RA basics, noise, measurements ...

Essential Radio Astronomy:
J. J. Condon and S. M. Ransom
http://www.cv.nrao.edu/course/astr534/ERA.shtml

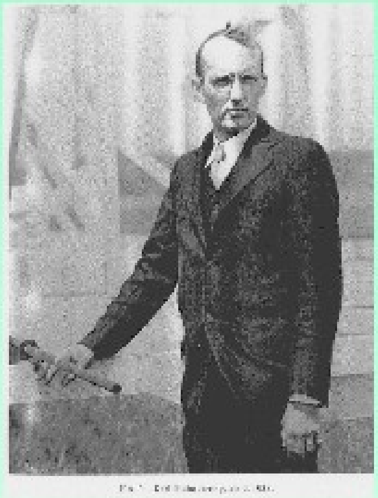
http://www.naic.edu/~astro/sdss5/

Single Dish Radio Astronomy, ASPCS 278

J. D. Kraus: Radio Astronomy

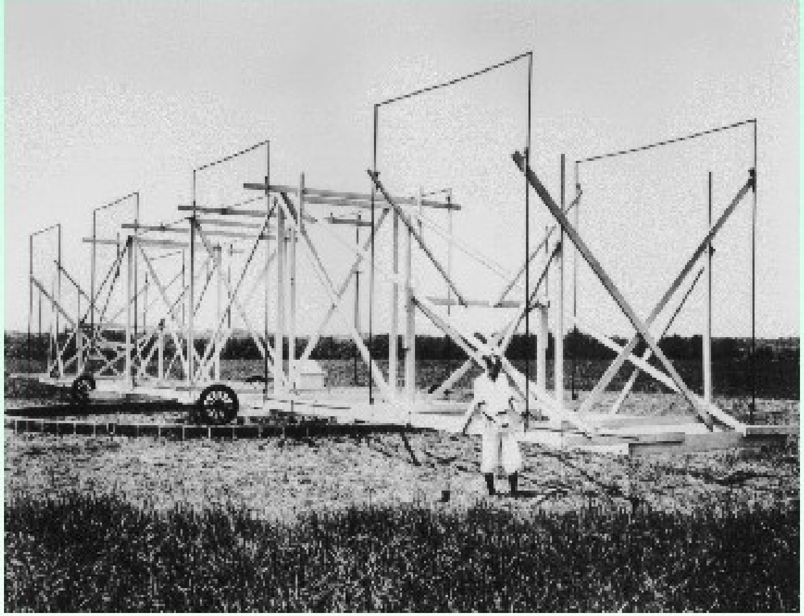
K. Rohlfs and T. L. Wilson: Tools of Radio Astronomy

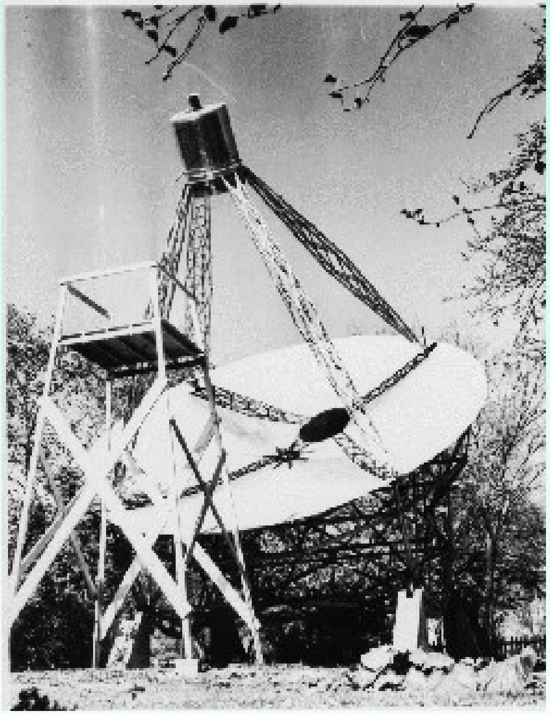
Pioneers of radio astronomy

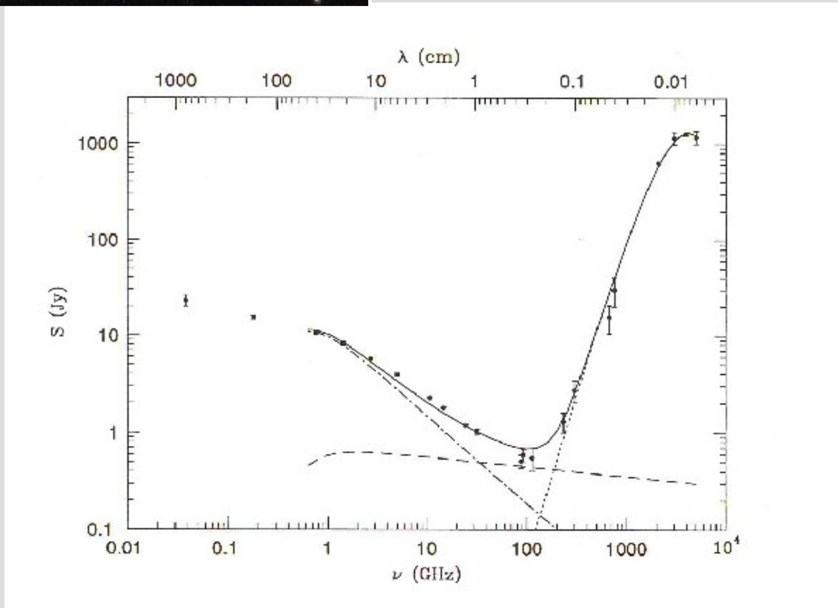


Karl Jansky
1932

Grote Reber
1938

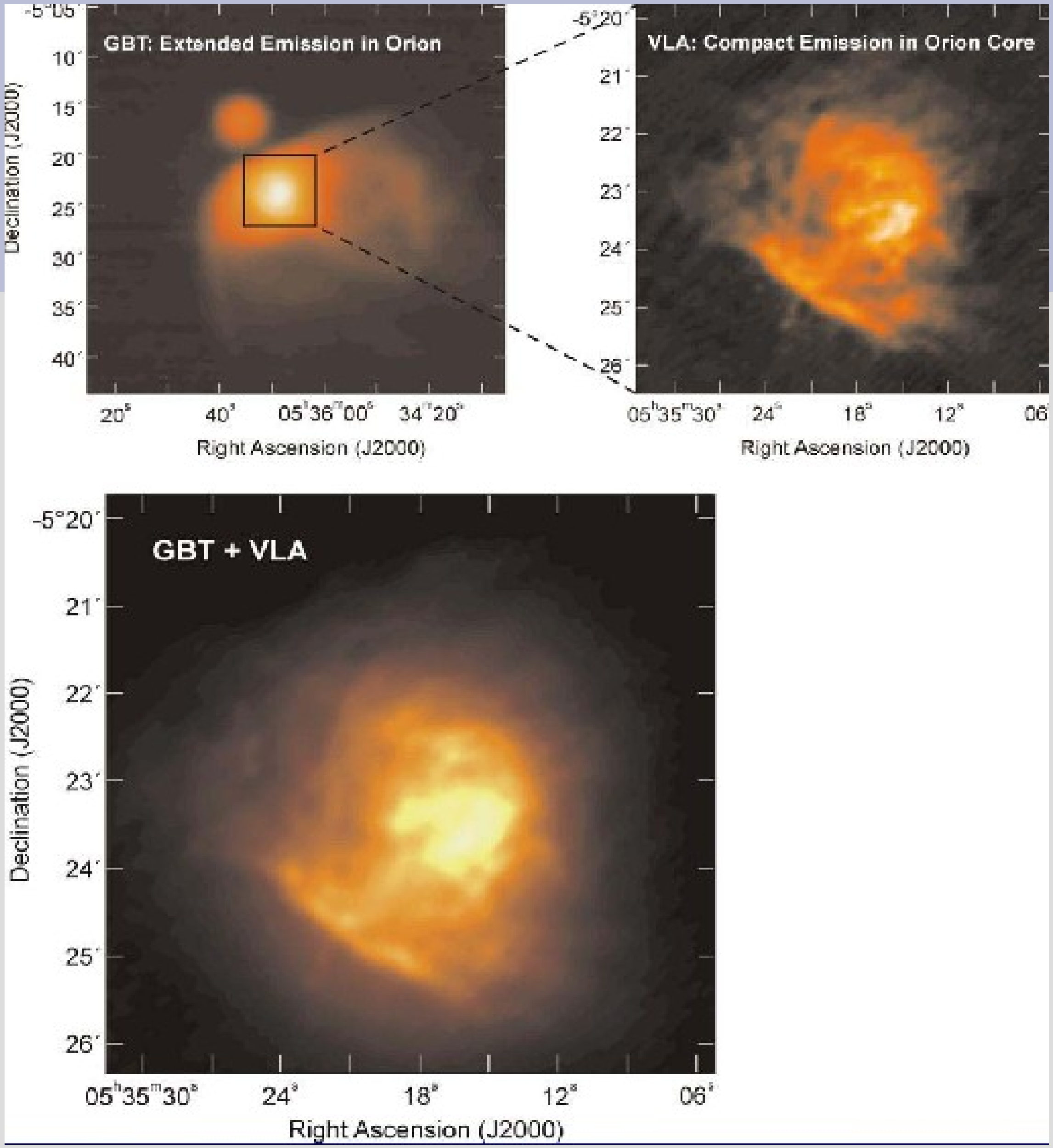






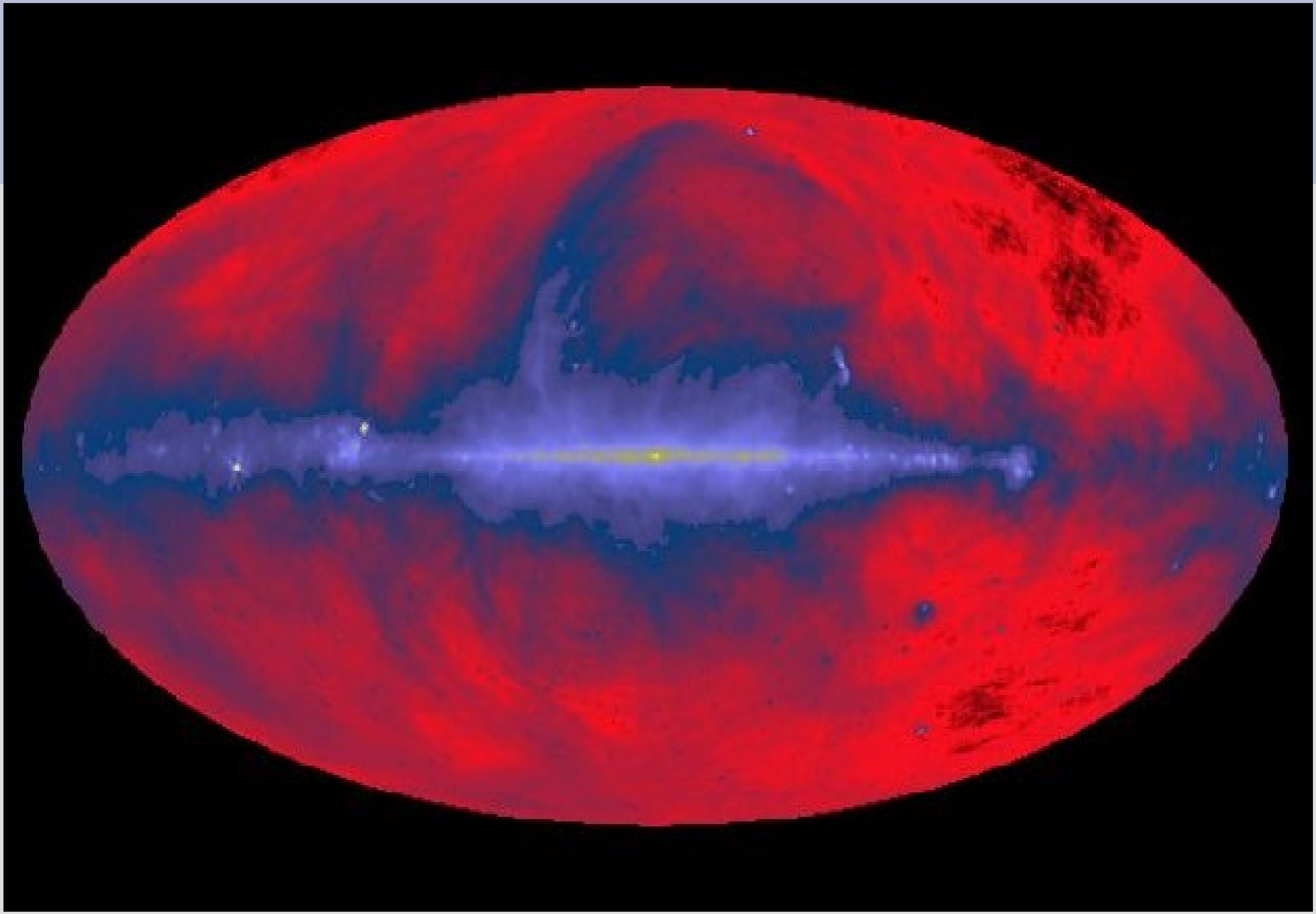
M82: starburst galaxy with a superwind
Radio spectrum: thermal + non-thermal

Photo: NASA, ESA and Hubble Heritage Team
Spectrum: Condon, 1992, ARA&A, 30, 575



Orion nebula (HII region): GBT + VLA

Slide from J. J. Condon, NAIC/NRAO School, 2003



A 408-MHz all-sky continuum survey

Haslam, Salter, Stoffel and Wilson 1982, A&AS, 47, 1

Revision: antenna fundamentals

Antenna: device for converting electromagnetic radiation in to currents (receiving) or vice versa (radiating)

in radio astronomy we use antennas for receiving radiation

A simple antenna: two collinear conductors driven at the gap by a current source (transmitter)

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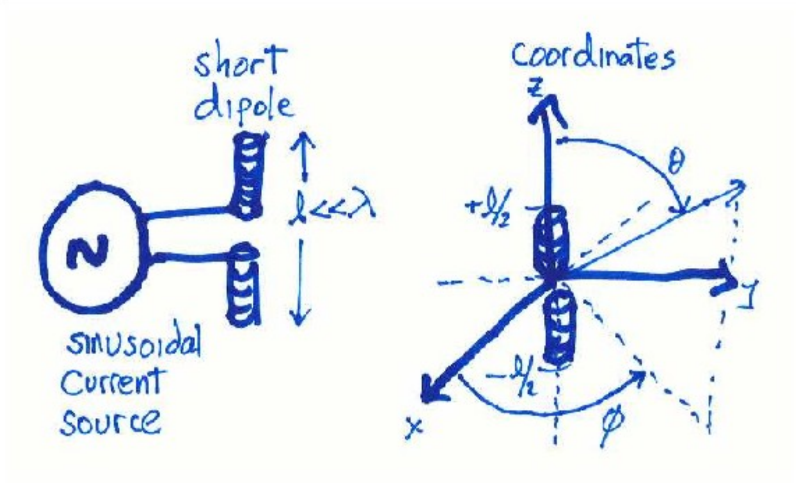


The coordinate system used to describe the radiation from a short dipole.

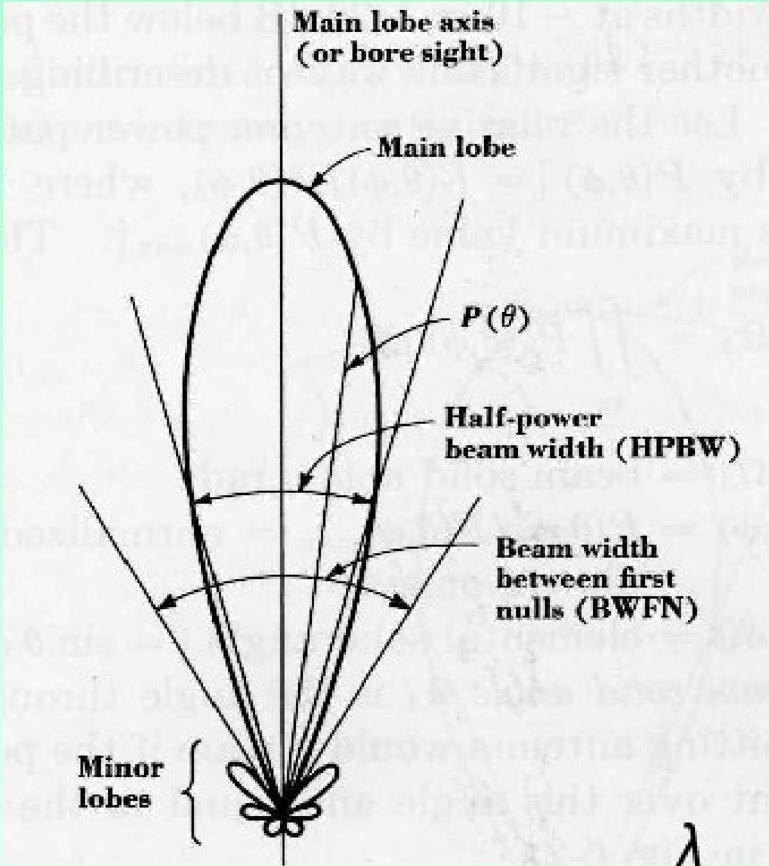
Revision: antenna fundamentals

Power pattern: angular distribution of radiated power, usually normalised to unity at the peak

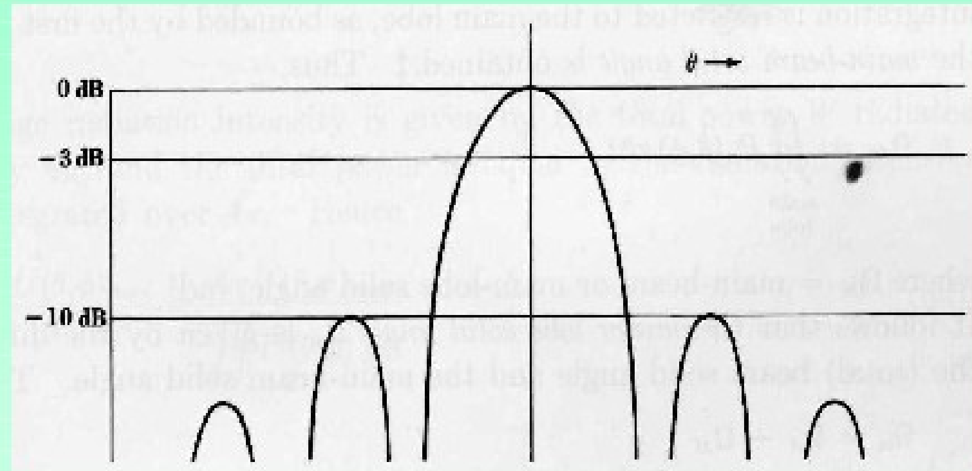
$$P \propto \sin^2\theta$$

dipole: power pattern similar to that of an accelerated charge

all the charges in the dipole are being accelerated along one short line



$$q_{HPBW} = \frac{\lambda}{D}$$



Beam solid angle (steradians) $$\Omega_A = \iint_{4\pi} P_n(\theta, \varphi)\, d\Omega$$

Antenna beam pattern or power pattern

J. D. Kraus: Radio Astronomy
F. D. Ghigo: Fourth NAIC-NRAO School, July 2007

Some definitions and relations

Main beam efficiency, $\boldsymbol{\varepsilon}$

$$\varepsilon_M = \frac{\Omega_M}{\Omega_A}$$

Antenna theorem

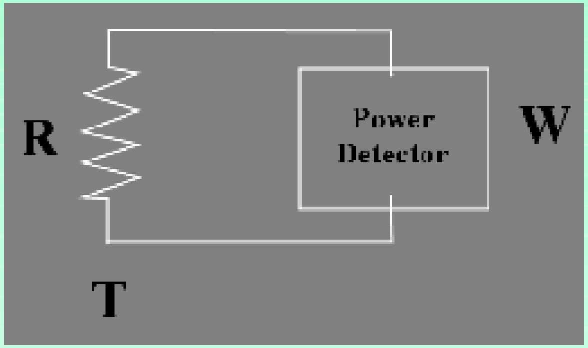
$$\Omega_A = \frac{\lambda^2}{A_e}$$

Aperture efficiency, $\boldsymbol{\varepsilon}_{ap}$
Effective aperture, A_e
Geometric aperture, A_g

$$\varepsilon_{ap} = \frac{A_e}{A_g}$$

$$\varepsilon_{ap} = \varepsilon_{pat}\,\varepsilon_{surf}\,\varepsilon_{block}\,\varepsilon_{ohmic}\cdots$$

Detected power (W, watts) from a resistor R
at temperature T (kelvin) over bandwidth β (Hz)



$$W = kT\beta$$

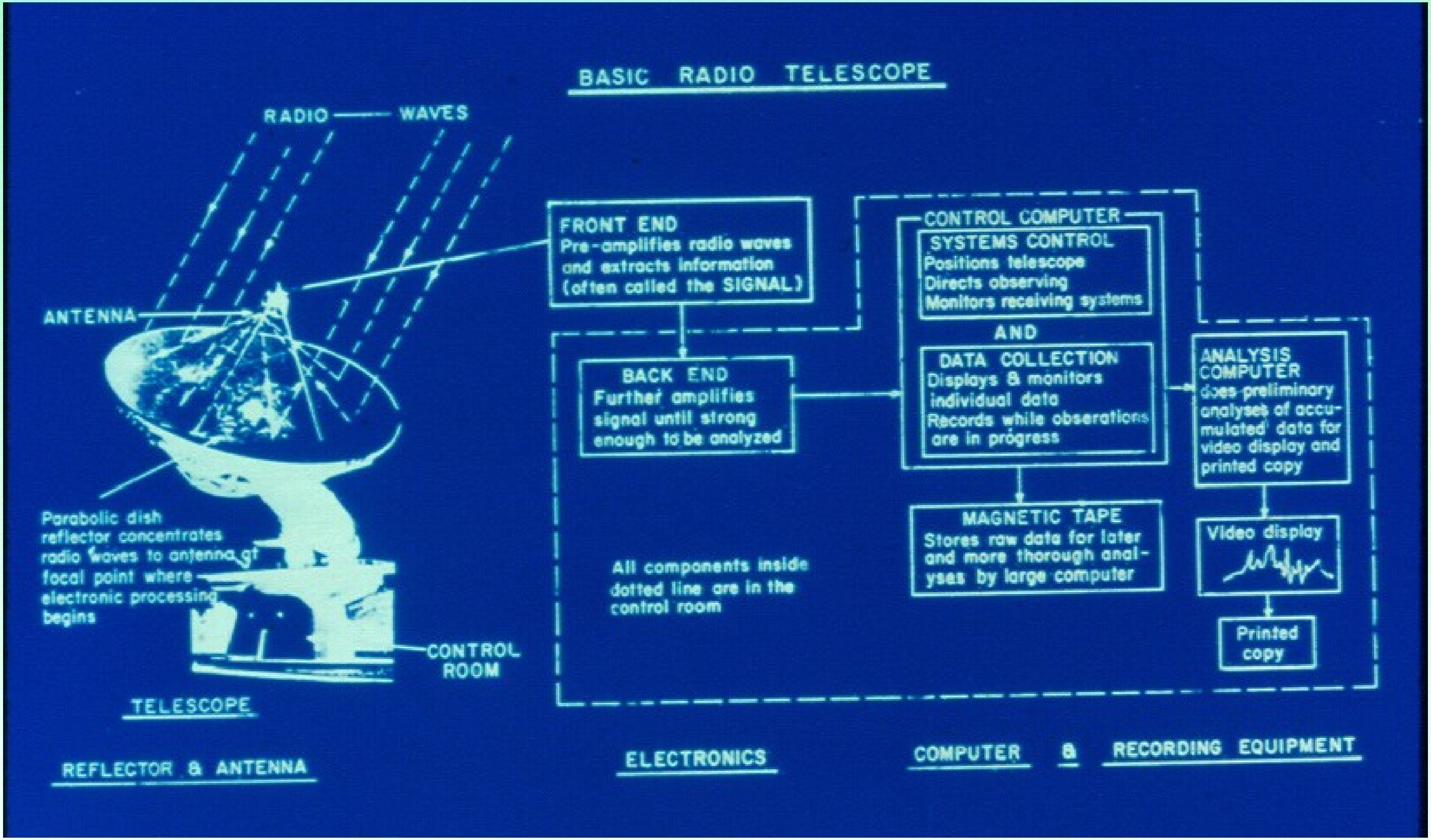
Power W_A detected in a radio telescope
Due to a source of flux density S

$$W_A = \frac{1}{2} A S \beta$$

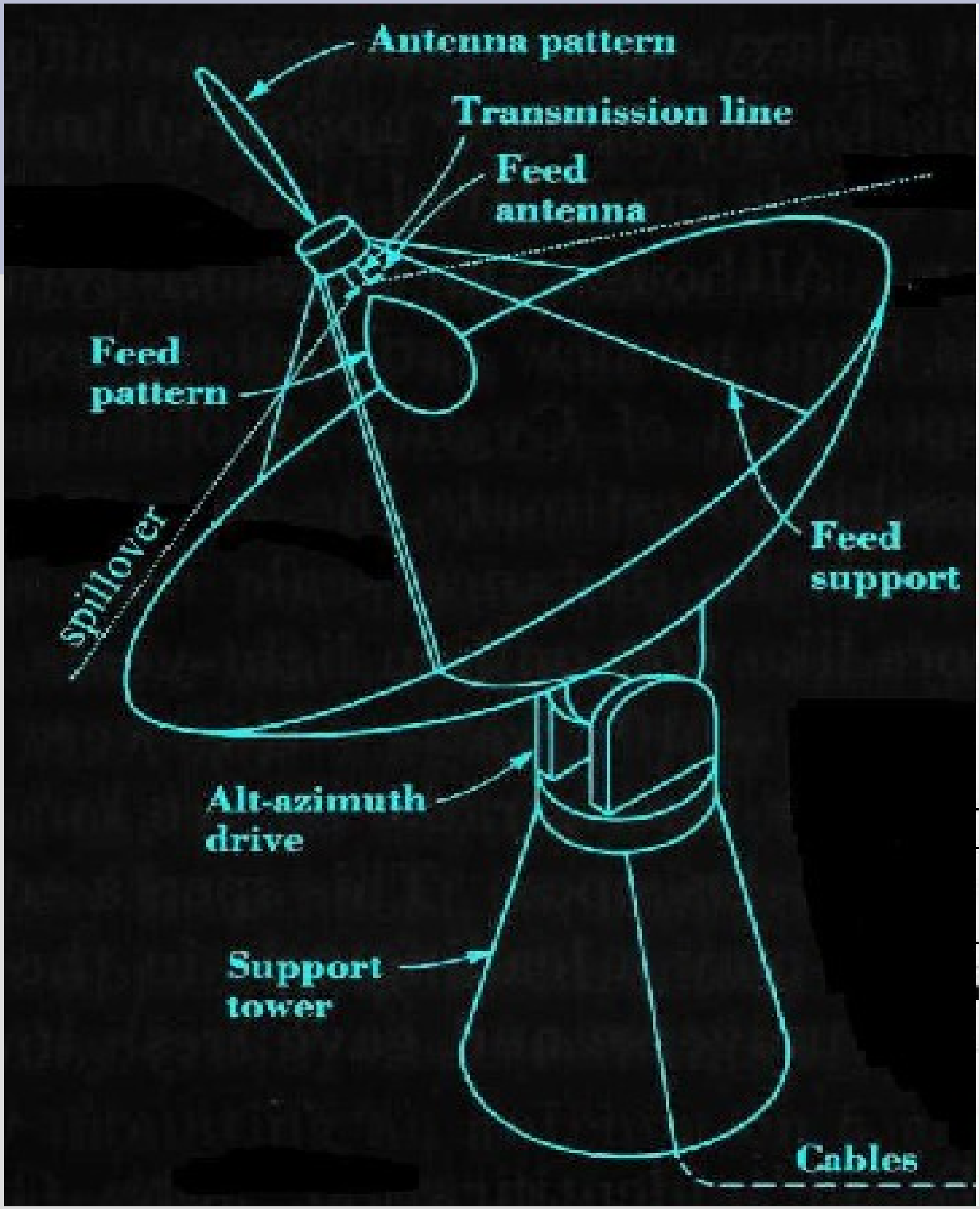
power as equivalent temperature.
Antenna Temperature T_A
Effective Aperture A_e

$$S = \frac{2kT_A}{A_e}$$

Basic Radio Telescope



Verschuur, 1985. Slide set produced by the Astronomical Society of the Pacific, slide #1.



Kraus: Radio Astronomy and Frank Ghigo, Fourth NAIC-NRAO School, July 2007

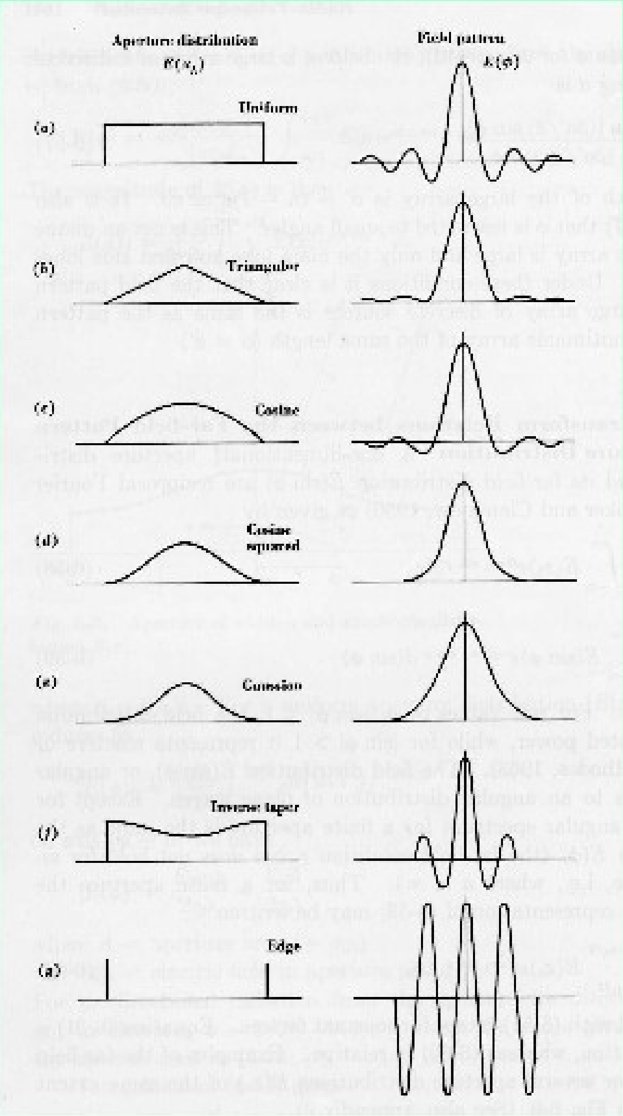
Aperture Illumination Function

←→

Beam Pattern

A gaussian aperture illumination gives a gaussian beam:

$$\varepsilon_{pat} \approx 0.7$$



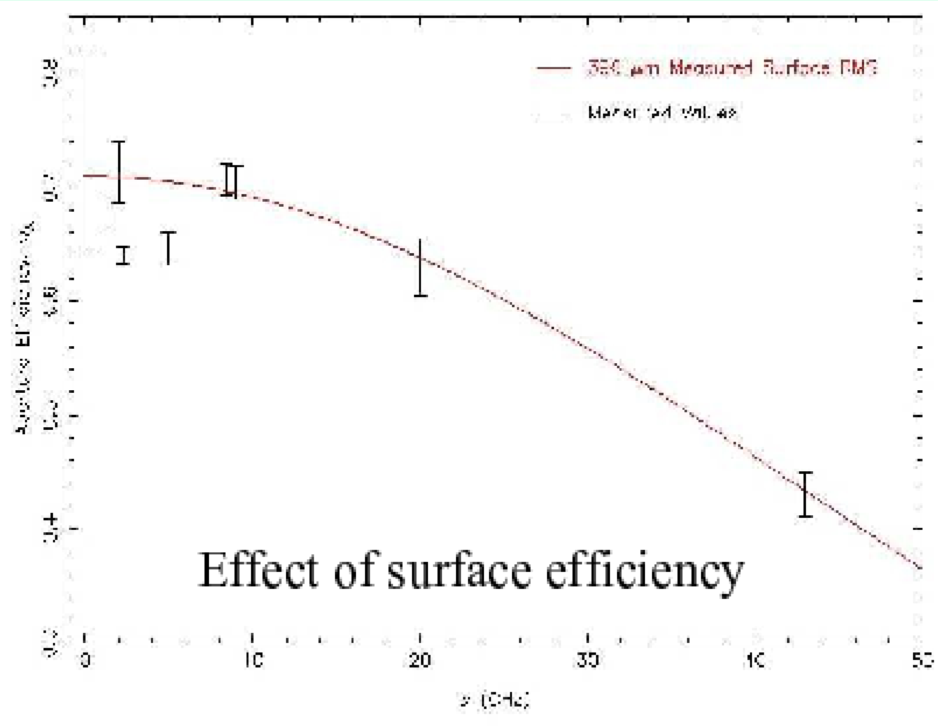
Kraus, 1966. Fig.6-9, p.168.

Gain(K/Jy) for the GBT

$$S = \frac{2kT_A}{A_e} \qquad G = \frac{T_A}{S} = \frac{e_{ap} A_g}{2k} \qquad G(K/Jy) = 2.84 \cdot \varepsilon_{ap}$$

Including atmospheric absorption:

$$S = \frac{2kT_A}{A_e} e^{\tau a}$$



Power Received:

$$P_{rec}(\nu) = 1/2 \; A_e \int_\Omega I_\nu(\theta,\varphi) \; P_n(\theta,\varphi) \; d\Omega \quad \mathrm{watts\,Hz^{-1}}$$

Effective Area ^

Source ^ ^ Antenna Pattern

Power Received in bandwidth Δv :

$$P_{rec} = \int_{-\Delta\nu/2}^{\Delta\nu/2} P_{rec}(\nu) \; d\nu \quad \mathrm{watts}$$

For thermal sources (Planck's Law):

$$I_\nu(\theta,\varphi) = \frac{2h\nu^3}{c^2} \; \frac{1}{e^{h\nu/kT(\theta,\varphi)} - 1} \quad \mathrm{watts\,m^{-2}\;ster^{-1}\;Hz^{-1}}$$

$$I_\nu(\theta, \varphi) = 2kT(\theta, \varphi)/\lambda^2$$

Substituting, this gives the following Rayleigh-Jeans approximation:

$$P_\nu = \frac{kA_e}{\lambda^2} \int_\Omega T(\theta, \varphi)\ P_n(\theta, \varphi)\ d\Omega \quad \text{watts Hz}^{-1}$$

Antenna Temperature

Power available at terminal of a resistor:

$$W = kT \quad \text{watts Hz}^{-1}$$

Replace the antenna with a matched resistor at a physical temperature that *gives* the same response:

$$P_\nu = kT_A \quad \text{watts Hz}^{-1}$$

$$\text{and} \quad T_A = \frac{A_e}{\lambda^2} \int_\Omega T(\theta,\varphi)\, P_n(\theta,\varphi)\, d\Omega$$

$$= \frac{1}{\Omega_A} \int_\Omega T(\theta,\varphi)\, P_n(\theta,\varphi)\, d\Omega,$$

T_A is defined as the ANTENNA TEMPERATURE.

Flux Density

Spectral flux density for a discrete source (one with a clear boundary):

$$S = \int_{source} I_\nu(\theta, \varphi)\ d\Omega \quad \mathrm{watts\,m^2\ Hz^{-1}}$$

Observed Flux Density:

$$S_o \ = \int_{source} I_\nu(\theta, \varphi)\ P_n(\theta, \varphi)\ d\Omega \quad \mathrm{watts\,m^{-2}\ Hz^{-1}}$$

This is $\leq$ S depending on the size of the source.

Large Source:

$$S_o = I_\nu(\theta,\varphi) \int P_n(\theta,\varphi)\ d\Omega \approx I_\nu(\theta,\varphi)\ \Omega_A \quad \mathrm{watts\,m^{-2}\ Hz^{-1}}$$

Small Source

$$S = S_o \;=\; P_n(0,0) \int_{source} I_\nu(\theta,\varphi)\ d\Omega$$

$$= \int_{source} I_\nu(\theta,\varphi)\ d\Omega \quad \mathrm{watts\,m^{-2}\ Hz^{-1}}$$

The standard unit of spectral flux density in radio astronomy is the Jansky:

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

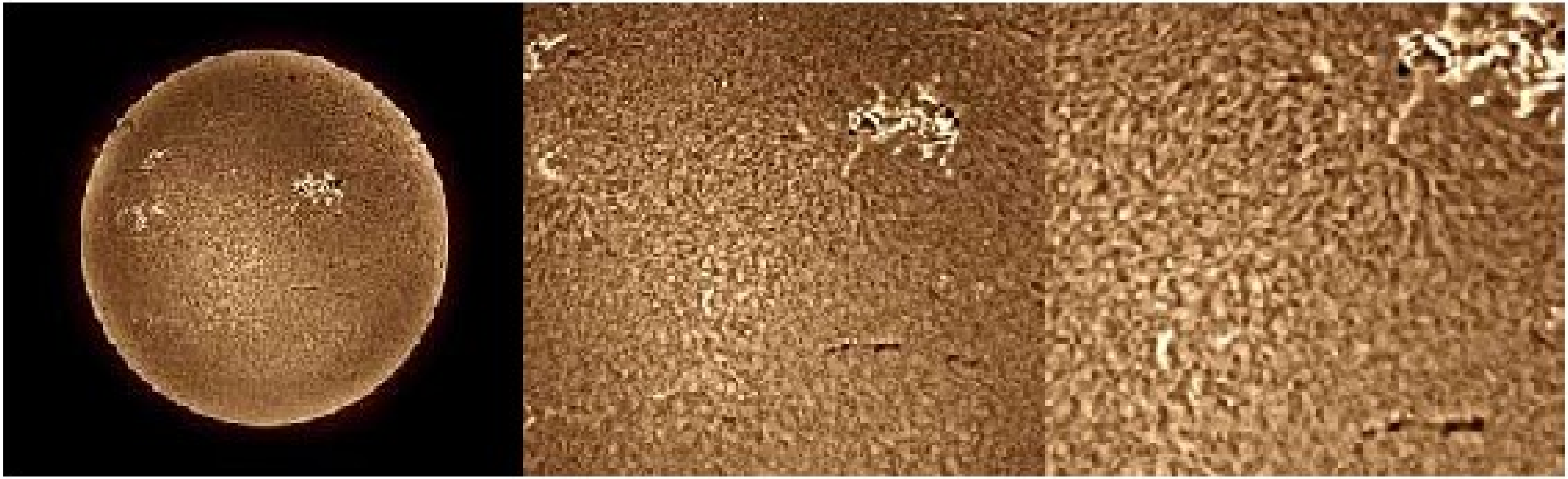
From earlier equations:

$$P_\nu = kT_A = 1/2 A_e \, S_o \quad \text{watts Hz}^{-1}$$

which gives:

$$T_A/S_{oJ} = A_e \, 10^{-26}/2k \quad \text{Kelvins/Jy}$$

An effective aperture of 2760 m^2 is required to give a sensitivity of 1.0 K/Jy.



The Sun in three imaginary photos taken from a long distance (left), medium distance (center), and short distance (right) would have a constant brightness but increasing angular size.

Brightness of a source (Sun) does not depend on the distance

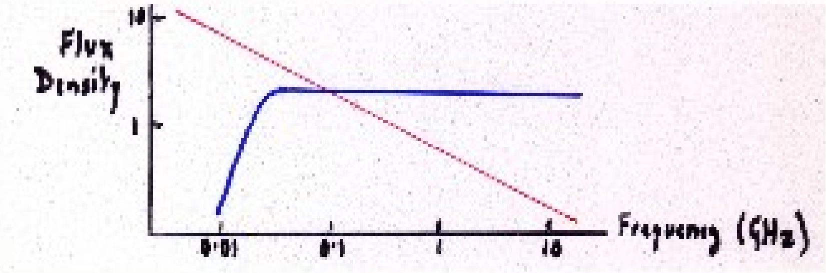
Flux density of a source (Sun) depends inversely on the square of its distance

Image from Essential Radio Astronomy: J. J. Condon and S. M. Ransom

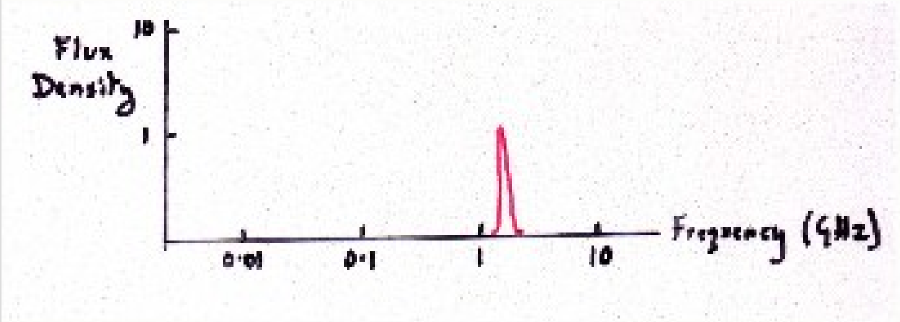
Radio continuum and line emission

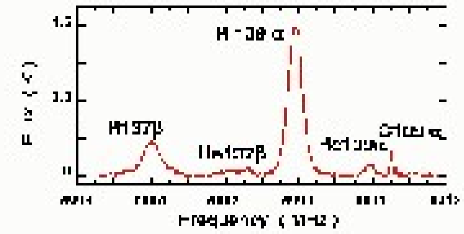
Celestial radio emission can be subdivided into two main spectral categories:

1. Broadband or Continuum Emission.
   Typical examples: (a) planetary surfaces, (b) HII regions, (c) the Cosmic Microwave Background & (d) those Galactic and extragalactic sources that emit via the synchrotron process.

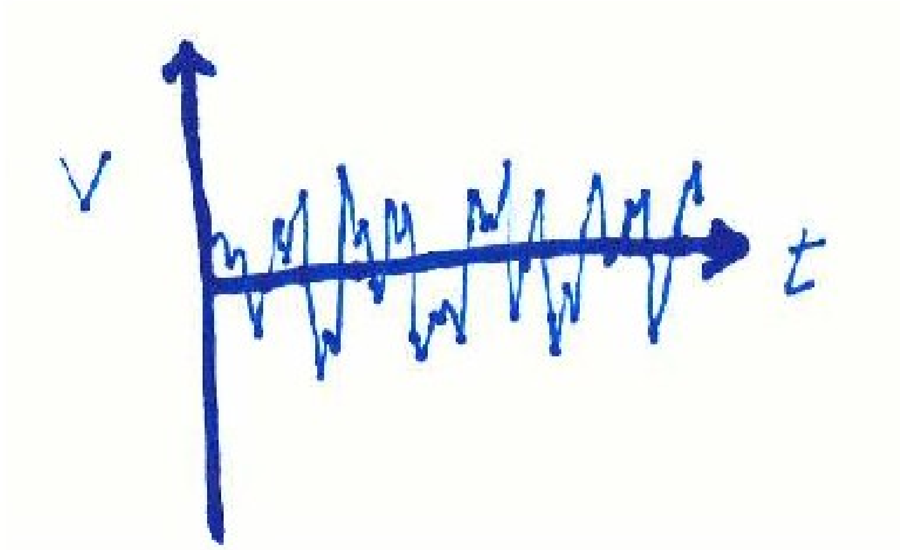


2. Line emission due to low-energy transitions within atoms and molecules in space.





Terzian & Lewis, (unpublished)



The antenna output voltage produced by an astronomical continuum source varies rapidly on short time scales, but the longer-term average power is steady.

The purpose of the simplest ***total-power radiometer*** is to measure the timed-averaged power of this noise in some well-defined radio frequency (RF) range

$$\nu_{\rm RF} - \frac{\Delta\nu_{\rm RF}}{2} \ \text{ to } \ \nu_{\rm RF} + \frac{\Delta\nu_{\rm RF}}{2},$$

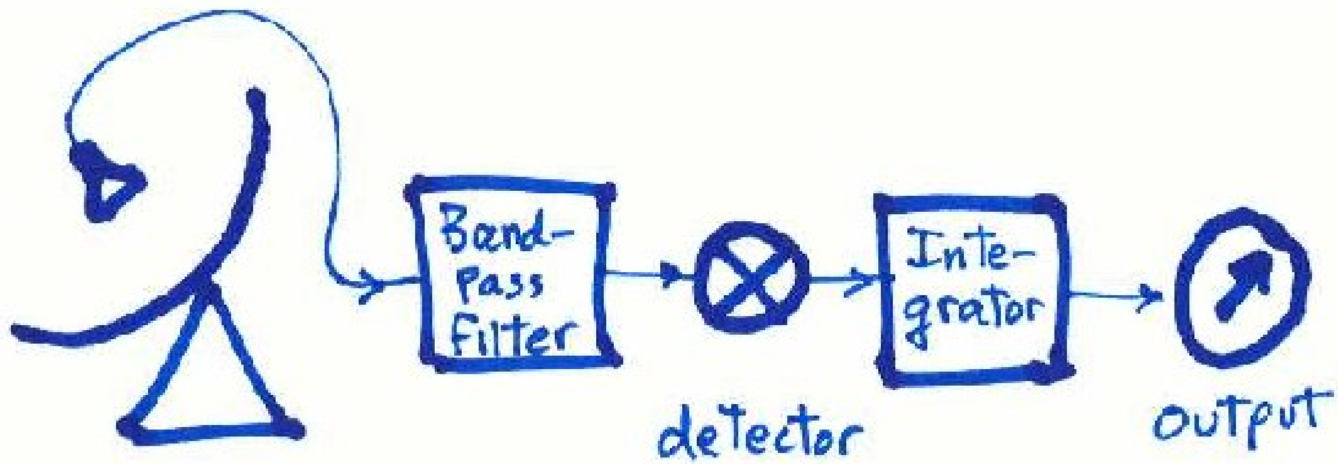
Radio emission from a celestial source is essentially random noise; nearly indistinguishable from noise generated by a warm resistor
Normally this noise is also stationary; its time-averaged power does not change during the course of the observations.
Instantaneous power produced by the source varies erratically on time scales as short as the inverse of the receiver bandwidth

$$T_N \equiv \frac{P_\nu}{k} \quad (3F1)$$

where $k \approx 1.38 \times 10^{-23}$ Joule K^{-1} is the Boltzmann constant.

The conceptually simplest radiometer consists of three stages in series:

(1) an ideal (lossless) ***bandpass filter*** that passes input noise only in the desired frequency range,
(2) an ideal ***square-law detector*** whose output voltage is proportional to the square of its input voltage; that is, its output voltage is proportional to its input power,
(3) and a signal averager or ***integrator*** that smoothes out the rapidly fluctuating detector output.



The simplest radiometer filters the broadband noise coming from the telescope, multiplies the signal voltage by itself (square-law detection), and smoothes the detected voltage, which can be read by a meter as shown.

The temperature equivalent to the *total* noise power from all sources referenced to the input of an ideal receiver input is called the **system noise temperature**:

$$T_{sys} = T_{cmb} + \Delta T_{source} + T_{atm} + T_{spillover} + T_{rcvr} + \ \ldots \qquad (3F2)$$

The contributions listed explicitly in Equation 3F2 are $T_{cmb} \approx 2.73$ K from the cosmic microwave background, ΔT_{source} from the astronomical source being observed, T_{atm} from atmospheric emission in the telescope beam, $T_{spillover}$ to account for radiation that the feed picks up in directions beyond the edge of the reflector, and T_{rcvr} to represent the noise power generated by the receiver itself, referenced to the receiver input. The desired signal ΔT_{source} was written with a Δ to emphasize that it is usually much smaller than the total system noise: $\Delta T_{source} \ll T_{sys}$. For example, in the $\nu_{RF} \approx 4.85$ GHz sky survey made with the 300-foot telescope, the system noise was $T_{sys} \approx 60$ K, but the faintest sources detected contributed only $\Delta T_{source} \approx 0.01$ K.

Contribution from the Milky Way galaxy and the CMB changes greatly with frequency. At 38 MHz T_Gal ~10**4 – 10**5 K. At 327 MHz T_Gal ~ 20 to 2000 K, and negligible above ~5 GHz At higher frequencies, contribution from the CMB dominates.

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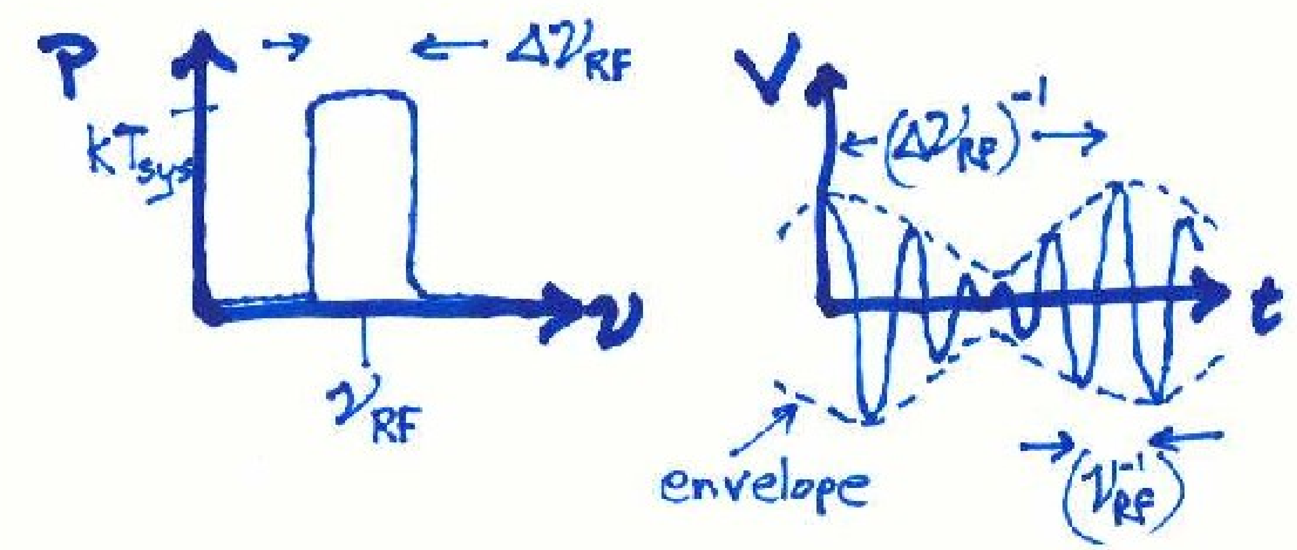
Chris Salter: NAIC-NRAO School; July 2005

After passing through an input filter of width $\Delta\nu_{\mathrm{RF}} < \nu_{\mathrm{RF}}$ the noise signal is no longer completely random; it becomes more like a sine wave of frequency $\approx \nu_{\mathrm{RF}}$ whose amplitude envelope is ***modulated*** (varies) on time scales $\Delta t \approx (\Delta\nu_{\mathrm{RF}})^{-1} > \nu_{\mathrm{RF}}^{-1}$. The positive and negative envelopes are similar so long as $\Delta\nu_{\mathrm{RF}} \ll \nu_{\mathrm{RF}}$.



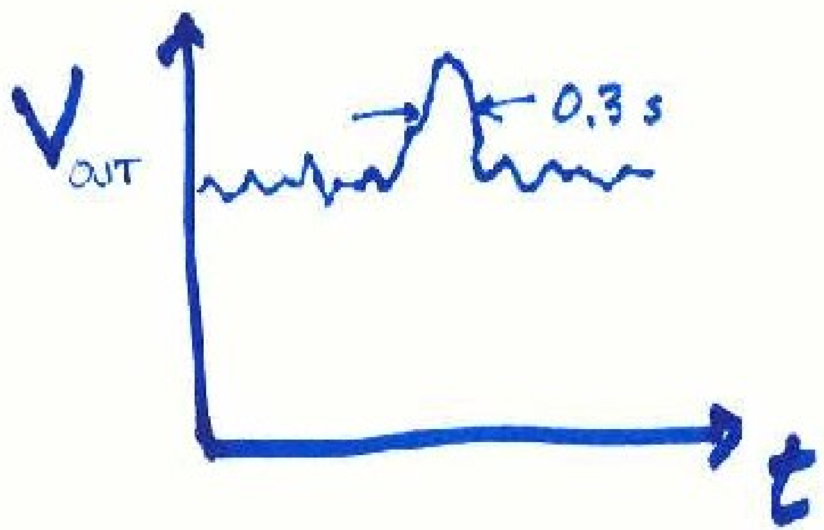
The noise voltage output of a filter with center frequency ν_{RF} and bandwidth $\Delta\nu_{\mathrm{RF}}$ is a sinusoid with frequency ν_{RF} whose envelope fluctuates on time scales $(\Delta\nu_{\mathrm{RF}})^{-1} > (\nu_{\mathrm{RF}})^{-1}$.

Since the input filter does not pass signals with zero frequency (DC), the time-averaged voltage is nearly zero. However, the average *power* at the filter output is not zero; it is

$$P \approx P_\nu \Delta\nu_{\mathrm{RF}}$$

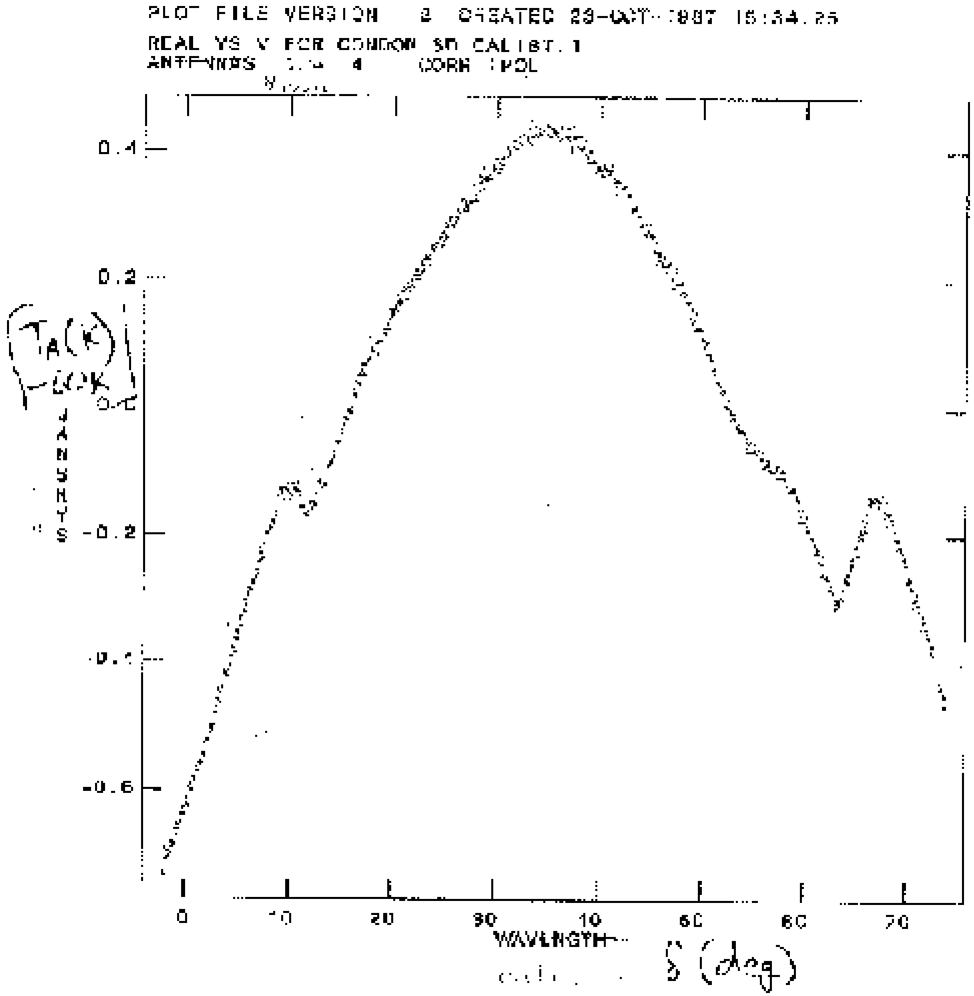
The filter output is sent to a square-law detector, a device whose output voltage is proportional to the square of the input voltage, which in turn is proportional to the input power. The detector

The scanning time between half-power points was thus ≈ 0.3 s.

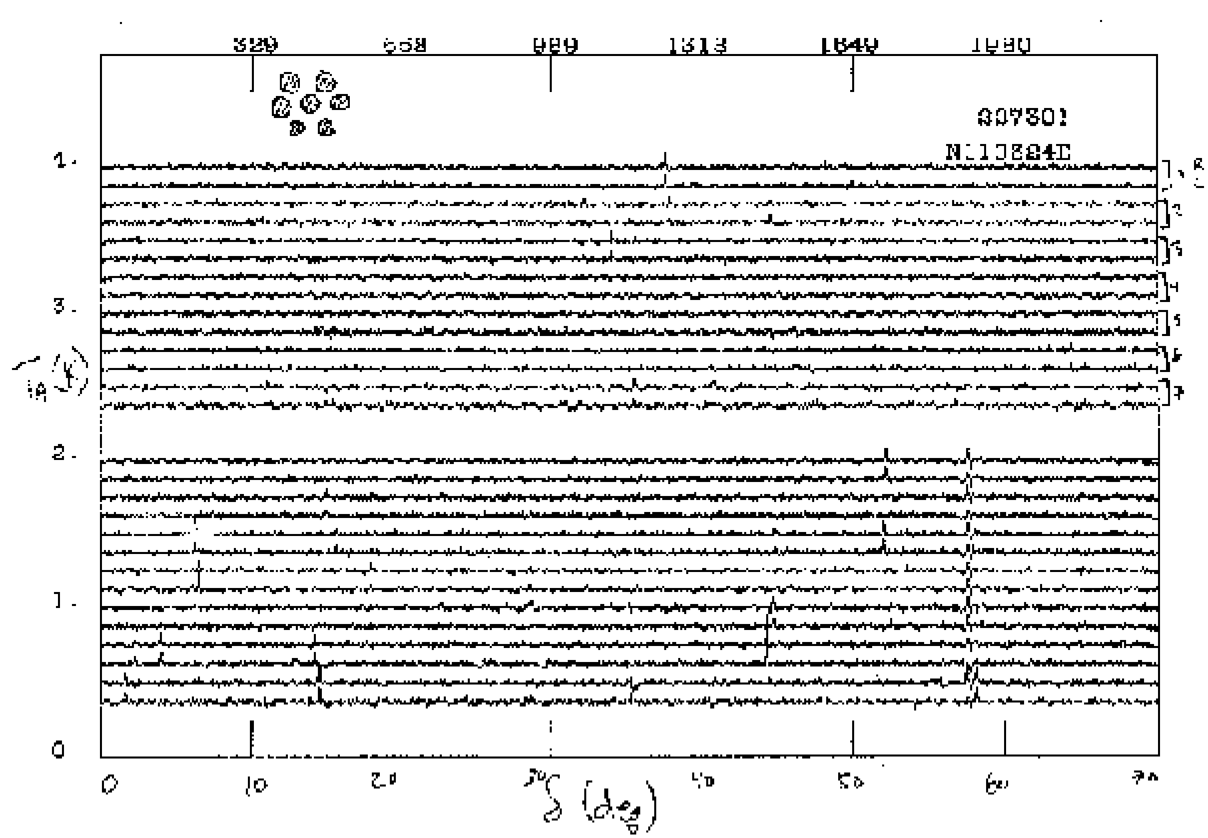


A point source appears as a Gaussian with FWHM duration 0.3 s in the receiver output.

The data were integrated and sampled every $\tau = 0.1$ s, so there were ≈ 3 samples per half-power beamwidth. A subset of the samples taken from one receiver during one scan covering the declination range $\delta \approx -2°$ to $\delta \approx +73°$ is shown.



The intensity scale has been calibrated in Kelvins, and the large mean $T_{sys} \approx 60$ K has been subtracted. By far the biggest time-dependent signal (spanning a range of about 1 K) is caused by ground radiation entering the prime-focus feed via leakage through the reflector mesh and spillover. Fortunately, this unwanted ground signal varies smoothly with telescope elevation, so subtracting a short (about 40 arcmin long) running-median baseline takes out the spillover signal without removing compact radio sources. The outputs from all 14 receiver channels (7 beams × 2 polarizations/beam) after baseline subtraction are shown in the next viewgraph. Only now are the faint radio sources visible above the noise fluctuations.



Data from all 14 receivers after subtraction of running-median baselines. Sources appear as spikes in both polarization channels (R and L) of one or two beams. Interference is usually visible in all 14 receivers simultaneously.

The rms noise observed is consistent with the prediction of the total-power radiometer equation:

$$\sigma_T \approx \frac{T_{sys}}{\sqrt{\Delta\nu_{RF}\tau}} \approx \frac{60\,\mathrm{K}}{\sqrt{6\times10^8\,\mathrm{Hz}\times0.1\,\mathrm{s}}} \approx 0.008\,\mathrm{K}$$

Note that the output of a total-power receiver scales in proportion to the overall gain G of the receiver:

$$P_\nu = GkT_{sys}$$

If G isn't perfectly constant, the change in output

$$\Delta P_\nu = \Delta GkT_{sys}$$

caused by a ***gain fluctuation*** ΔG produces a change

$$\Delta T_G = T_{sys}\left(\frac{\Delta G}{G}\right)$$

which is indistinguishable from a comparable change ΔT in the system noise temperature produced by an astronomical source. Since gain fluctuations and input noise fluctuations are independent random processes, their ***variances*** (the variance is the square of the rms) add, and the total receiver output fluctuation becomes:

$$\sigma^2_{total} = \sigma^2_{noise} + \sigma^2_G$$

$$\sigma^2_{total} = T^2_{sys}\left[\frac{1}{\Delta\nu_{RF}\tau} + \left(\frac{\Delta G}{G}\right)^2\right]$$

The ***practical total-power radiometer equation*** is thus:

$$\sigma_T \approx T_{sys}\left[\frac{1}{\Delta\nu_{RF}\tau} + \left(\frac{\Delta G}{G}\right)^2\right]^{1/2} \quad (3F4)$$

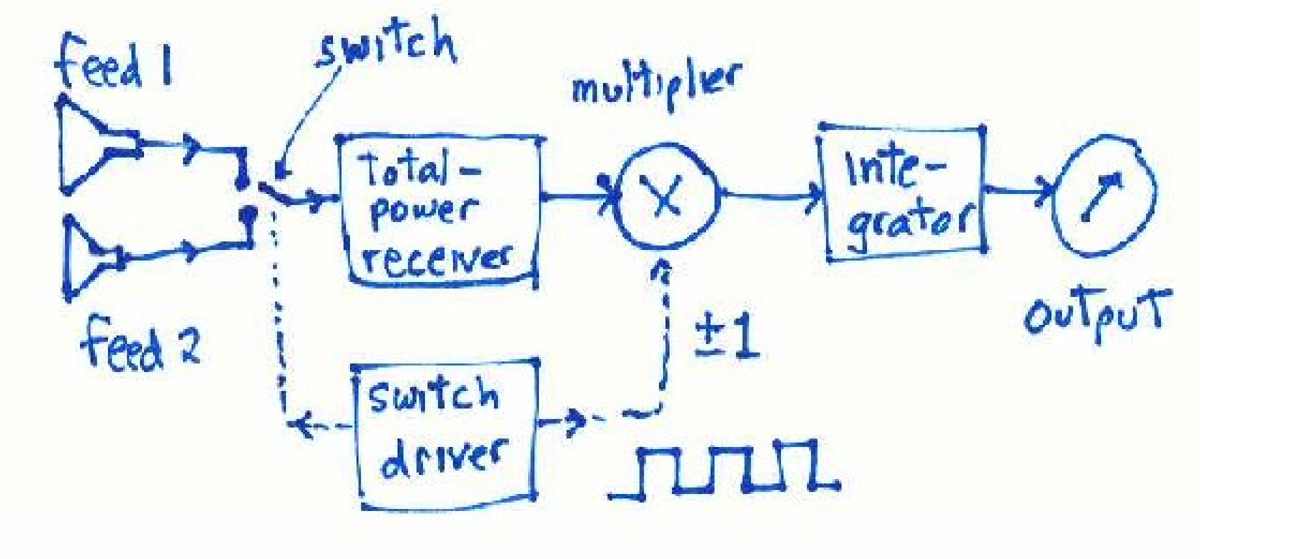
Clearly, gain fluctuations will significantly degrade the sensitivity unless

$$\left(\frac{\Delta G}{G}\right) \ll \frac{1}{\sqrt{\Delta\nu_{RF}\tau}}$$

For example, the 5 GHz receiver used to make the sky survey with the 300-foot telescope had $\Delta\nu_{RF} \approx 6\times10^8$Hz and $\tau \approx 0.1$ s, so the fractional gain fluctuations on time scales up to a few seconds (the time to scan one baseline length) had to satisfy

$$\frac{\Delta G}{G} \ll \frac{1}{\sqrt{6\times10^8\ \mathrm{Hz}\ \times 0.1\ \mathrm{s}}} = 1.3\times10^{-4}$$

This is difficult to achieve in practice.



Block diagram of a beamswitching differential radiometer.

If the system temperatures are T_1 and T_2 in the two positions of the switch, then the receiver output is proportional to $T_1 - T_2 \ll T_1$ and the effect of gain fluctuations is only

$$\Delta T_G \approx (T_1 - T_2)\frac{\Delta G}{G} \ll T_1 \frac{\Delta G}{G} \ .$$

Likewise, the atmospheric emission in two nearly overlapping beams through the troposphere is nearly the same, so most of the tropospheric fluctuations cancel out. The main drawback with Dicke switching is that the receiver output fluctuations, relative to the source signal in a single beam, are doubled, so the radiometer equation for a Dicke switching receiver is:

$$\sigma_T = \frac{2T_{sys}}{\sqrt{\Delta\nu_{RF}\tau}} \qquad (3F5)$$

Few actual radiometers are this simple. Nearly all practical radiometers are ***superheterodyne*** receivers, in which a ***mixer*** multiplies the RF signal by a sine wave of frequency $\nu_{\rm LO}$ generated by a ***local oscillator***. The product of two sine waves contains the sum and difference frequency components

$$2\sin(2\pi\nu_{\rm LO}t) \times \sin(2\pi\nu_{\rm RF}t) = \cos[2\pi(\nu_{\rm LO} - \nu_{\rm RF})t] - \cos[2\pi(\nu_{\rm LO} + \nu_{\rm RF})t] .$$

The difference frequency is called the ***intermediate frequency*** (IF). The advantages of superheterodyne receivers include doing most of the amplification at lower frequencies ($\nu_{\rm IF} < \nu_{\rm RF}$), which is usually easier, and precise control of the $\nu_{\rm RF}$ range covered via tuning *only*

- Long cables less lossy at lower frequencies (nowadays one uses optical optical fibres
- Fear of positive feedback causing receiver oscillations
- If nu_LO can be varied over a wide range, a standard fixed frequency IF chain can service a wide range of front ends

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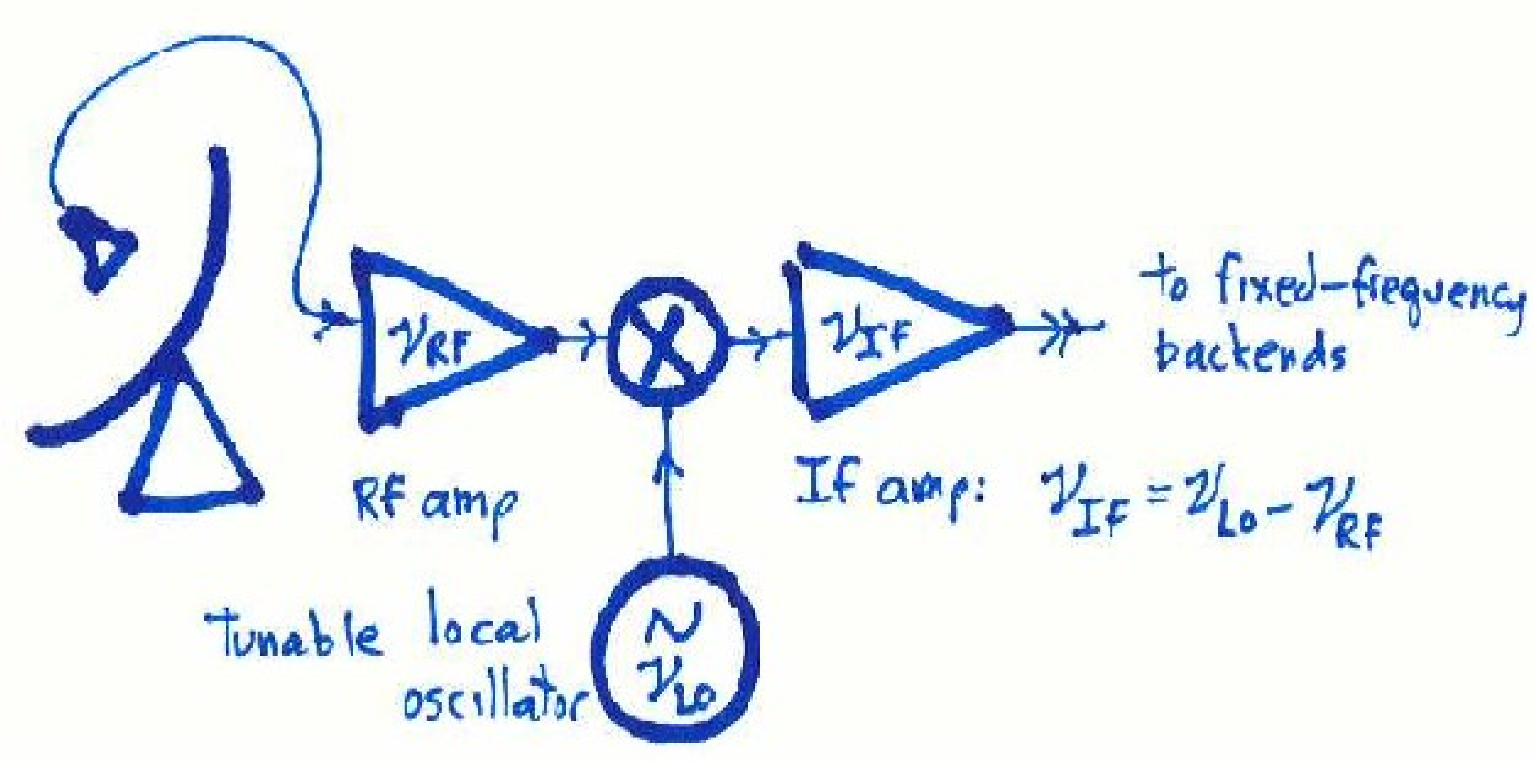
Chris Salter: NAIC-NRAO School; July 2005

the local oscillator so that ***back-end*** devices following the untuned IF amplifier, multichannel filter banks or digital spectrometers for example, can operate over fixed frequency ranges.

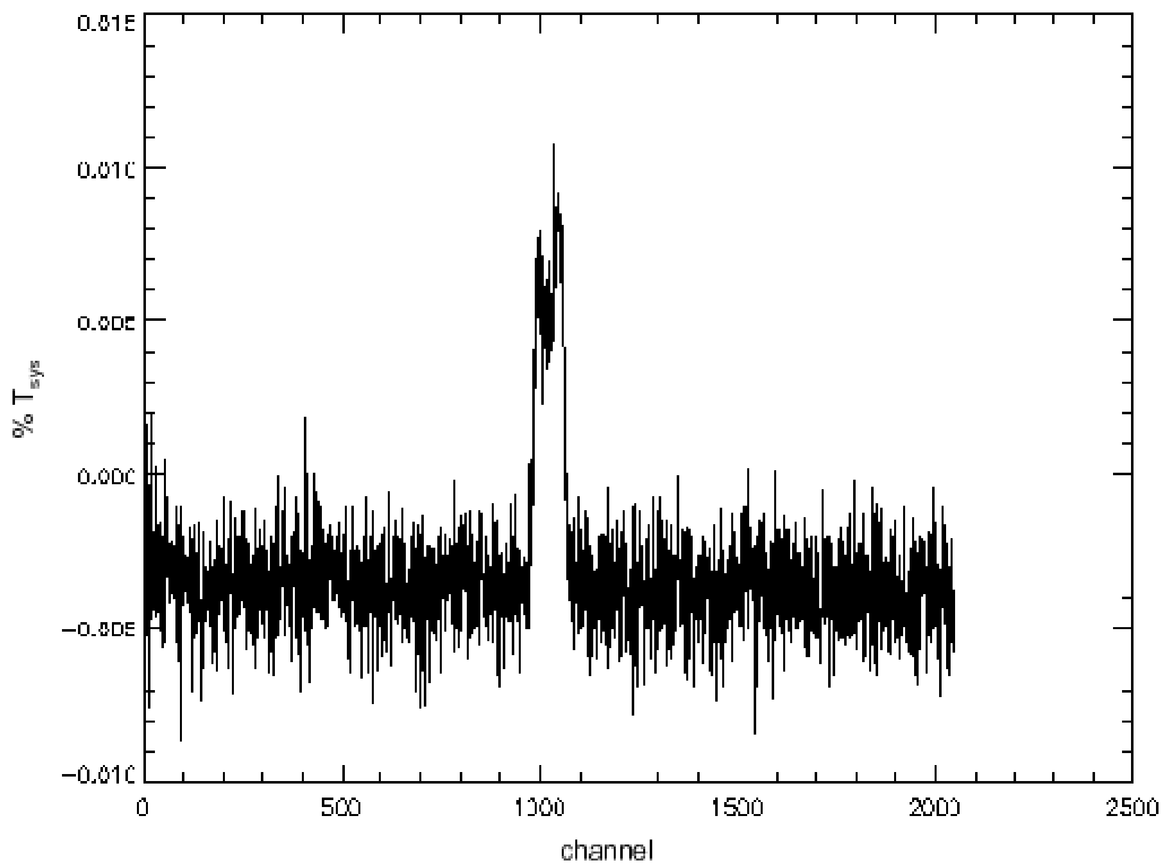


Block diagram of a simple superheterodyne receiver. Only the local oscillator is tuned to change the observing frequency range.

Determining T_{source}

(ON – OFF)/OFF

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



Determining T_{source}

(ON – OFF)/OFF

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

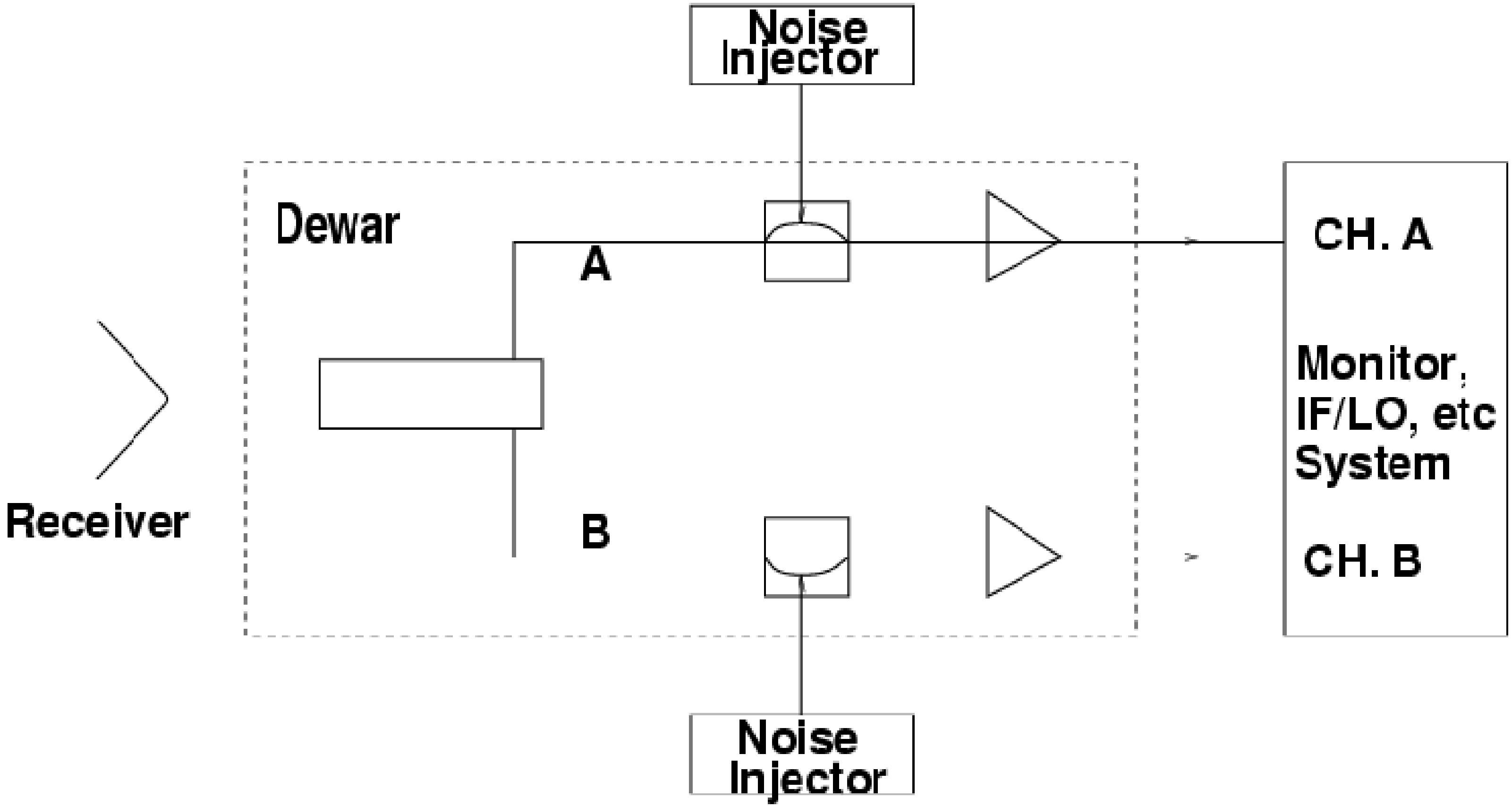
$$\text{Result} = \frac{T_{source}}{T_{system}}$$

Units are % * System Temperature

Need to determine system temperature to calibrate data

Determining T_{sys}

Noise Diodes



Determining T_{sys}

Noise Diodes

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

.

.

.

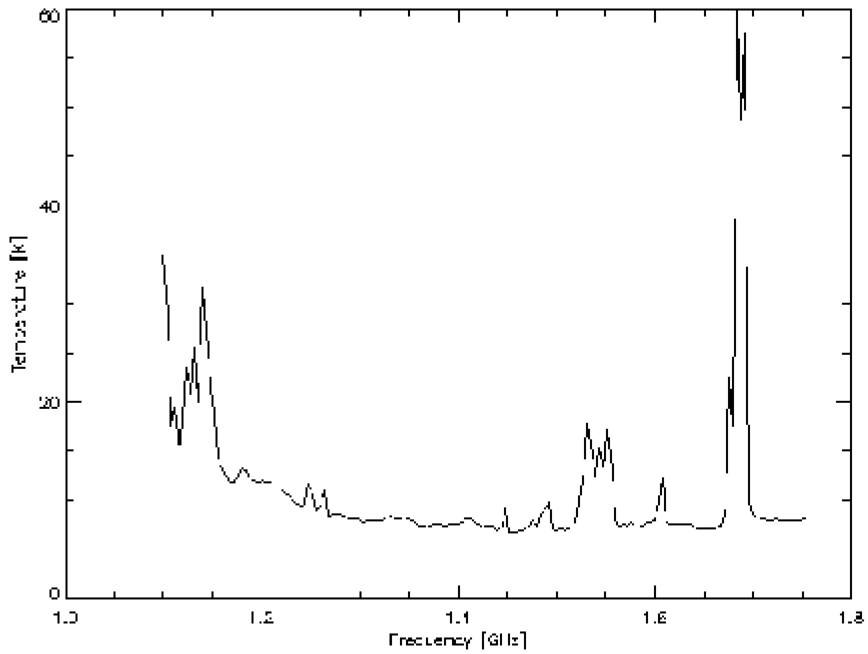
$$T_{diode}/T_{sys} = (On - Off)/Off$$

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

Determining T_{sys}

Noise Diodes - Considerations

- Frequency dependence

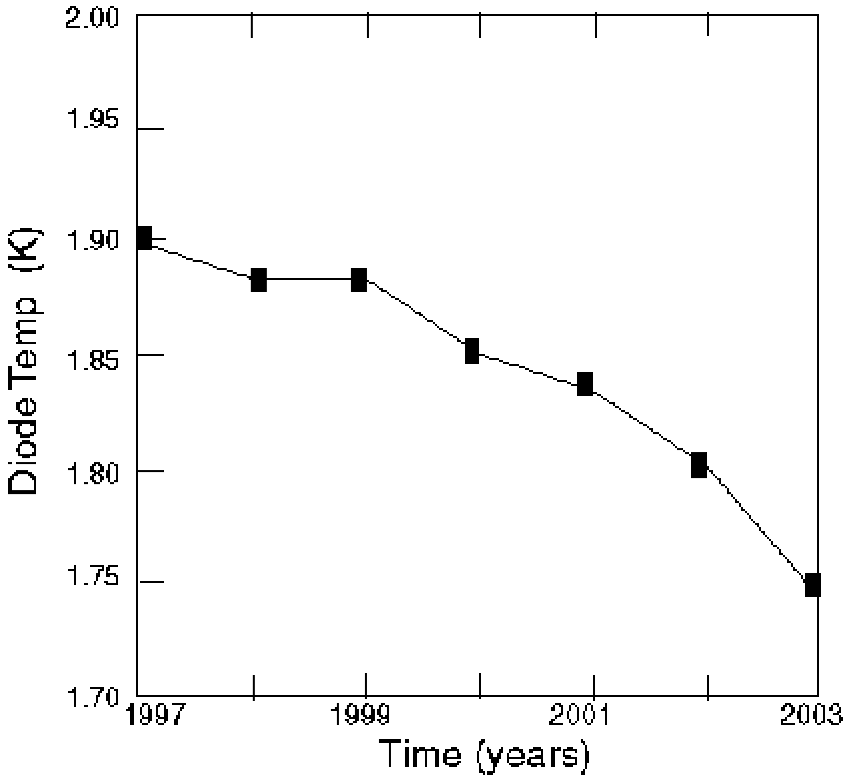


Lab measurements of the GBT L-Band calibration diode, taken from work of M. Stennes & T. Dunbrack - February 14, 2002

Determining T_{sys}

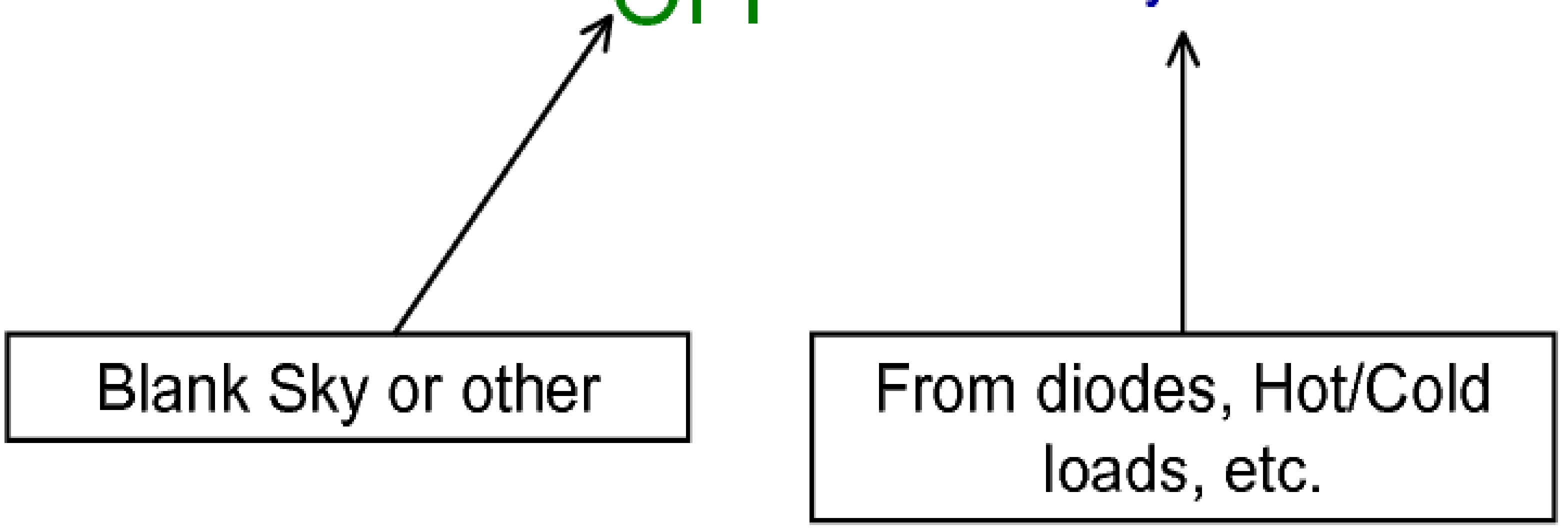
Noise Diodes - Considerations

- Frequency dependence
- Time stability



Determining T_{source}

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



Telescope response has not been accounted for!

Determining T_{source}

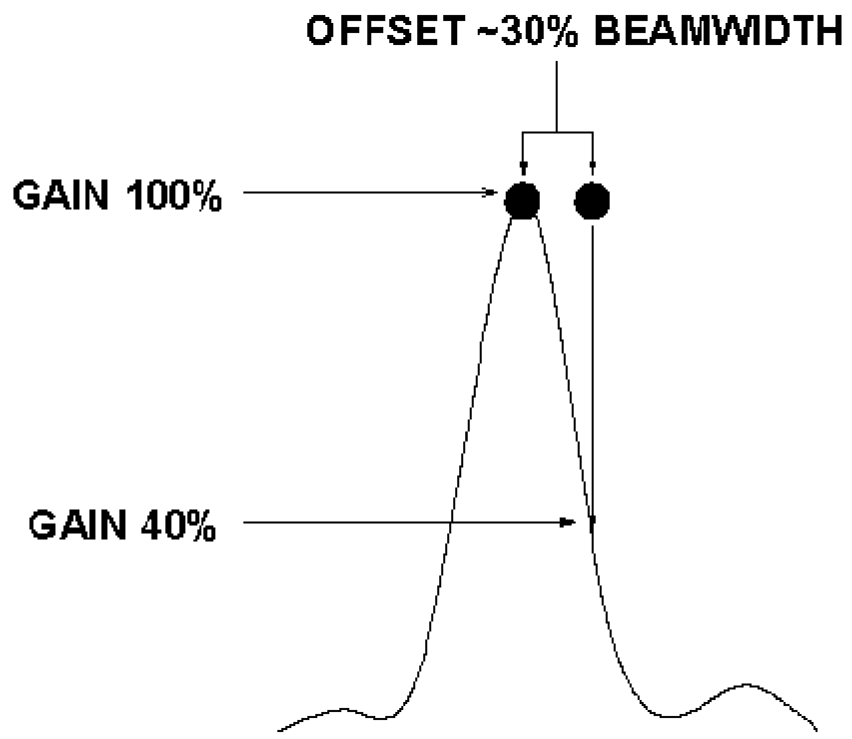
$$T_{source} = \frac{(ON - OFF)}{OFF} \; T_{system} \; \frac{1}{GAIN}$$

OFF: Blank Sky or other

T_{system}: From diodes, Hot/Cold loads, etc.

GAIN: Theoretical, or Observational

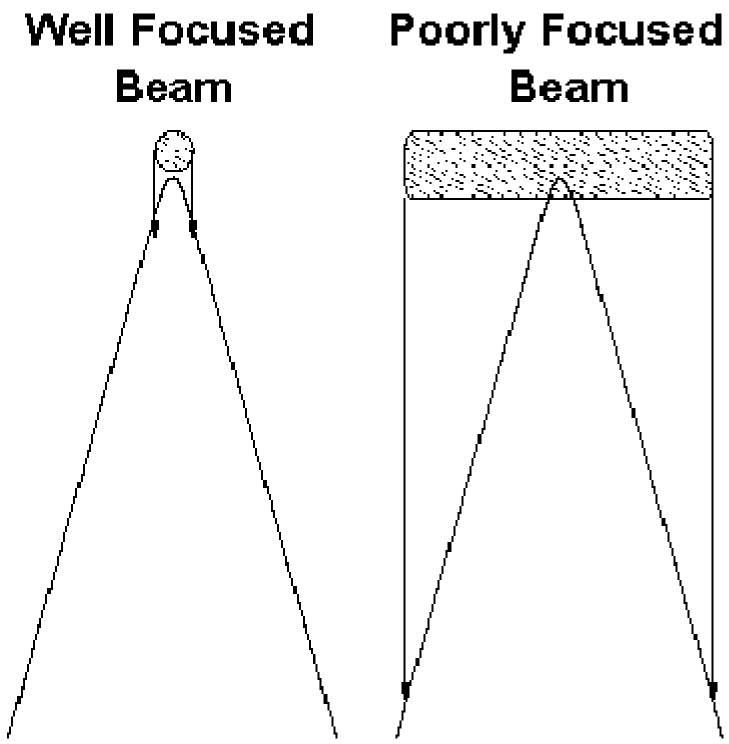
Other Issues: Pointing



Results in reduction of telescope gain

Typically can be corrected in software

Other Issues:
Focus

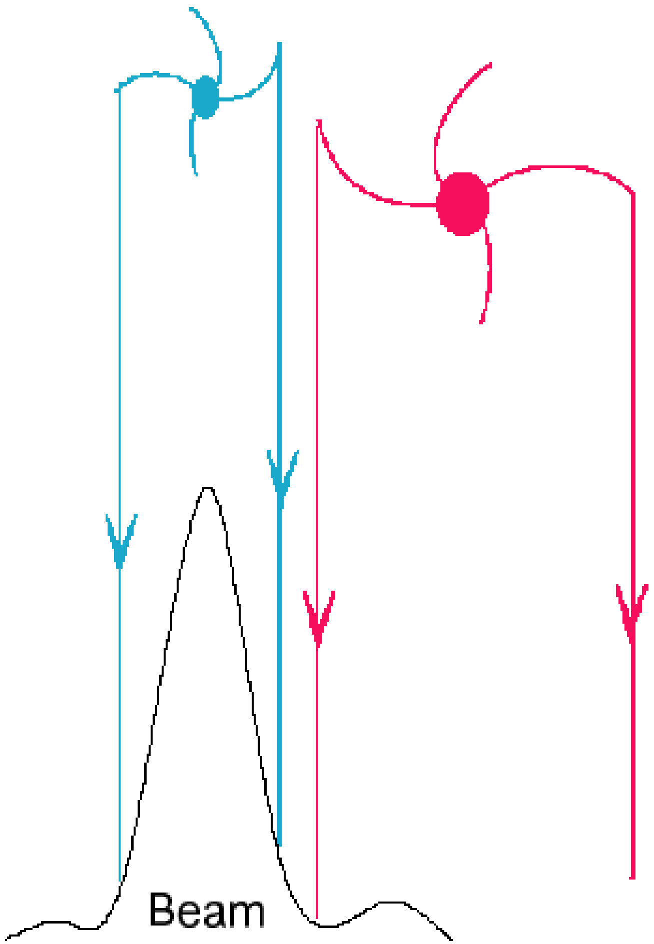


Results in reduction of telescope gain

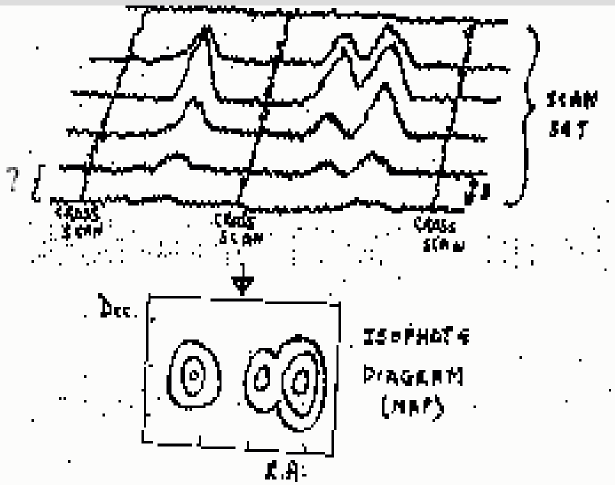
Corrected mechanically

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

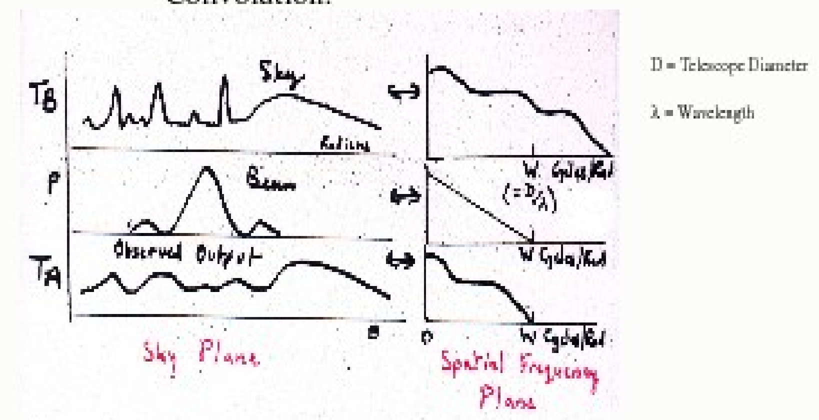


mapping

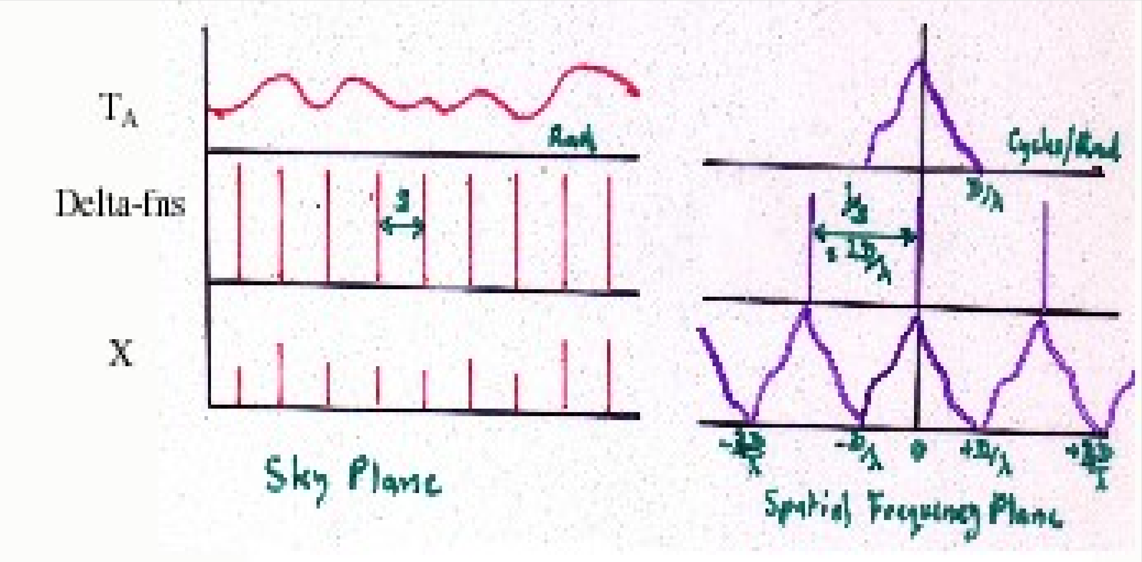


How far apart should we place our scans (and how often should We sample along a scan) in order to lose no information which our telescope is capable of passing?

Convolution:

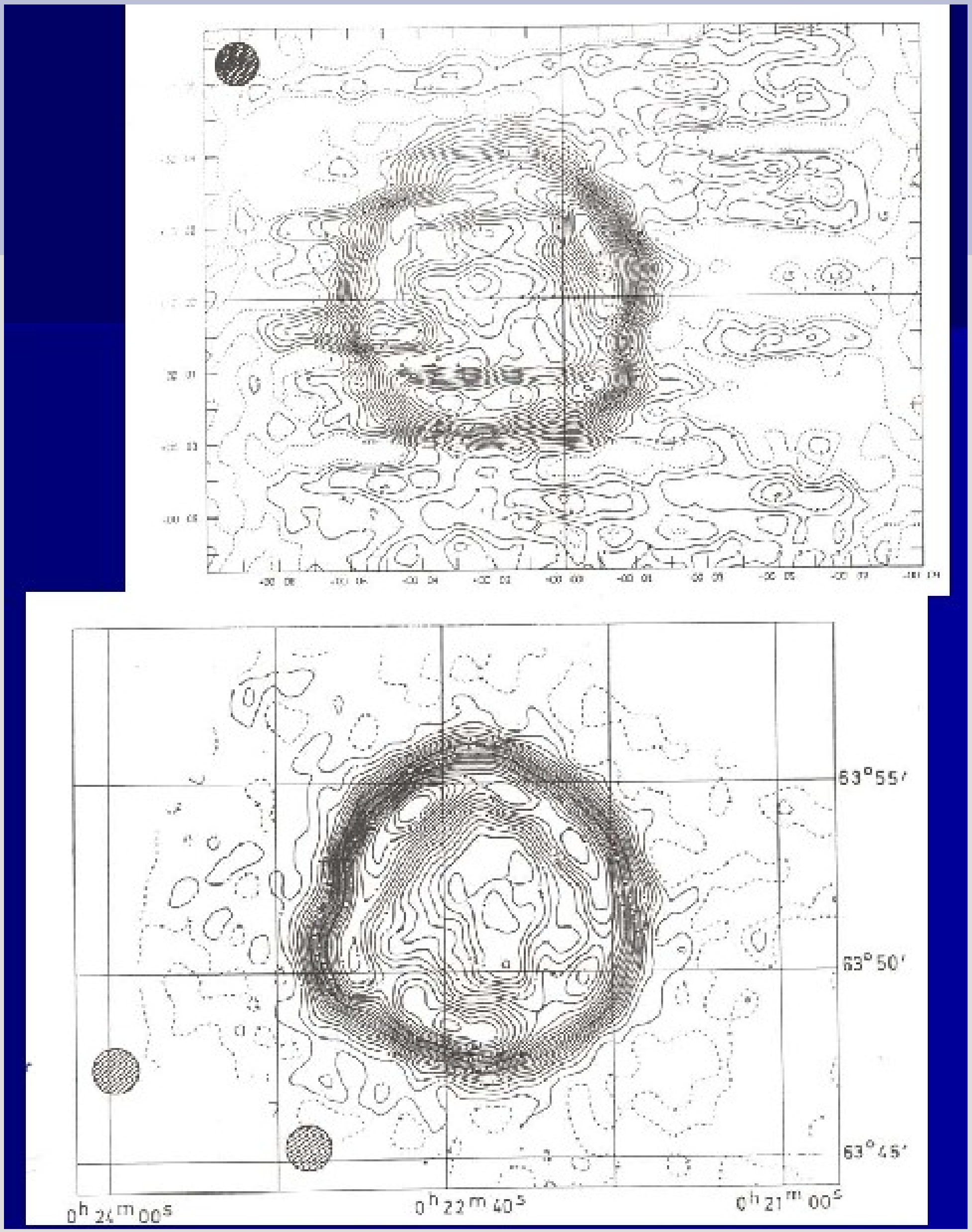


mapping



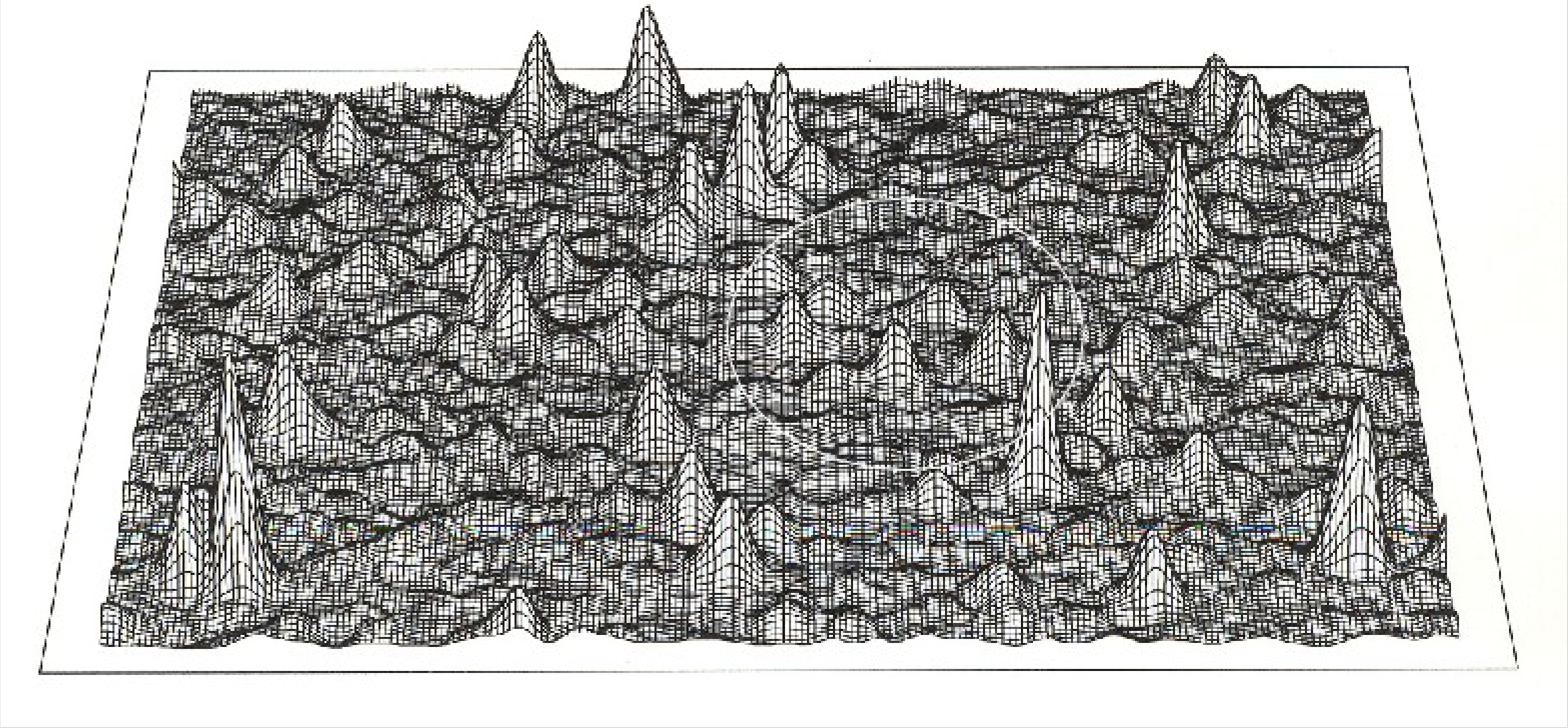
T_A
Delta-fns
X
Rad
Sky Plane
Cycles/Rad
0
Spatial Frequency Plane

The SNR 3C10 imaged at 10.7 GHz by horizontal scans (top) and basket-weaving (bottom)



Slide from J. J. Condon,
NAIC-NRAO school, 2003

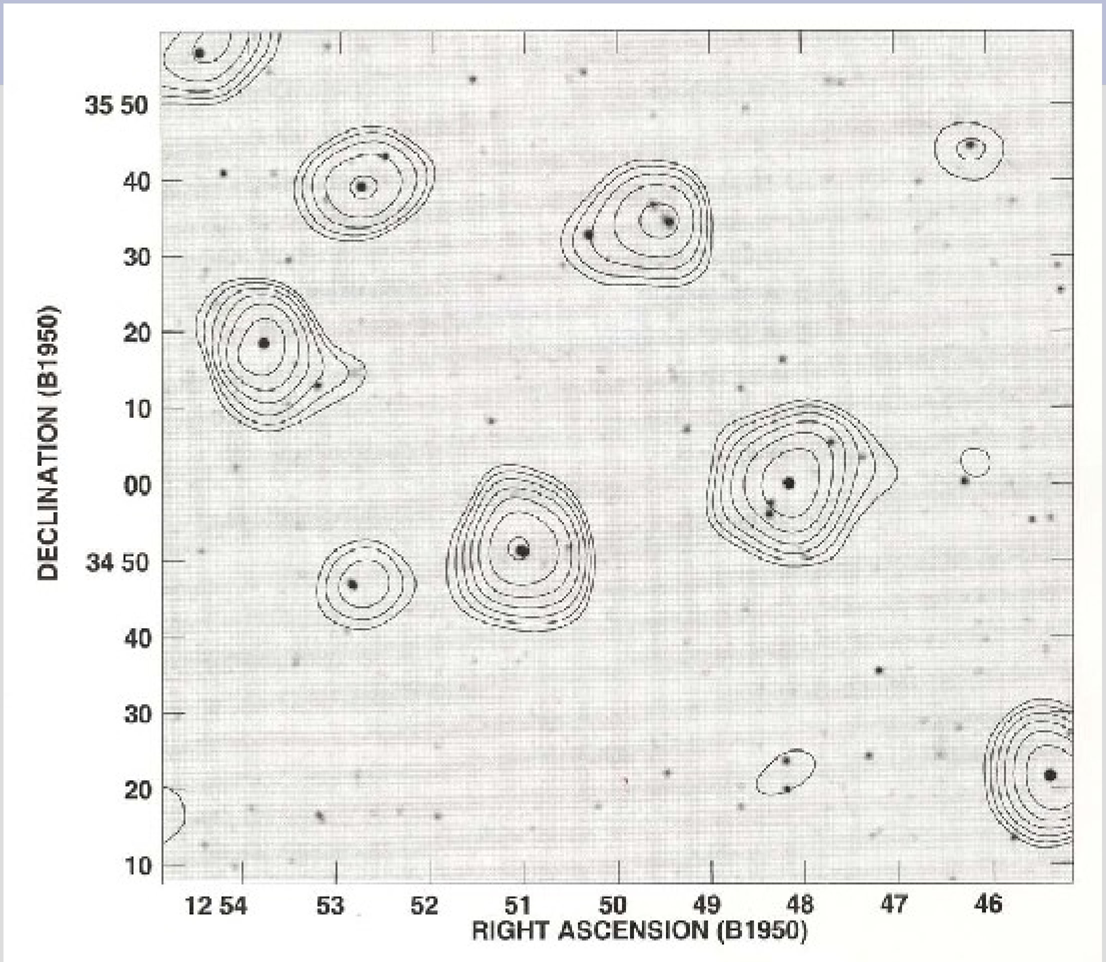
confusion



Profile of 45 deg sq near the North Galactic Pole imaged with 12 arcmin resolution at 1.4 Ghz. The strongest source seen has a flux density of ~1.5 Jy.

J. J. Condon, NAIC-NRAO school, 2003

confusion

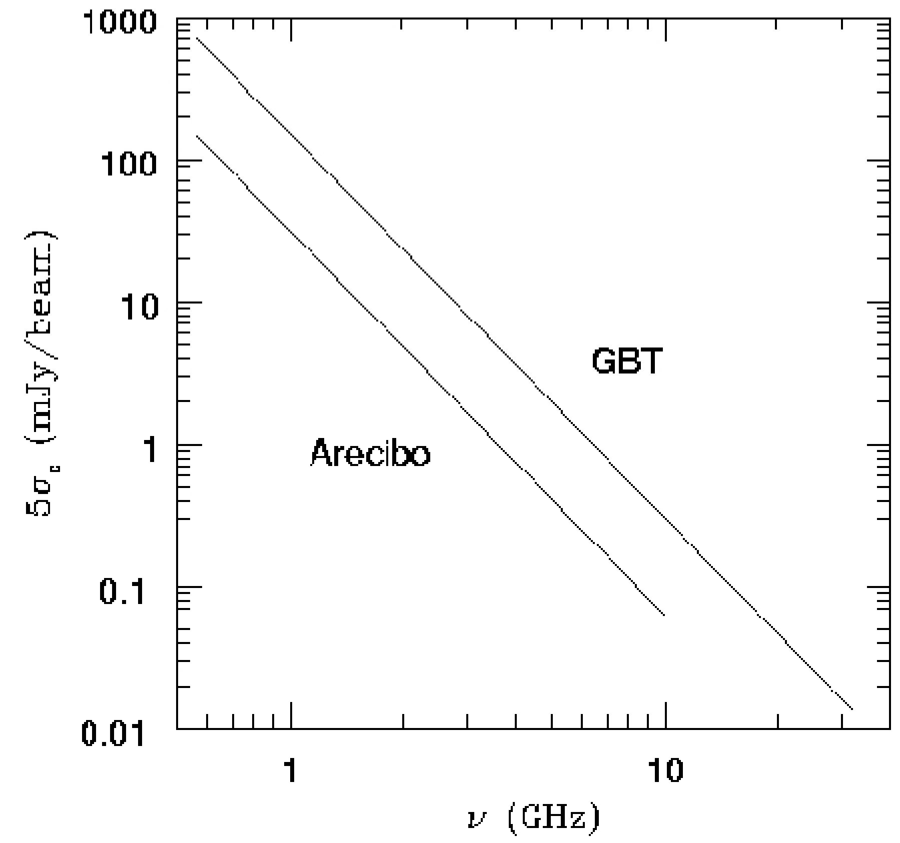


NVSS (45 arcsec) in gray scale and GB6 (12 arcmin) in contours shows source blending. Lowest contour: 45 mJy/beam

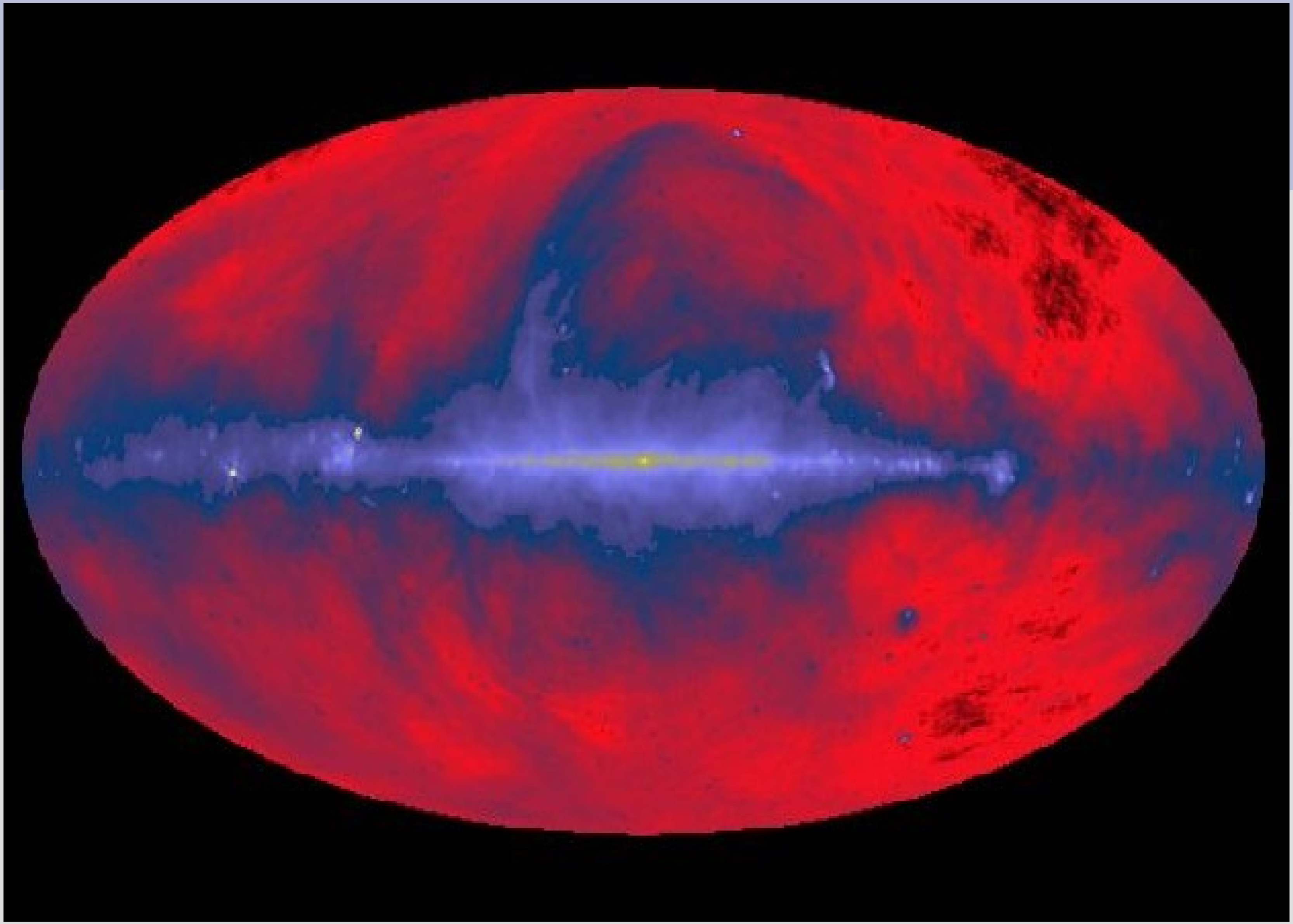
J.J. Condon: NAIC-NRAO School, 2003

confusion

$$\left(\frac{\sigma_c}{\mathrm{mJy\ beam^{-1}}}\right) \approx 0.2\left(\frac{\nu}{\mathrm{GHz}}\right)^{-0.7}\left(\frac{\theta_M\theta_m}{\mathrm{arcmin^2}}\right)$$



J.J. Condon: NAIC-NRAO School, 2003



408-MHz all-sky image: Haslam, Salter, Stoffel, Wilson 1982