Observing Techniques

Will Armentrout
With much help from David Frayer & Larry Morgan

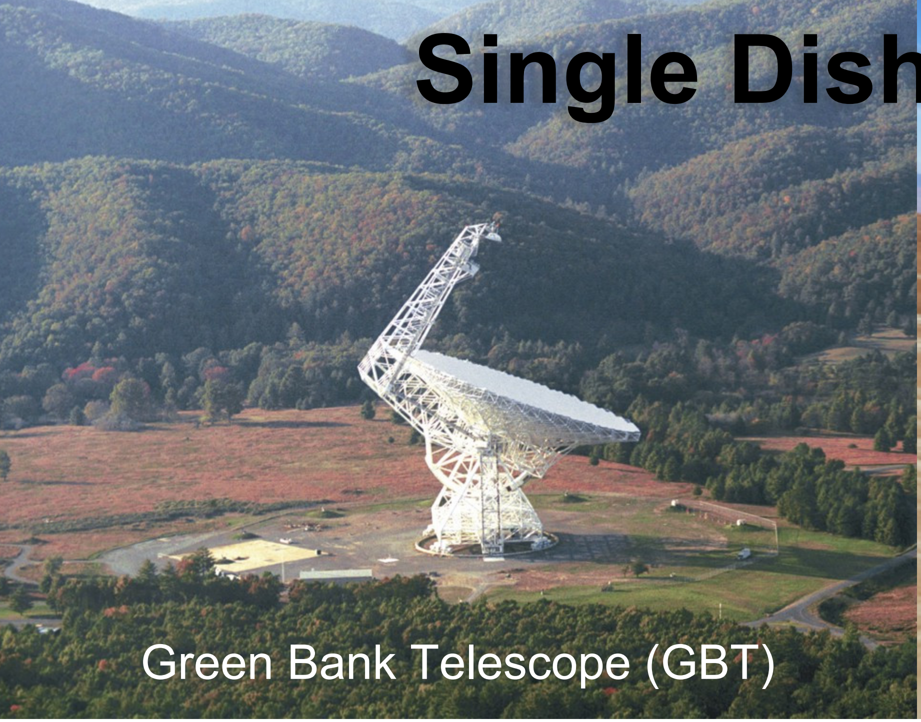
Planning an Observation

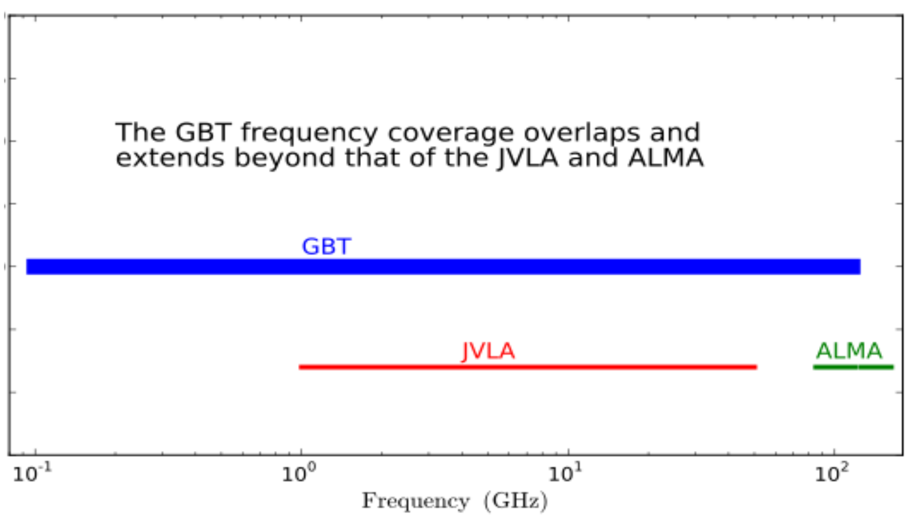
- What is your science goal?
- Decide what you want to observe
  - Select Target
  - Decide on Frequency / Wavelength
- Spectral line? Continuum? Time variable?
- Pick a telescope and receiver
- Do you want to make a map or single pointing?
- How do you want to calibrate your data?

Planning an Observation

- What is your science goal?
- Decide what you want to observe
  - Select Target
  - Decide on Frequency / Wavelength
- Spectral line? Continuum? Time variable?
- Pick a telescope and receiver
- Do you want to make a map or single pointing?
- How do you want to calibrate your data?

Single Dishes and Arrays





Choose Your Adventure

- Types of Radio Observations
  - Spectral Line
  - Continuum
  - Pulsar / FRB (Transient)
- Types of Radio Receivers
  - Feed Horns
  - Bolometers
- Observation Strategies
  - Track
  - Map

+ Calibration!

Choose Your Adventure

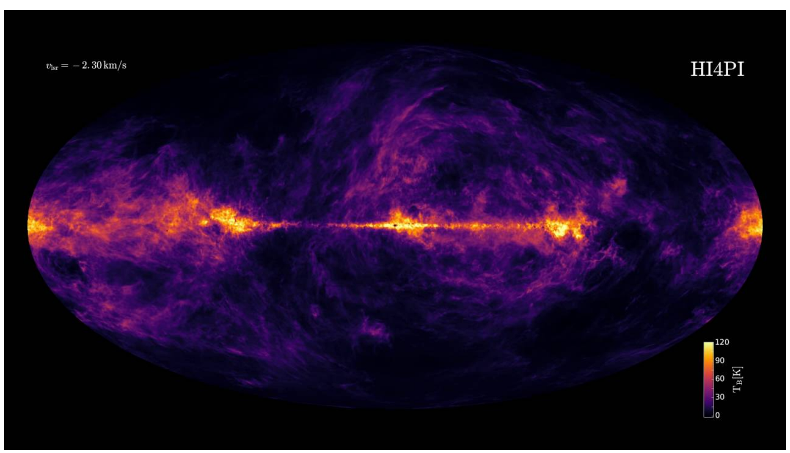
- Types of Radio Observations
  - Spectral Line
  - Continuum
  - Pulsar / FRB (Transient)
- Types of Radio Receivers
  - Feed Horns
  - Bolometers
- Observation Strategies
  - Track
  - Map

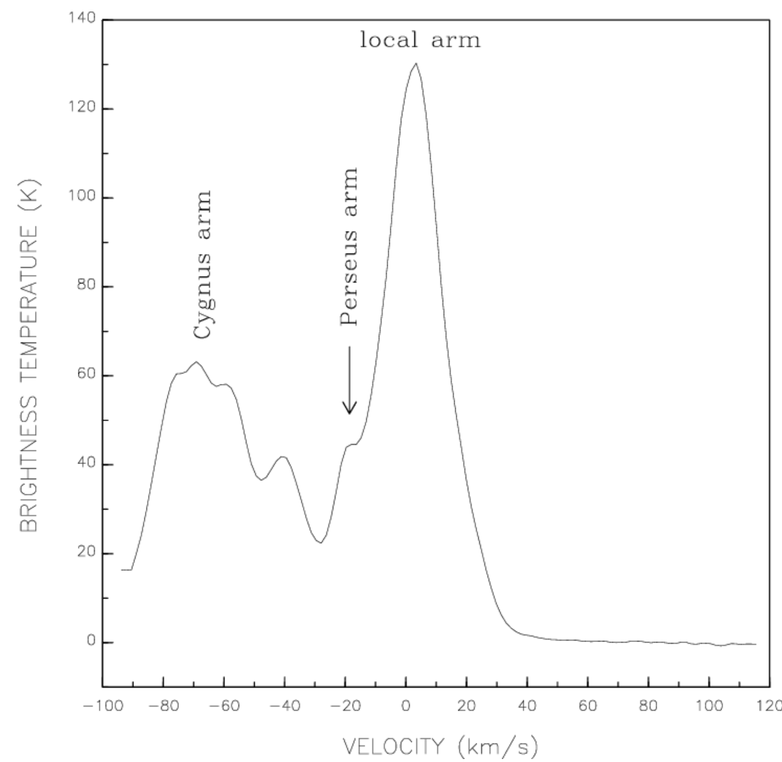
+ Calibration!

Spectral Lines

- Spectral features at specific frequencies from molecular or atomic transitions
  - These can be red or blue-shifted based on the source velocity

- Examples
  - Carbon Monoxide (115 GHz)
  - Neutral Hydrogen (1.421 GHz, shown)

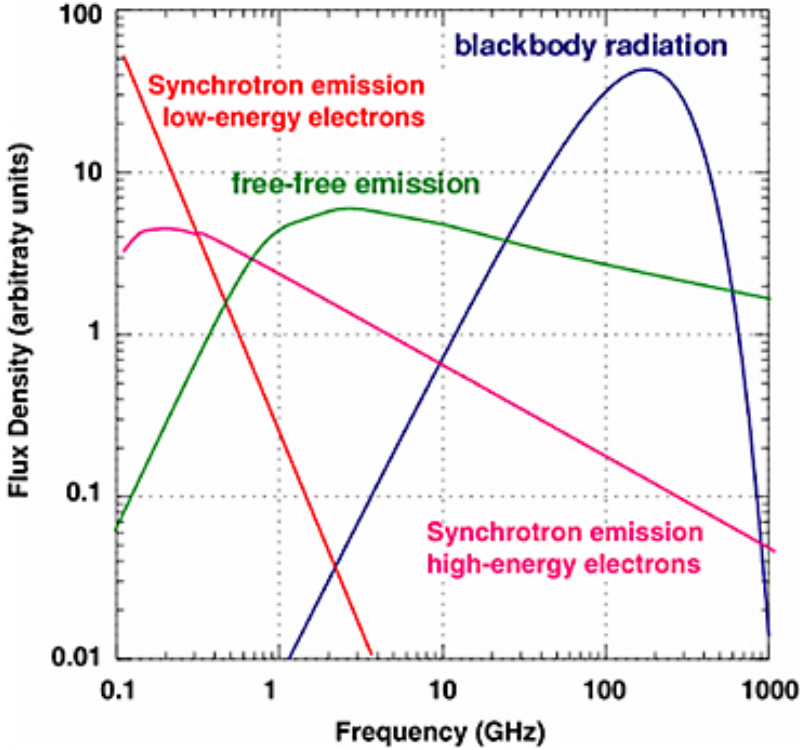




Continuum Emission

- Broadband emission from a "continuum" of energies
  - Not specific frequencies
  - You could think of this as the "total brightness" of an object

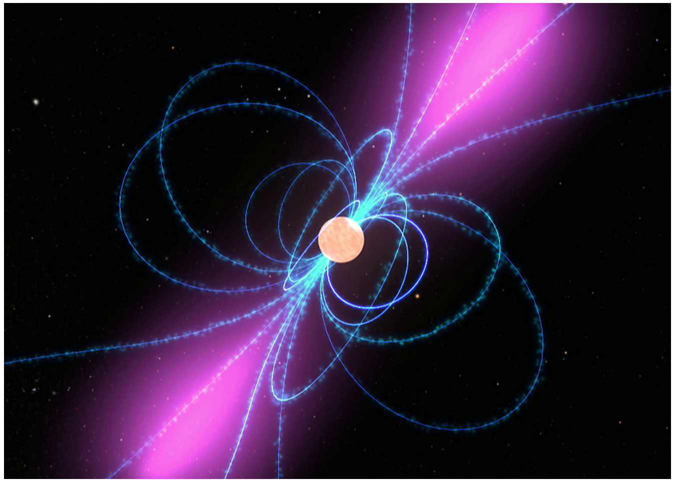
- Examples
  - Free-Free Emission
    - Electrons accelerating around ions
  - Synchrotron
    - Ions spinning around magnetic field lines



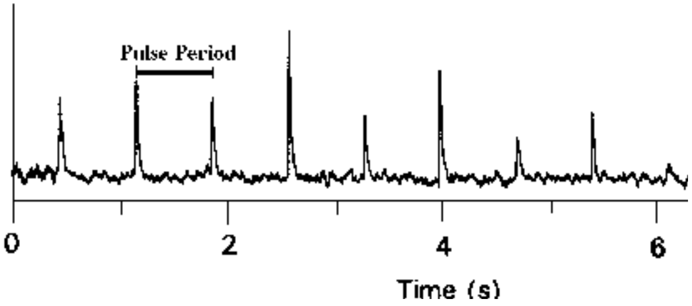
Time Variable / Transients

- Examples
  - Pulsars
  - Fast Radio Bursts

- What's important here?
  - Saving data very quickly (millisecond)
  - Time stamps on data
  - Ideally, wide bandwidth
    - See "pulse shape" across many frequencies



Pulsar Schematic (above),
Pulsar Plot (below)



Choose Your Adventure

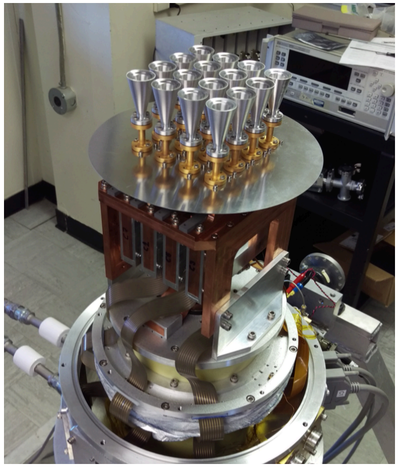
- Types of Radio Observations
  - Spectral Line
  - Continuum
  - Pulsar / FRB (Transient)
- Types of Radio Receivers
  - Feed Horns
  - Bolometers
- Observation Strategies
  - Track
  - Map

+ Calibration!

Types of Radio Receivers

- Feed Horns *(think: spectrometer)*
  - Spectral Lines
    - Individual atomic / molecular transitions
  - Pulsars / Fast Radio Bursts
    - Transient Events
  - Continuum
    - "Total brightness" of a region

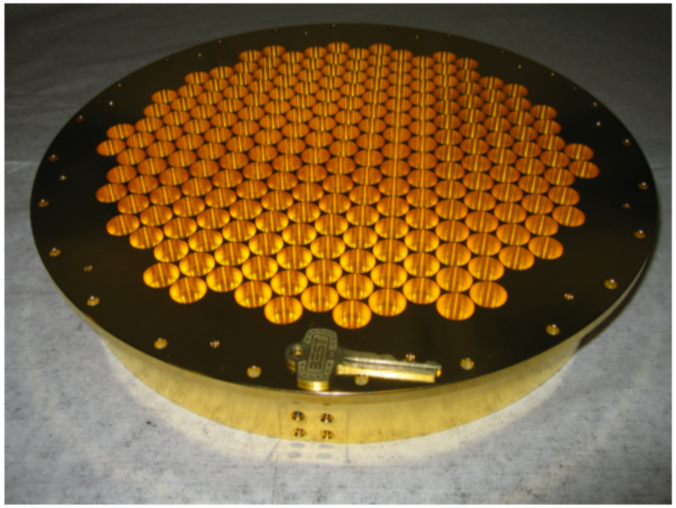
- Single or multi-pixel



GBT Argus Array (above),
GB Calibration Horn (below)

Types of Radio Receivers

- Bolometers
  - Continuum (Total Power)
  - Good for :
    - Ionized Gas
    - Synchrotron Emission
    - Dust



MUSTANG-2 Bolometer on the GBT

How do bolometers work? Photon hits detector, increases temperature, temperature change is read off as a voltage.

Choose Your Adventure

- Types of Radio Observations
  - Spectral Line
  - Continuum
  - Pulsar / FRB (Transient)
- Types of Radio Receivers
  - Feed Horns
  - Bolometers
- Observation Strategies
  - Track
  - Map

+ Calibration!

Track (Single Pointing)

- Point the telescope at your coordinates
- Slew the telescope to follow the source throughout the observation
- Noise goes down as $\sim\sqrt{time}$ and $\sim\sqrt{number\ of\ samples}$

Thermal noise ΔT

= minimum detectable signal

$$\Delta T = k_1 \frac{T_{sys}}{\sqrt{\Delta\nu \cdot t_{\text{int}}}}$$

The Radiometer Equation

Screenshot of equation from Frank Ghigo's previous talk.

Track (Single Pointing)

- Point the telescope at your coordinates
- Slew the telescope to follow the source throughout the observation
- Noise goes down as $\sim\sqrt{time}$ and $\sim\sqrt{number\ of\ samples}$

Exercise time! Radio recombination lines (RRLs) come from areas of ionized gas, the hallmark of HII Regions (high-mass star forming regions). These RRLs can be "stacked" with adjacent lines to give you better sensitivity.

If you have rms noise of 15 mK in a one minute observation with the GBT looking at one line, what would your noise be for a 6 minute observation looking at 40 lines?

Track (Single Pointing)

Exercise time! Radio recombination lines (RRLs) come from areas of ionized gas, the hallmark of HII Regions (high-mass star forming regions). These RRLs can be “stacked” with adjacent lines to give you better sensitivity.

If you have rms noise of 15 mK in a one minute observation with the GBT looking at one line, what would your noise be for a 6 minute observation looking at 40 lines?

$$final\ noise = (15\ mK) * \sqrt{\frac{1\ minute}{6\ minutes}} * \sqrt{\frac{1\ line}{40\ lines}} = 0.97\ \text{mK}$$

Track (Single Pointing)

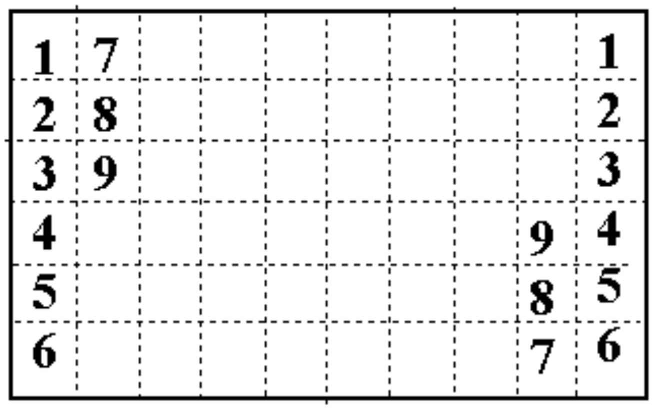
Exercise time! You can also "smooth" your data. Let's say you have a frequency resolution of 0.1 kHz, but you only need 1 kHz resolution. You can smooth by a factor of 10.

How would your noise go down with this smoothing? Yep - by $\sqrt{10}$

$$final\ noise = (15\ mK) * \sqrt{\frac{1\ minute}{6\ minutes}} * \sqrt{\frac{1\ line}{40\ lines}} = 0.97\ \text{mK}$$

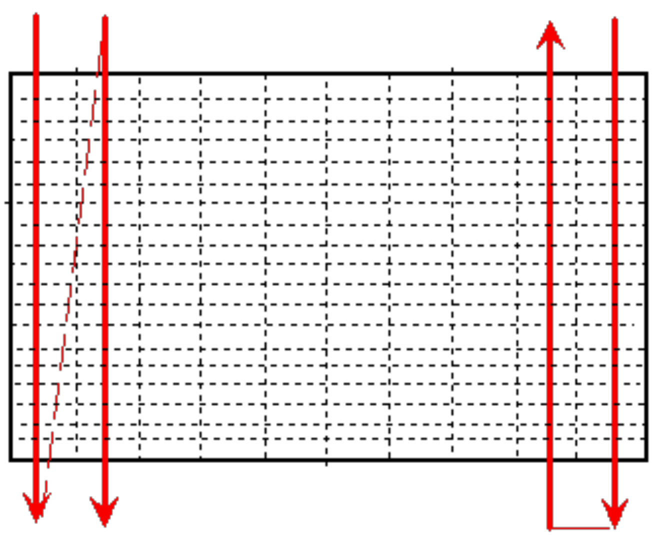
$$final\ noise\ (smoothed) = (0.97\ mK) * \sqrt{\frac{0.1\ kHz}{1\ kHz}} = 0.31\ \text{mK}$$

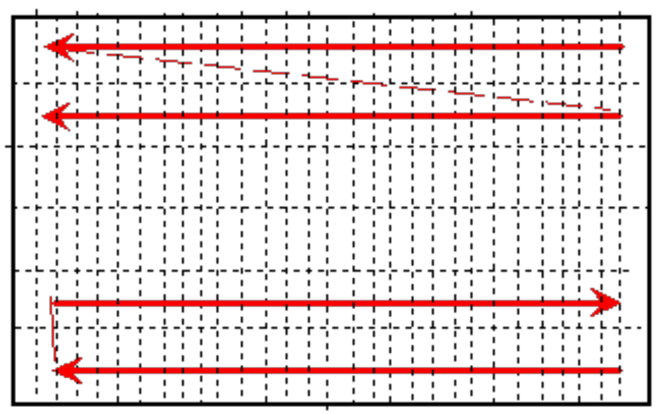
Mapping Techniques



- **Point map**
  - Sit, Move, Sit, Move, etc.

- **On-The-Fly Mapping**
  - Slew a column or row while collecting data
  - Move to next column row
  - Basket weave
  - Reference/OFF from a “source-free” map position or separate “OFF” spectrum taken.

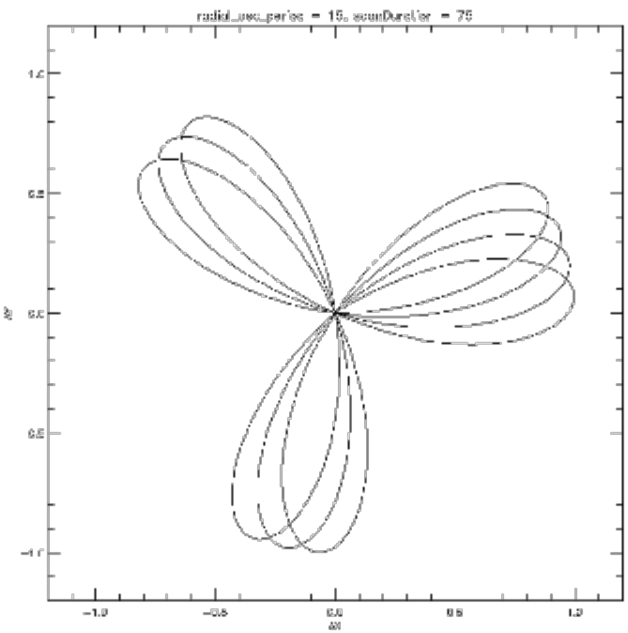




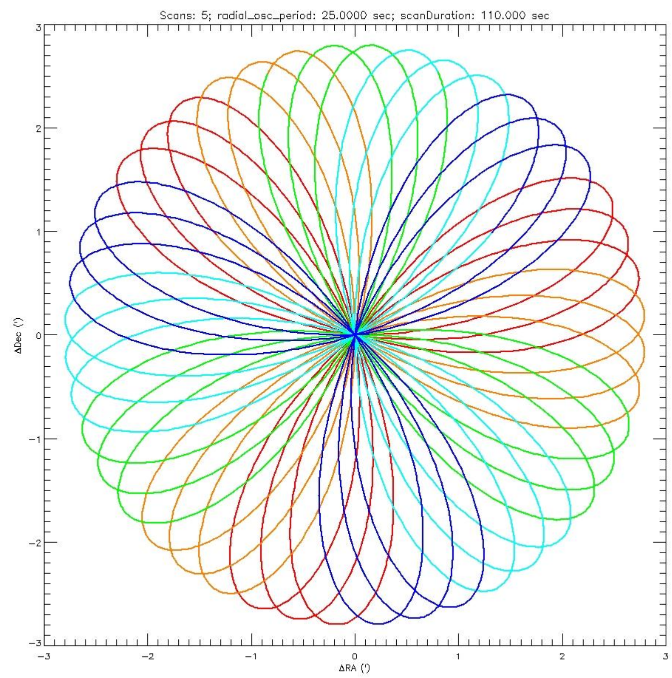
Mapping Techniques

Daisy Map

- Useful for multi-beam arrays
- Best for smaller regions (6')
- Most sensitive towards the center of the daisy



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

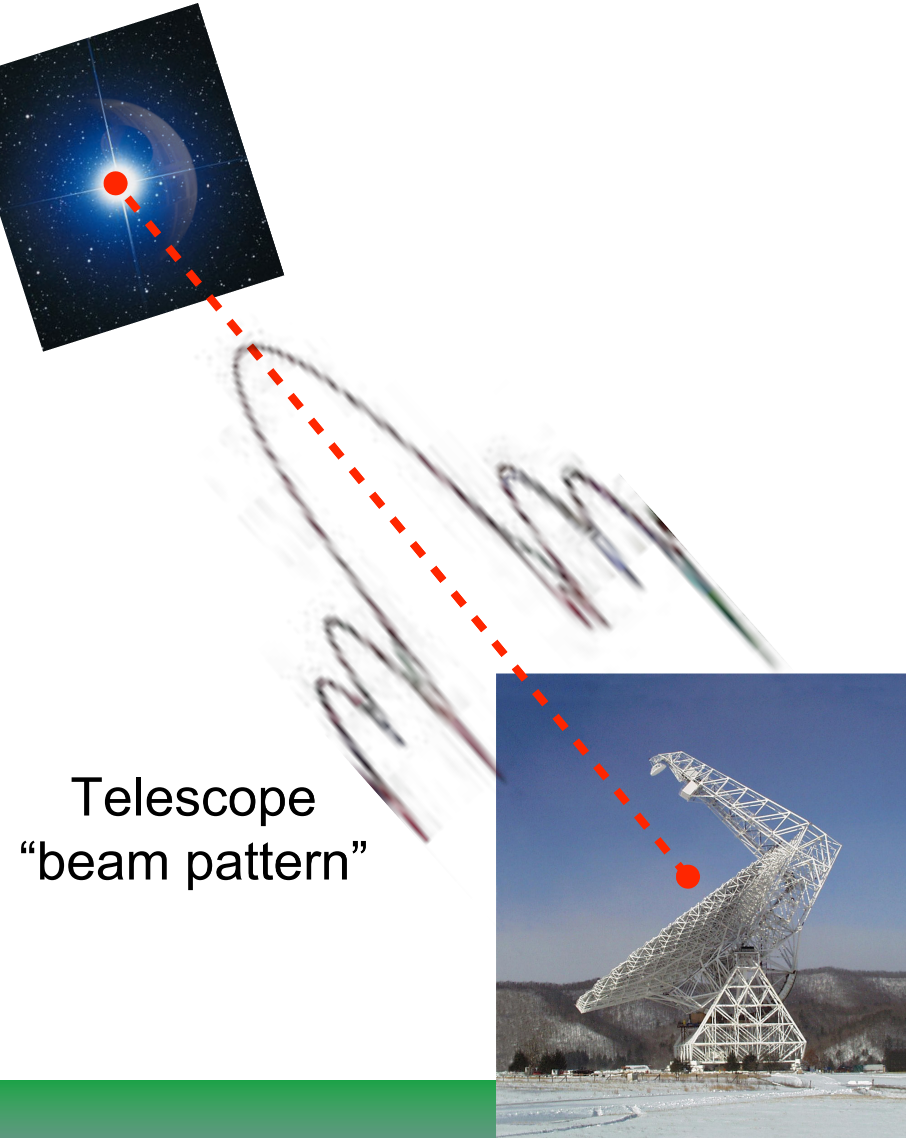


Choose Your Adventure

- Types of Radio Observations
  - Spectral Line
  - Continuum
  - Pulsar / FRB (Transient)
- Types of Radio Receivers
  - Feed Horns
  - Bolometers
- Observation Strategies
  - Track
  - Map

+ Calibration!

Antenna Temperature



We want to measure the source intensity by measuring a temperature incident on the telescope, that is:

$$T_{Antenna} = T_{source}$$

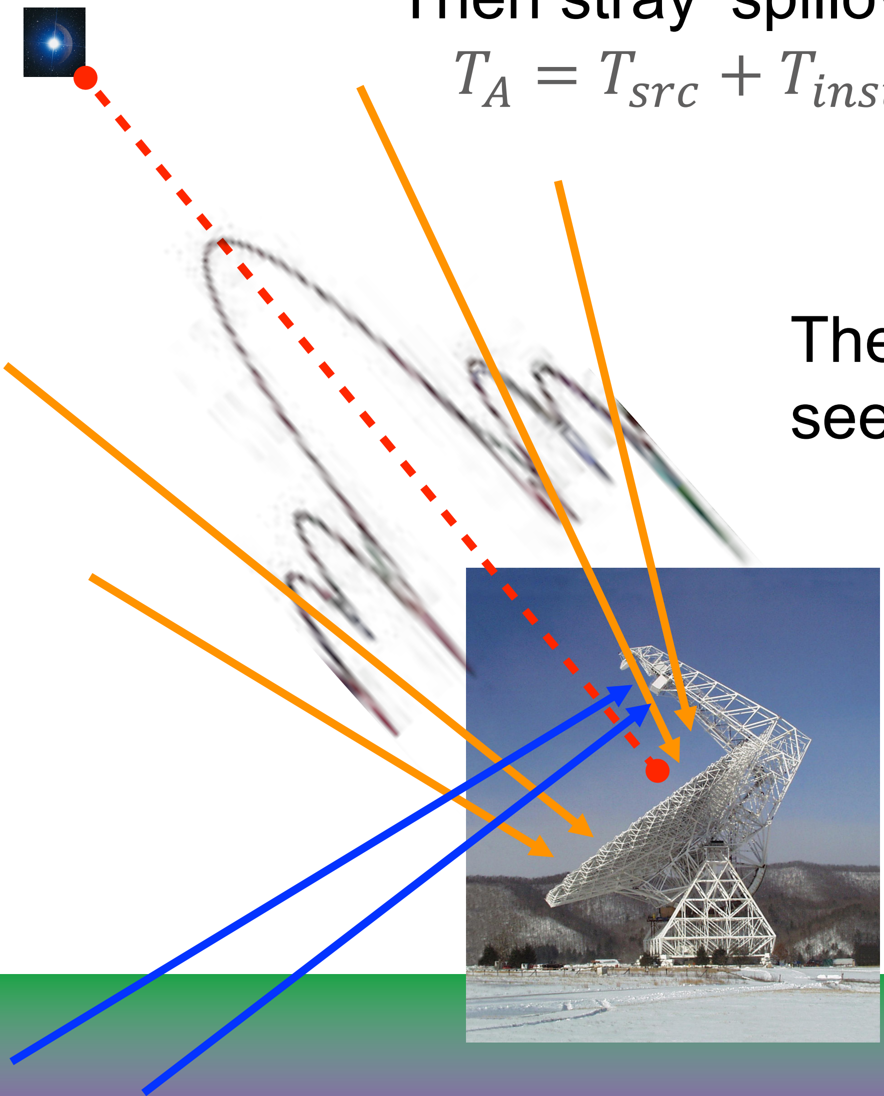
Of course, the system itself adds some heat to the measurement

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

Antenna Temperature

Then stray ‘spillover’ radiation

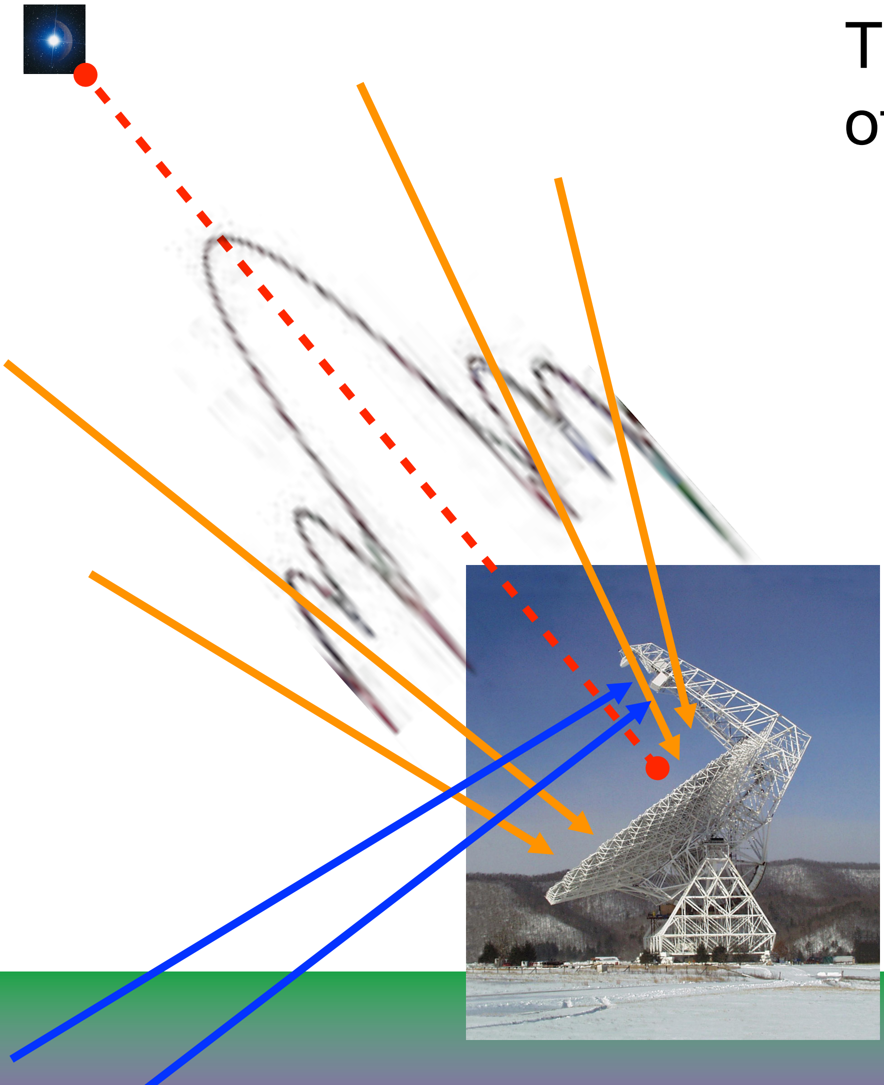
$$T_A = T_{src} + T_{instrumentation} + T_{spillover}$$



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

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

We don't care about **any** of this except for T_{src} !

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 by going to an "off" position.

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

Different Observing Modes to derive the reference data (OFF)

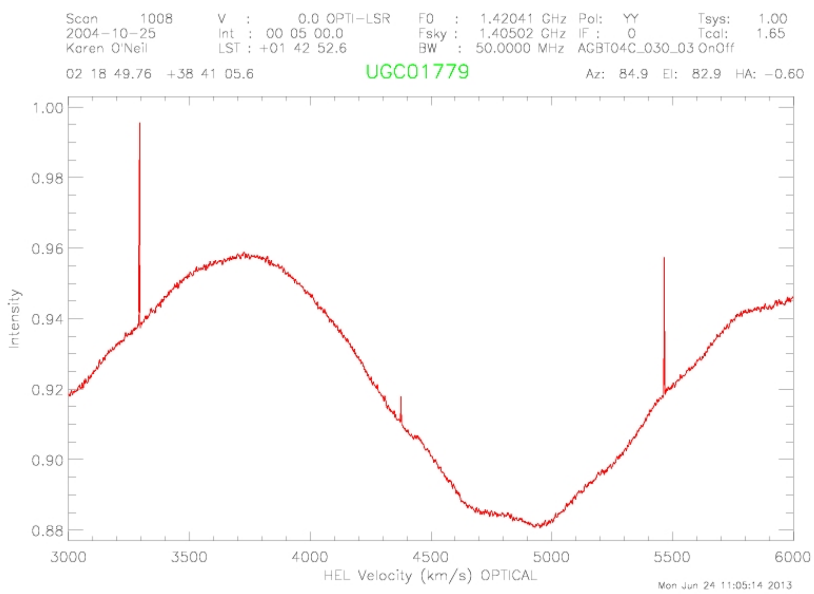
Two main types of reference observations:

- ➢Position Switching
  - Reference-Off
  - Mapping-Off
- ➢Frequency Switching
  - In or Out-of-band

Position Switching

ON source

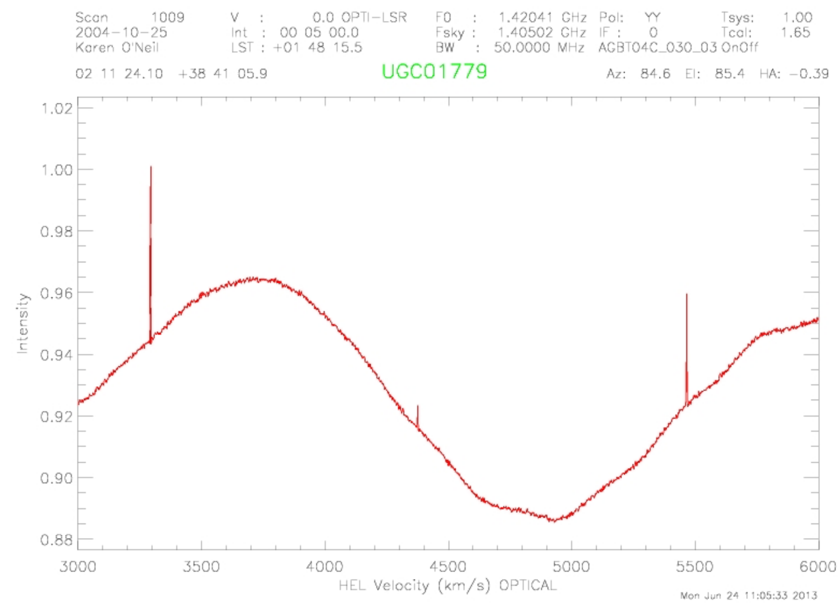
$T_{source} + T_{everything\ else}$



OFF source

$T_{everything\ else}$

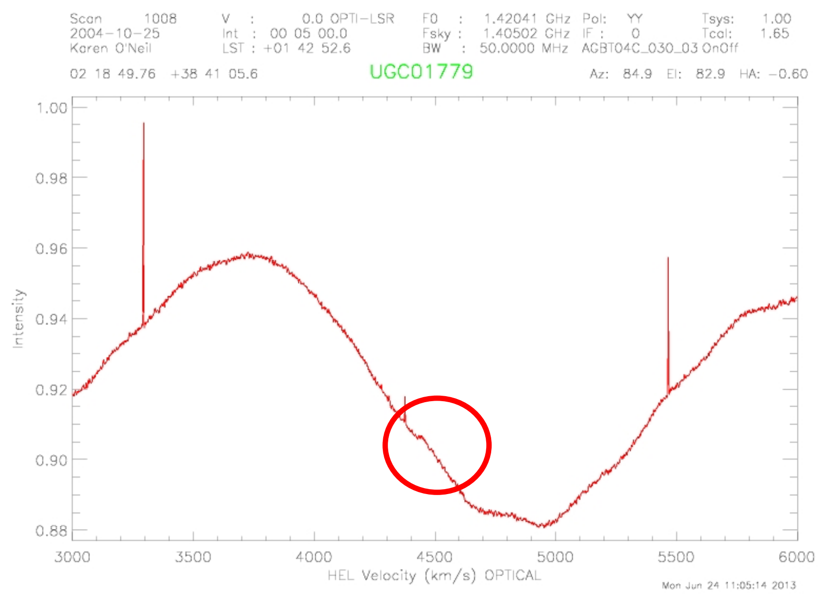
Arbitrary Units



Position Switching

ON source

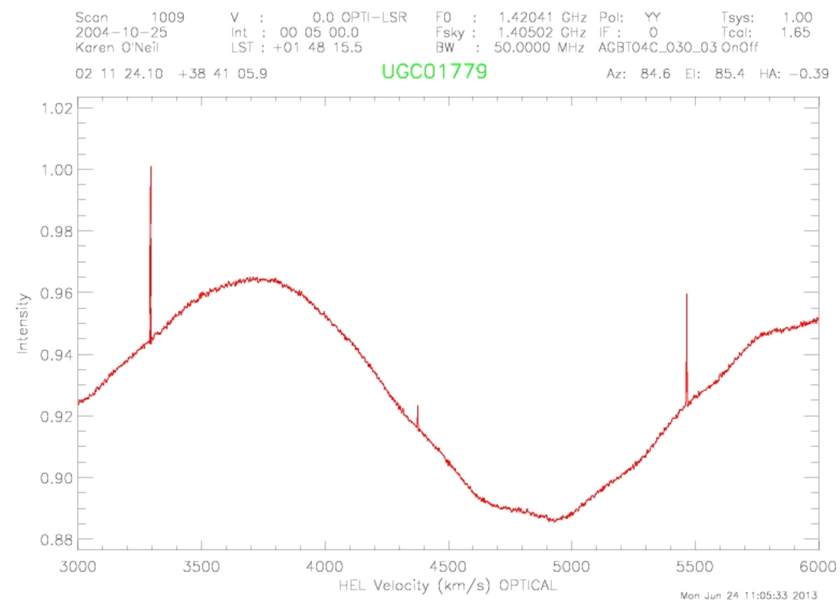
$T_{source} + T_{everything\ else}$



OFF source

$T_{everything\ else}$

Arbitrary Units

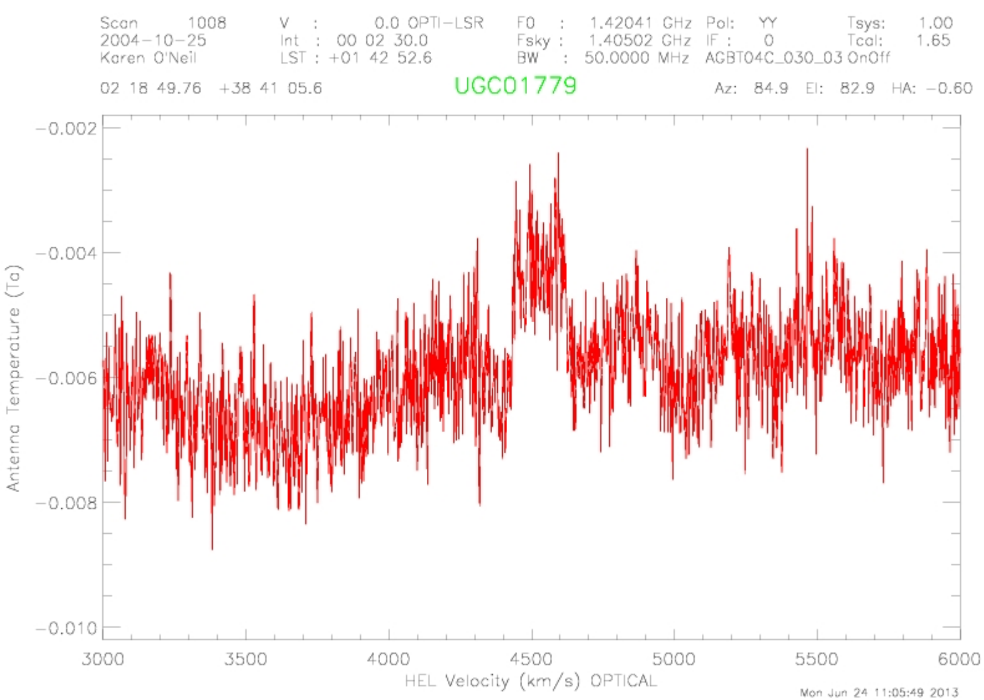


Position Switching: ON-OFF on Sky

ON - OFF

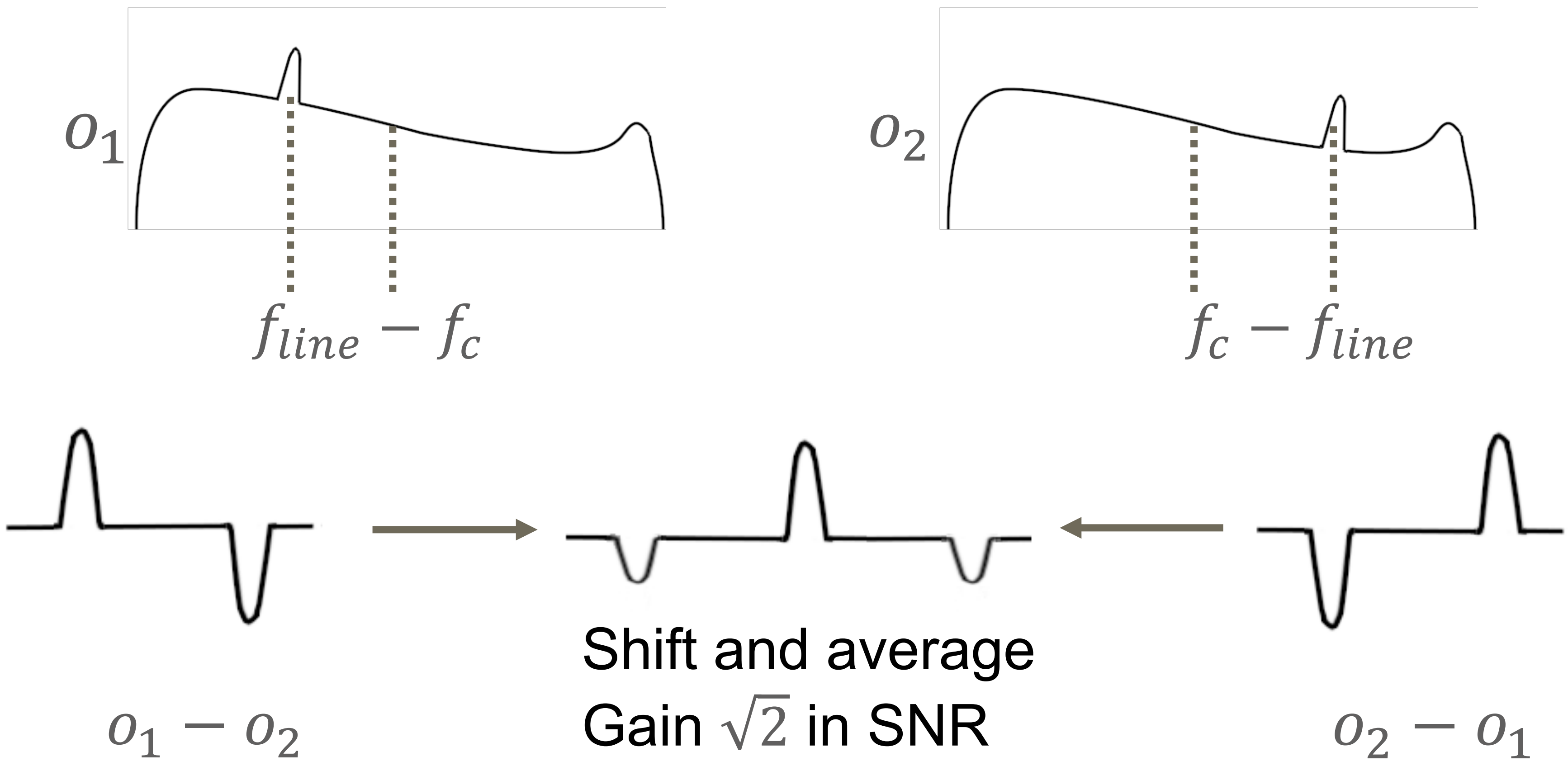
$$(T_{source} + T_{everything\ else}) - (T_{everything\ else})$$

Arbitrary Counts



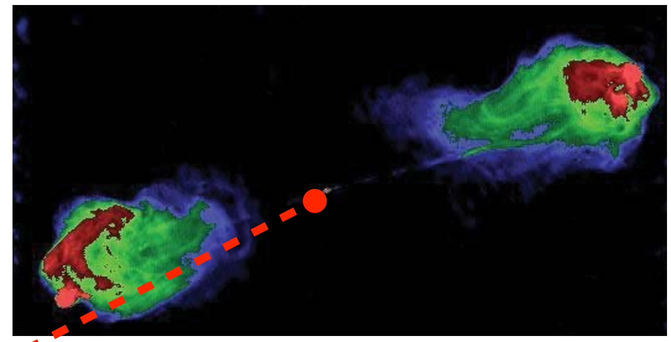
In-band Frequency Switching

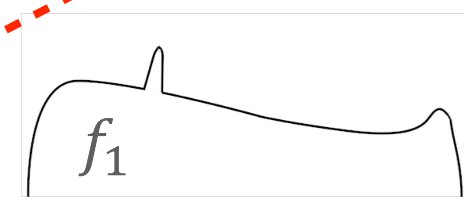
- Very efficient method of observing.

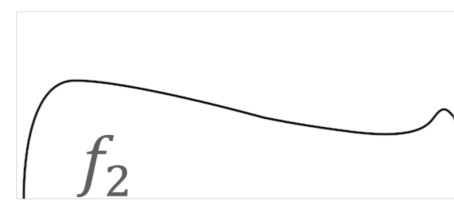


Out-of-band Frequency Switching

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







Frequency vs Position Switching

- Narrow line in non-crowded spectrum ➔ Frequency Switching (FS)
- Narrow line in crowded spectral region or significant RFI ➔ Position Switching (PS)
- Broad line ➔ PS

➢ Narrow line < 10 km/s

➢ Broad line > 100 km/s

Calibration

How do we know the "true flux" of our target, though? So far, we have only taken out any systematic effects, and our units are arbitrary "counts", not anything with physical meaning (Watt, erg, Jansky, etc.) .

(1) Observe standard targets of known brightness. *("Calibrator Sources")*

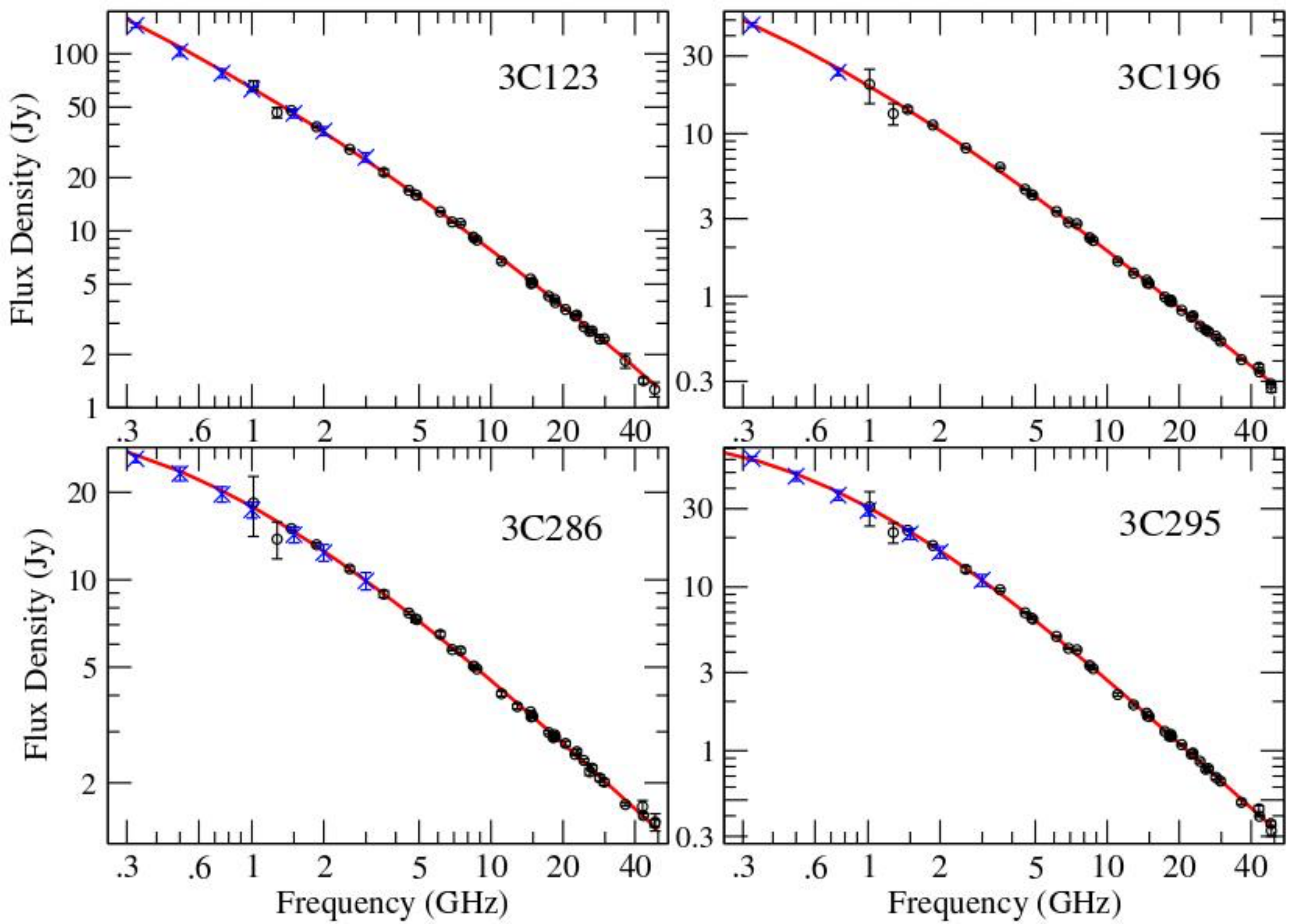
(2) Introduce noise of a known amplitude. *("Noise Diodes")*

(3) Observe something near the telescope of known temperature. *("Hot and cold loads")*

Calibration
Calibrator Sources

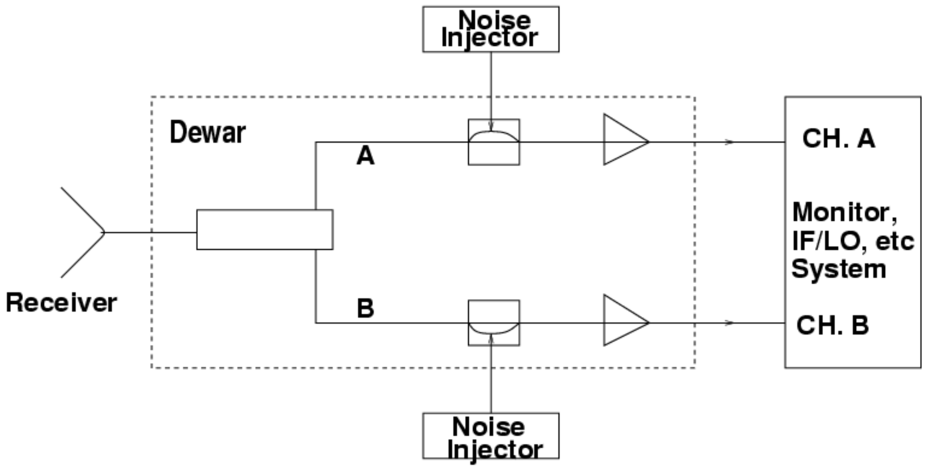
The VLA and ALMA maintain a list of calibration sources with precise fluxes at many different wavelengths.

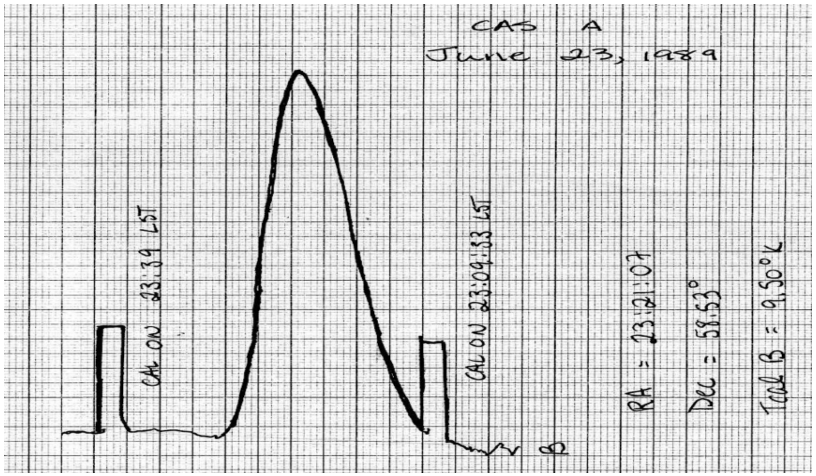
Observe one of these along with your science target and scale the measured flux to the recorded value.



Calibration

Noise Diodes



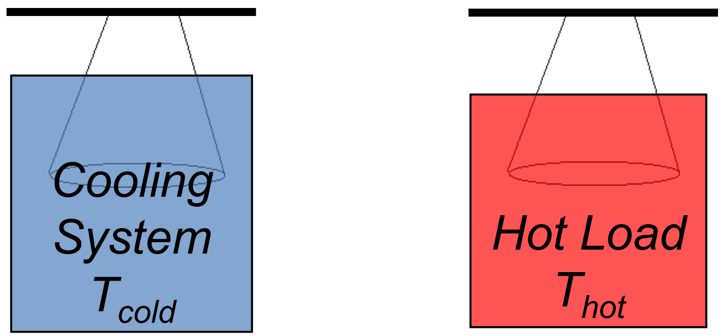


Inject noise of a known amplitude into the system. Scale your measured values accordingly.

All GBT receivers besides 4mm, Argus, and MUSTANG use noise diodes.

Calibration

Hot & Cold Loads



This is similar to a “flat field” in optical astronomy, where you place something in front of the receiver (with a known temperature) in order to calibrate.

Example: Argus on GBT has a “chopper wheel” that goes in front of the receiver before and after each observation.

Choose Your Adventure (Recap)

- Types of Radio Observations
  - Spectral Line
  - Continuum
  - Pulsar / FRB (Transient)
- Types of Radio Receivers
  - Feed Horns
  - Bolometers
- Observation Strategies
  - Track
  - Map

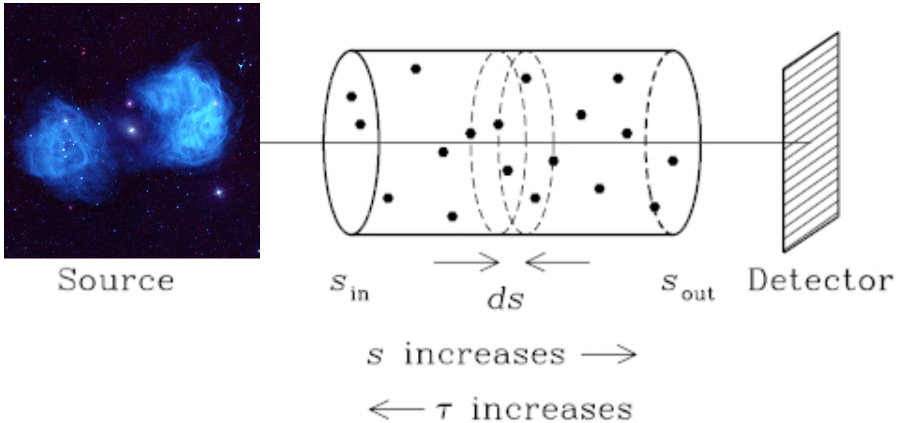
+ Calibration!

Calibration Sources,
Noise Diodes,
Hot/Cold Loads

Happy observing!

Backup Slides

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)

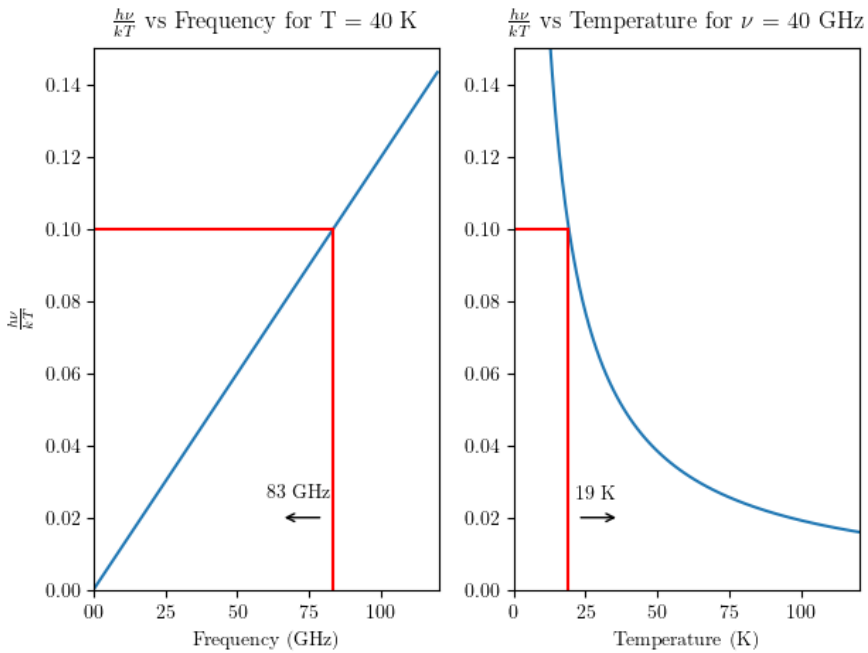
Blackbody Equation

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

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 $Jysr^{-1}$

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

Available GBT receivers

What frequency do you need?

Table 1: GBT Receivers

Receiver	Frequency Range
Prime Focus 1	290-920 MHz
Prime Focus 2	910-1230 MHz
L-band	1.15-1.73 GHz
S-band	1.73-2.60 GHz
C-band	3.8-8.0 GHz
X-band	8.0-11.6 GHz
Ku-band	12.0-15.4 GHz
K-band Focal Plane Array (7 pixels)	18.0-26.0 GHz
Ka-band	26.0-39.5 GHz
Q-band	38.2-49.8 GHz
W-band	67-93.3 GHz
MUSTANG 2 bolometer array (shared risk)	80-100 GHz
ARGUS (shared risk)	75-115.3 GHz, Private PI instrument

Available GBT Backends

Table 2: GBT Backends and Observing Modes

Backend	Observing Modes
Versatile Green Bank Astronomical Spectrometer (VEGAS)	Continuum, pulsar, spectral line
Digital Continuum Receiver (DCR)	Continuum
Green Bank Ultimate Pulsar Processing Instrument (GUPPI)	Pulsar
Mark V Very Long Baseline Array Disk Recorder	Very Long Baseline Interferometry
Caltech Continuum Backend (CCB) (Ka-band)	Continuum
Zpectrometer (Ka-band)	Private PI instrument
Radar	Private PI instrument

GBT Specs:

Location	Green Bank, West Virginia, USA
Coordinates	Longitude: 79°50′23.406″ West (NAD83) Latitude: 38°25′59.236″ North (NAD83) Track Elevation: 807.43 m (NAVD88)
Optics	110 m x 100 m unblocked section of a 208 m parent paraboloid Offaxis feed arm
Telescope Diameter	100 m (effective)
Available Foci	Prime and Gregorian f/D (prime) = 0.29 (referred to 208 m parent parabola) f/D (prime) = 0.6 (referred to 100 m effective parabola) f/D (Gregorian) = 1.9 (referred to 100 m effective aperture)
Receiver mounts	Prime: Retractable boom with Focus-Rotation Mount Gregorian: Rotating turret with 8 receiver bays
Subreflector	8-m reflector with Stewart Platform (6 degrees of freedom)
Main reflector	2004 actuated panels (2209 actuators) Average intra-panel RMS 68 μm
FWHM Beamwidth	Gregorian Feed: $\sim 12.60/f_{GHz}$ arcmin Prime Focus: $\sim 13.01/f_{GHz}$ arcmin (see Section 3.1.1)
Elevation Limits	Lower limit: 5 degrees Upper limit: $\sim$ 90 degrees
Declination Range	Lower limit: ~ -46 degrees Upper limit: 90 degrees
Slew Rates	Azimuth: 35.2 degrees/min Elevation: 17.6 degrees/min
Surface RMS	Passive surface: 450 μm at 45° elevation, worse elsewhere Active surface: $\sim$ 250 μm, under benign night-time conditions
Pointing accuracy	1σ values from 2-D data 5″ blind 2.7″ offset

GREEN BANK
OBSERVATORY