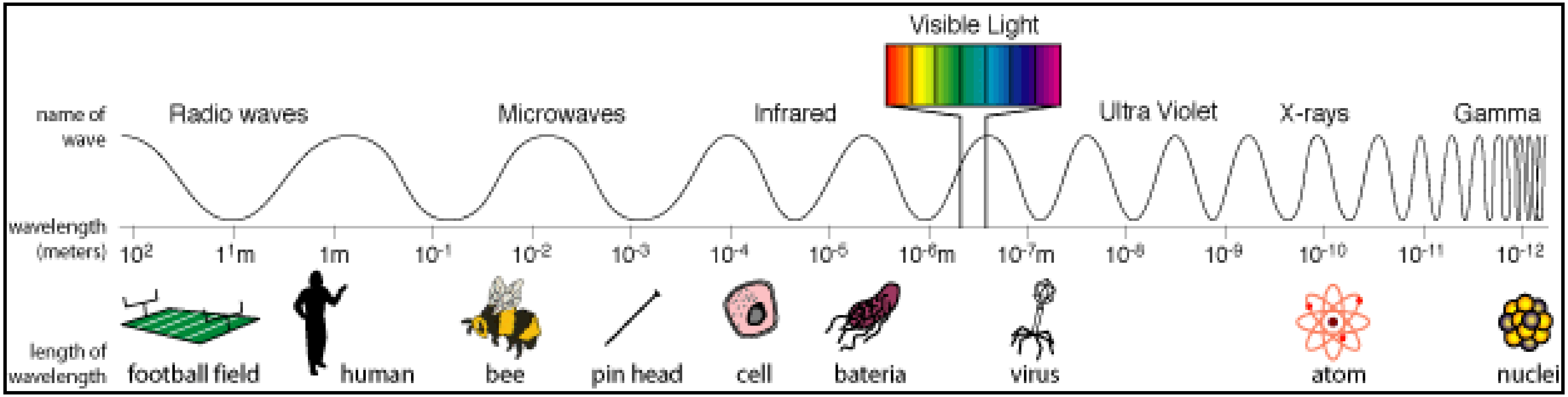
Introduction to Radio Astronomy

- Sources of radio emission
- Radio telescopes - collecting the radiation
- Processing the radio signal
- Radio telescope characteristics
- Observing radio sources

Sources of Radio Emission

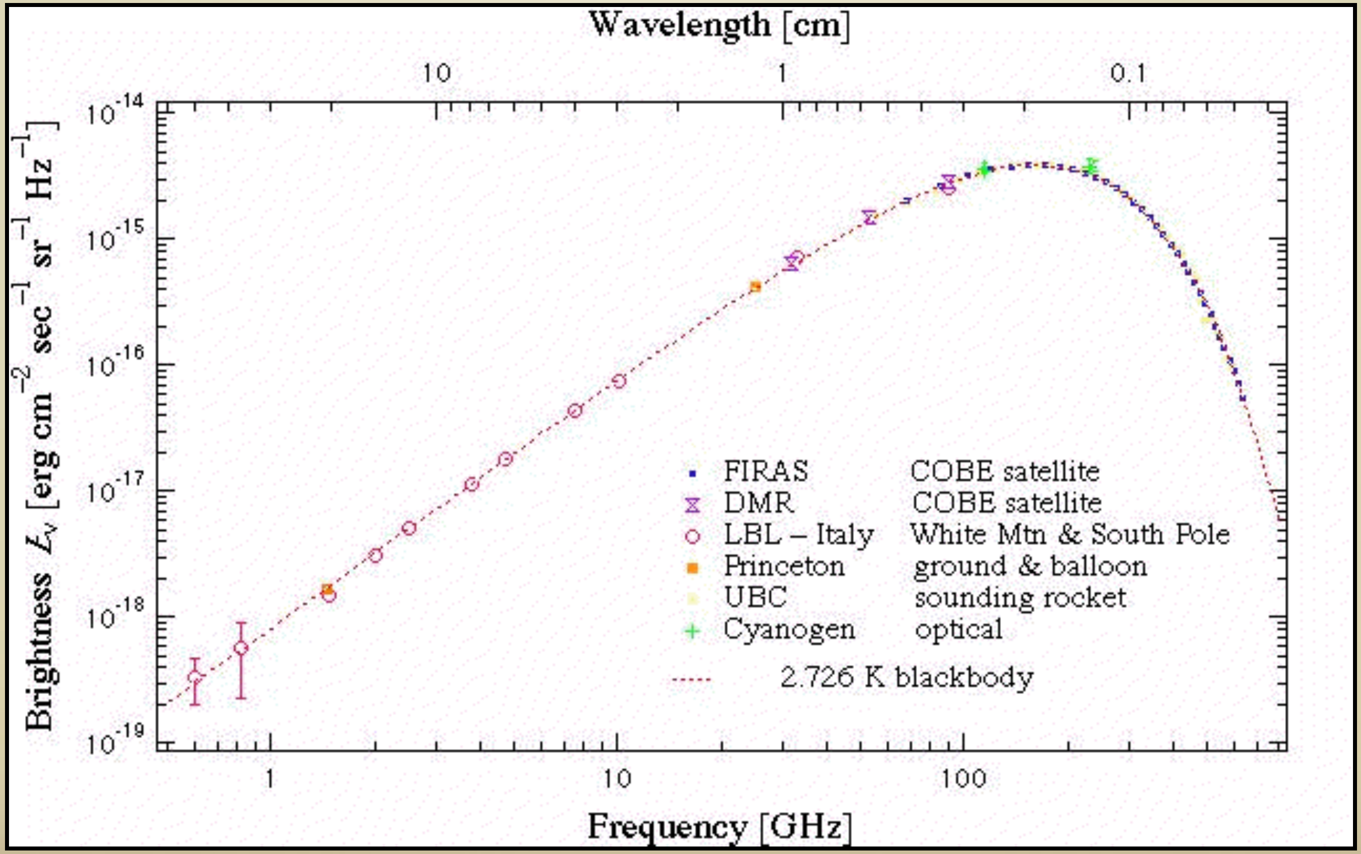
- Blackbody (thermal)
- Continuum sources (non-thermal)
- Spectral line sources



Blackbody Sources:

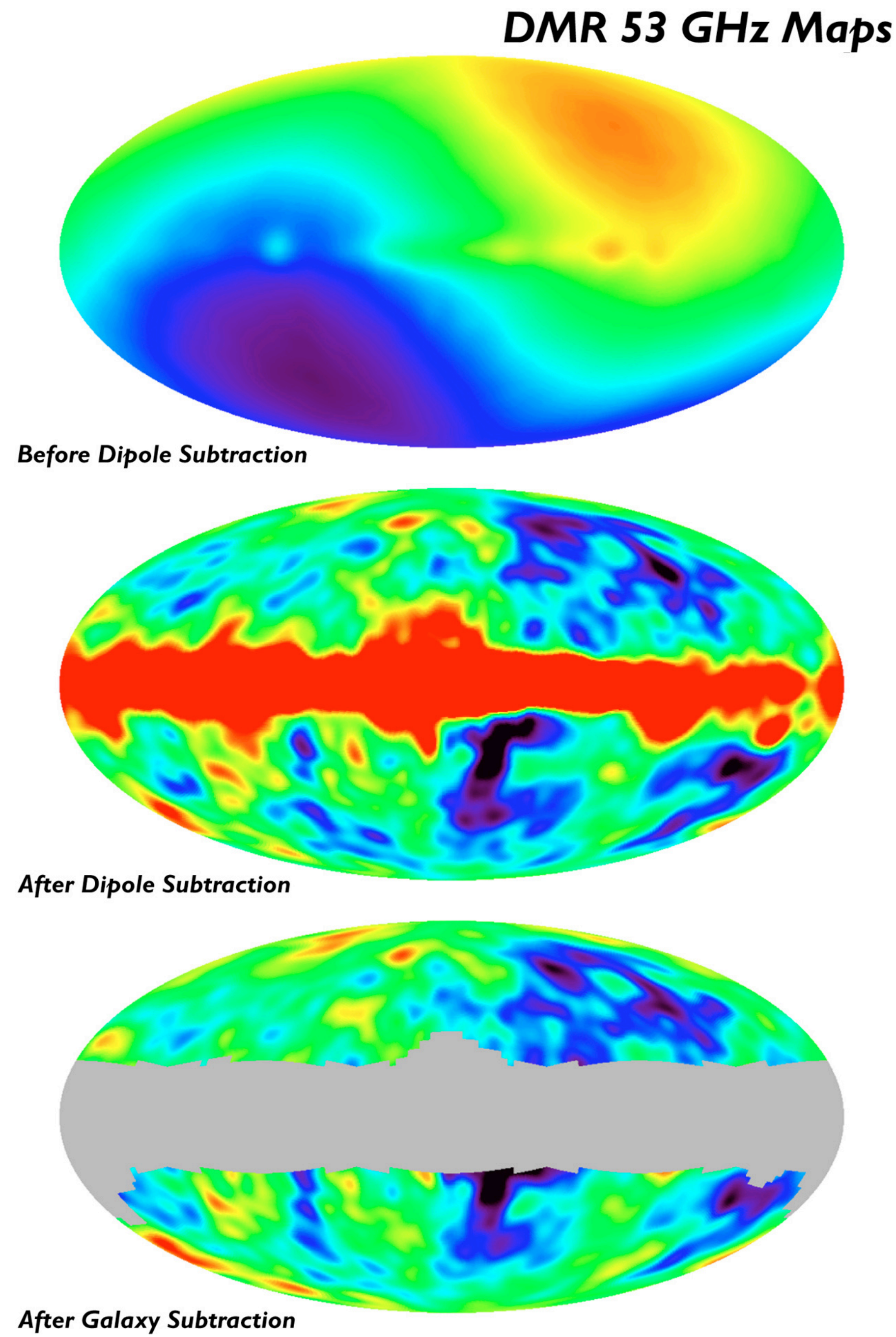
The cosmic microwave background, the planets

- Obs in cm requires low temperature: $\lambda_m T = 0.2898$ cm K
- Flux = const $\times\ \nu^{\alpha} \times$ T
- For thermal sources α is ~2 (flatter for less opaque sources)



Blackbody Emission

The Cosmic Microwave Background

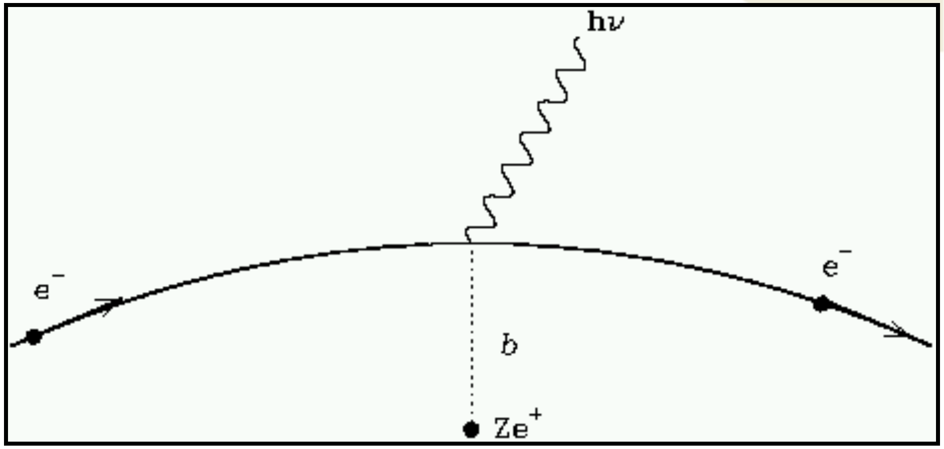


Continuum (non-thermal) Emission:

Emission at all radio wavelengths

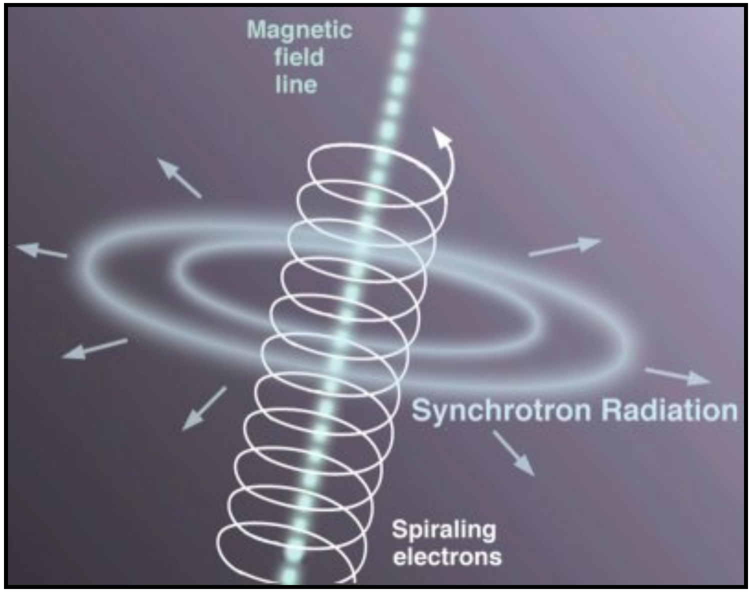
Bremsstralung (free-free):

Electron is accelerated as it passes a charged particle thereby emitting a photon

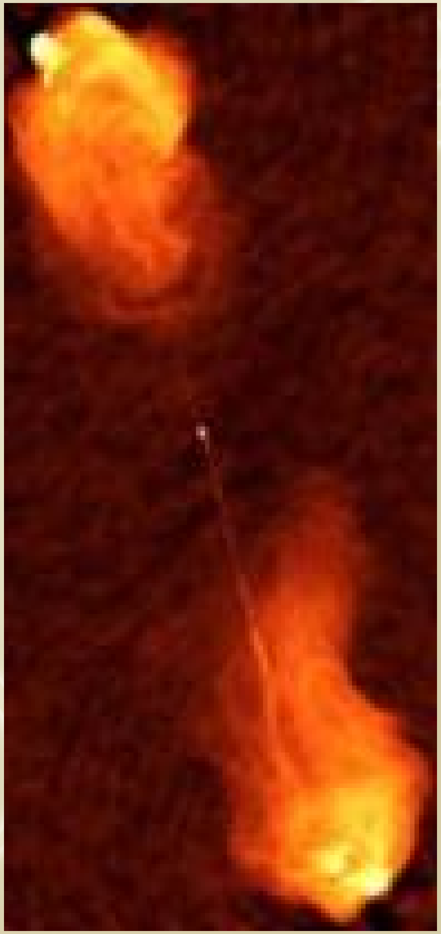


Synchrotron:

A charged particle moving in a magnetic field experiences acceleration and emits a photon

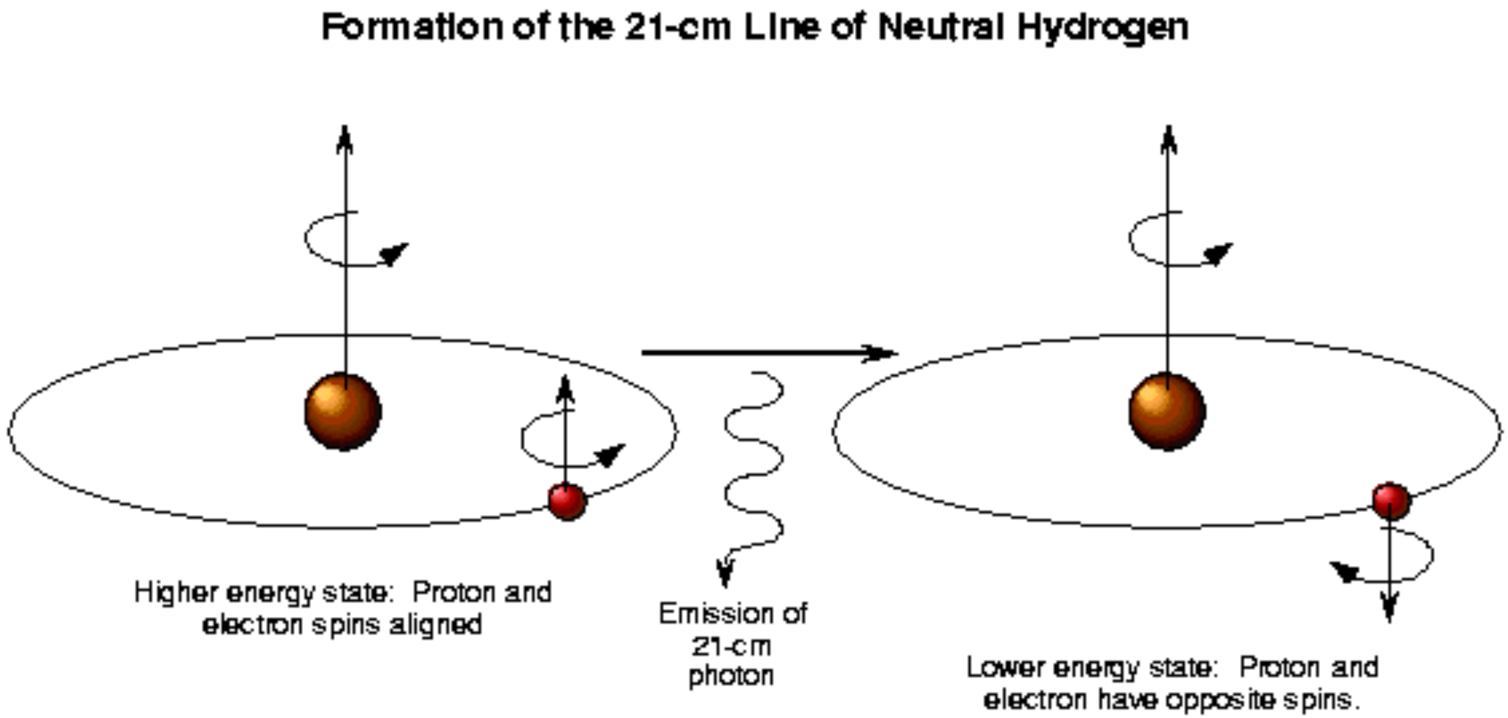


Sources of Continuum Emission



Radio Emission Lines

- Neutral hydrogen (HI) spin-flip transition
- Recombination lines (between high-lying atomic states)
- Molecular lines (CO, OH, etc.)

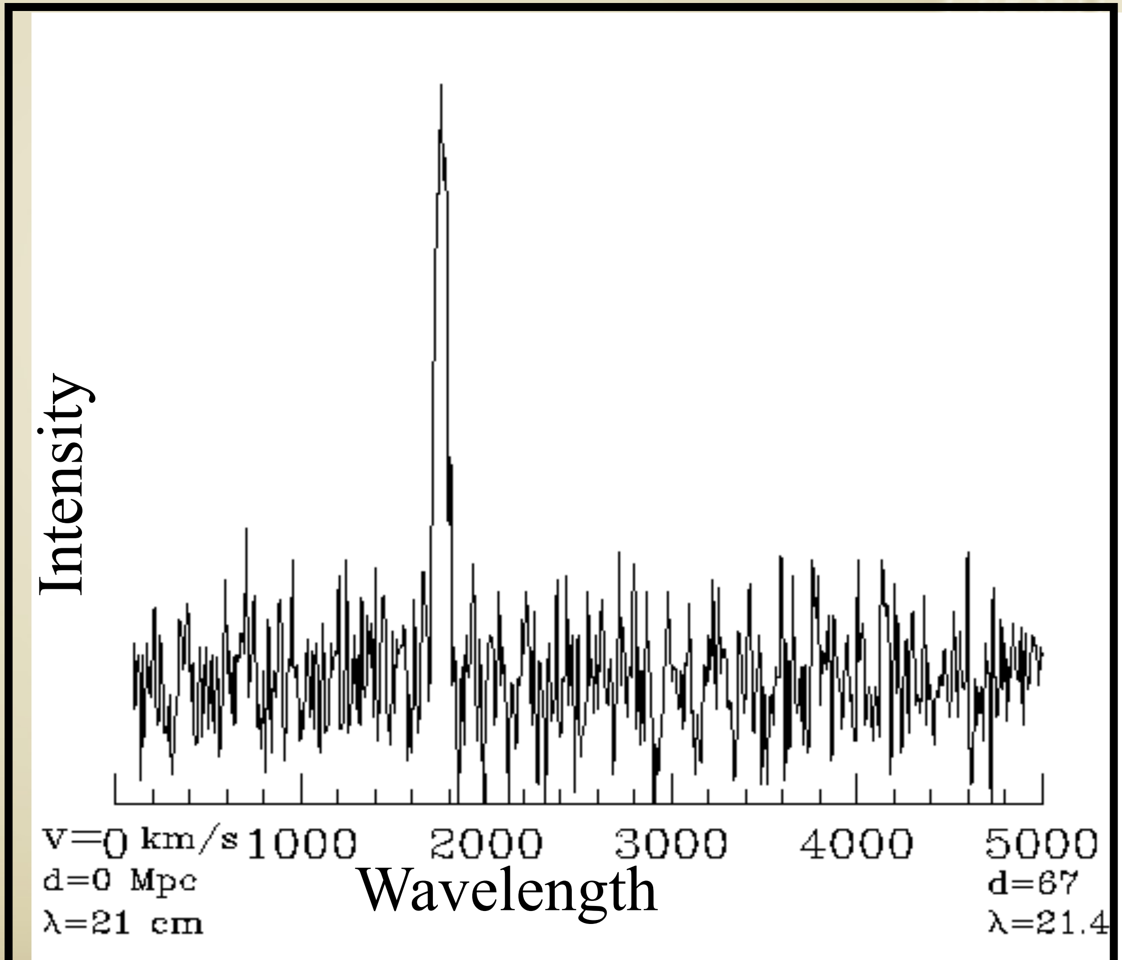


21cm Line of Neutral Hydrogen

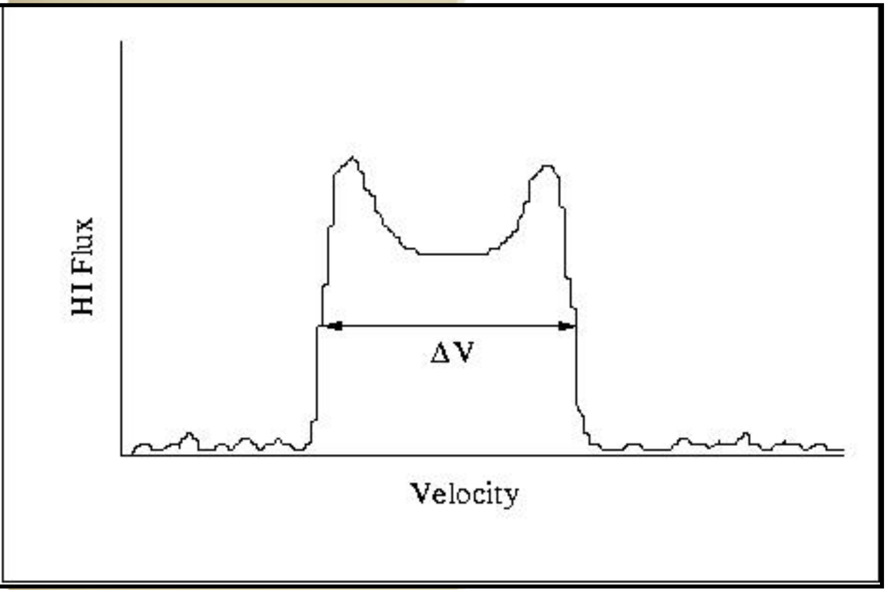
Not only are λ, ν, and E equivalent, but for the most part velocity and distance are as well.

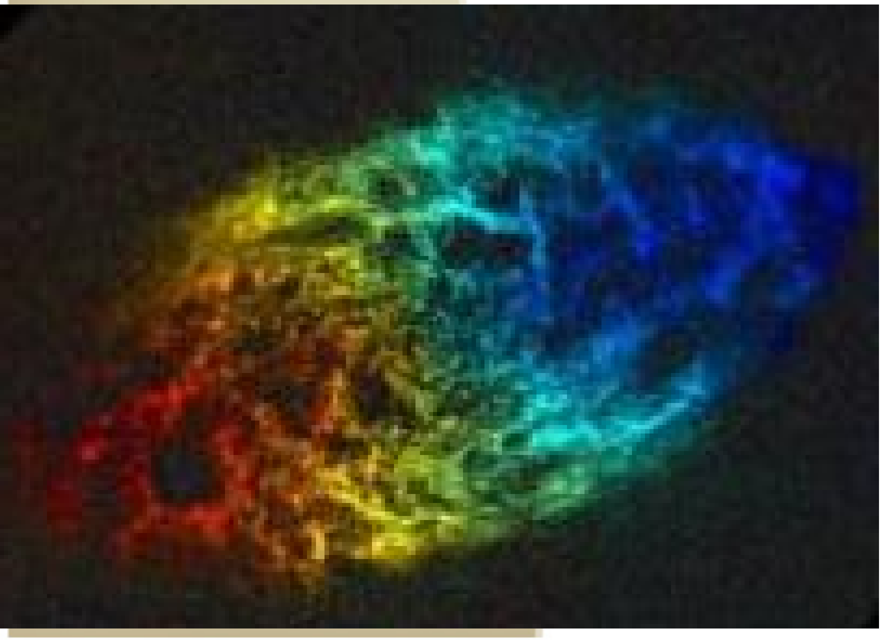
$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta v}{c}$$

$$d = v / H_0$$



21cm Line of Neutral Hydrogen, cont.

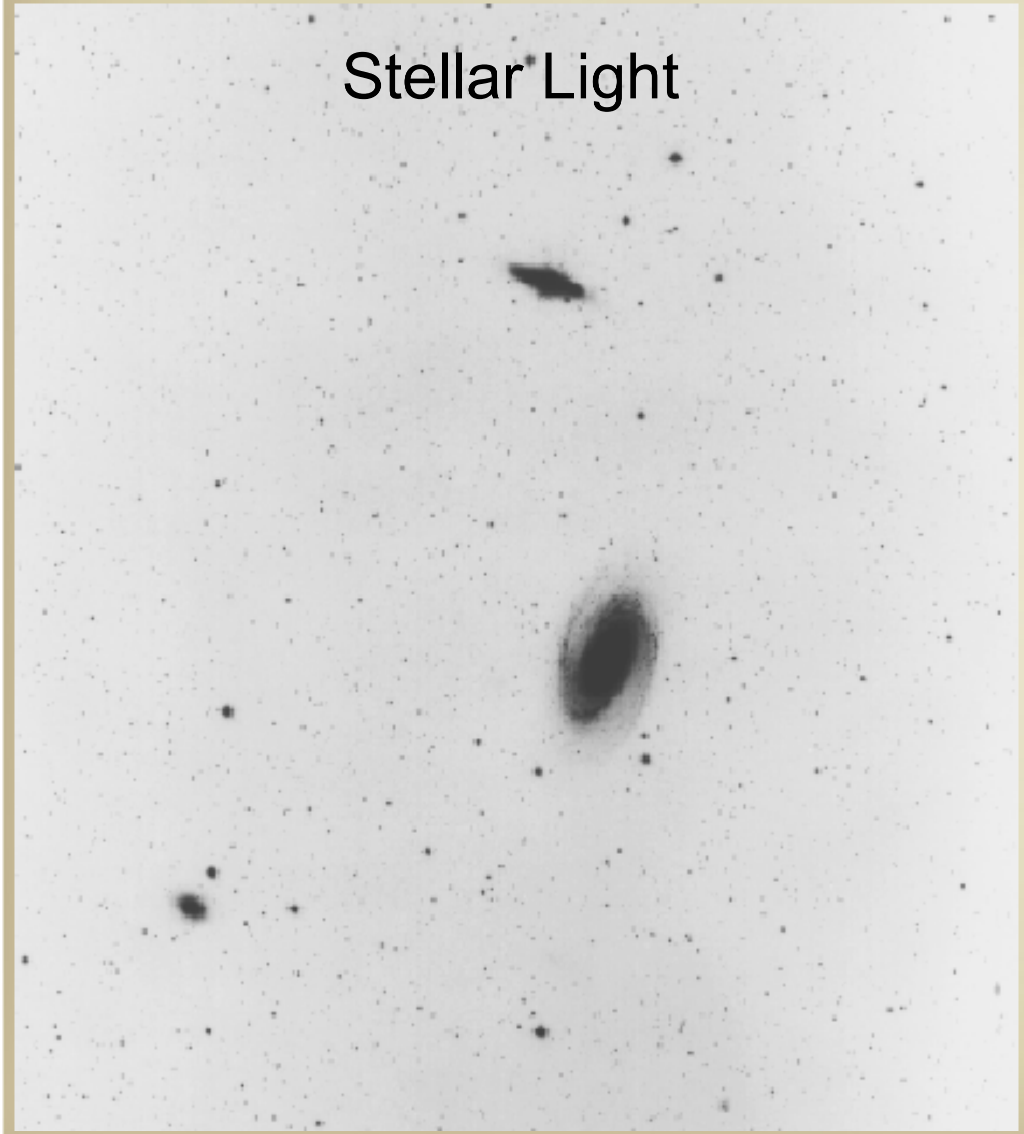


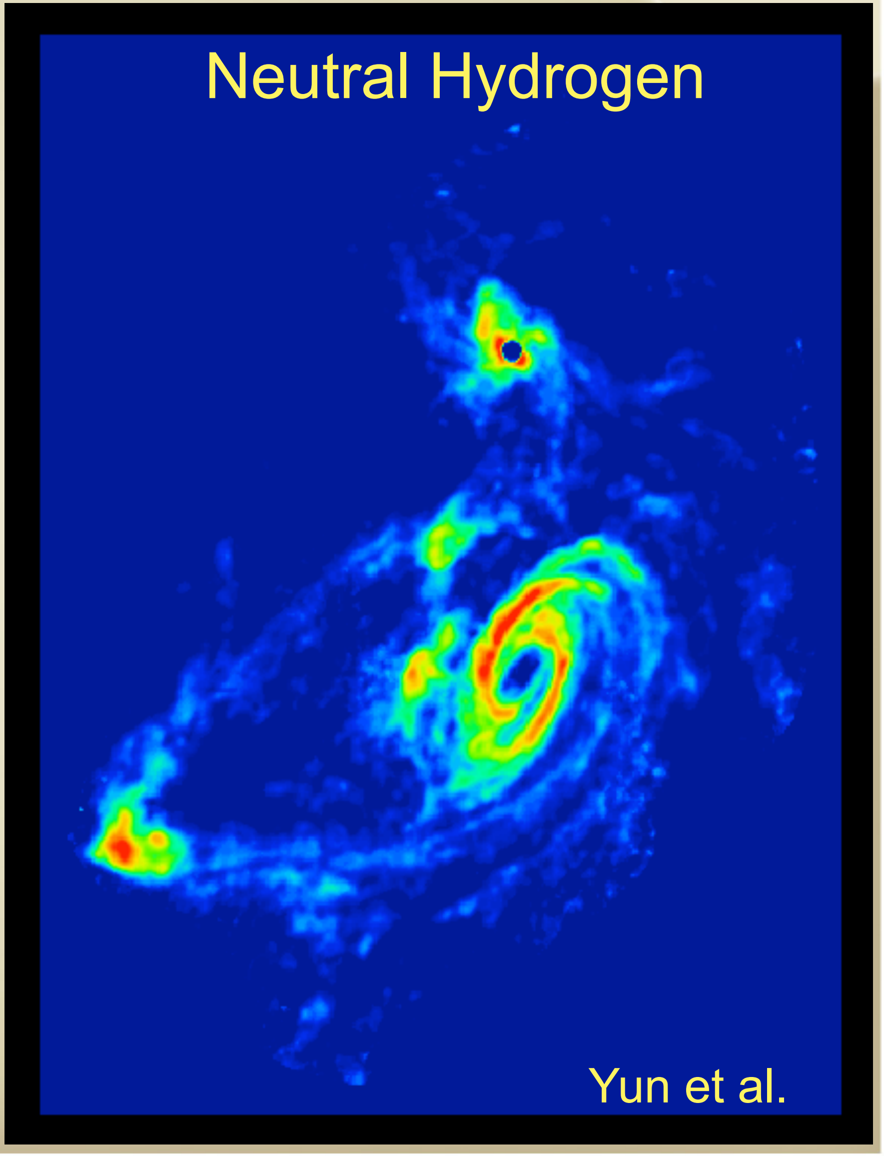


- HI spectral line from galaxy
- Shifted by expansion of universe ("recession velocity")
- Broadened by rotation

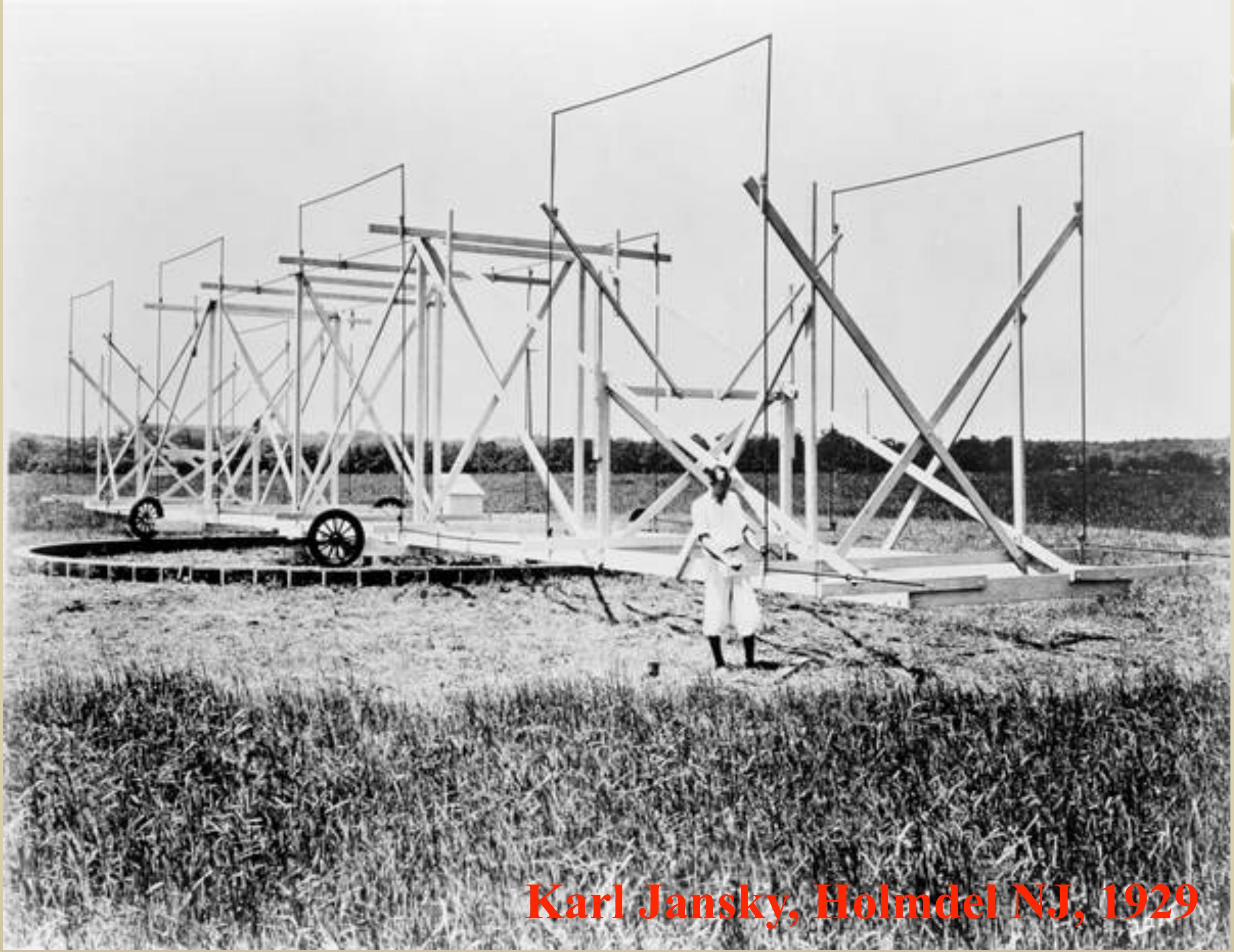
21 cm Line Emission:

The M81 Group



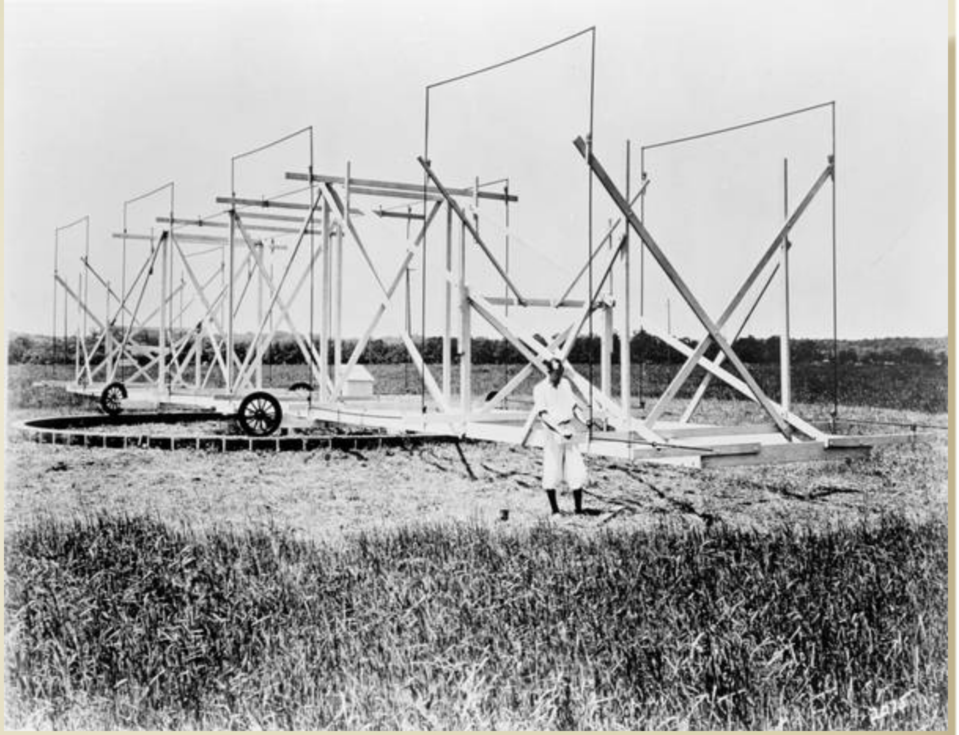


Radio Telescopes



Antennas

- Radio emission is just an EM wave
- An antenna is a device for converting EM radiation into electrical currents or vice-versa.
- Often done with dipoles or feedhorns.
- Basic "telescopes" are antennas + electronics



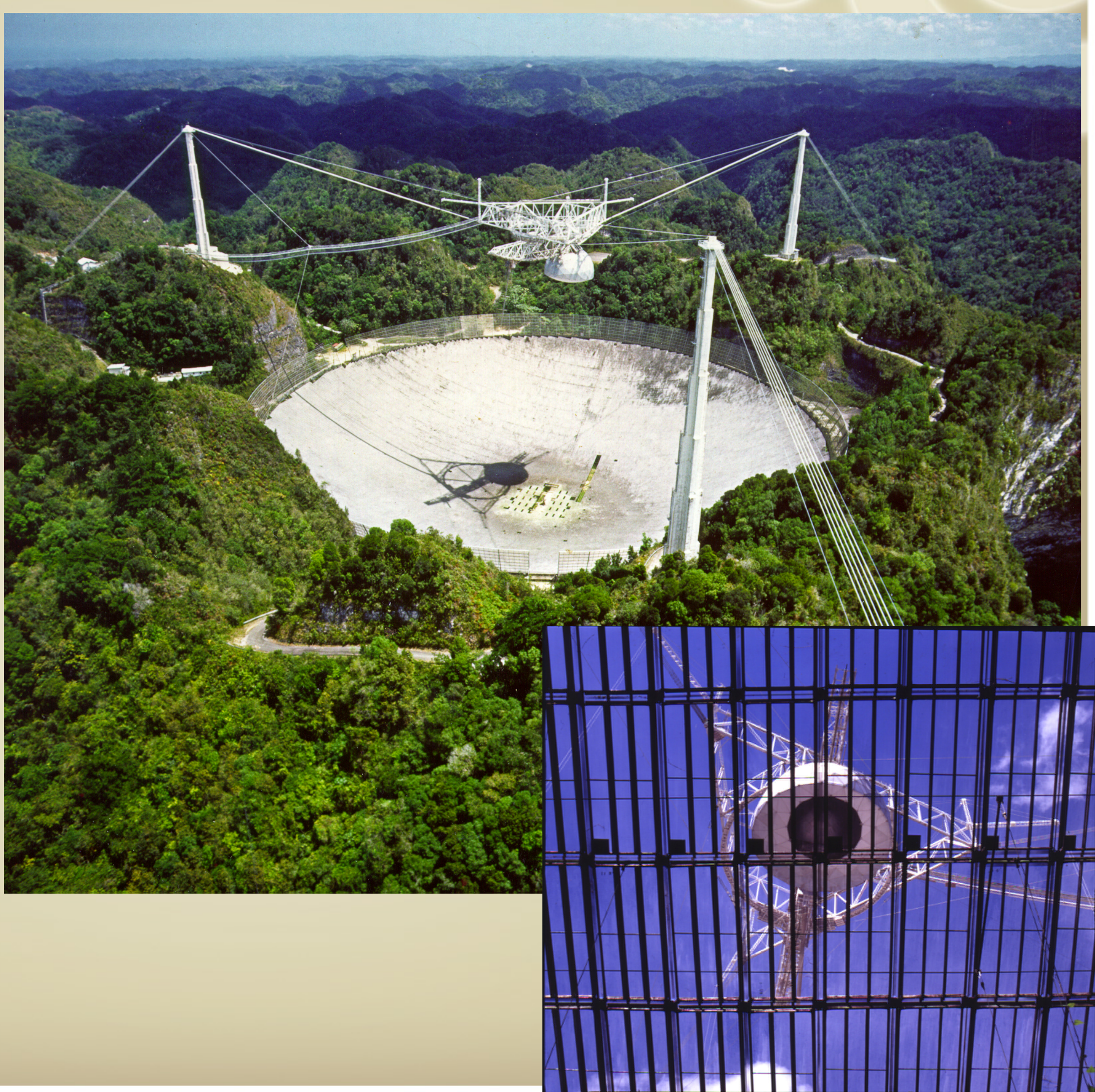
Karl Jansky, Holmdel NJ, 1929

Telescopes

- Collect the electromagnetic radiation
  - The more radiation from the source that is intercepted the more sensitive your telescope
- Convert the radiation into an electrical current
- Use electronics to move detected signal to a more manageable frequency
- Measure the frequency distribution of the incoming signal (spectrum)

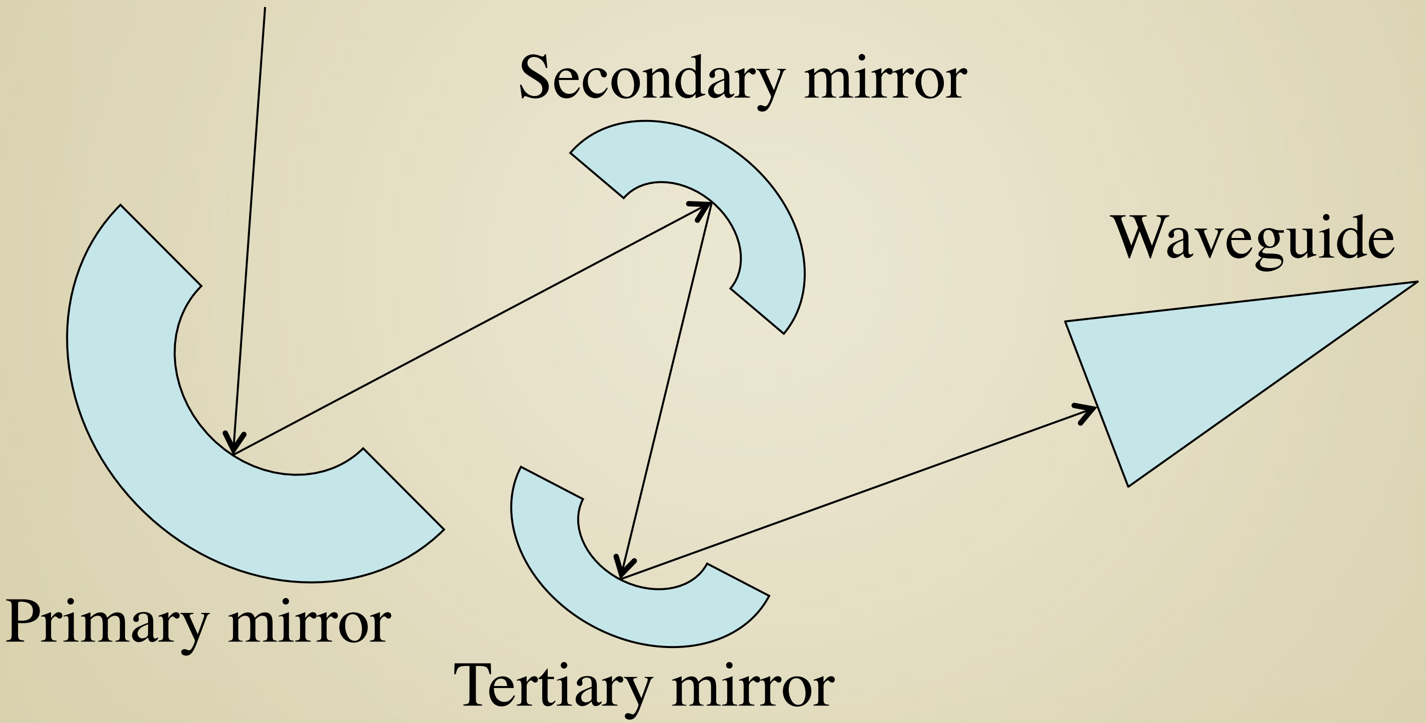
Radio Telescope Components

- Reflector(s)
- Feed horn(s)
- Low-noise amplifier
- Filter
- Downconverter
- IF Amplifier
- Spectrometer



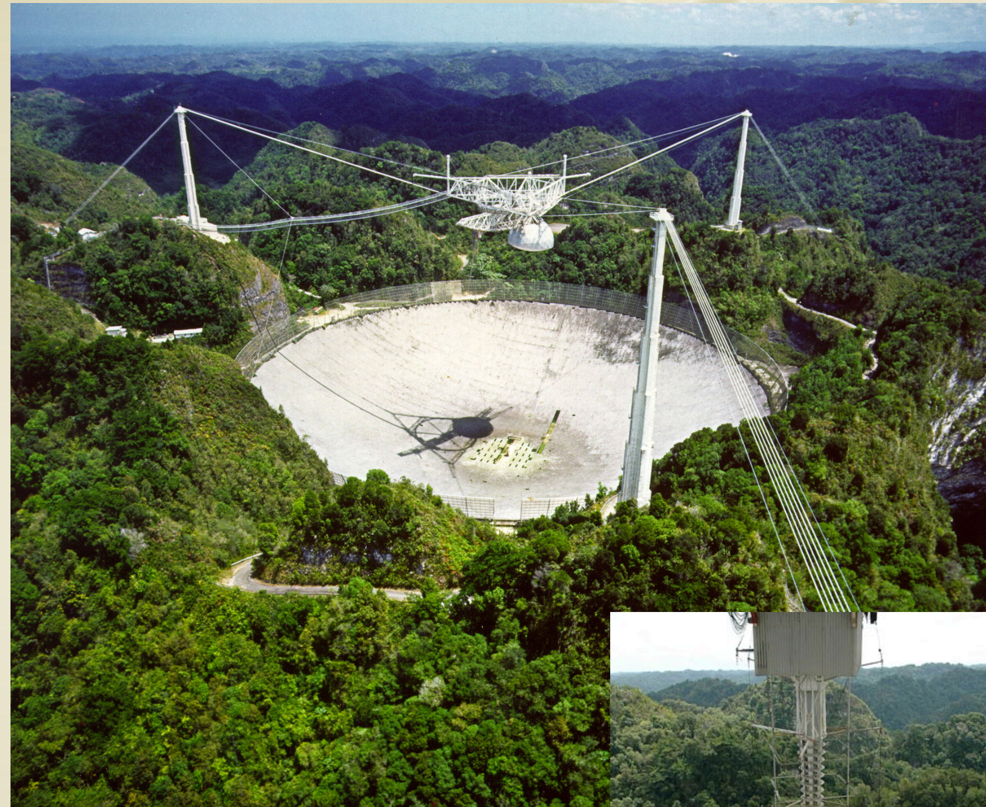
Signal Path – Front End

"Detecting" the Source



Reflector (primary mirror)

- Increases the collecting area
- Increases sensitivity
- Increases resolution
- Must keep all parts of on-axis plane wavefront in phase at focus
- Spherical surface focuses to a line

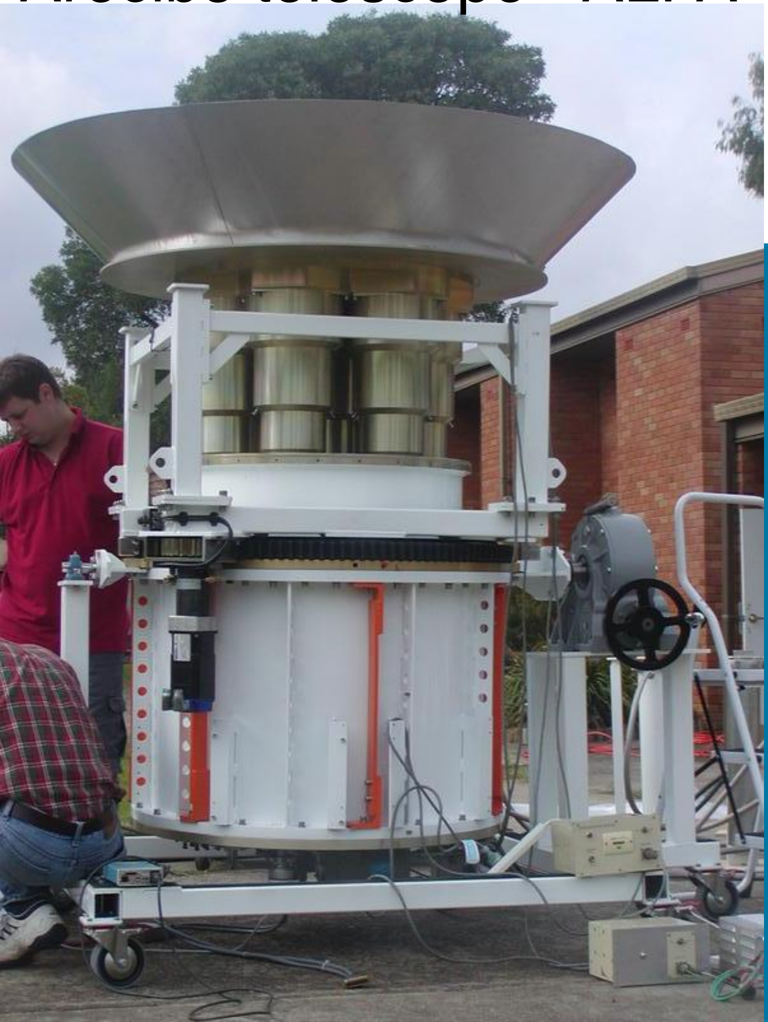


430 MHz
line feed

Antenna/Feedhorn

Hardware that takes the signal from the reflector to the electronics

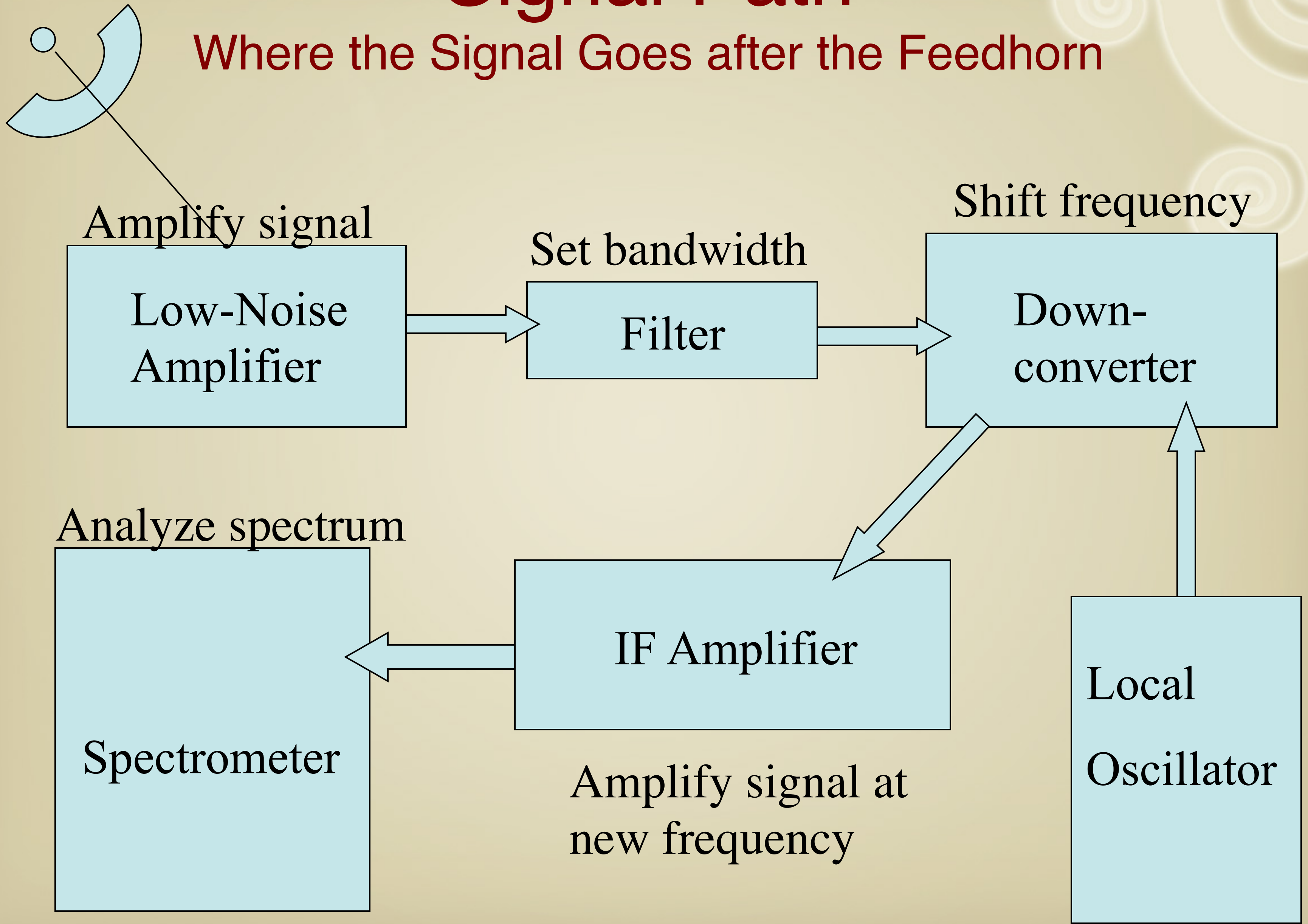
Array of 7 feedhorns on the Arecibo telescope - ALFA



Typical cm-wave feedhorn

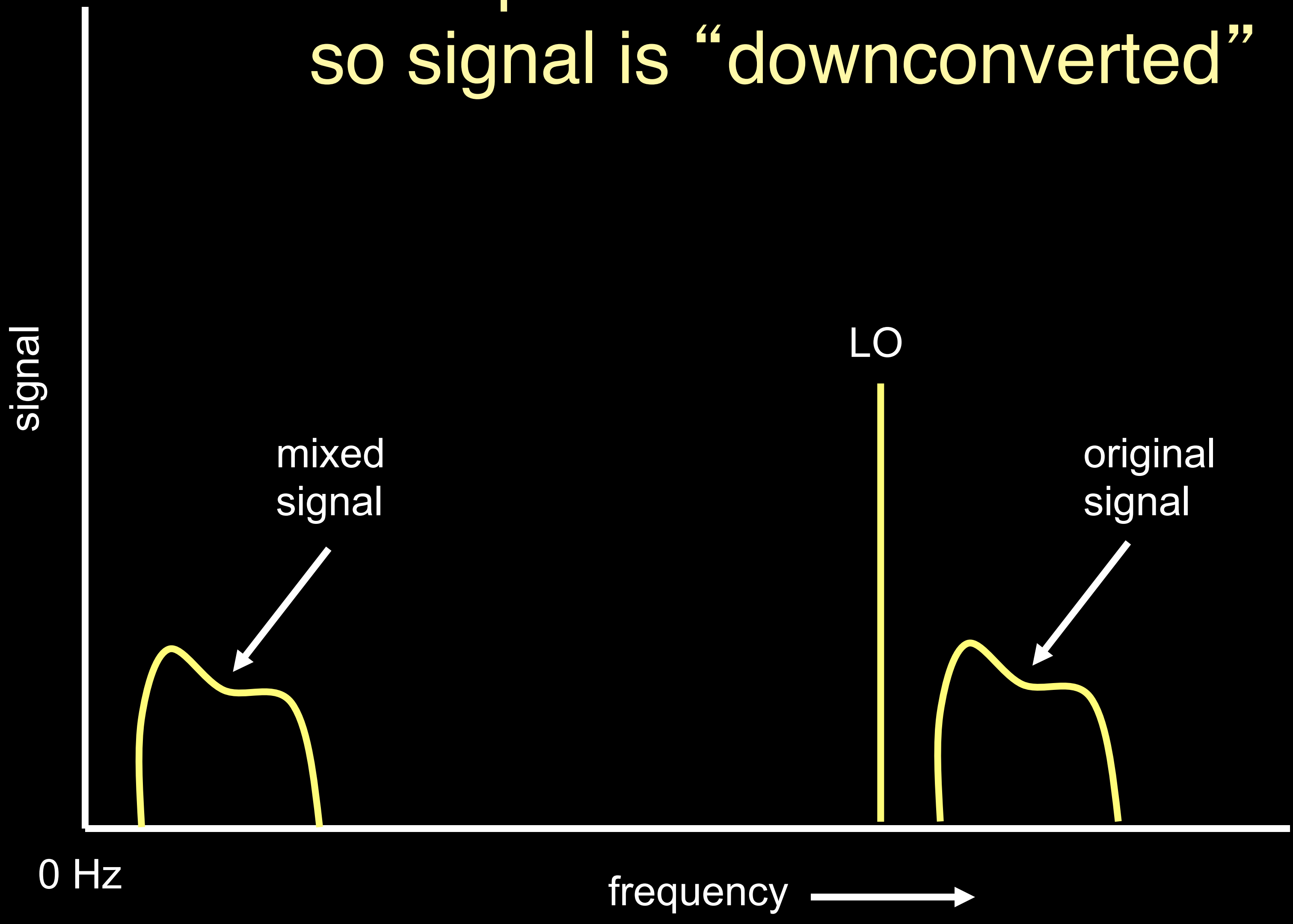
Signal Path

Where the Signal Goes after the Feedhorn

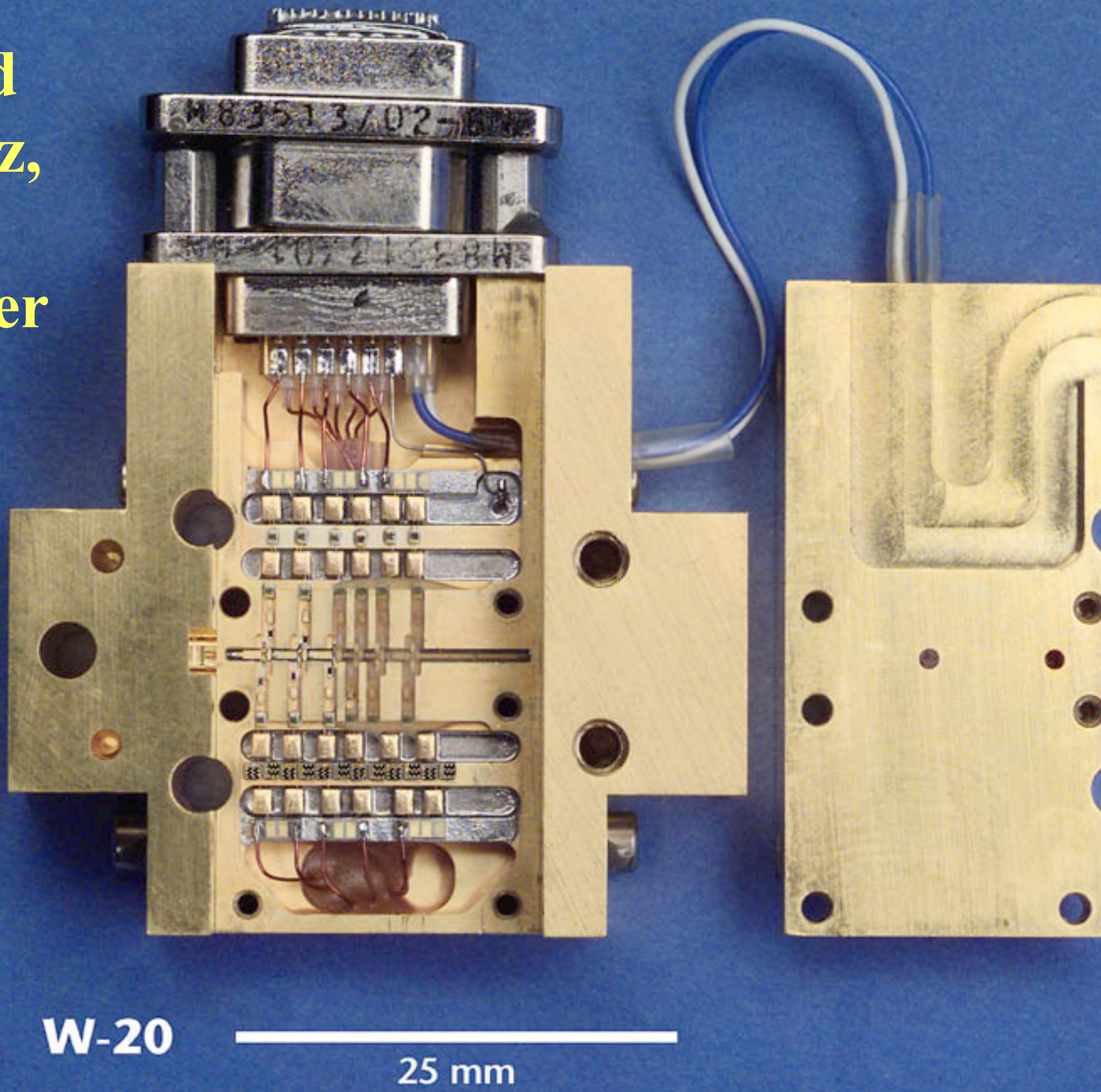


Mixers/Downconverters

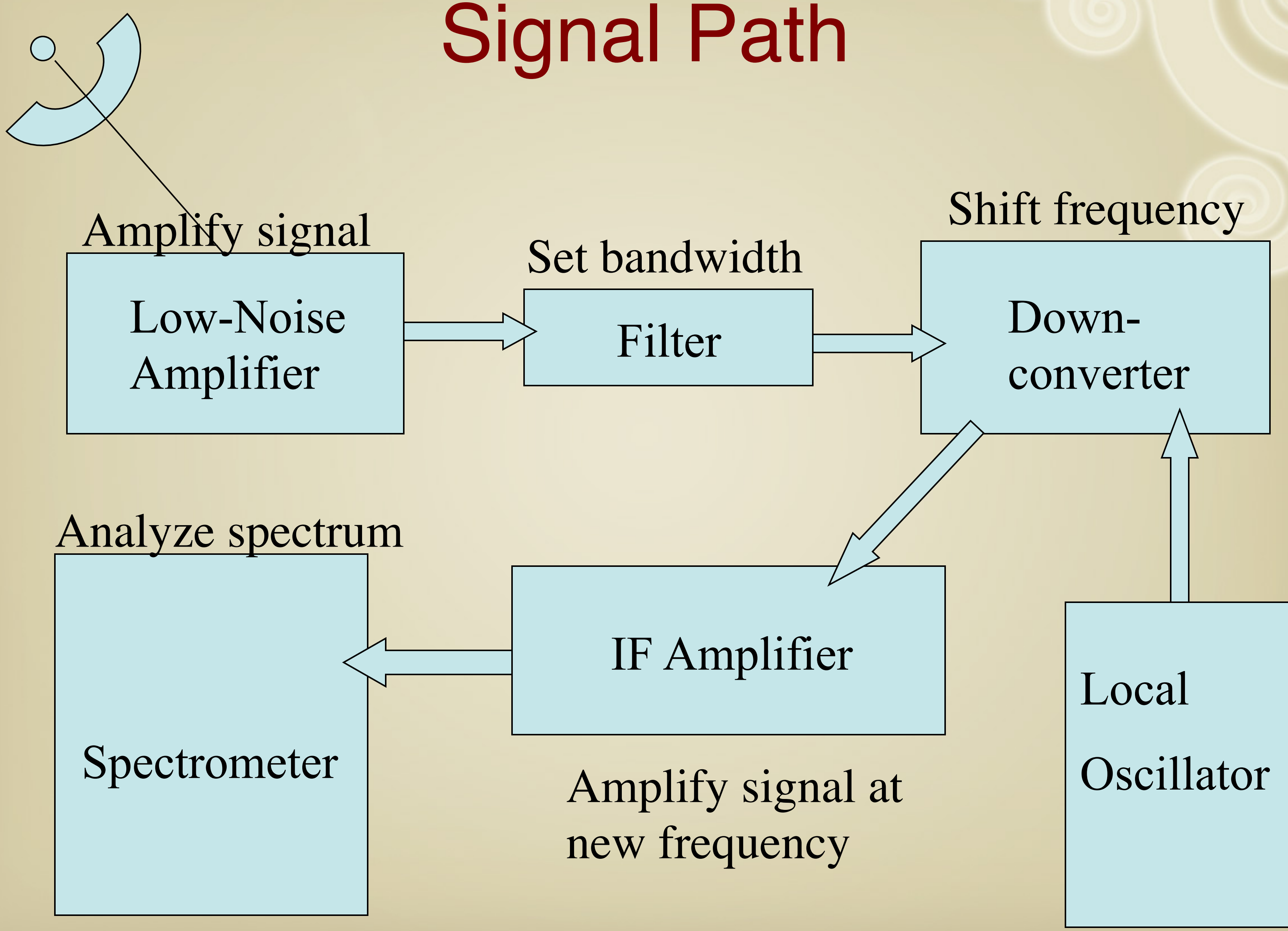
Smaller frequencies are more convenient so signal is "downconverted"



W-band
(94 GHz,
4 mm)
amplifier



Signal Path


Amplify signal
Low-Noise Amplifier
Set bandwidth
Filter
Shift frequency
Down-converter
Analyze spectrum
Spectrometer
IF Amplifier
Amplify signal at new frequency
Local Oscillator

Autocorrelation Spectrometer (WAPPS or Interim Correlator)

Or how we make sense out of the signal

- Measures the fourier transform of the power spectrum
- Special-purpose hardware computes the correlation of the signal with itself:

$$R_n = N^{-1} \Sigma_1^N [\upsilon(t_j)\upsilon(t_j+n\delta t)]$$

where δt is *lag* and υ is signal voltage; integer n ranges from 0 to $(\delta t\ \delta f)^{-1}$ if frequency channels of width δf are required

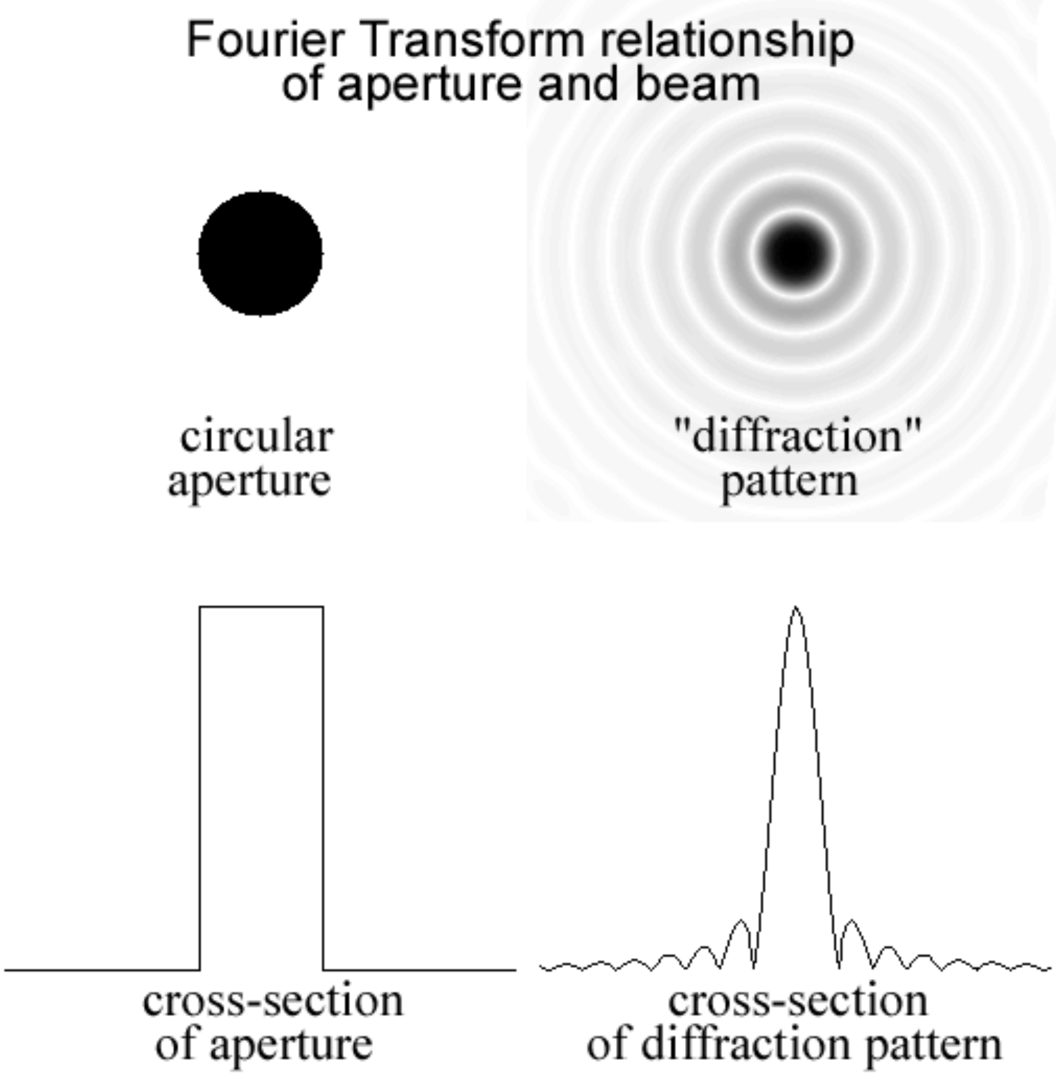
- Power spectrum is discrete Fourier transform (FFT) of R_n

Spectral Resolution

- The spectral resolution in a radio telescope can be limited by several issues:
  - integration time (signal-to-noise)
  - filter bank resolution (if you're using a filter bank to generate a power spectrum in hardware)

What a Radio Telescope "Sees"

A circular aperture, like most telescopes have, has a diffraction pattern like the one shown here – central beam plus sidelobe rings



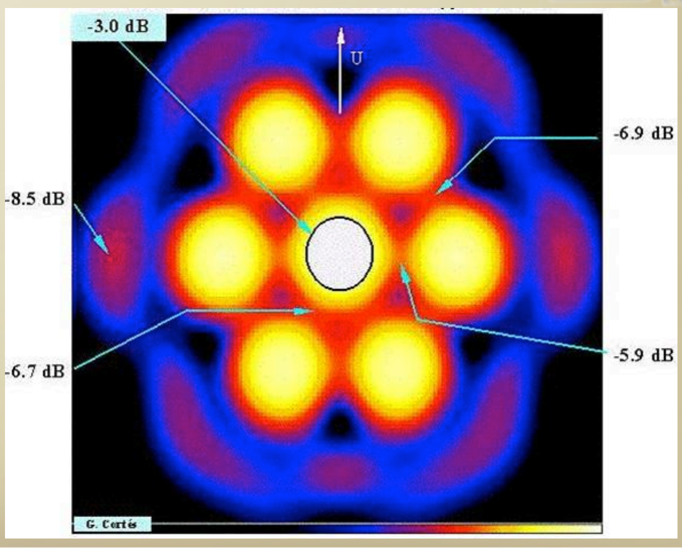
Radio Telescope Characteristics

beam and sidelobes

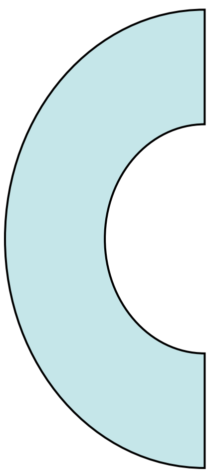
- Diffraction pattern shows sensitivity to sources on sky
- FWHM of central beam is called the *beamwidth*

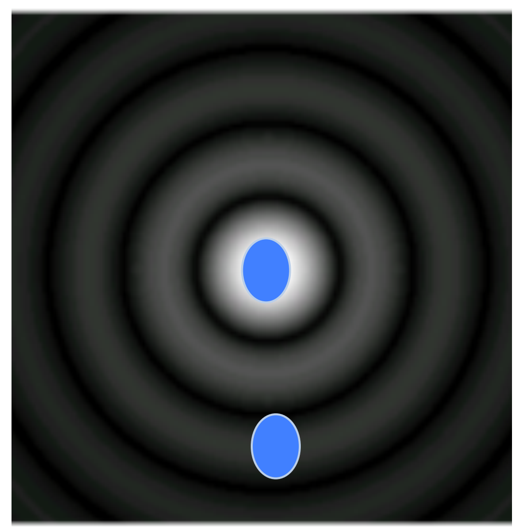
$$\sin\theta = 1.22\ (\lambda/D)$$

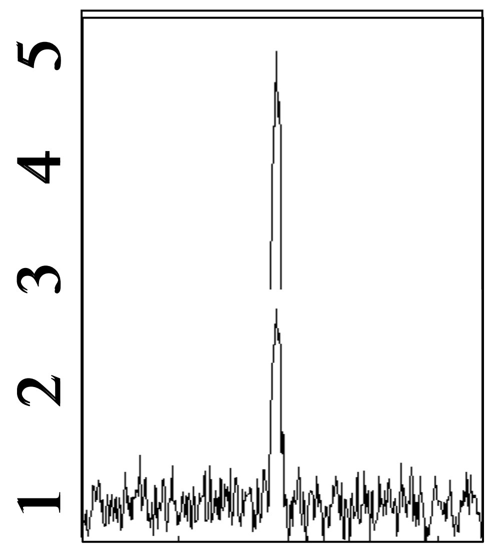
- Note that you are sensitive to sources away from beam center



Implications of Beam Size and Sidelobes







Radio Telescope Characteristics
semantics

- **Preferred unit of flux density:** (requires calibration) is Jansky:

  $$1\text{Jy} = 10^{-26}\ \text{W m}^{-2}\ \text{Hz}^{-1}$$

- **Brightness:** Flux density per unit solid angle. Brightness of sources are often given in temperature units

Radio Telescope Characteristics

Temperatures

In radio astronomy power is often measured in "temperature" - the equivalent temperature of a blackbody producing the same power

•**System temperature**: temperature of blackbody producing same power as telescope + instrumentation without a source

• **Brightness temperature:** Flux density per unit solid angle of a source measured in units of equivalent blackbody temperature

• **Antenna temperature:** The flux density transferred to the receiver by the antenna. Some of the incoming power is lost, represented by the aperture efficiency

Radio Telescope Characteristics
sensitivity

- **Sensitivity is a measure of the relationship between the signal and the noise**
- **Signal:** the power detected by the telescope
- **Noise:** mostly thermal from electronics but also ground radiation entering feedhorn and the cosmic microwave background. Poisson noise is ALWAYS important. Interference is also a HUGE problem (radar, GPS, etc.)

Radio Telescope Characteristics
power and gain

- The power collected by an antenna is approximately:

$$P = S \times A \times \Delta\nu$$

S = flux at Earth, A = antenna area, $\Delta\nu$ = frequency interval or bandwidth of measured radiation

- The gain of an antenna is given by:

$$G = 4\pi A / \lambda^2$$

- Aperture efficiency is the ratio of the effective collecting area to the actual collecting area

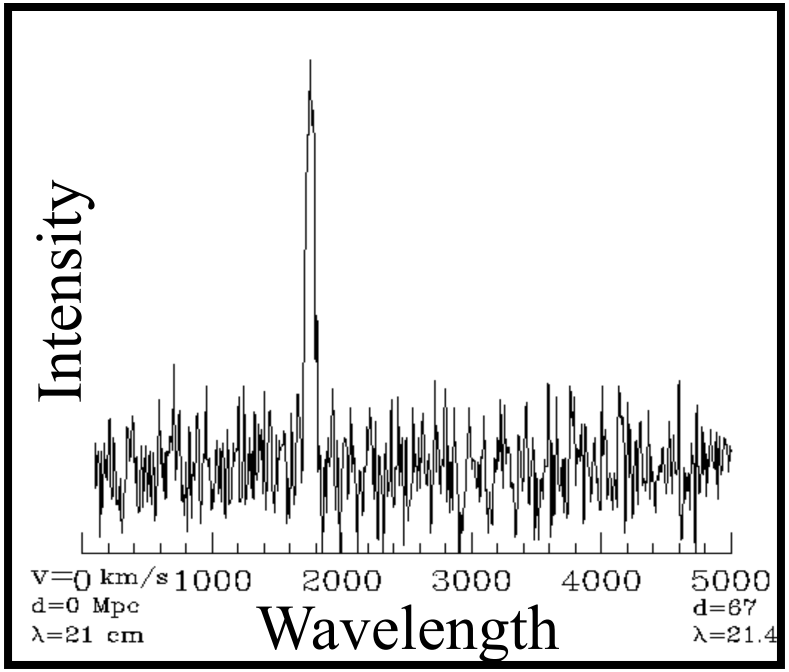
Radiometer Equation

$$T_{rms} = \alpha T_{sys} / \sqrt{\Delta \nu t}$$

- T_{rms} = rms noise in observation
- $\alpha \sim (2)^{1/2}$ because half of the time is spent off the source

  off-source = position switch

  off-frequency = frequency switch
- T_{sys} = System temperature
- $\Delta\nu$ = bandwidth, i.e., frequency range observed
- t = integration time



Radio Telescope Characteristics

polarization

- H I sources are un-polarized
- Synchrotron sources are often polarized – ***E***-field in plane of electron's acceleration
- Noise sources (man-made interference) are often polarized
- Each receiver can respond to one polarization – one component of linear or one handedness of circular polarization
- Usually there are multiple receivers to observe both polarization components simultaneously

Parameterization of Polarization

- Linear E_x and E_y with phase difference ϕ
- Stokes' parameters:

  $I = E_x^2 + E_y^2$

  $Q = E_x^2 - E_y^2$

  $U = 2E_xE_y\cos\phi$

  $V = 2E_xE_y\sin\phi$
- Unpolarized source: $E_x = E_y$ and $\phi = 0$
- Un-polarized $Q = 0$, $V = 0$, and $I = U$;
- Stokes' I = total flux (sum of x and y polarizations)

Observing Schemes: Your Technique

Our observations will implement the On-Off method. During the on exposure, the target will be tracked actively by the telescope. Next, the telescope will be moved to the position of the object at the beginning of the observation in order to flat field the image. We will observe blank sky over the same altitude and azimuth path travelled by the target. These two exposures will allow us to subtract the background from the target source, decreasing the noise in the detection. On and off pair exposures take 7 minutes total, 3 minutes on source, 1 minute to move the dish and 3 minutes off source followed by a 10 second Cal On, and a 10 second Cal Off.

Observing Radio Sources

- Signal is MUCH small than thermal noise so strong amplification and stable receivers are required
- Variations in amplifier gain monitored and corrected using switching techniques:
  – between sky and reference source
  – between object and ostensibly empty sky
  – between frequency of interest and neighboring passband.

Observing Schemes

- Position switching helps remove systematics in data

  Reduced spectrum = (ON-OFF)/OFF

  - ON: Target source observation
  - OFF: blank sky observed over the same altitude and azimuth path traveled by target (on source).
  - corrections for local environmental noise as well as background sky noise

- Two polarizations can be compared to identify RFI or averaged to improve signal for an unpolarized source

Happy Observing!!!