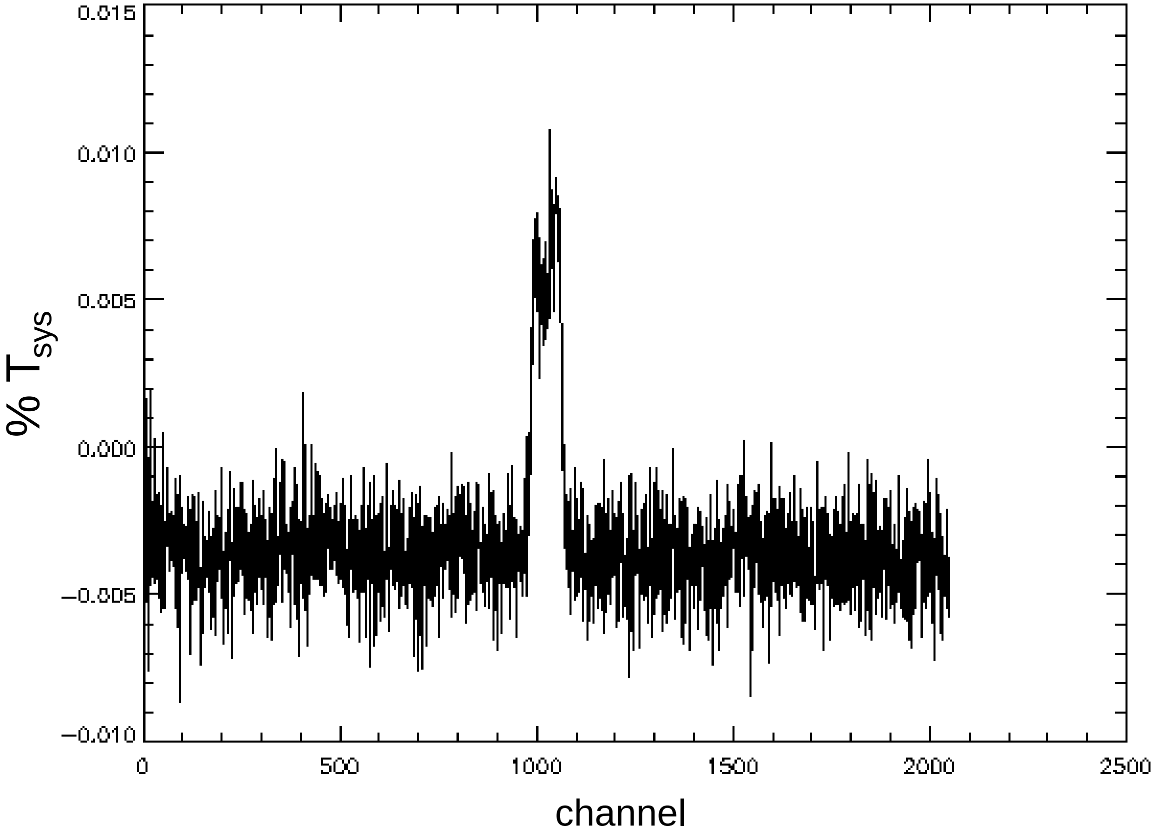
$$[(T_{source} + T_{everything\ else}) - (T_{everything\ else})]/ T_{everything\ else}$$



Determining T_{source}

$$(\mathrm{ON} - \mathrm{OFF})/\boxed{\mathrm{OFF}} \rightarrow ???$$

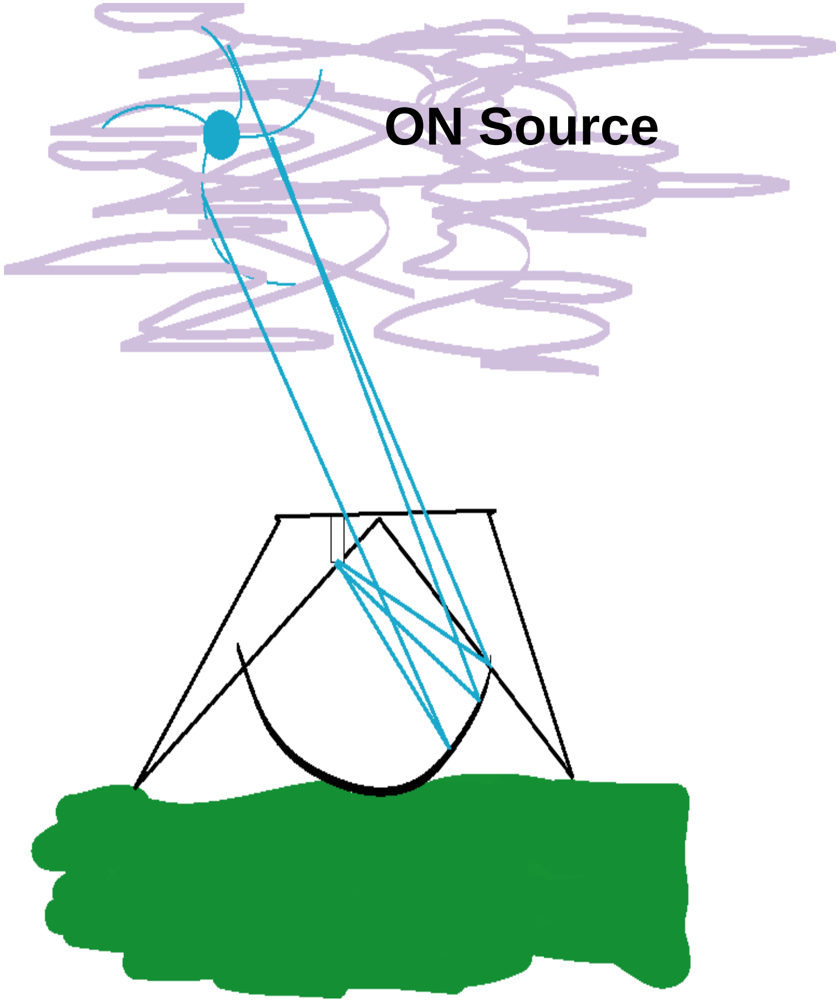
$$[(T_{source} + T_{everything\ else}) - (T_{everything\ else})]/\ T_{everything\ else}$$

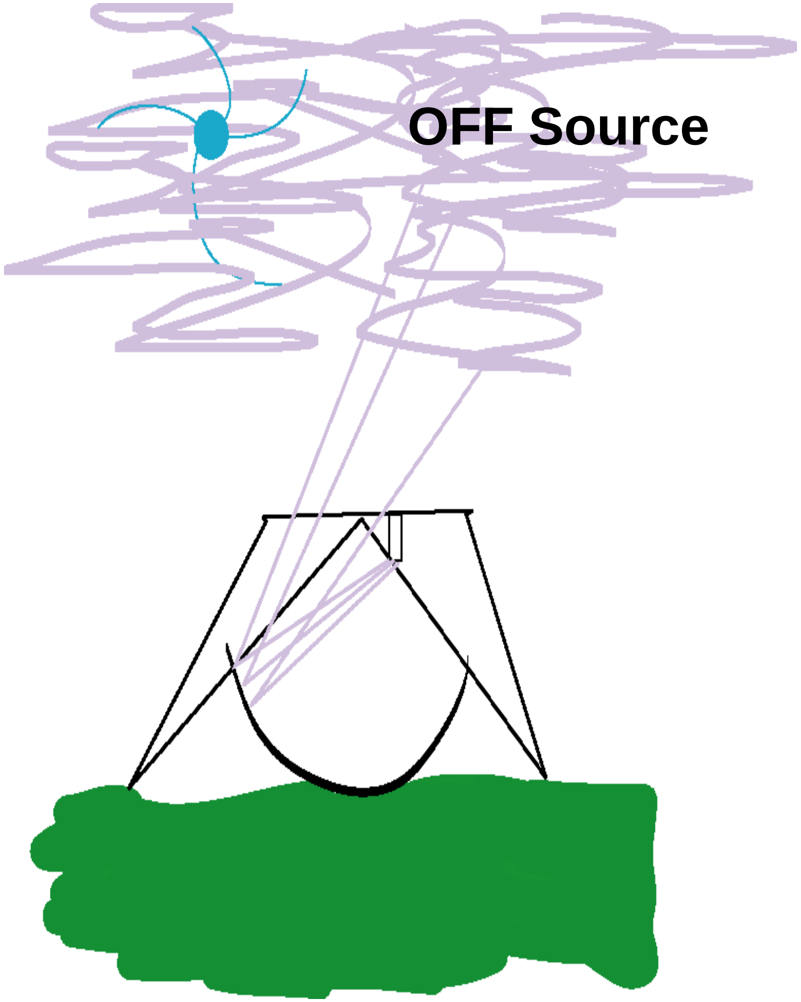


Choosing the Best OFF

Off Source Observations

Position Switching





Off Source Observations

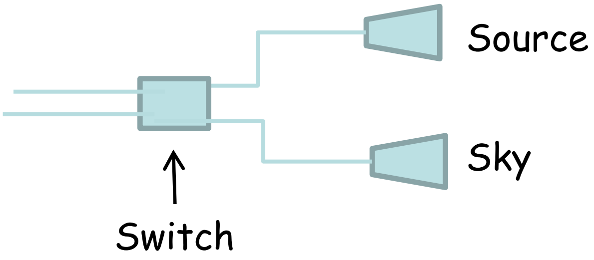
Position Switching

- Little a priori information needed
- Typically gives very good results
- Can also be done with tertiary throw
- Disadvantages:
  - System must be stable over time of pointings
  - Requires re-pointing the telescope*
  - Sky position must be carefully chosen
  - Source must not be extended beyond positions
  - Can take significant time*

*But not always….

Off Source Observations

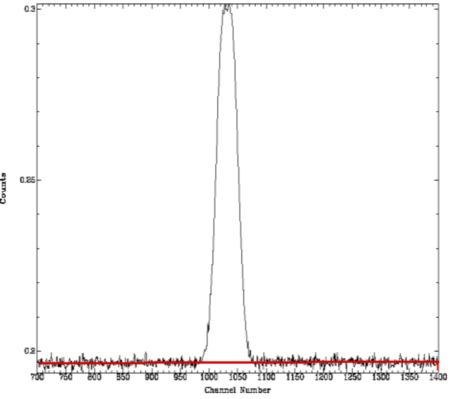
Beam Switching



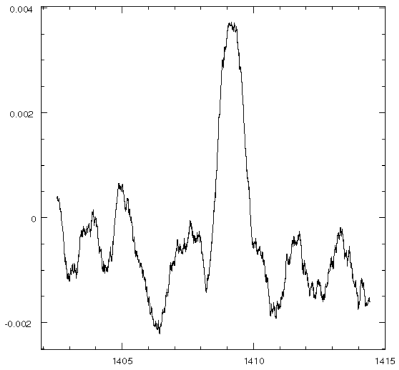
- Same idea as position switching
- Hardware switch, not telescope move
- Removes need to move telescope
- Source is always in one beam

- Disadvantages/Caveats:
  - Requires two receivers, very precise hardware
  - Switch sources/beams periodically
  - Sky position must be carefully chosen
  - Source must not be extended beyond throw

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
  - Do not know frequency/width of line of interest

- Errors are primarily from quality of fit

Off Source Observations

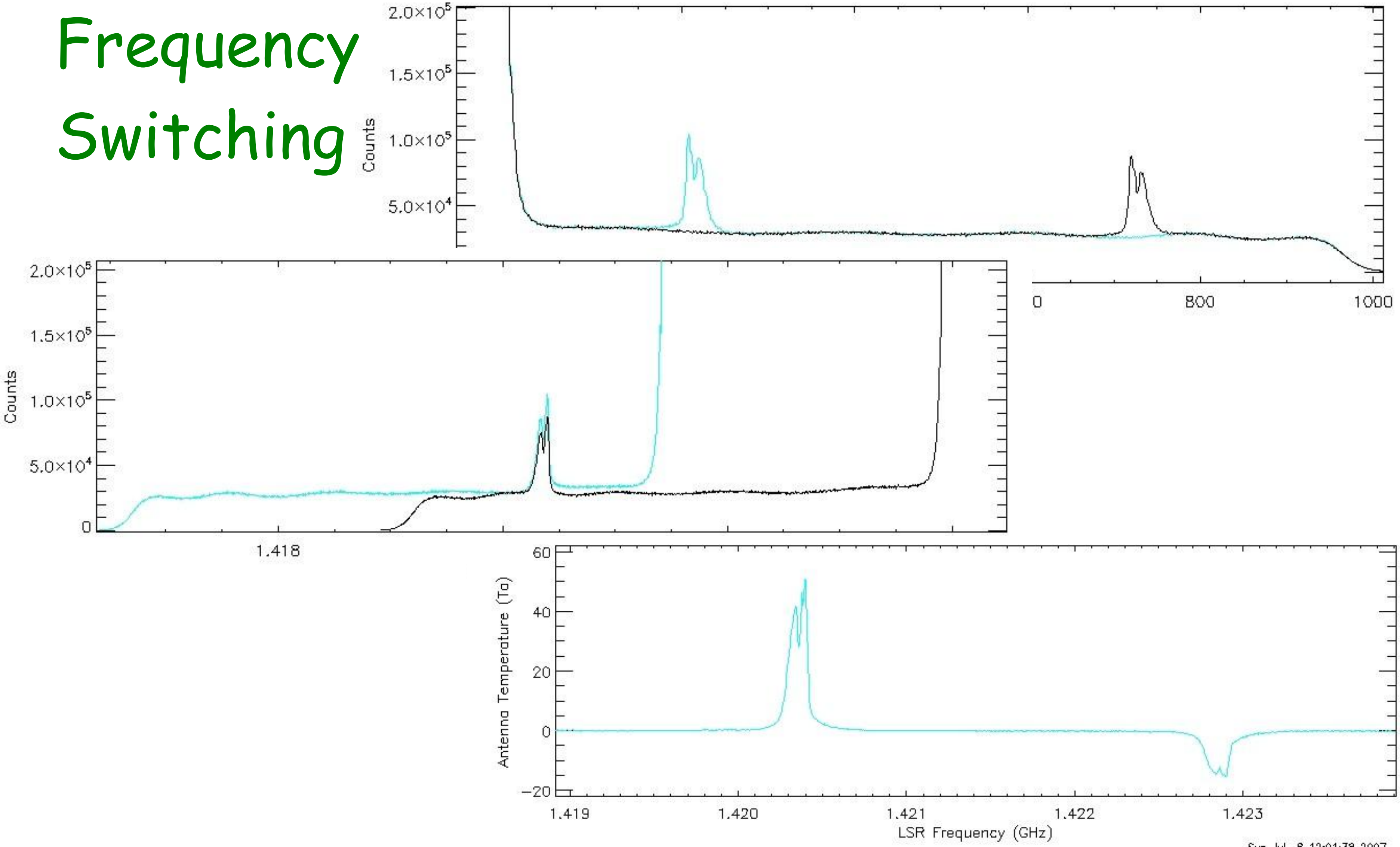
Baseline Fitting

with an average fit

- Can offer a very good fit
- Removes most issues with poor individual baselines
- System must be very stable with time
- Errors are still primarily due to accuracy of fit

Off Source Observations

Frequency Switching



Off Source Observations

Frequency Switching

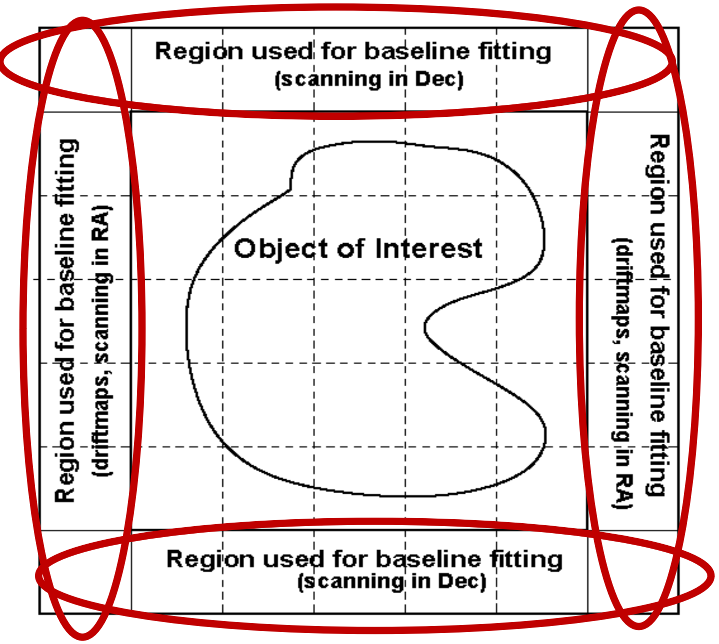
- Allows for rapid switch between ON & OFF observations
- Does not require motion of telescope
- Can be very efficient
- Disadvantages:
    - Frequency of line of interest should be known
    - System must be stable in channel space
    - Will not work with changing baselines, wide lines

Off Source Observations

Variations

Mapping an Extended Source

Possible alternative if frequency switching is not an option



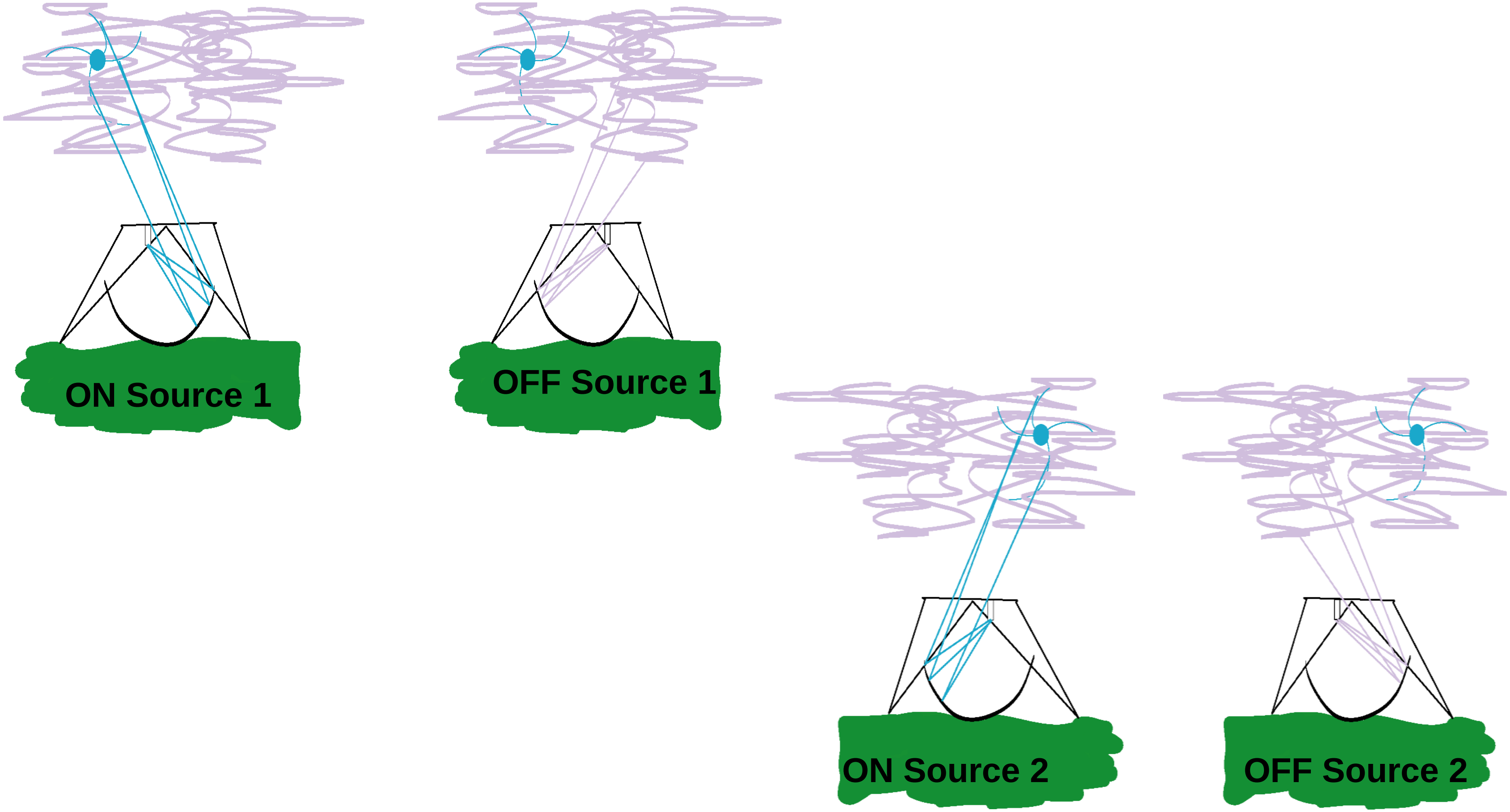
System must be very stable

Off source must truly be off!

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
- Requires two source with similar power levels
- Result:

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

From ATOM 2001-02 by Ghosh & Salter

Off Source Observations

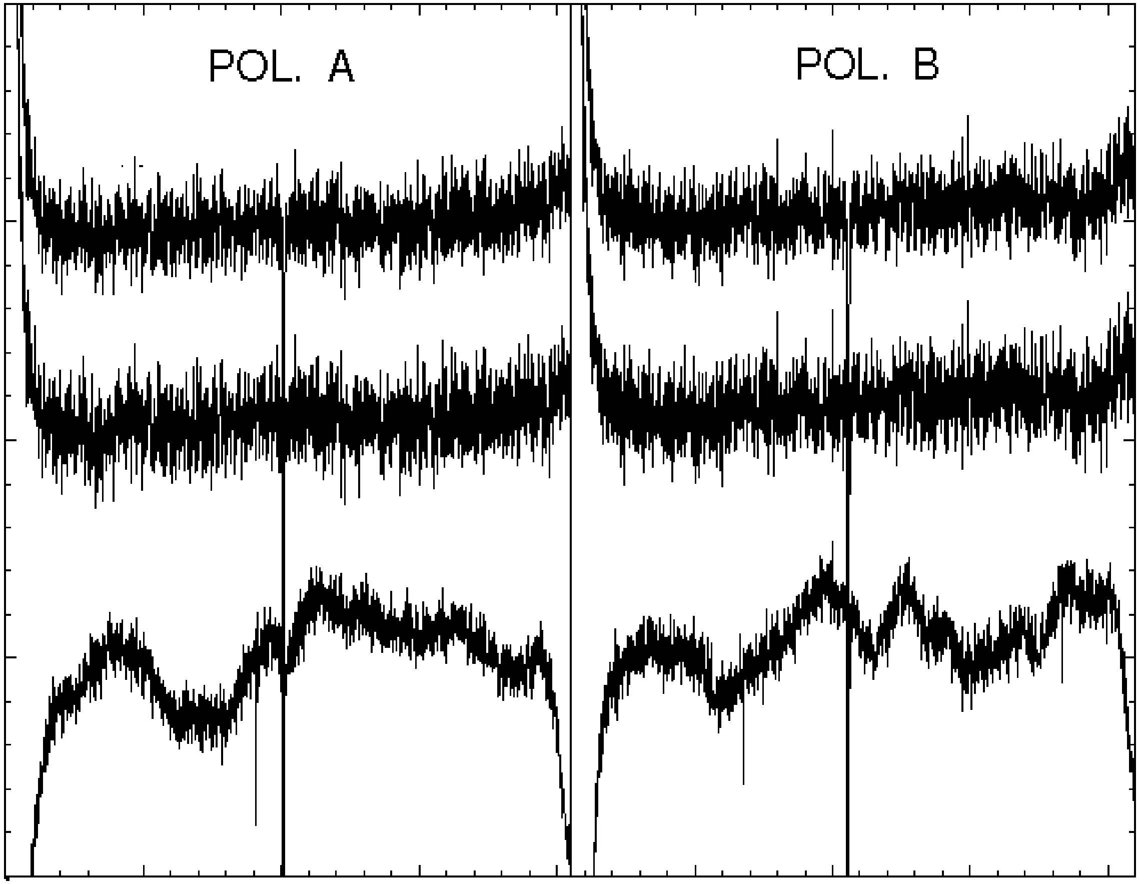
Variations

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



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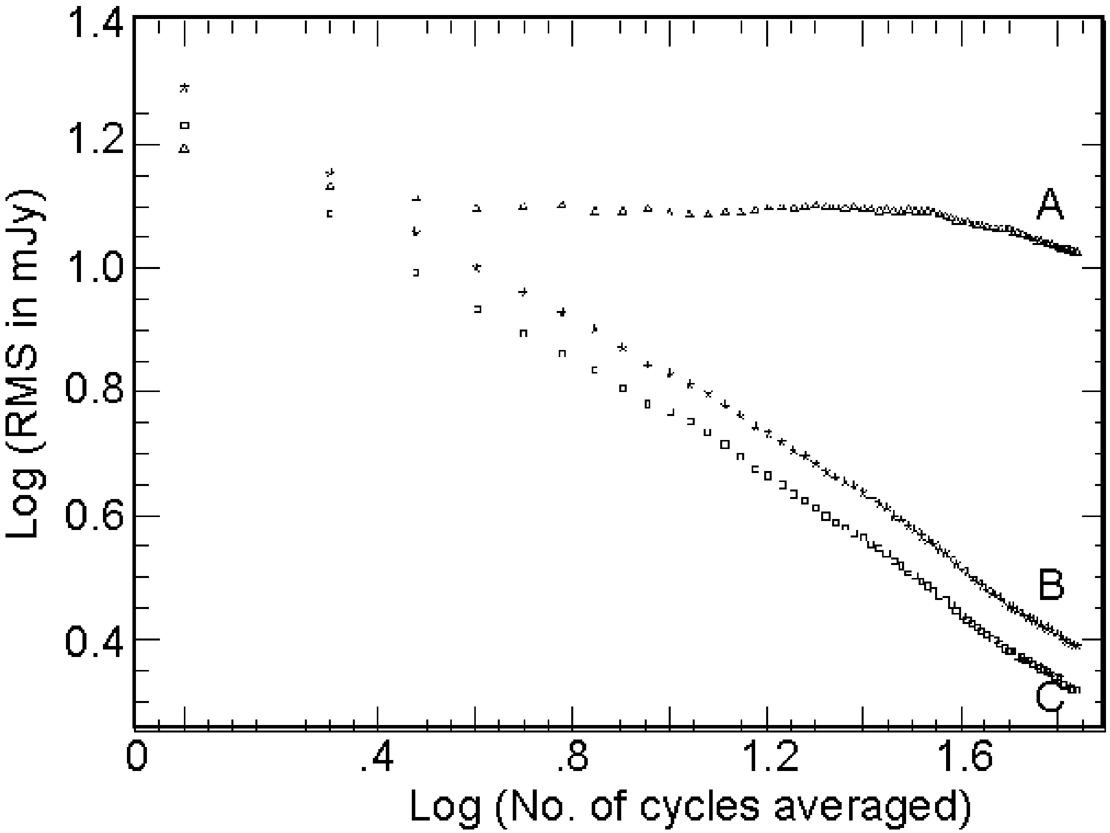
Off Source Observations

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_{system}

Theory

Measure various components of T_{sys}:

Decreasing Confidence

T_{CMB} – Well known (2.7 K)

$T_{RX,\ hardware}$ – Can be measured/monitored

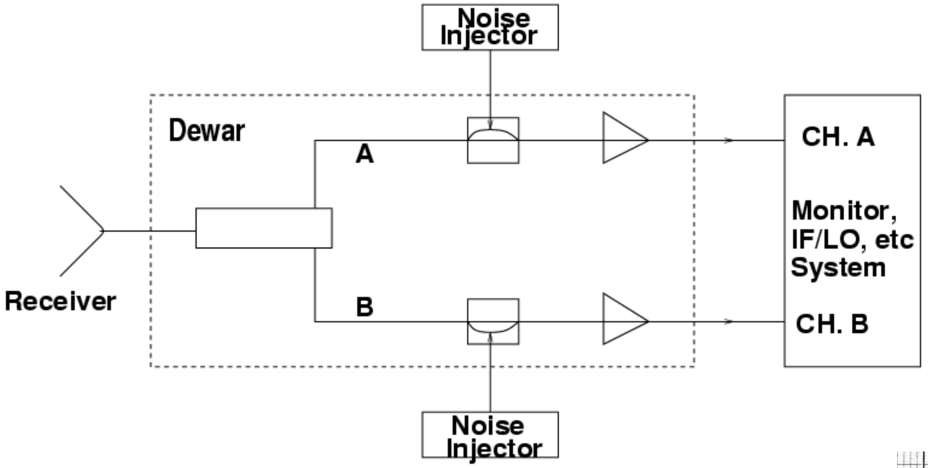
$T_{cel}(\alpha,\delta,t)$ – Can be determined from other measurements

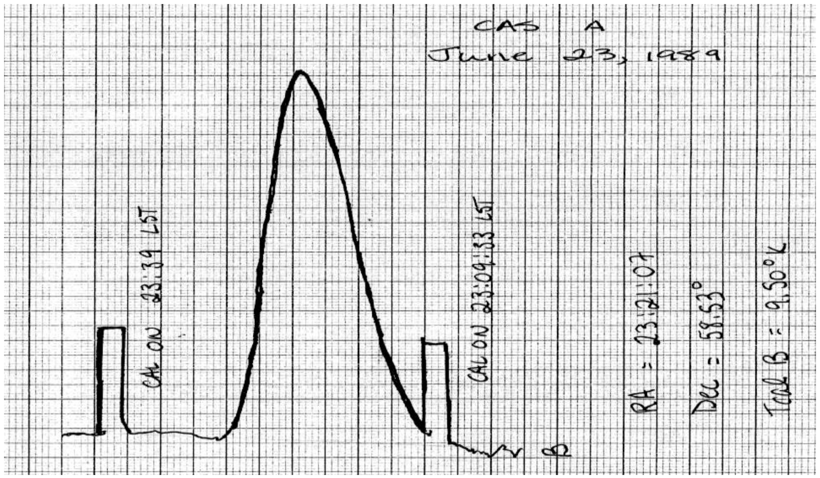
$T_{atm}(za)$ – Can be determined from other measurements

$T_{gr}(za,az)$ – Can be calculated

Determining T_{sys}

Noise Diodes





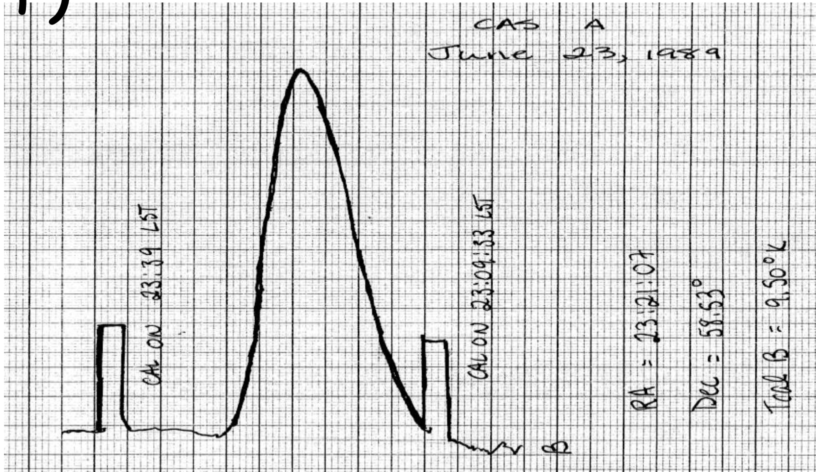
Determining T_{sys}

Noise Diodes

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

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

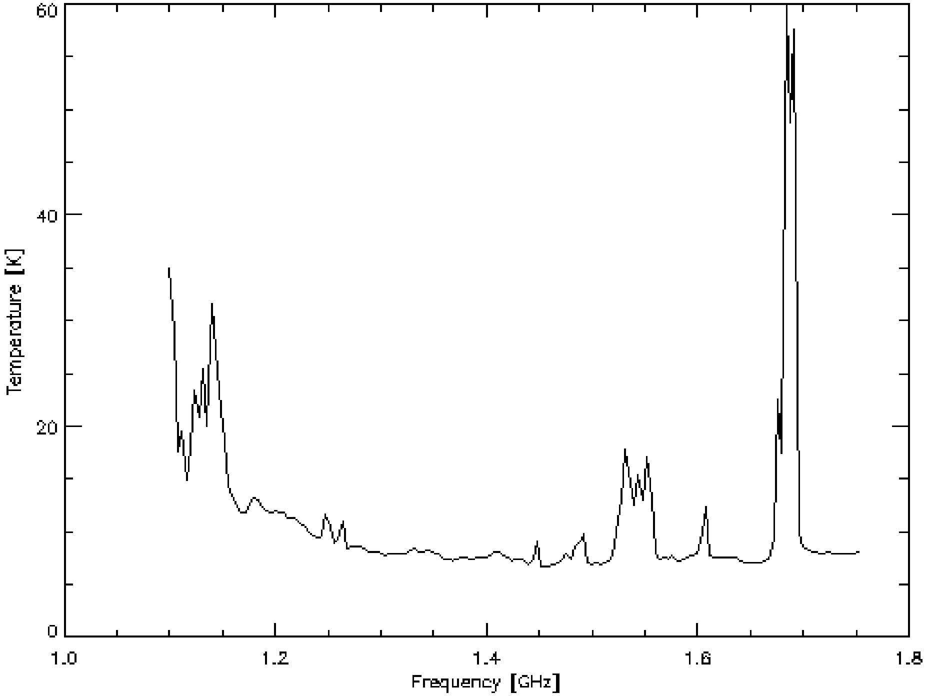
$$T_{sys} = T_{diode} * Off/(On - Off)$$



Determining T_{sys}

Noise Diodes - Considerations

- Frequency dependence

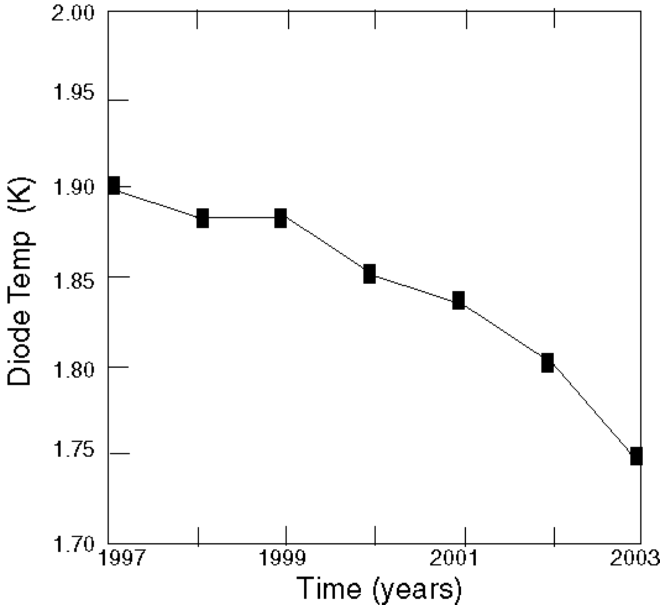


Lab measurements of the GBT L-Band calibration diode, taken from work of M. Stennes & T. Dunbrack - February 14, 2002

Determining T_{sys}

Noise Diodes - Considerations

- Frequency dependence
- Time stability



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
- 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 -> 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}

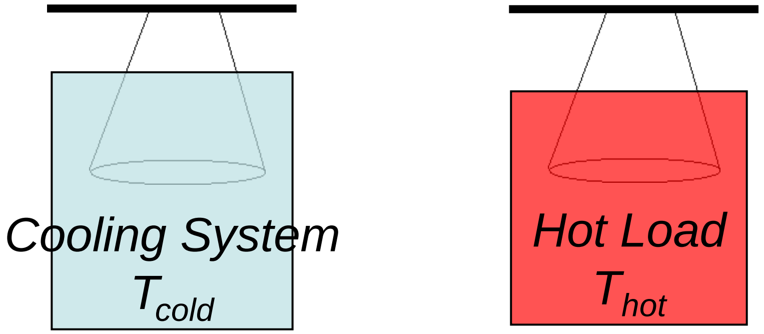
Noise Diodes - Considerations

- Frequency dependence
- Time stability
- Accuracy of measurements

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

Determining T_{sys}

Hot & Cold Loads



- Takes antenna into account
- True temperature measurement

Determining T_{sys}

A Relevant Aside :

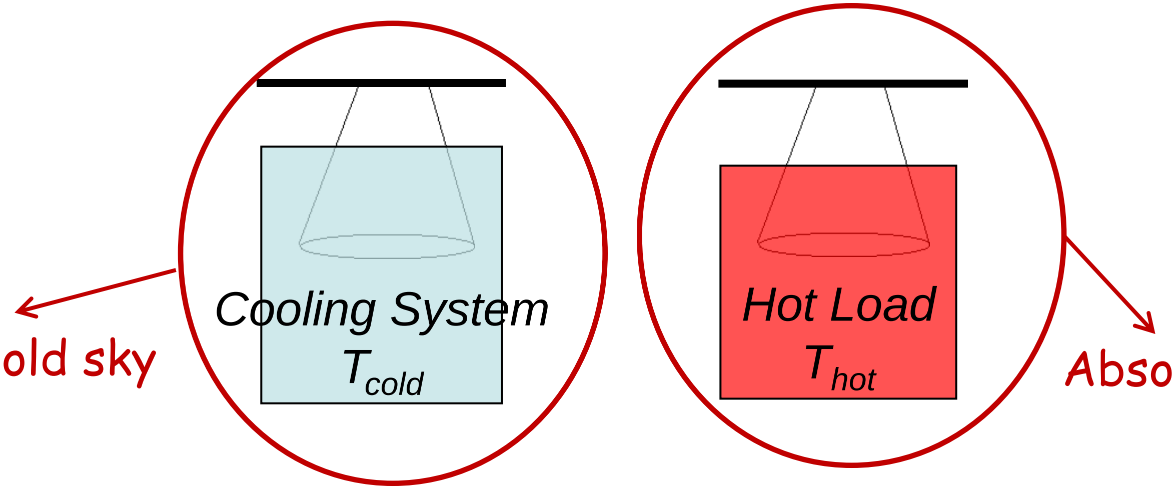
(The Y-Factor)

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

- Measured with two noise sources in the lab

Determining T_{sys}

Hot & Cold Loads



Cooling System T_{cold}

Hot Load T_{hot}

Cold source or cold sky

Absorber, typically

$$T_{off} = \frac{T_1 - yT_2}{y - 1}$$

Determining T_{sys}

Hot & Cold Loads

- Takes antenna into account
- True temperature measurement

Requires:

- Reliable loads able to encompass the receiver
- 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:

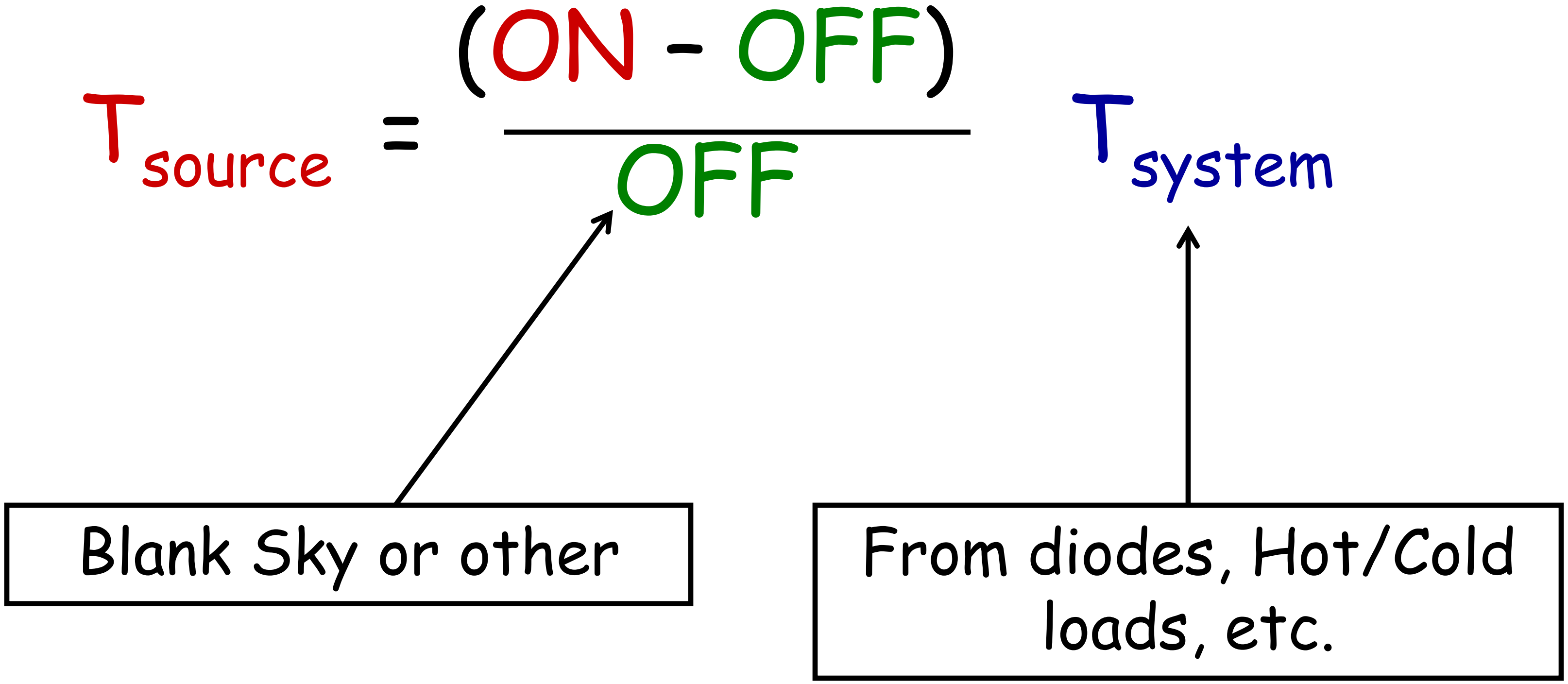
Can be very accurate

Observations not possible when load on

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

In reality, all three methods should be combined for best accuracy

Determining T_{source}



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

Blank Sky or other

From diodes, Hot/Cold loads, etc.

Telescope response has not been accounted for!

Determining Telescope Response

Telescope Response

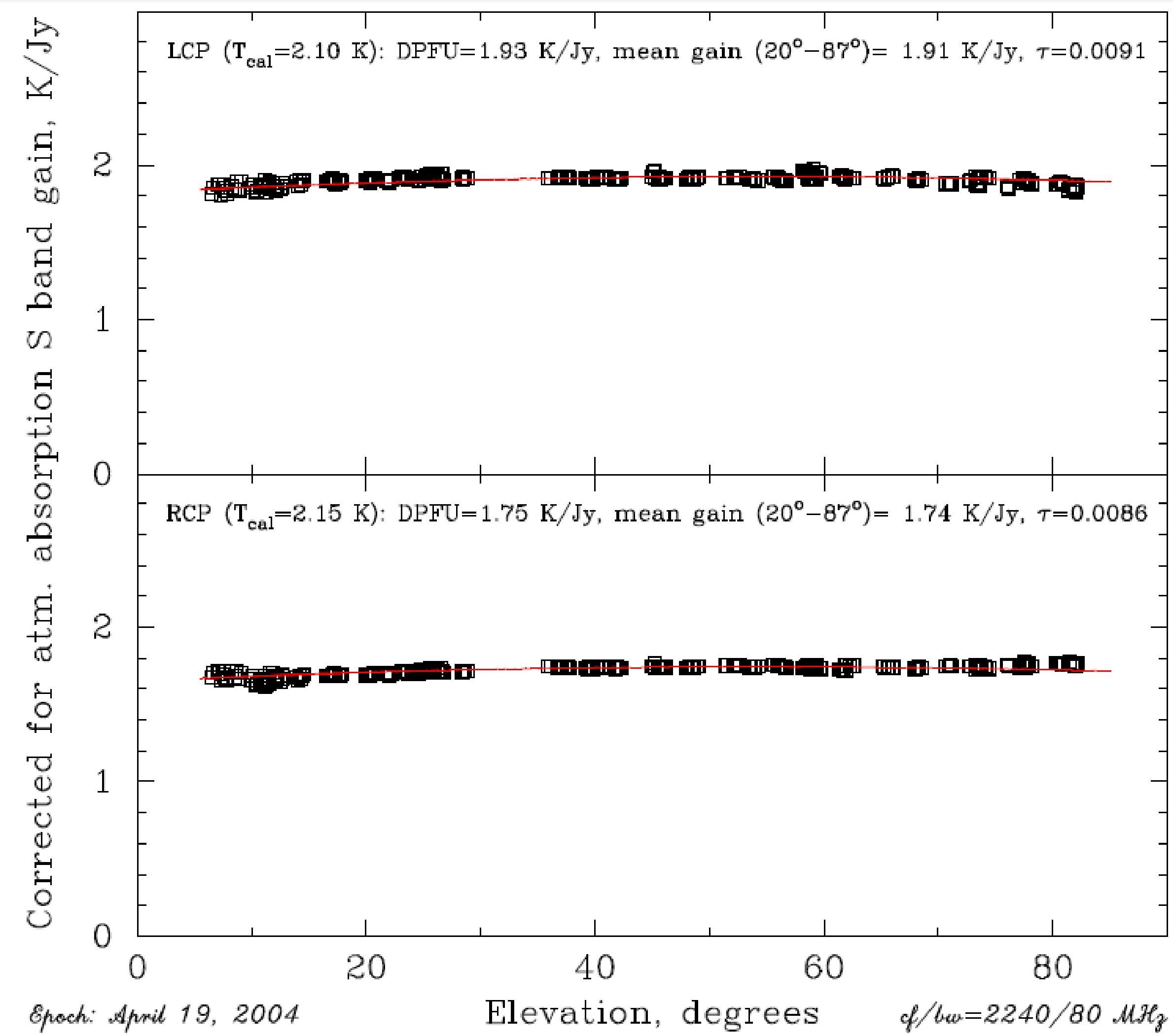
Ideal Telescope:

- 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

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

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

Telescope Response

- 'Bootstrapping':

  Useful when gain is not readily modeled
  Offers ready means for determining telescope gain

  Requires calibrator flux to be well known in advance
  Not practical if gain changes rapidly with position

Telescope Response

Pre-determined Gain curves:

Allows for accurate gain at all positions

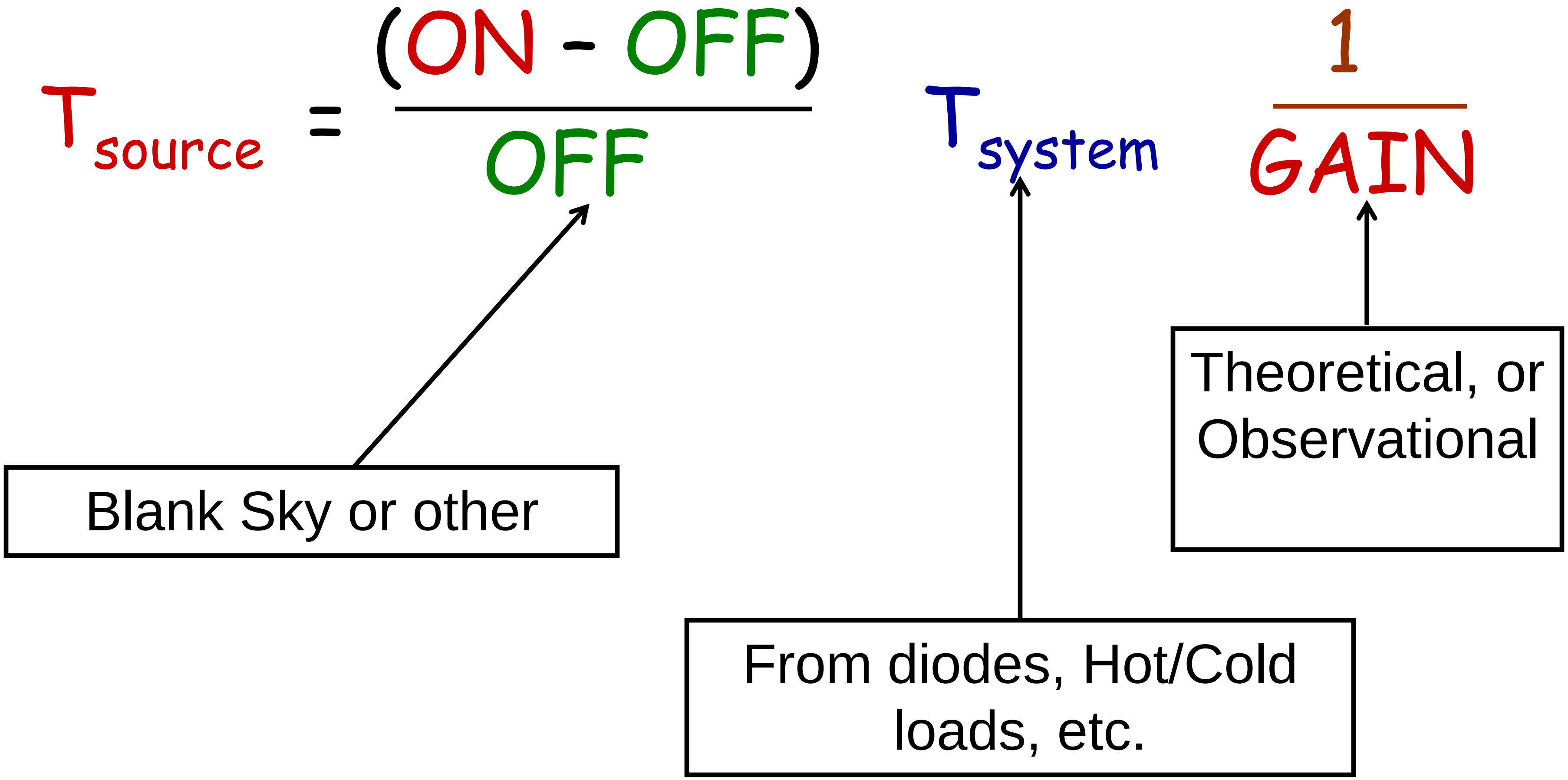
Saves observing time

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

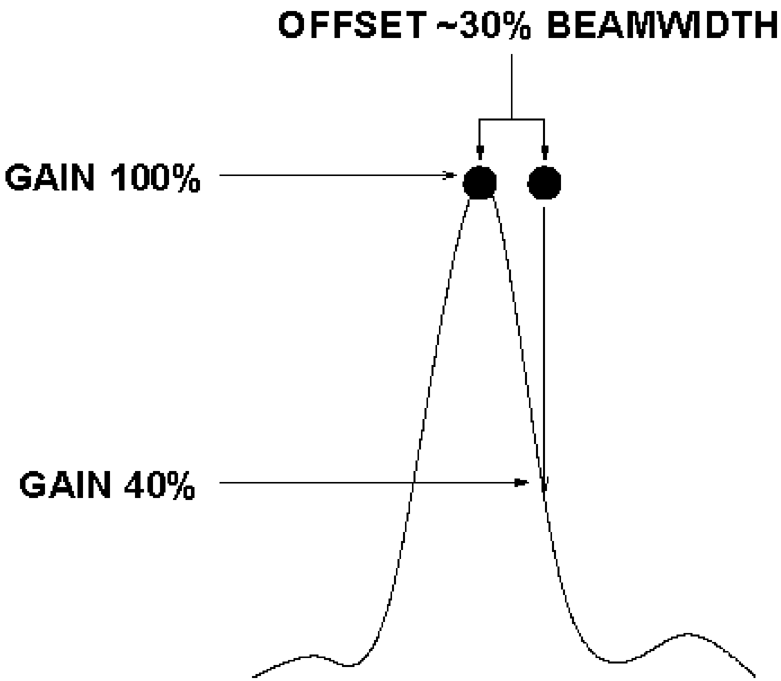
From diodes, Hot/Cold loads, etc.

Theoretical, or Observational

Great, you're done?

A Few
Other Issues

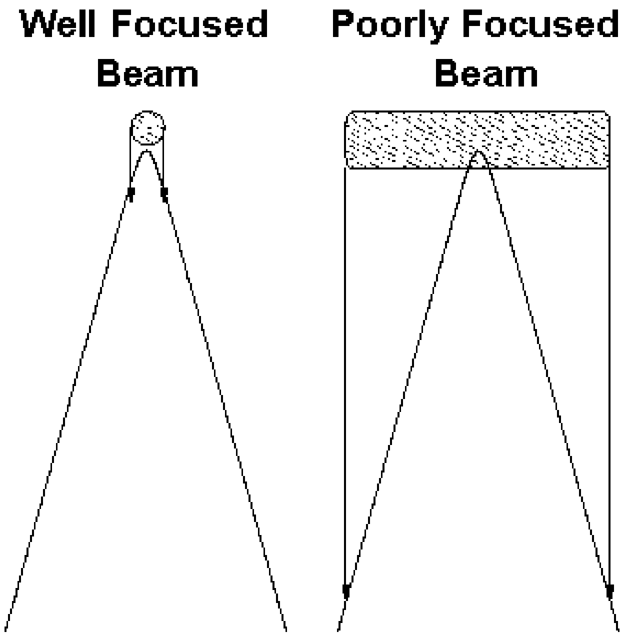
Other Issues:
Pointing



Results in reduction of telescope gain

Always check telescope pointing!

Other Issues:
Focus

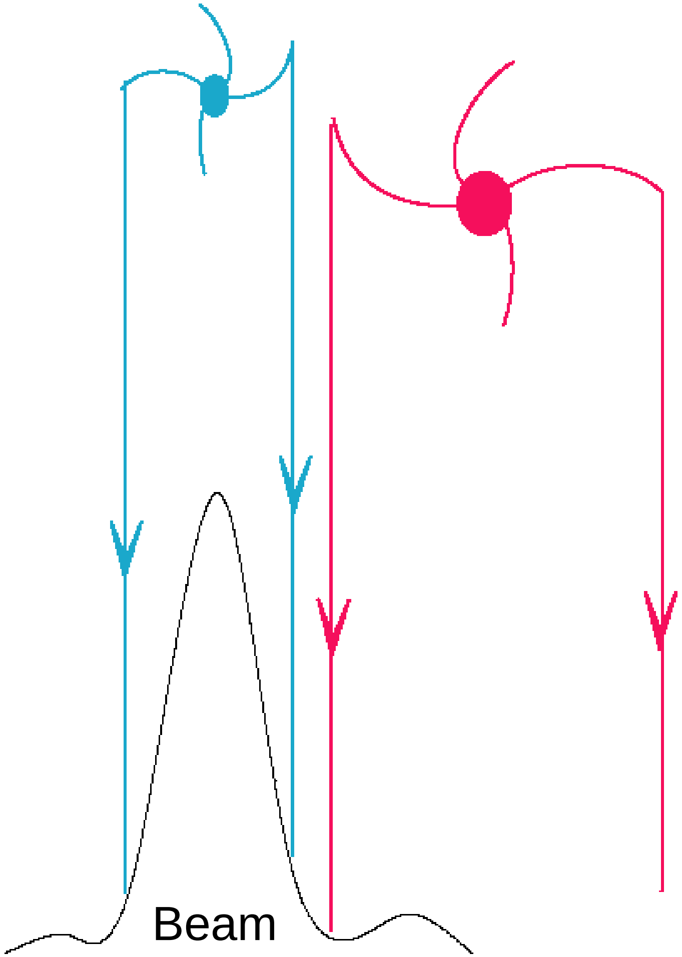


Results in reduction of telescope gain

Corrected mechanically

Always check focus!!!

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

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*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

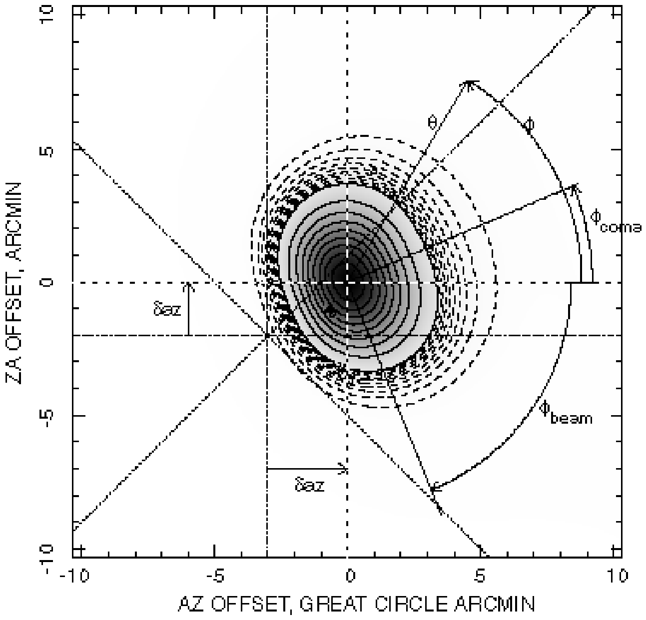
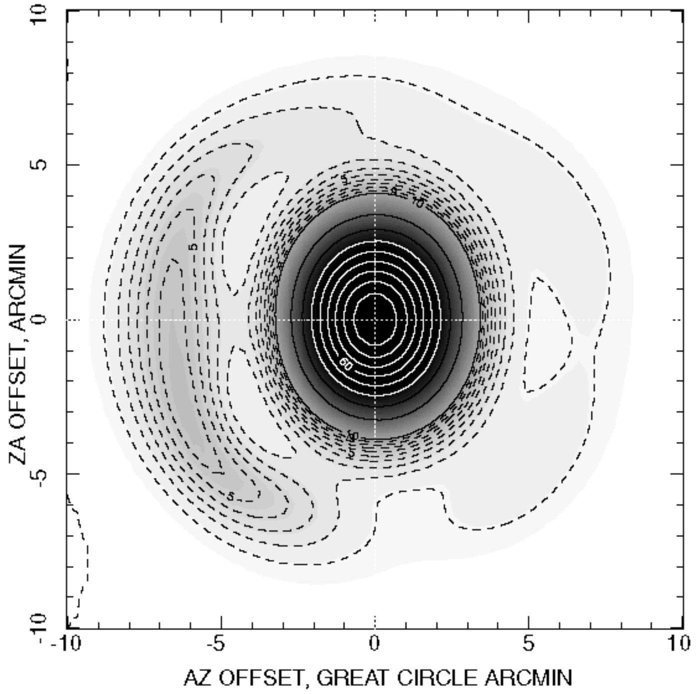


Image from ATOM 99-02, Heiles

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

Conclusion:

(applies to all science research)

- Astronomy instrumentation and calibration is complicated
- Learn the system you are using well
- Talk with the instrument staff frequency, and visit often
- To produce good science you must understand the instrument and techniques you are using

You are ultimately responsible for the quality of your data!

The End