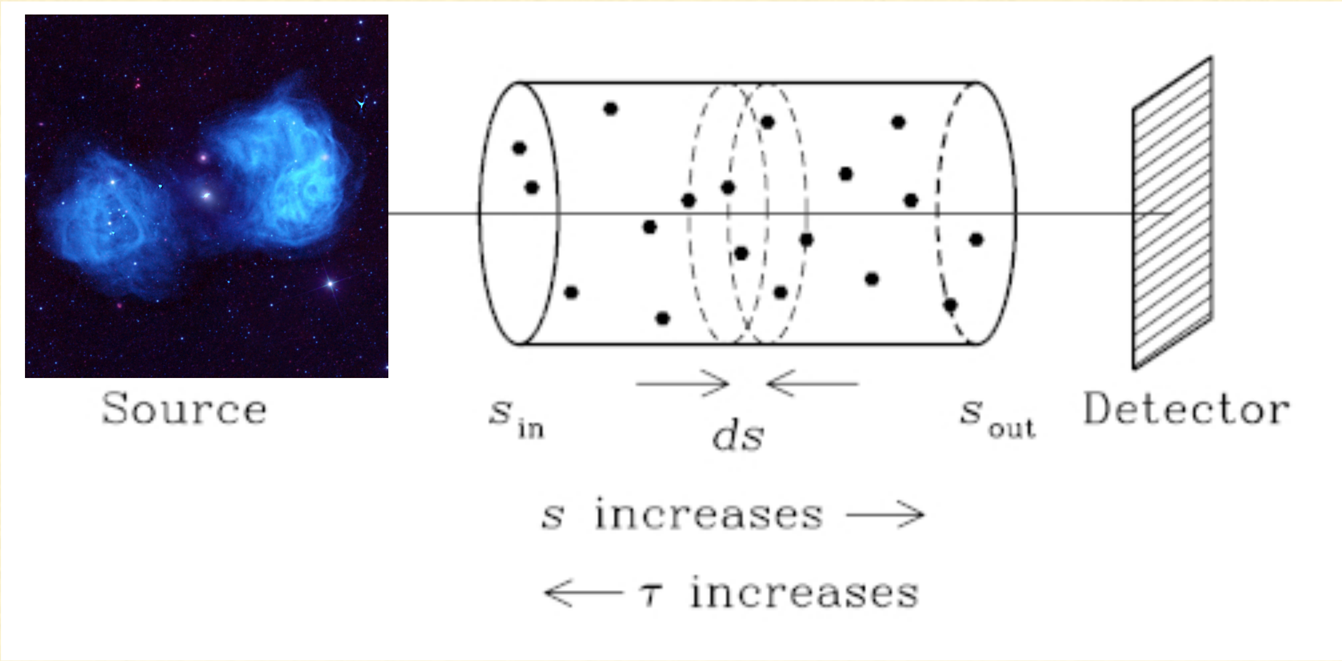
CALIBRATION & OBSERVING TECHNIQUES I

Larry Morgan, including material from K. O’Neil, D.Frayer and R.Maddalena

We wish to establish a consistent system of measurement to quantify the radiation intensity coming from astronomical sources

Blackbody radiation and radiative transfer covered in detail by N.Palliyaguru, A.Roshi, F.Ghigo and A.Seymour

Radiative Transfer



$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + \epsilon_\nu$$

Absorption

Emission

$$I_\nu = B_\nu(T) = \frac{\epsilon_\nu}{\kappa_\nu}$$

Kirchoff's Law (for thermal equilibrium)

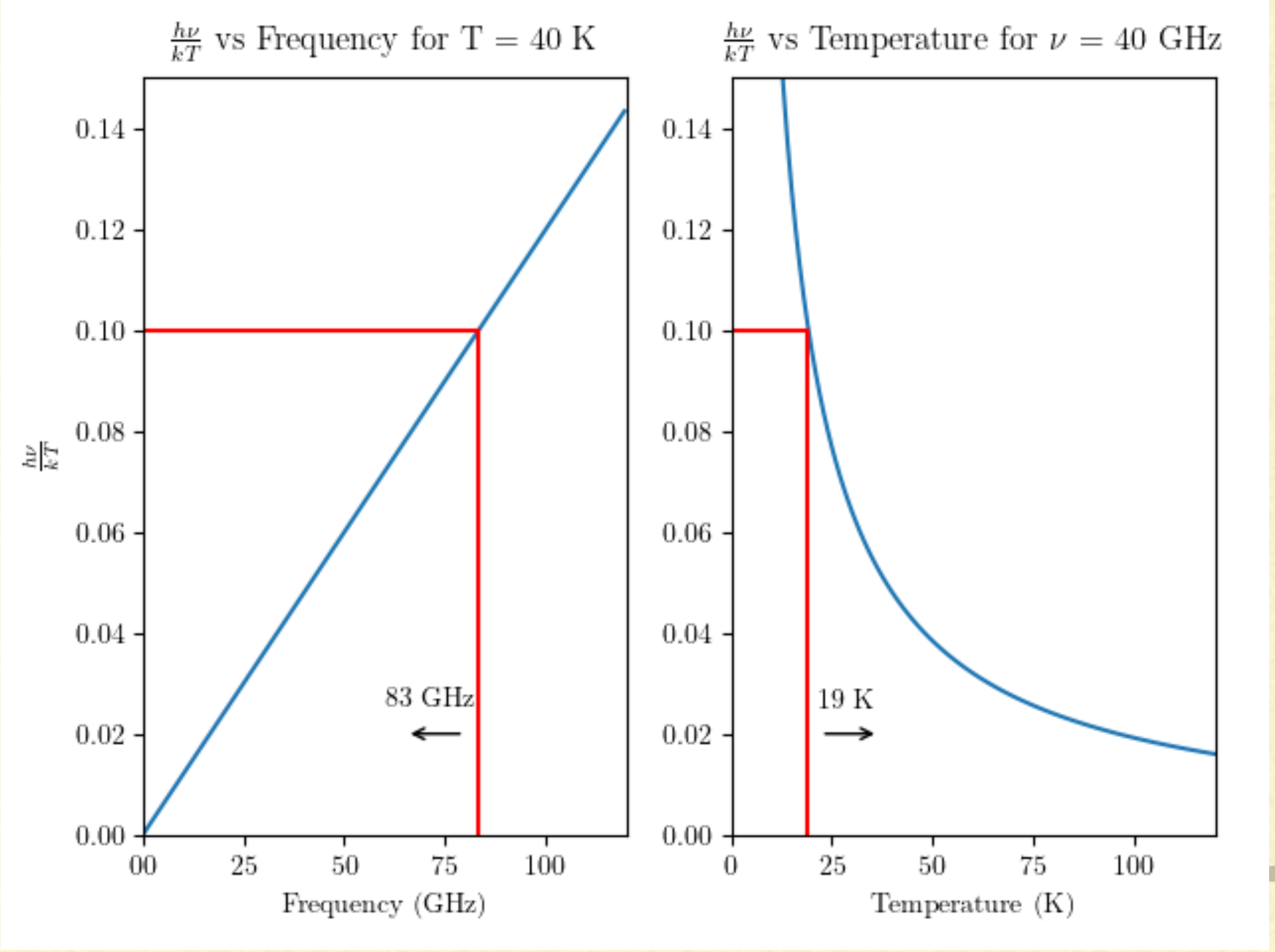
Blackbody Equation

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

Planck's Law

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

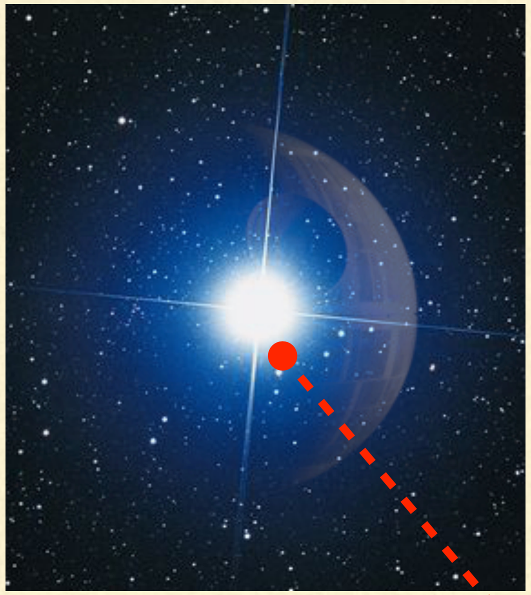
Rayleigh - Jeans approximation
for $h\nu \ll kT$



Note units of B:
$Wm^{-2}Hz^{-1}sr^{-1}$ or $Jy\,sr^{-1}$

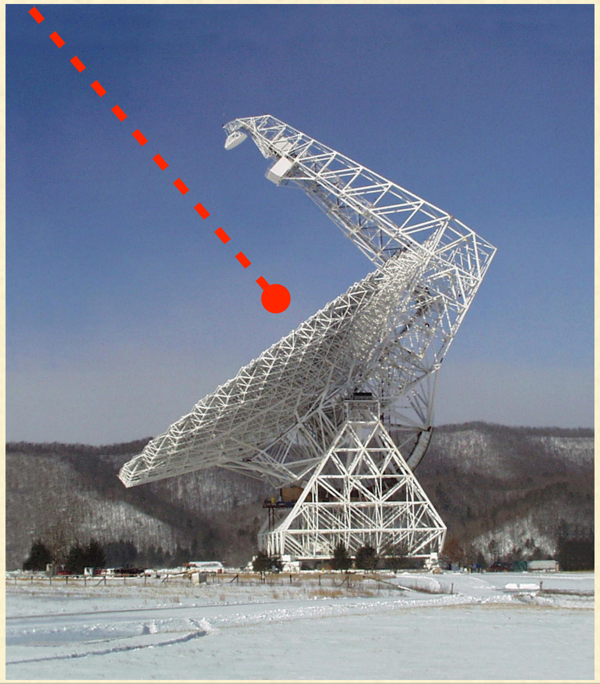
May sometimes see $B = 8\pi h\nu^3 \ldots$
instead of $B = 2h\nu^3 \ldots$

Temperature in Radio Astronomy



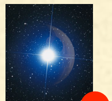
We often assume a uniform temperature T for a discrete radio source, emitting over a solid angle Ω_s

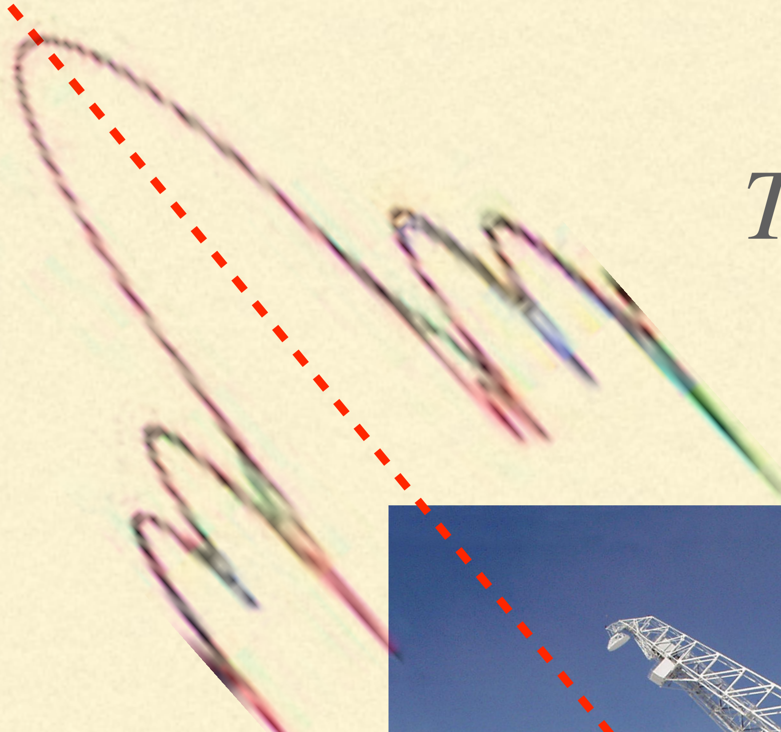
$$s = \frac{2kT}{\lambda^2}\Omega_s$$

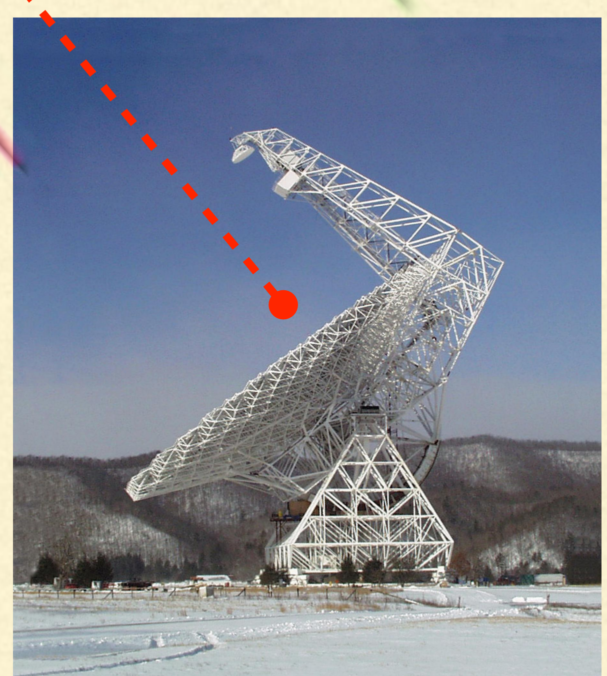


Measuring system at the telescope is T_A, the antenna temperature

Antenna Temperature







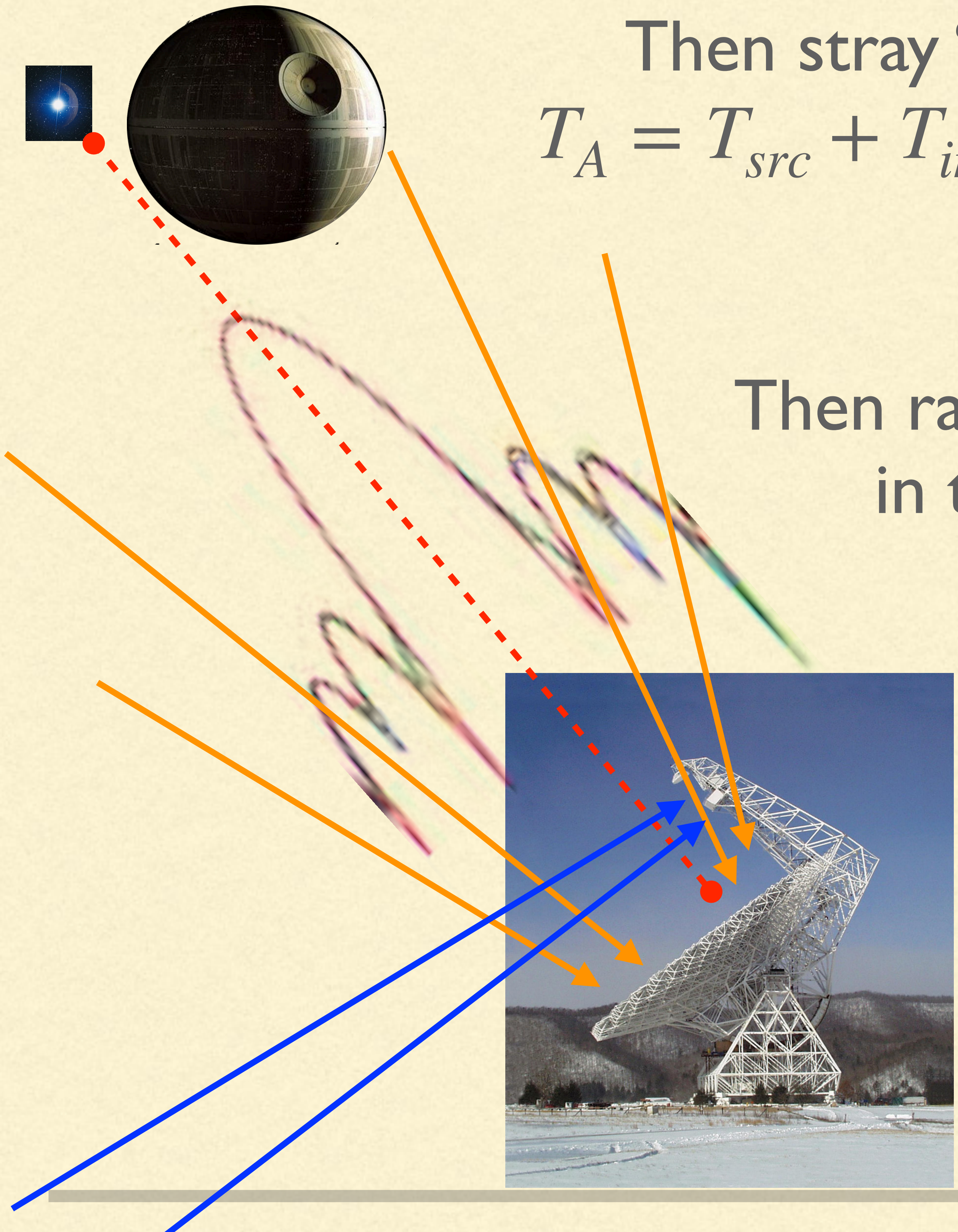
In basic principle we want to measure the source temperature by measuring a temperature incident on the telescope, that is

$$T_A = T_{src}\text{(after Kirchoff's law processing)}$$

Of course, the system itself adds some heat to the measurement

$$T_A = T_{src} + T_{instrumentation}$$

Antenna Temperature



Then stray 'spillover' radiation

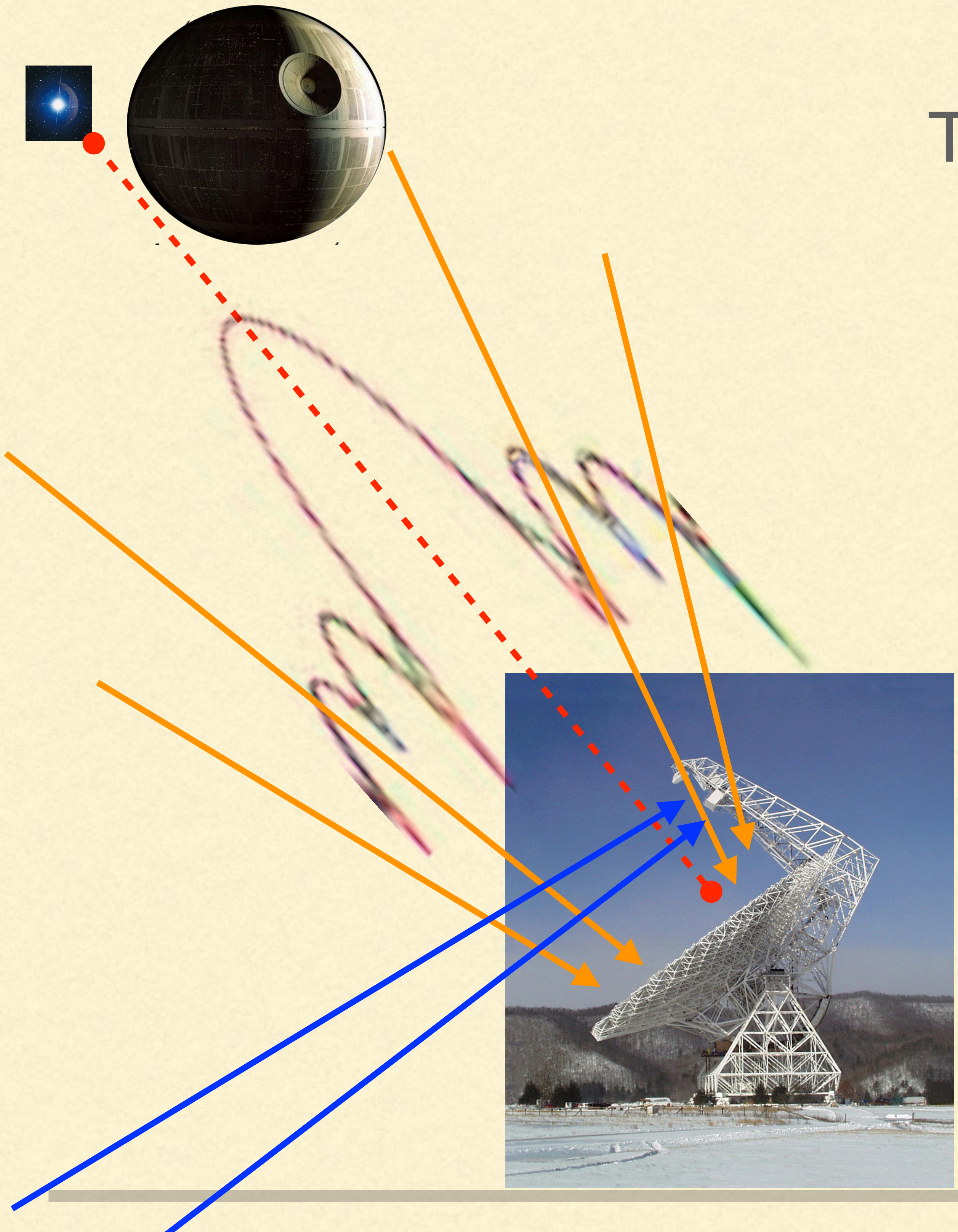
$$T_A = T_{src} + T_{instrumentation} + T_{spillover}$$

(from and)

Then radiation from sources we might see in the beam but don't care about

$$T_A = T_{src} + T_{instrumentation} + T_{spillover} + T_{confusion}$$

Antenna Temperature



Then there's the CMB and, of course, the atmosphere

$$T_A = T_{src} + T_{instrumentation} + T_{spillover} + T_{confusion} + T_{CMB} + T_{atm}$$

Antenna Temperature

$$\boxed{T_A = T_{src}} + \boxed{T_{instrumentation} + T_{spillover} + T_{confusion} + T_{CMB} + T_{atm}}$$

$$T_A = T_{src} + T_{everythingelse}$$

Antenna Temperature

$$T_A = T_{src} + T_{instrumentation} + T_{spillover} + T_{confusion} + T_{CMB} + T_{atm}$$

$$T_A = T_{src} + T_{everythingelse}$$

Rather than eliminate all of these unknowns, it's considerably easier to eliminate the source

$$T_{on} = T_{src} + T_{everythingelse} \qquad T_{off} = T_{everythingelse}$$

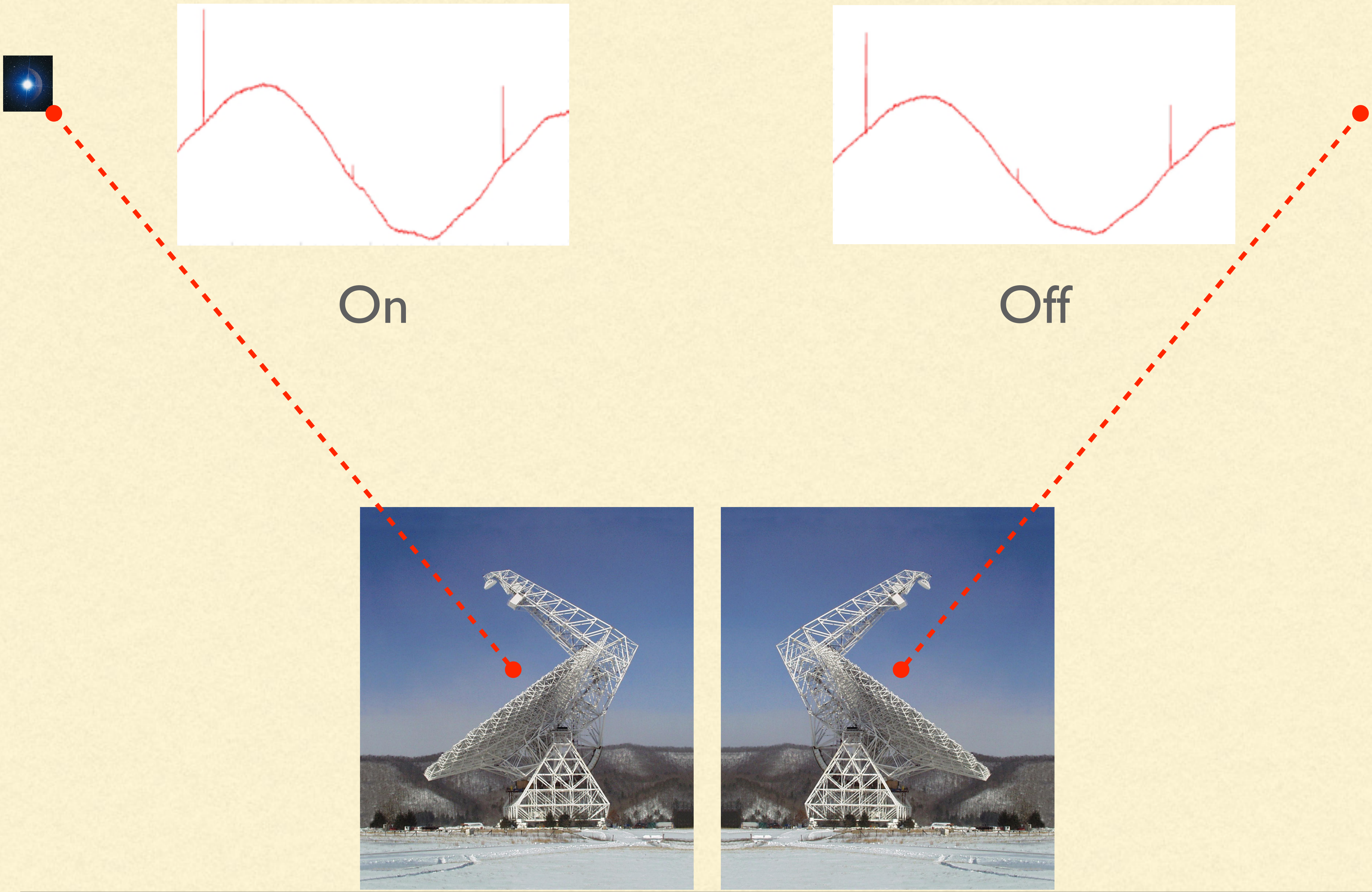
Determining Source Temperature

Several methods for determining T_{on} and T_{off}

T_{off} is a ‘reference’ observation and can be obtained through

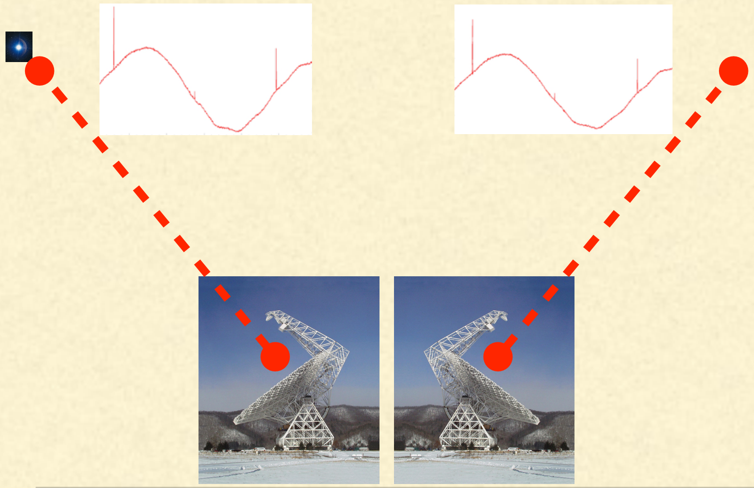
- Position switching
- Frequency switching
  - in-band or out-of-band
- Beam switching
  - move subreflector
  - receiver beam-switch
- Dual beam nodding
  - move telescope
  - move subreflector

Position Switching



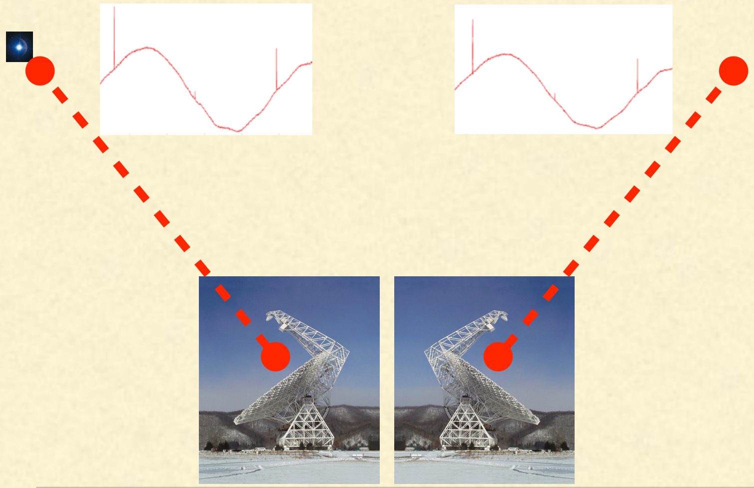
Position Switching

- Good when you have little prior knowledge of sources. So long as line of interest is in bandpass, you don't need frequency/velocity of source.
- Care must be taken when observing extended sources. Make sure off-source position is emission-free
- Successful position switching relies upon good time stability of the telescope and, given that you're moving the telescope, fast switching is often not feasible.
  - Though, see nodding and chopping.

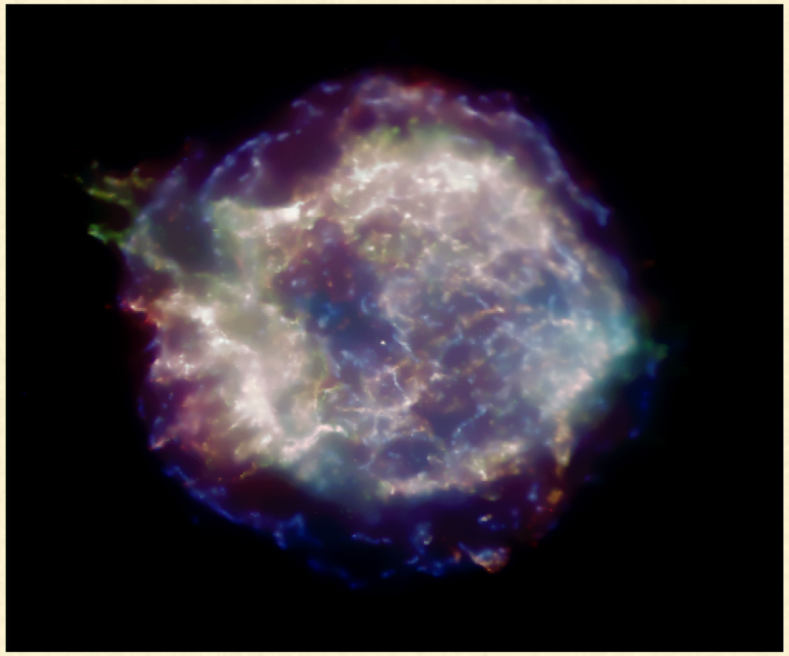


Position Switching

- Some telescopes have different illuminations of the dish at different positions, as well as different standing wave patterns. Also, different positions will have different contributions from ground and telescope structure reflections.
- Often useful to maintain declination (elevation) for off position, especially if telescope doesn't have constant illumination across the sky (like Arecibo) or at high-frequency.



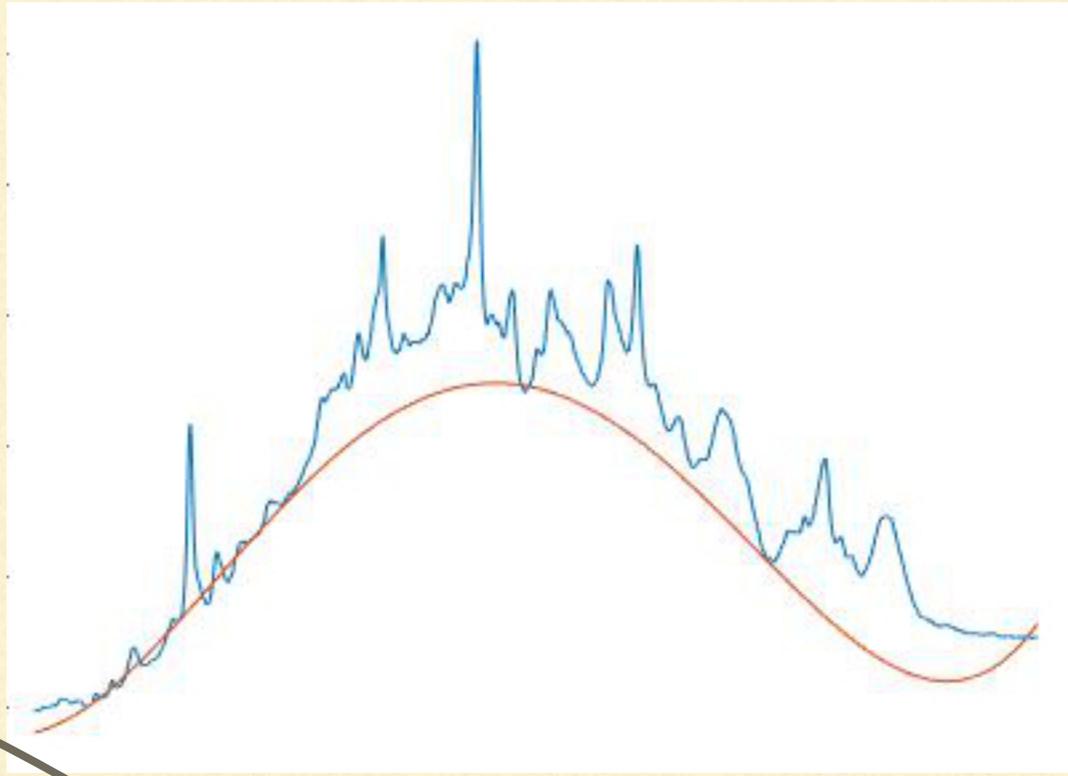
Position Switching

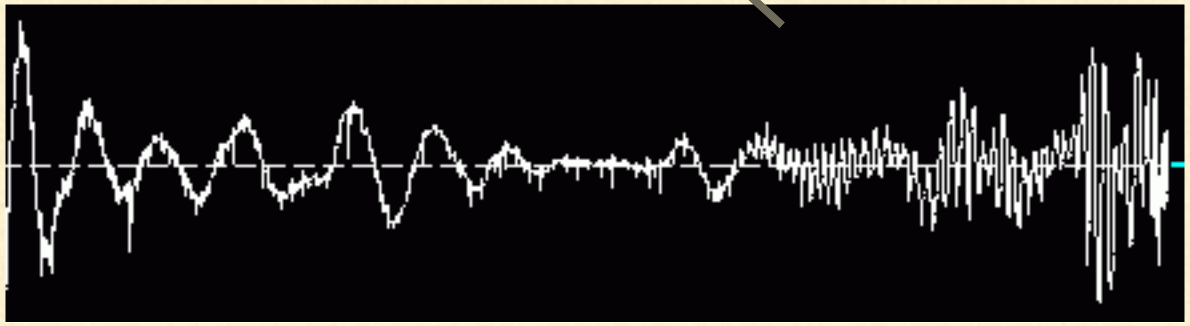


- Strong continuum sources can produce different standing-wave patterns between the on and the off, thus baselines aren't cancelled in on-off calculation (particularly for occluded apertures)
- In this case it's possible to use an 'off' centered on a slightly weaker source and use ratios to determine flux densities. This is 'double position switching'.

Baseline Fitting

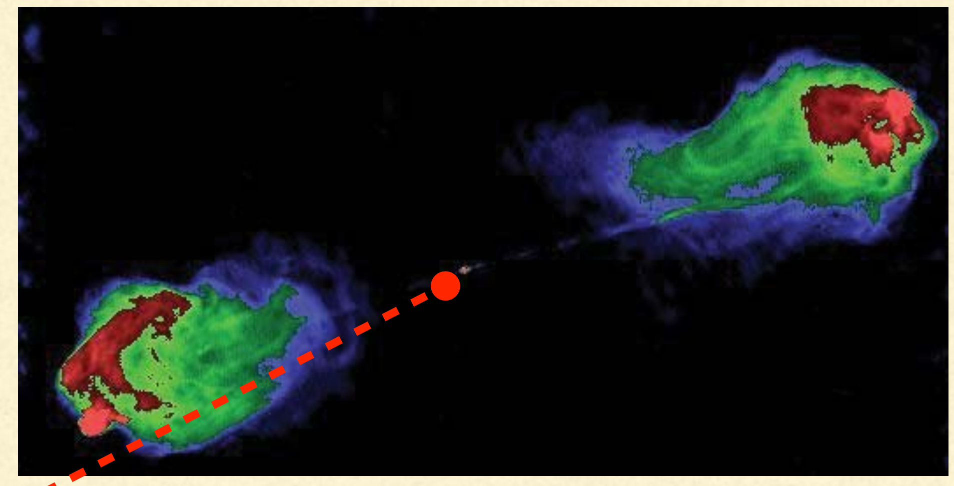
- Baseline around spectral line can be treated as 'blank sky'
  - ~ need lots of blank channels
  - ~ also baseline has to be reasonably flat (see)
  - ~ errors come predominantly from quality of fit.
  - ~ RFI (even outside bandpass) could also be messing with your power levels.

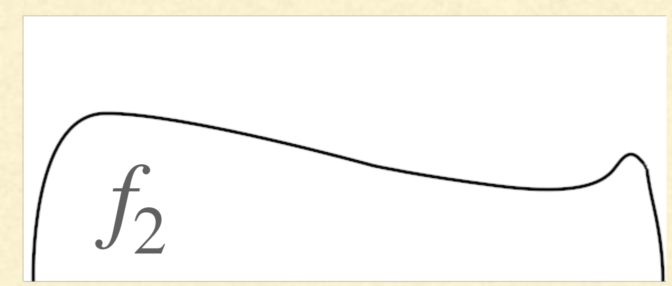




Out-of-band Frequency Switching

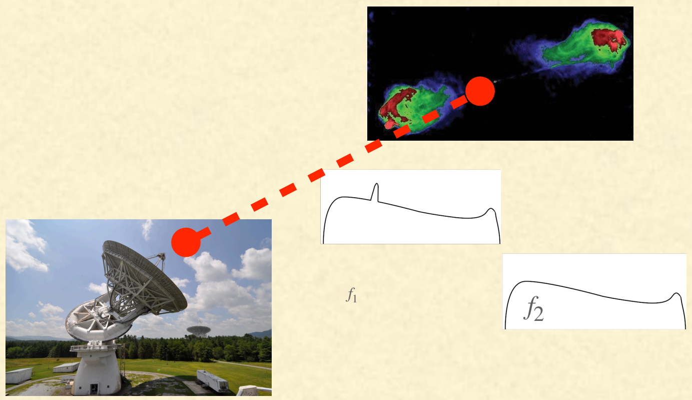
- Bandpass shapes can be removed efficiently without moving telescope
- This is usually better than fitted-baseline removal due to fitting errors





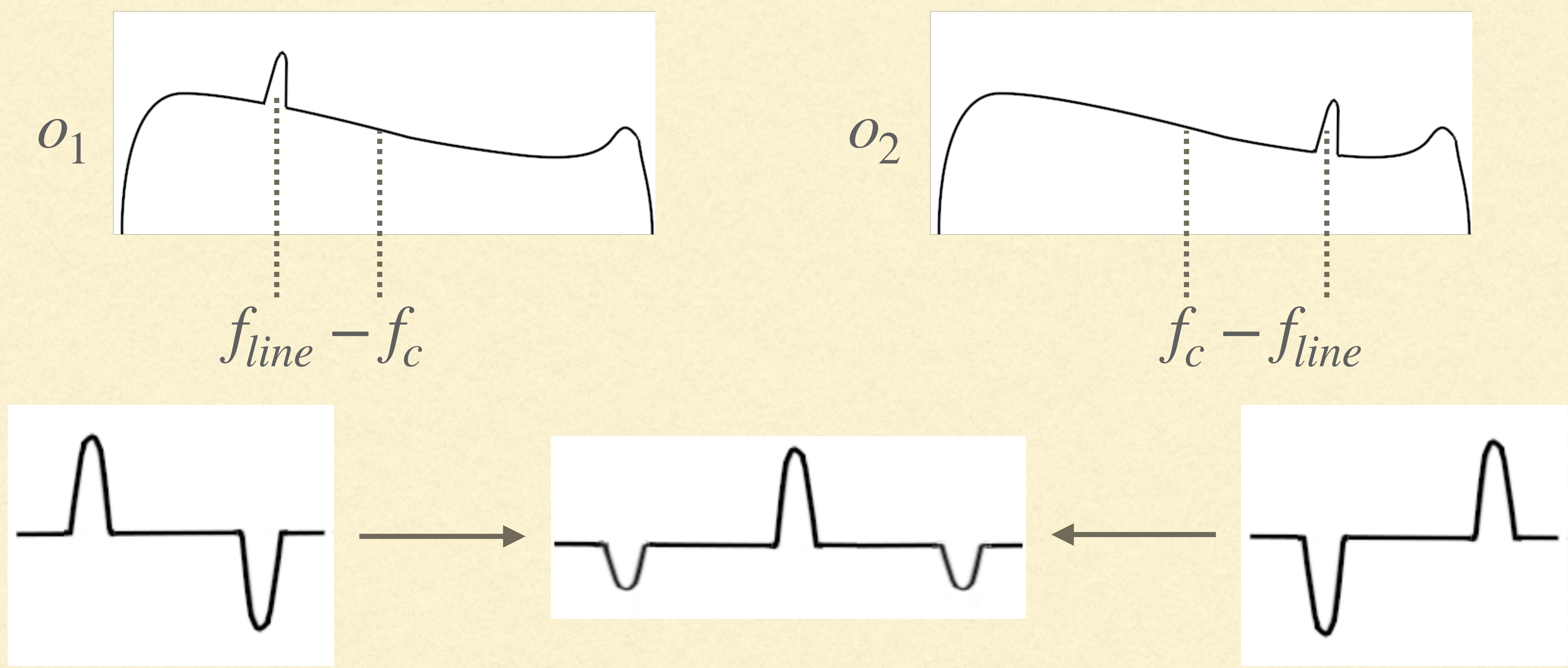
Out-of-band Frequency Switching

- Can give high spectral resolution as large numbers of blanks channels not needed for good baseline
- Fast switching (<1s) is possible so can cancel variations on this, or longer, time scales.
- Must know frequency of interest beforehand.
- Must have baseline stability between on and off.
- Freq-switching may not be able to eliminate standing patterns in the case of occluded apertures or strong continuum sources.



In-band Frequency Switching

- Very efficient method of observing.

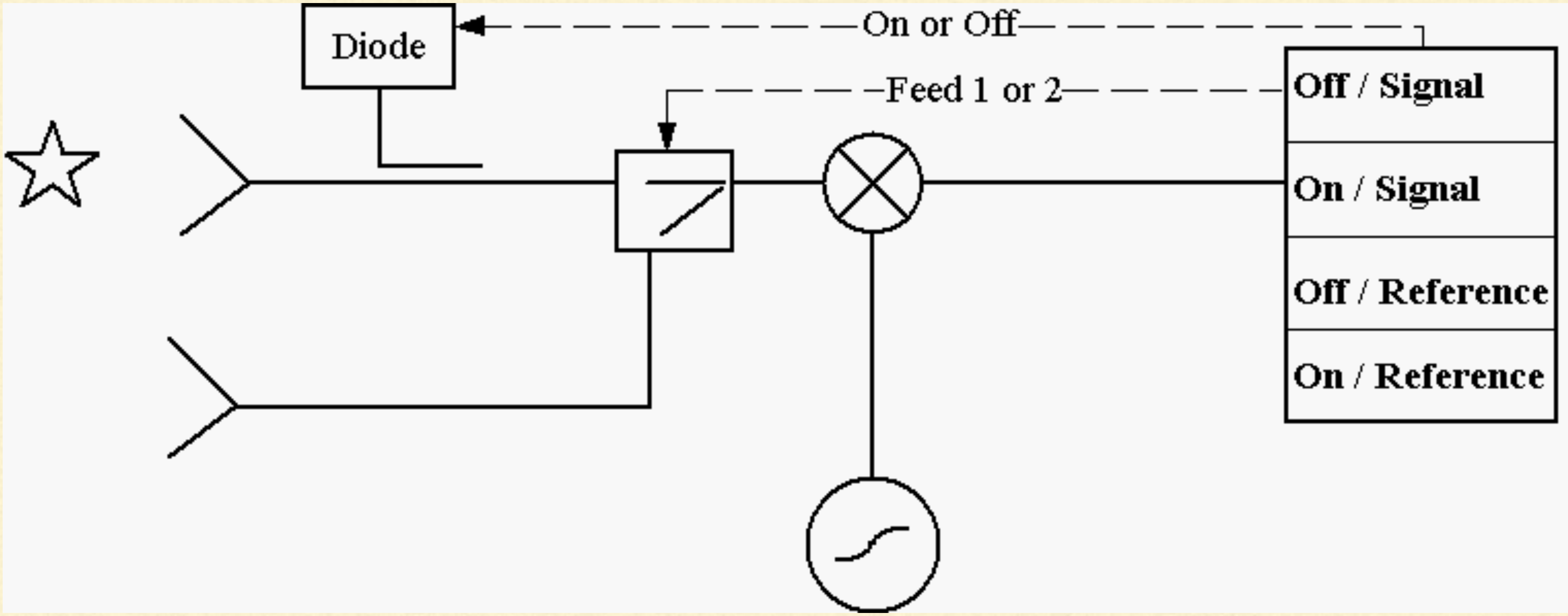


$o_1 - o_2$

Shift and average
Gain $\sqrt{2}$ in SNR

$o_2 - o_1$

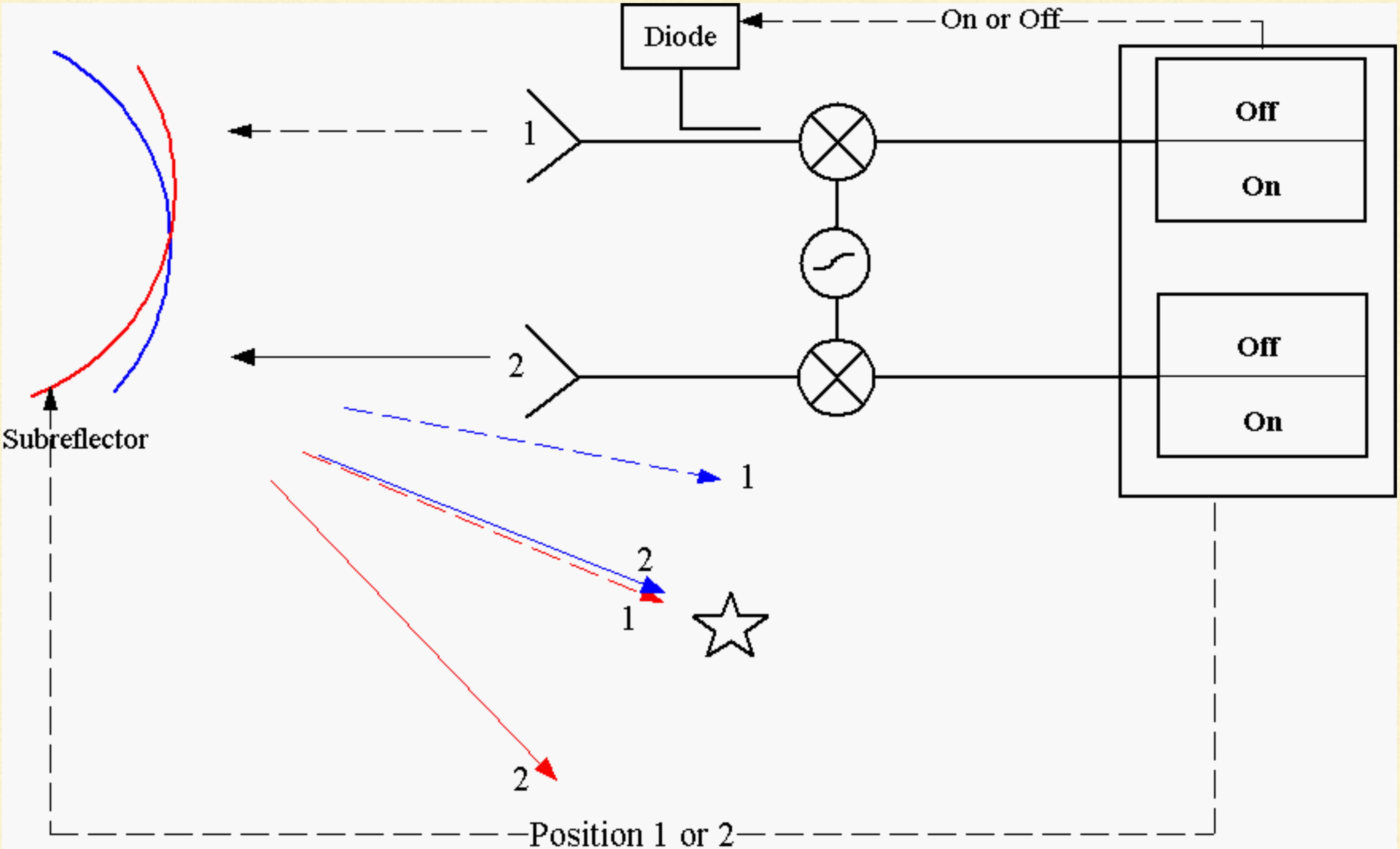
Beam Switching - Internal 'Dicke Switching'



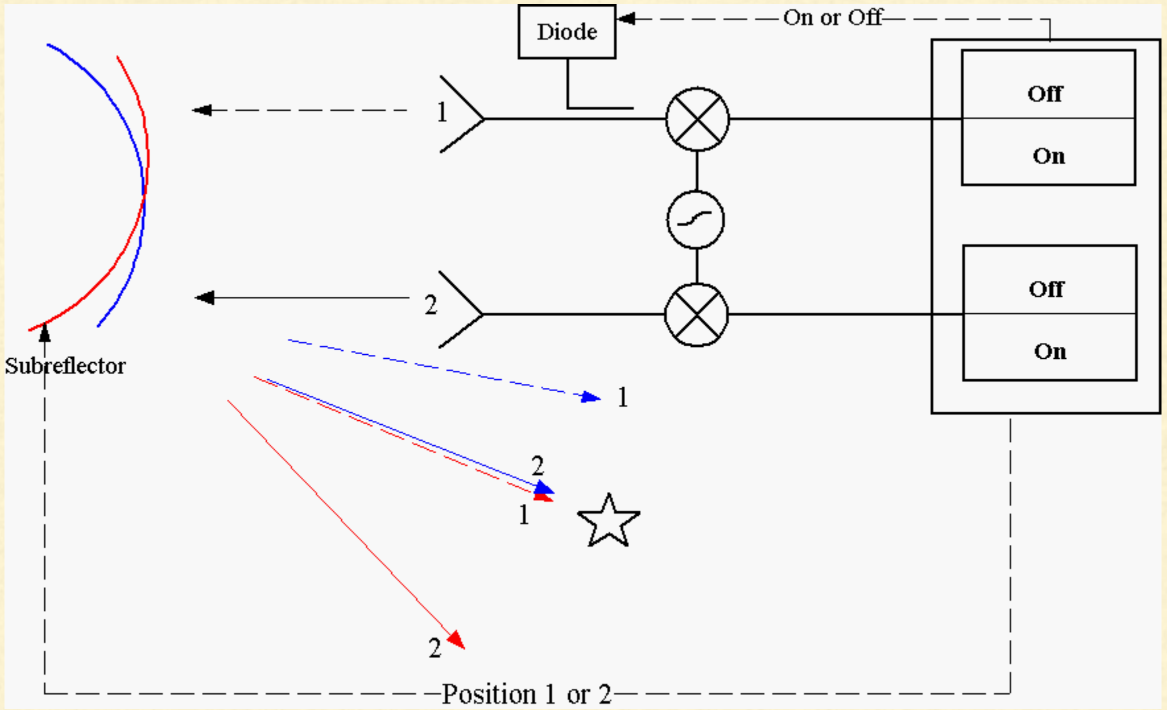
Advantages include:

- Stationary telescope
- Difference spectra eliminate post-switch contributions to bandpass
- Low overhead BUT 1/2 time spent off-source

Beam Switching/Nodding



Beam Switching/Nodding



Advantages include:

- Stationary telescope (technically)
- Removes 'fast' bandpass changes
- Low overhead AND all time spent on-source

Potential for confusion between 'nodding' and 'chopping'

- 'Nodding' usually refers to moving the telescope to alternate between beams
  - ~ at the GBT we also 'sub-beam nod' which does the same thing using the subreflector rather than the telescope
- At higher frequencies (using a mirror) a sub-beam nod would be called a chop

Chopping, beam-switching and nodding may all be combined

Actual Calibration

$$T_{src} = T_{on} - T_{off}$$

- Requires good absolute calibration

$$\frac{T_{src}}{T_{off}} = \frac{[T_{on} - T_{off}]}{T_{off}}$$

- Use relative scale, so

$$T_{src} = \frac{[T_{on} - T_{off}]}{T_{off}} \times T_{off}$$

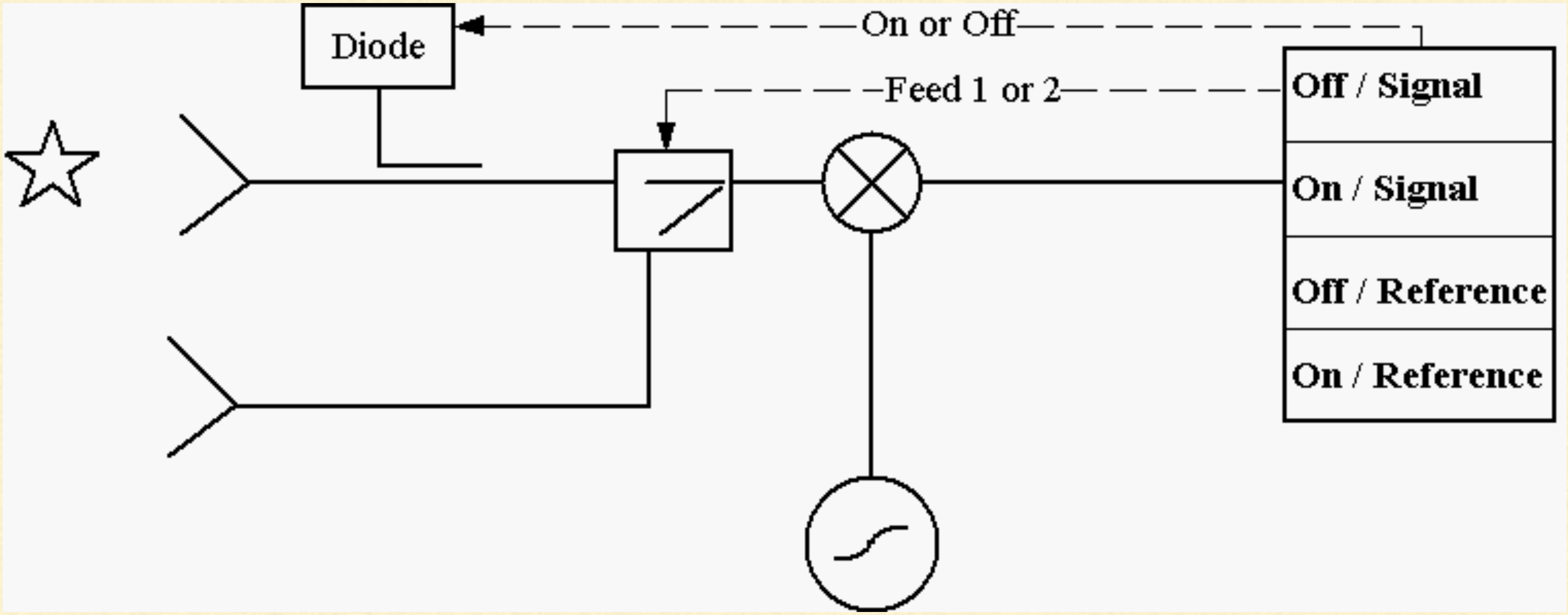
- Now go back to try and define $T_{everythingelse}$ and things become telescope-specific

So $T_A = \frac{[T_{on} - T_{off}]}{T_{off}} \times T_{sys}$

- This is the GBT definition of T_A

Finding T_{sys}

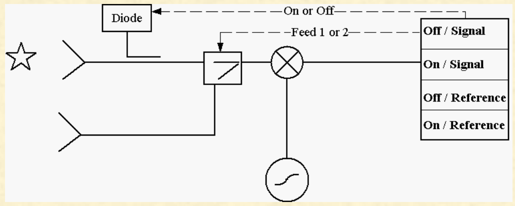
Noise Diodes



- Nearly all GBT receivers use noise diodes (exceptions are high-frequency)

Finding T_{sys}

Noise Diodes



- A noise diode with known effective temperature (at given frequency) is coupled to the telescope system. Then measure blank sky temperature with diode on (OnCal) and diode off (OffCal)
- Then

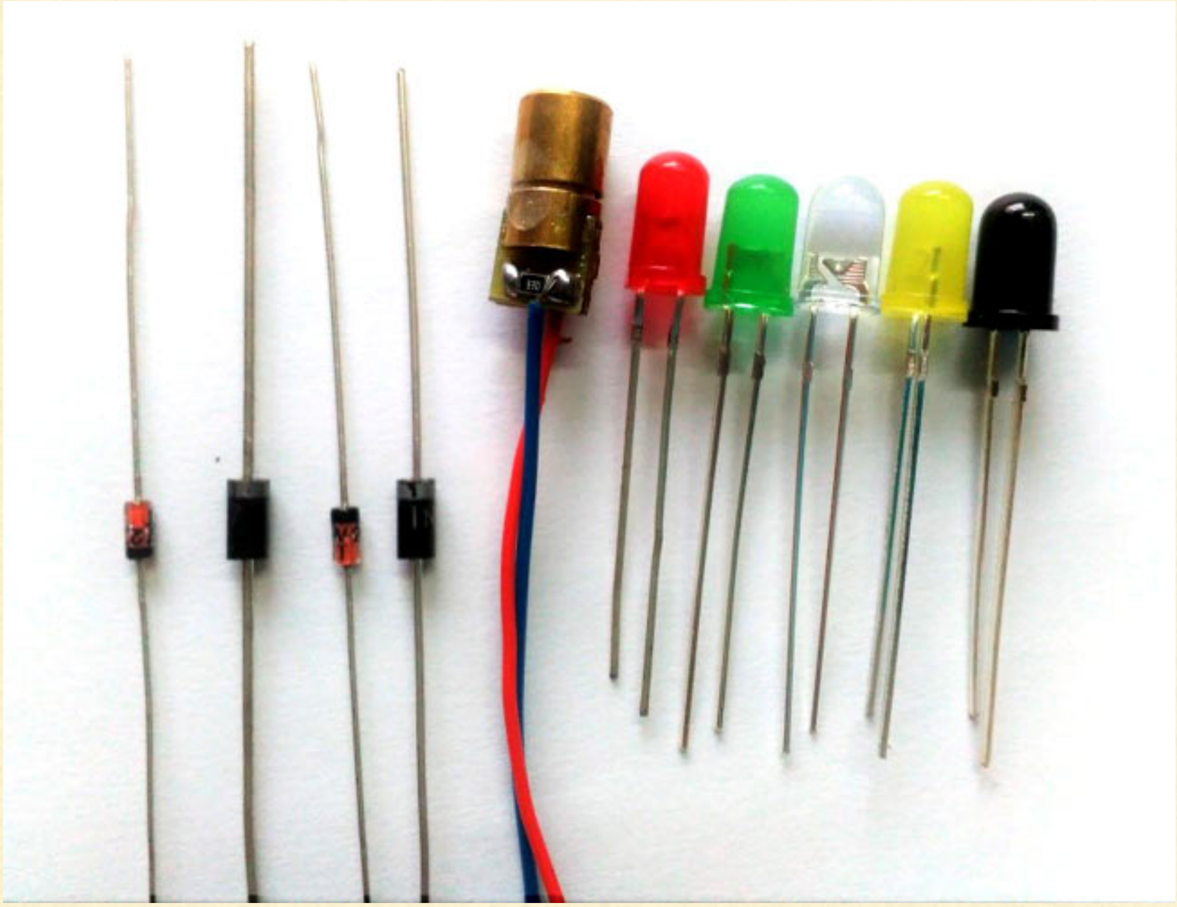
$$OnCal = T_{sys} + T_{cal} \;\&\; OffCal = T_{sys}$$, or

$$\frac{T_{off}}{T_{cal}} = \frac{OffCal}{(OnCal - OffCal))}$$

$$\Longrightarrow \quad T_{off}(K) = T_{sys} = \frac{OffCal}{(OnCal - OffCal)} \times T_{cal}(K)$$

Noise Diodes

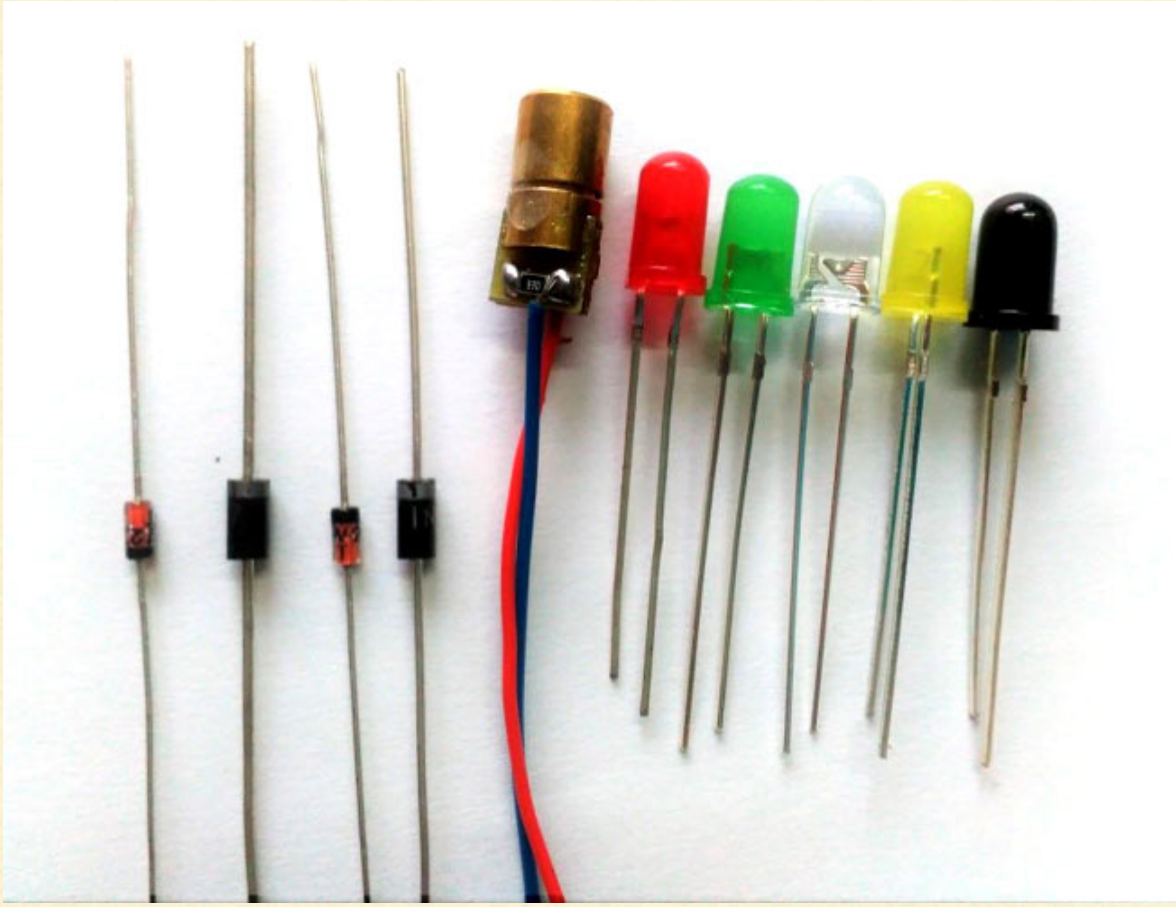
- The effective temperature of noise diodes is frequency dependent, although the shape of the function can normally be determined.



- Diodes don't remain stable over long timescales, should be checked at least bi-annually.
- Diodes often good to ~2%

Noise Diodes

- Diode temperature values are often bootstrapped from other diodes. There are measurement errors inherent to this process, particularly as it's usually actually a voltage which is measured.



- Can use two diodes to eliminate antenna properties through $Y = \frac{T_1 + T_{off}}{T_2 + T_{off}}$ can then get $T_{off} = \frac{T_1 - YT_2}{Y - 1}$

Noise Diodes

At the GBT we flicker the diode on and off

$$T_{sys} = \frac{OffCal}{OnCal - OffCal} \times T_{cal}(K) + \frac{T_{cal}}{2}$$

Hot and Cold loads

Usually physical objects of a known temperature placed in front of the telescope beam

These might be as simple as blank sky for a cold load or foam at ambient temperature for a hot load

More precise calibration can be obtained with more precisely known temperatures (canisters of liquid nitrogen/heated paddles)

Calibration achieved through same method as noise diodes

Can be superior to diodes as temperatures are easier to measure and have no conversion errors (from voltage)

Hot and Cold loads

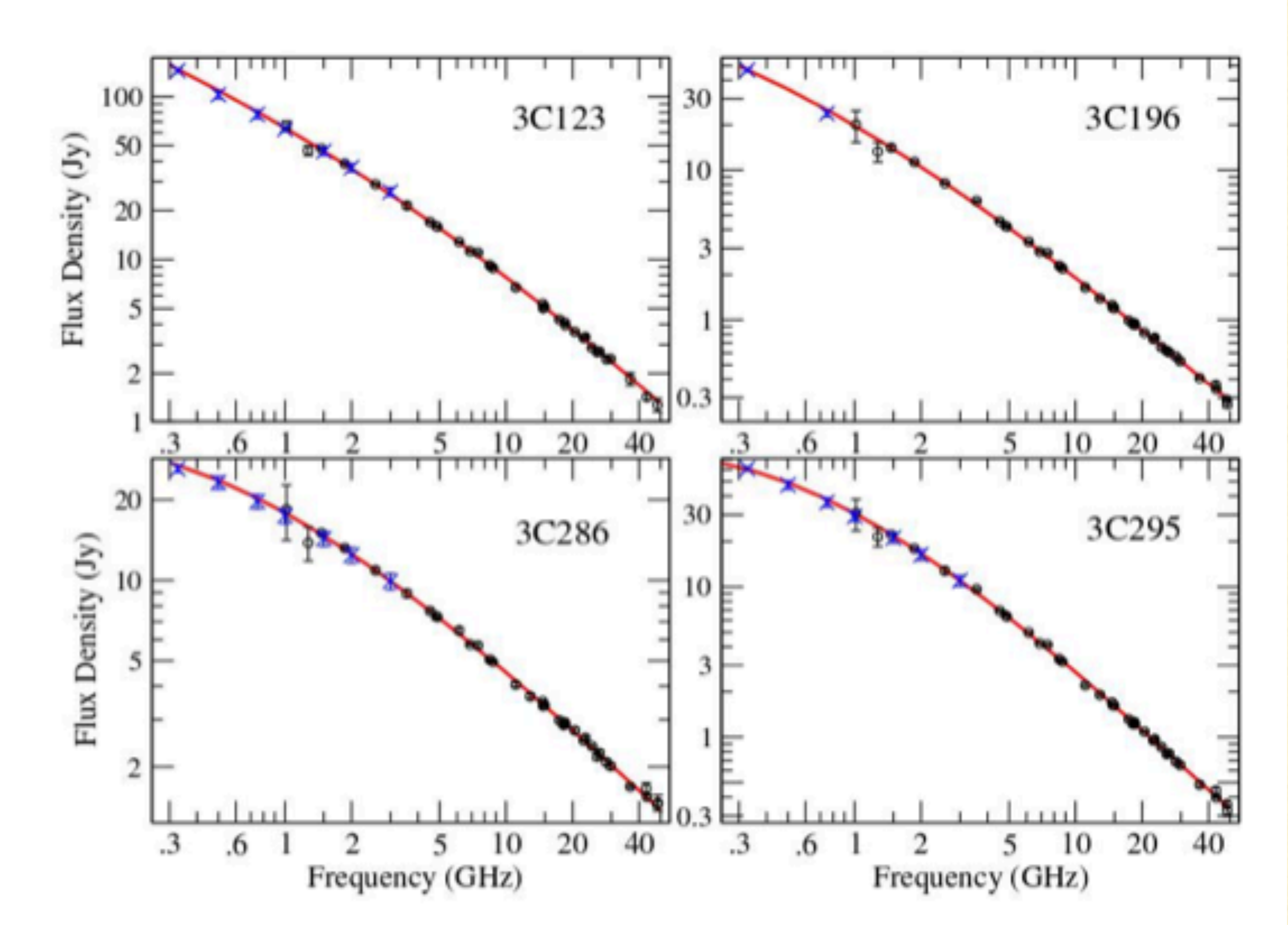
At $\lambda > 5/6$ cm feeds tend to be too large to easily allow for a 'paddle' which can be quickly and easily put in and out of the beam on-the-fly.

Hot and cold loads are used at Green Bank for occasional tests, including checking the noise diode values

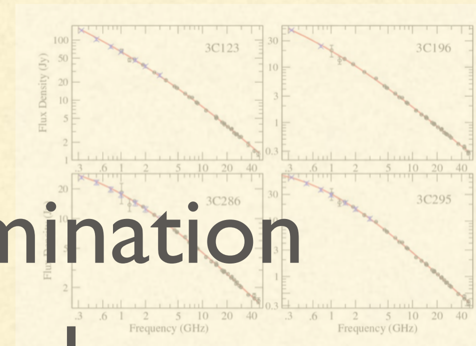
Calibration from known sources

VLA Stable Calibrators

These are good at
1- 50 GHz
ALMA sources used
above 50 GHz



Calibration from known sources

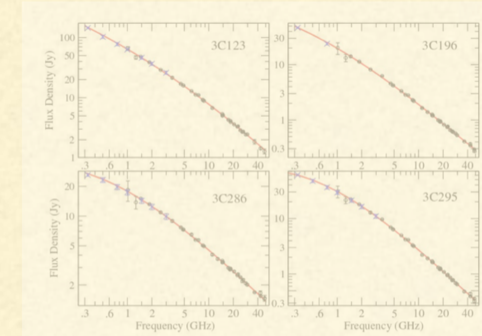


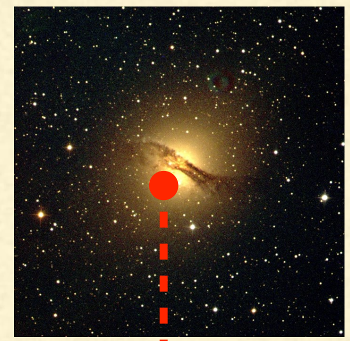
There may be many reasons why a theoretical determination of a telescope's gain (input/output ratio) is complicated.

Large or complicated blockage of the aperture, uncertain electronics setup, uneven reflection from the ground.

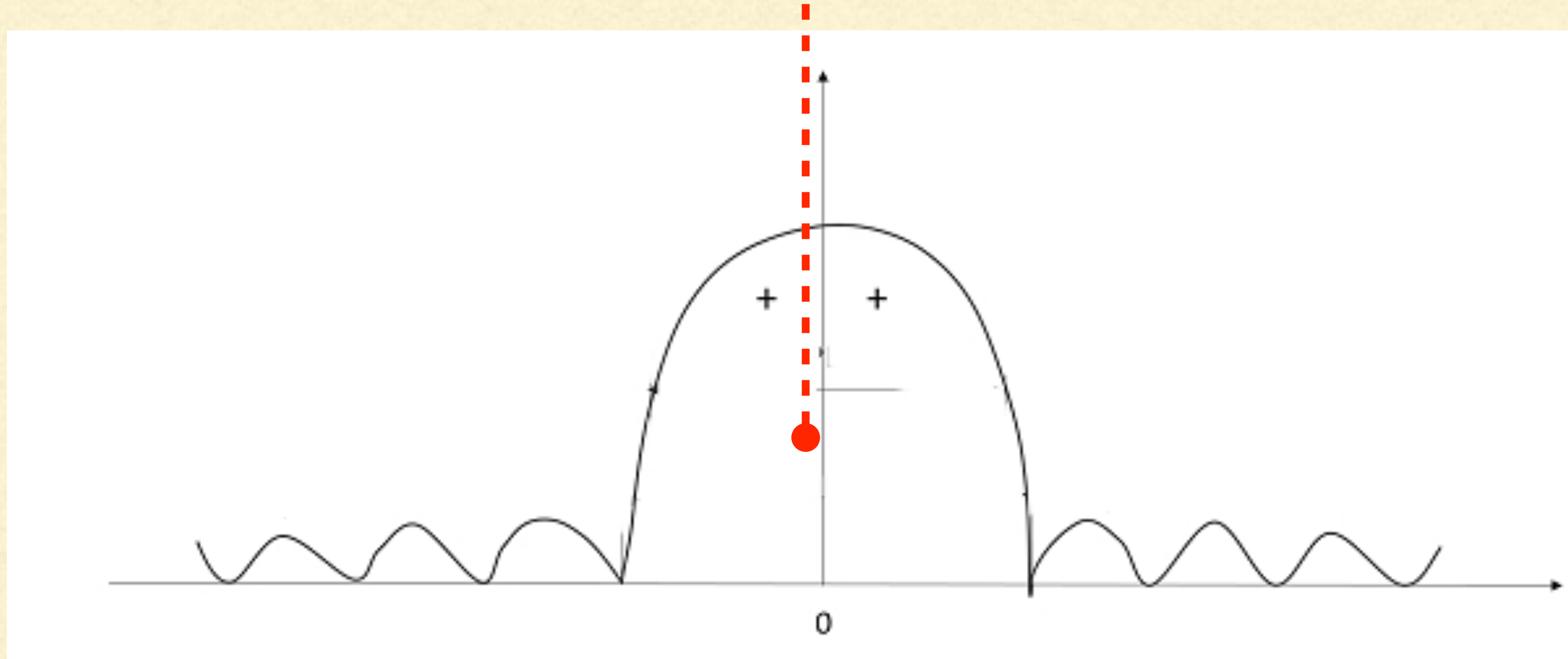
Bootstrapping from a known source can solve this issue

Calibration from known sources



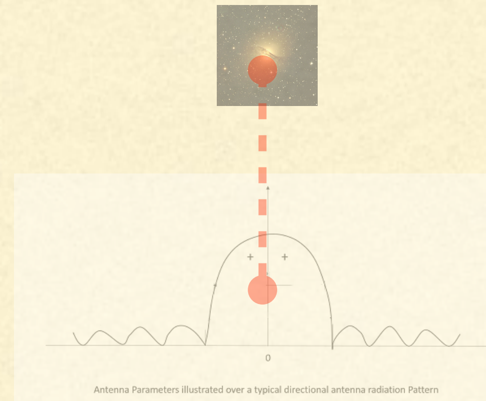


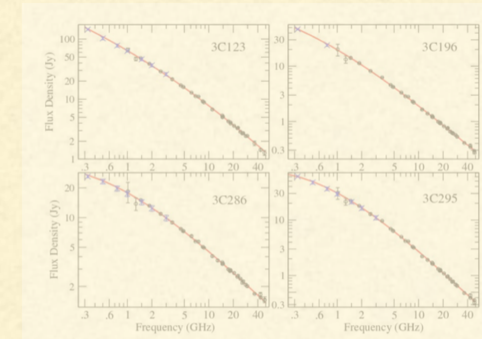
Source size relative to beam is important



Antenna Parameters illustrated over a typical directional antenna radiation Pattern

Calibration from known sources

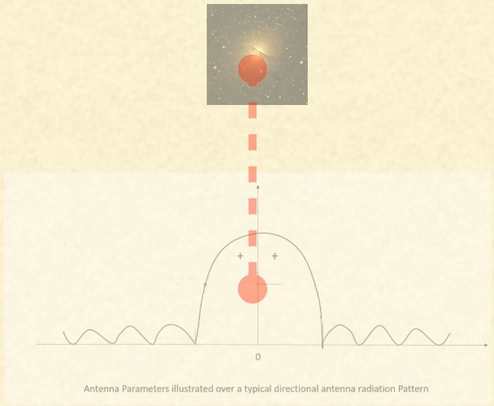


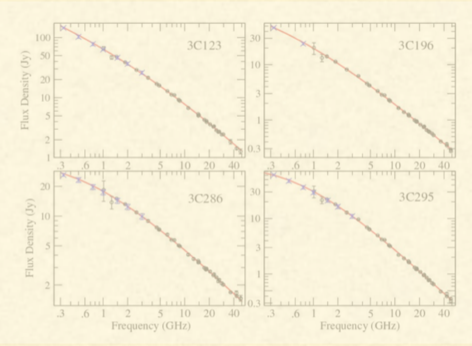


Source size relative to beam is important

- If source is $> \dfrac{1}{10}$ beam size at chosen frequency then beam shape and spillover become important
- Need a strong source for high SNR but not so strong that baseline ripples are introduced
- Source should be non-variable with a well-determined flux at frequency of interest

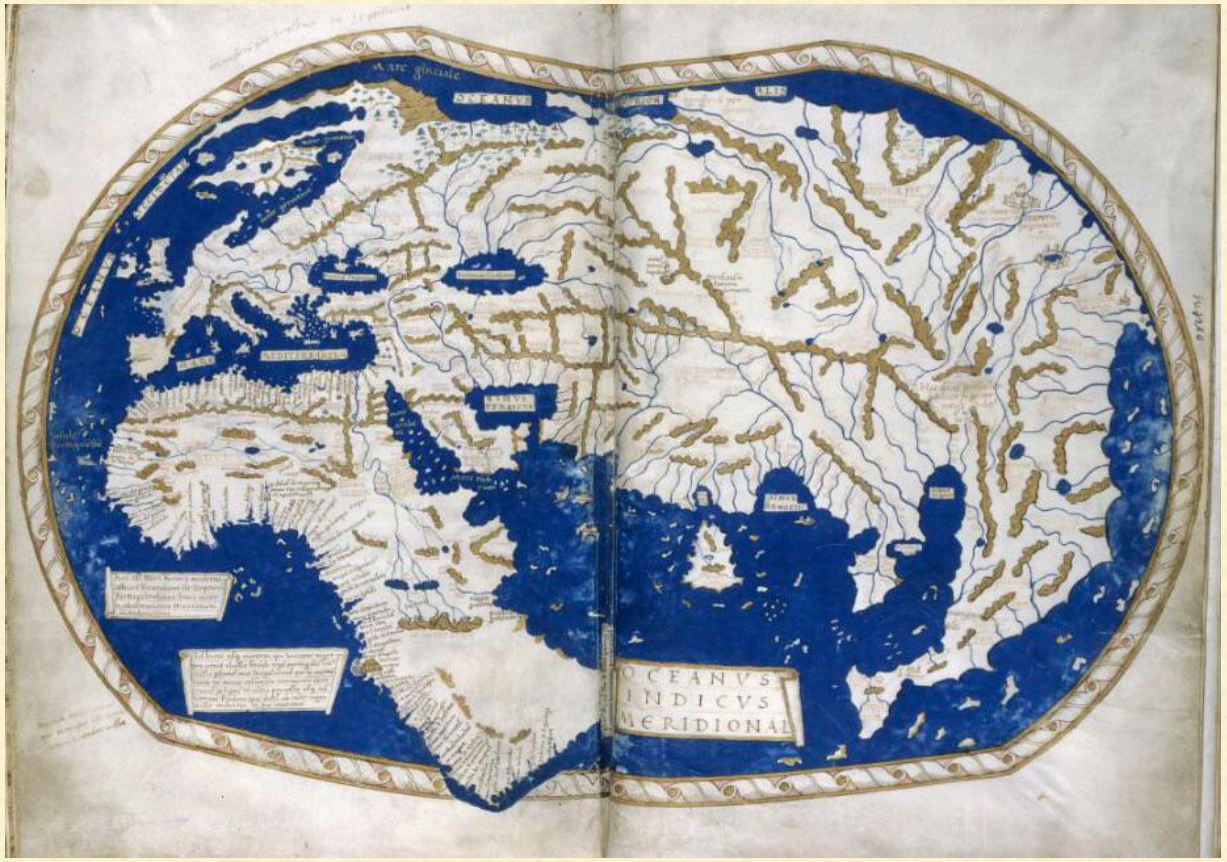
Calibration from known sources

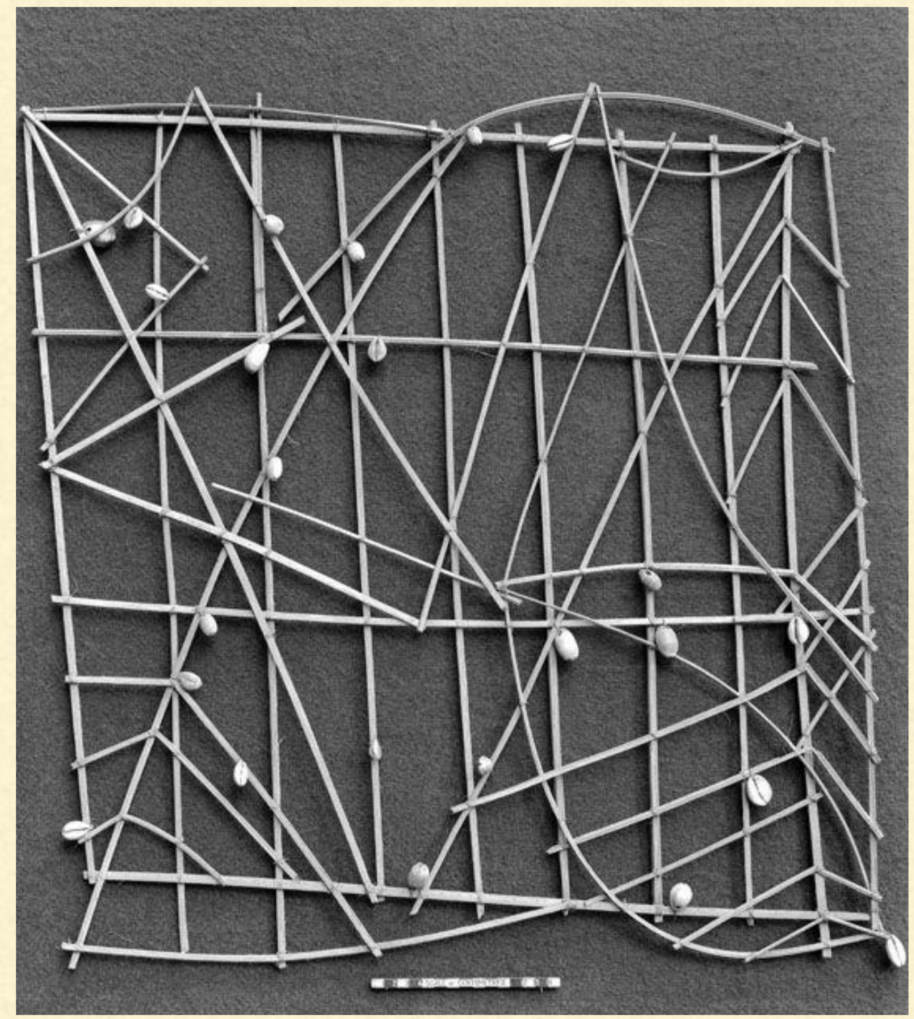




- Errors in source flux densities dominate all other sources of error in telescope gain, thus reducing the error gives a linear reduction in gain error
- Observing many sources at many positions can give good estimates of telescope gain
- If telescope gain is a significant function of sky position (through atmospheric or illumination/blockage changes, i.e. Arecibo), the amount of time taken to get good bootstrap calibration will exceed all other time requirements

Mapping





Mapping

Nyquist Sampling

Nyquist sampling defines the minimum number of discrete samples required to capture all of the information from a continuous distribution

In simple terms this corresponds to a pixel spacing of at least $\frac{\lambda}{2D}$ radians,

More often, $0.9\frac{\lambda}{2D}$

Mapping

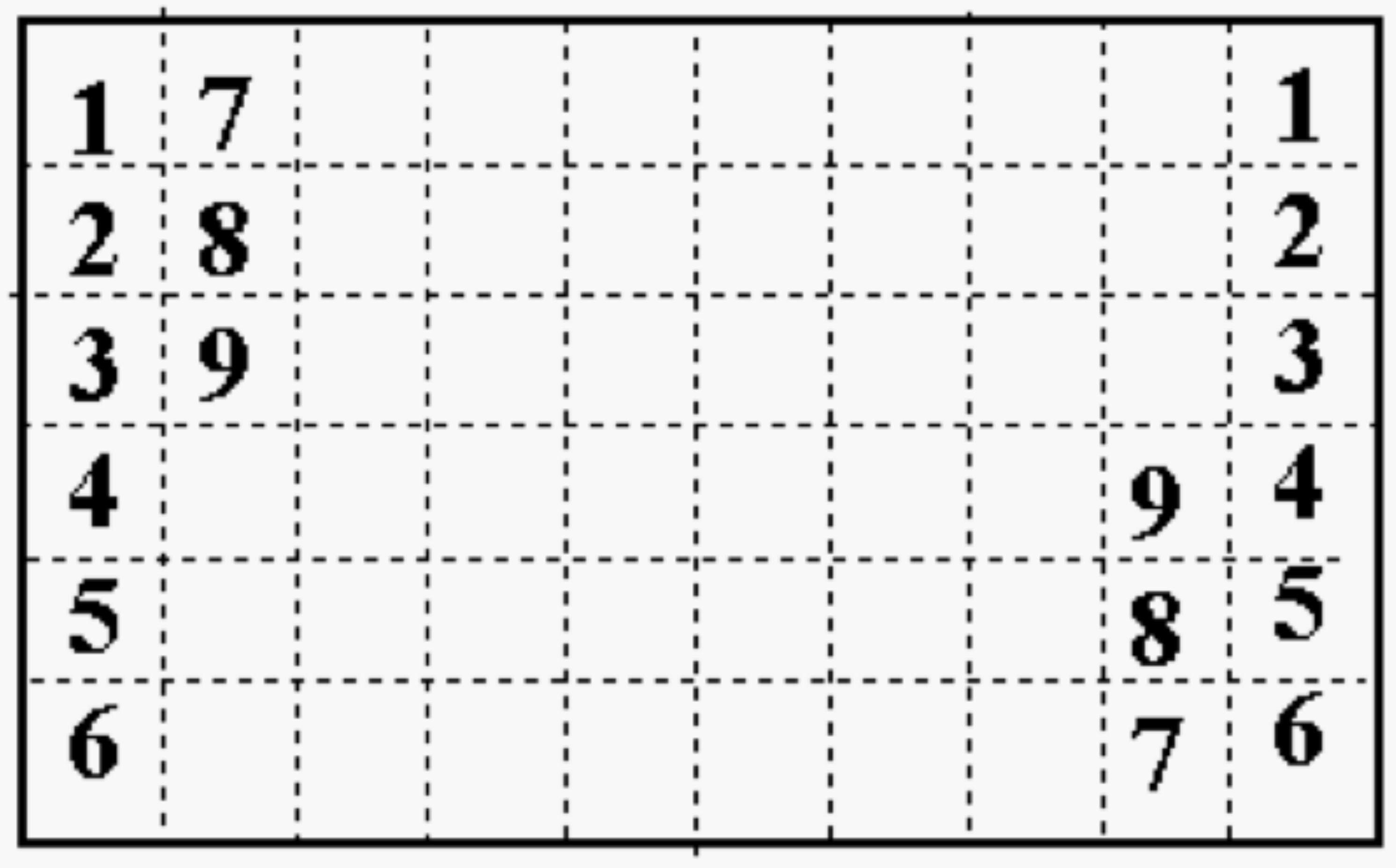
Nyquist Sampling

Undersampling hurts you twice, firstly you will lose the spatial information present in the dish baselines you are missing (e.g. if you use 90m rather than 100m for the diameter of the GBT), secondly, those spatial frequencies will be reflected back onto the outer baselines and potentially corrupt them, meaning that data from 80m-90m is now suspect (see Mangum, Emerson and Greisen, 2007)

The problem is even worse when considering how often you need to sample in time but wait…

Mapping

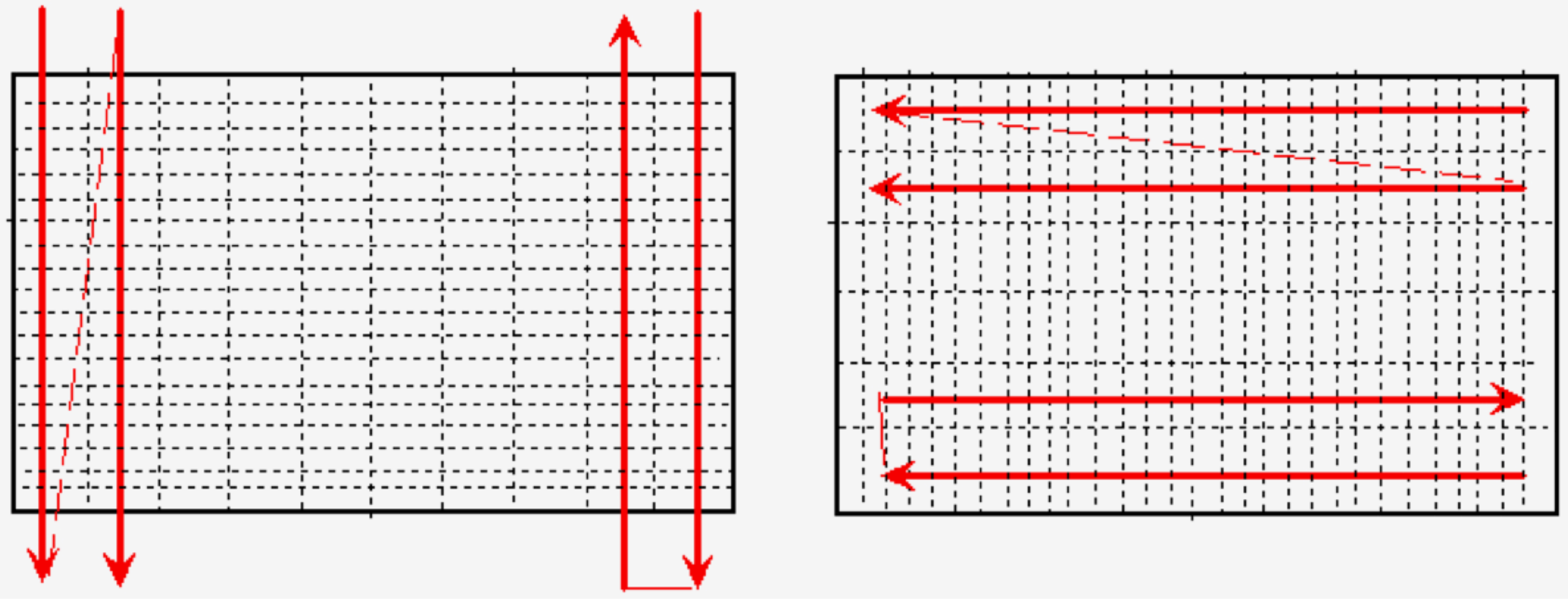
Point Maps



Observe, move, sit, repeat
Keeps things simple but beware of settle times, overheads.
For all types of maps, ensure that time taken to complete map is less than timescale for gain/baseline stability

Mapping

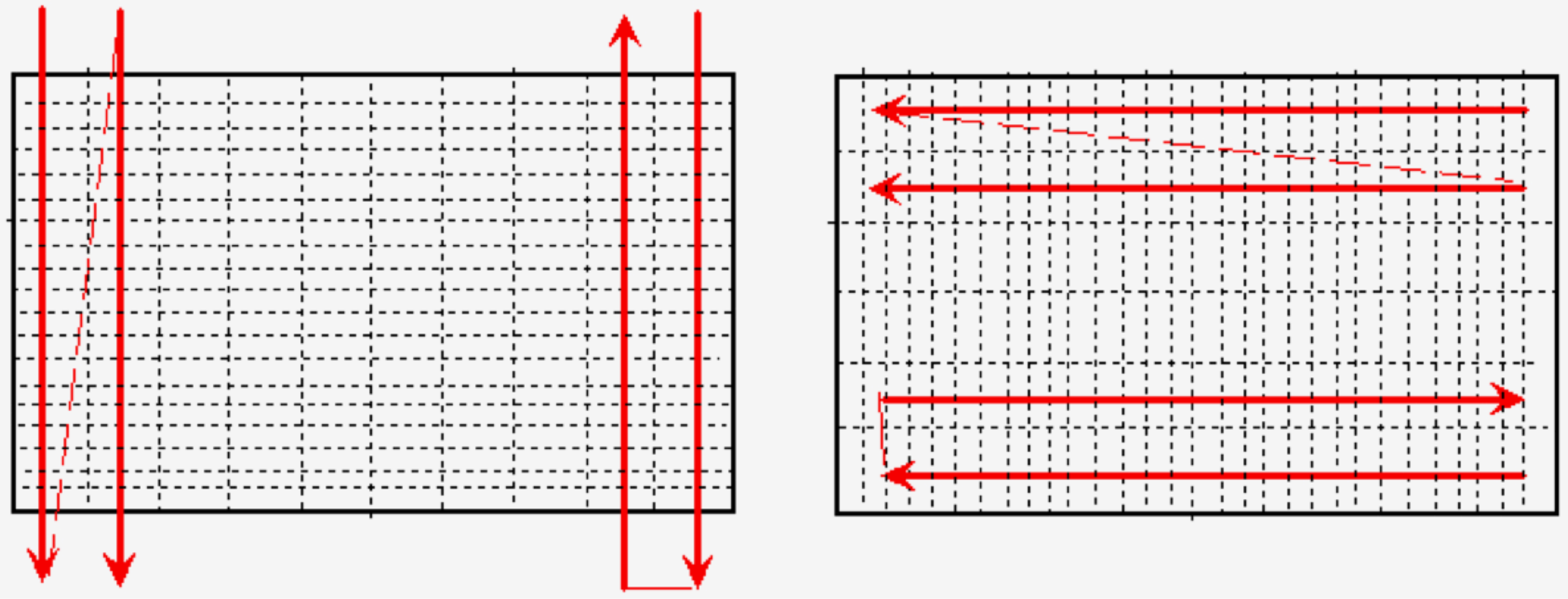
On-The-Fly (OTF) Maps



Slew telescope across sky while collecting data, now necessary to incorporate sampling rate in Nyquist consideration. Due to digitization of signal telescope beam is effectively broadened

Mapping

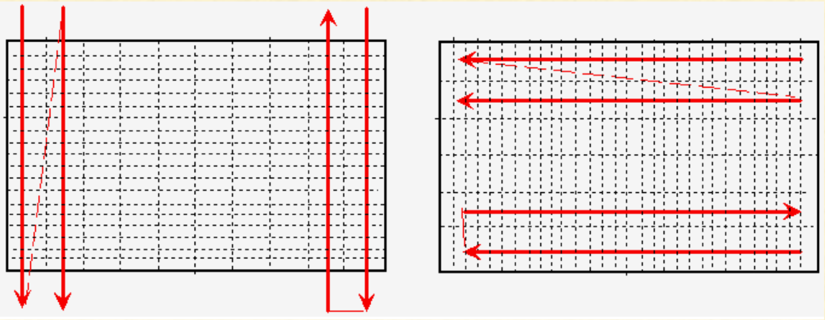
On-The-Fly (OTF) Maps



Using an arbitrary limiting value of 1% for effects of beam broadening and to avoid loss of SNR we need to sample at 2 x Nyquist, or ~5 points per FWHM

Mapping

On-The-Fly (OTF) Maps



It's good to perform short maps and 'stack' them, especially at high frequencies

This is to ensure that sky conditions are relatively stable over the duration of the map. You probably don't want to go too long without pointing/focussing and stopping/starting a map halfway through is likely to introduce artifacts, due to changes in the sky and/or instrumentation

Mapping

Some nuance

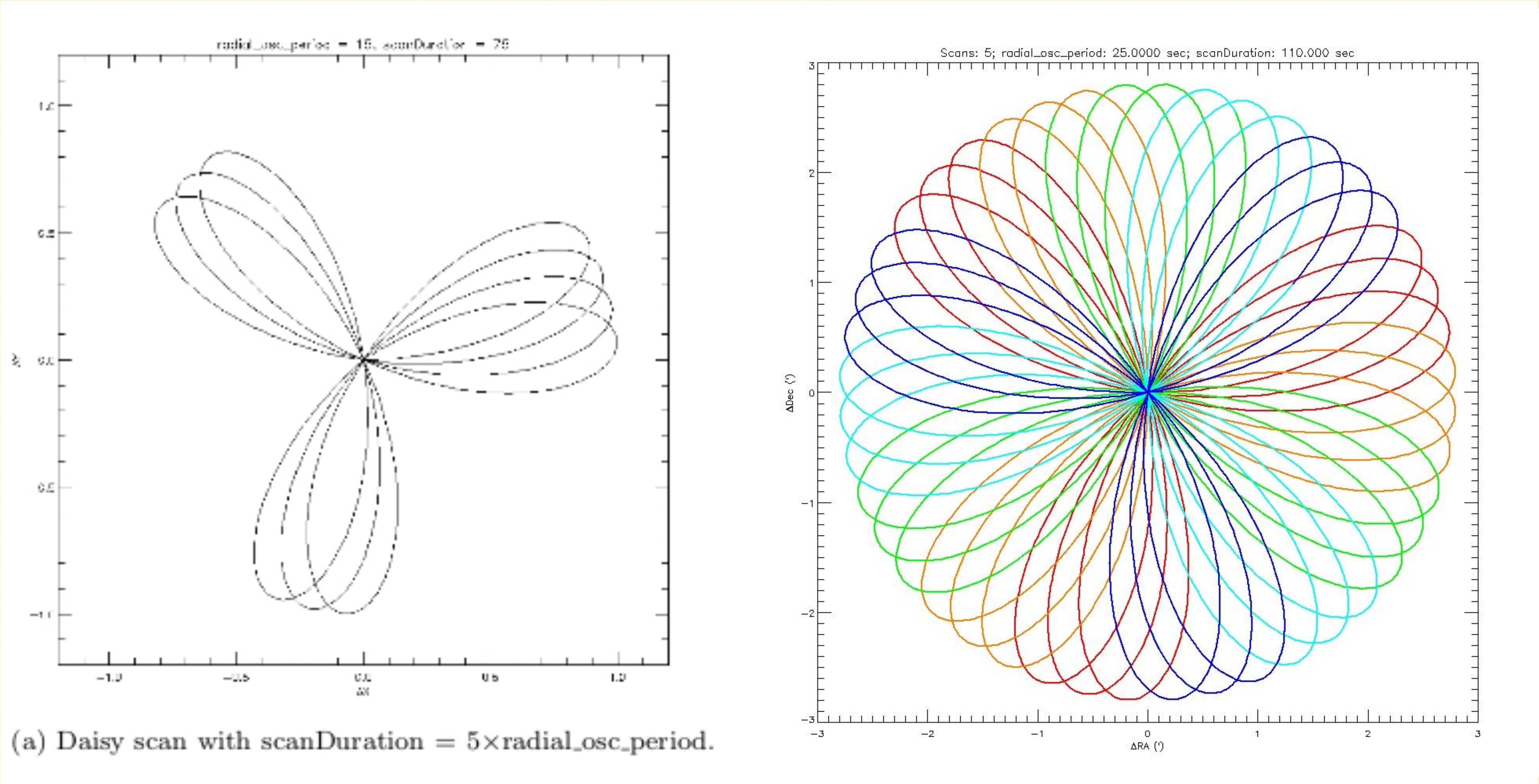
- For the same reasons, it's a good idea to perform maps consisting of Right Ascension stripes and Declination stripes, alternating between the two. This is called 'basket-weaving'

- Utilise 'boustrophedon' mapping to save on overheads also, with pointing, the less distance you move the better

Mapping

<u>Daisy Mapping</u>

- Useful for multi-beam arrays (in order to fully sample mapped region)
- Best for smaller regions (6’)

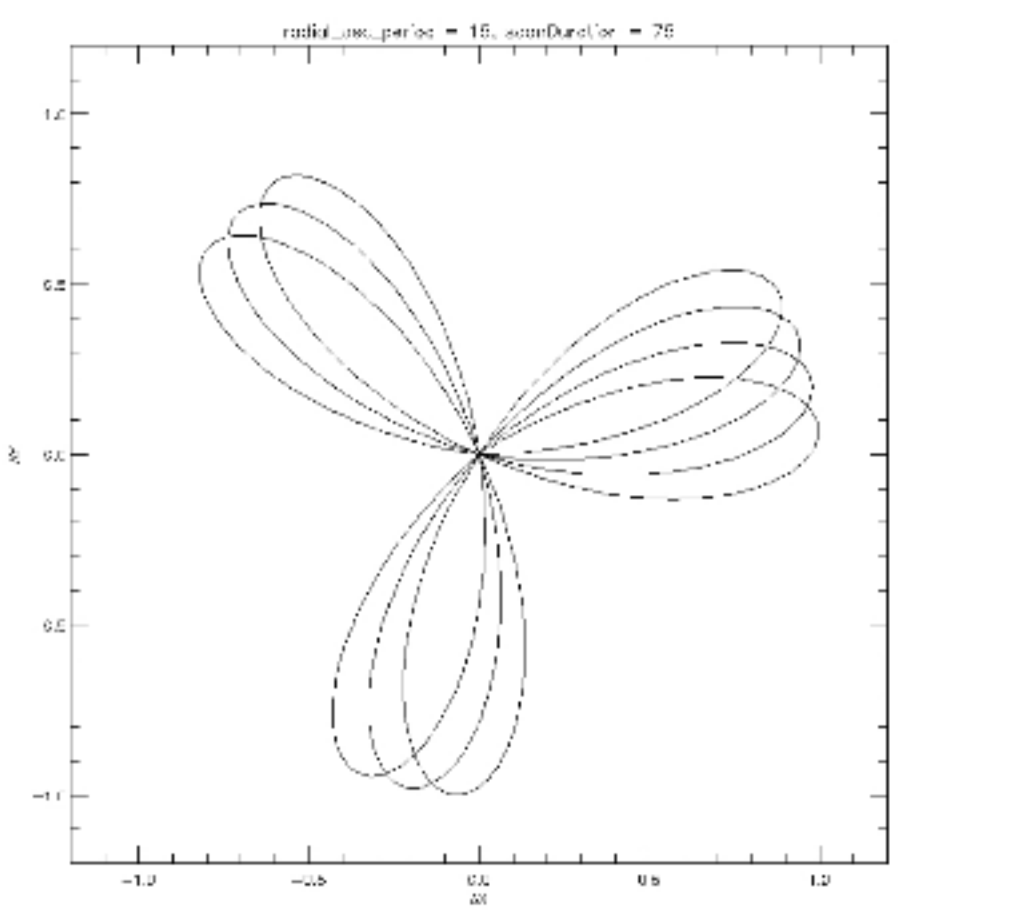


(a) Daisy scan with scanDuration = 5×radial_osc_period.

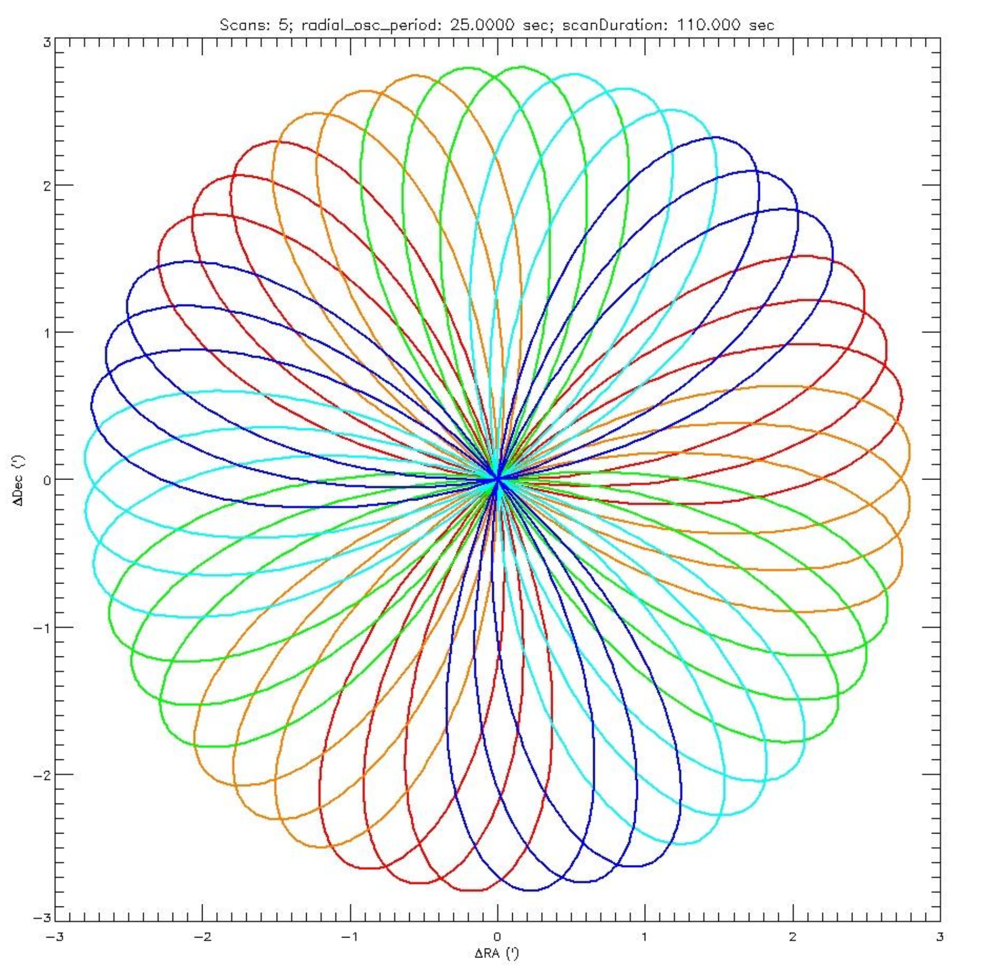
Mapping

Daisy Mapping

- Can be time-consuming to calculate trajectories, many points (i.e. short sampling time) can increase overhead
- Rule of thumb is 10-20 FWHM for map size, < 15 minutes



(a) Daisy scan with scanDuration = 5×radial_osc_period.




Thank you for listening