GREEN BANK OBSERVATORY

# Brief Introduction to Radio Telescopes

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NRAO/GBO Summer Student Workshop May 26, 2020

# Terms and Concepts

Parabolic reflector
Blocked/unblocked
Subreflector
Frontend/backend
Feed horn
Local oscillator
Mixer
Noise Cal
Flux density

Jansky
Bandwidth
Resolution
Antenna power pattern
Half-power beamwidth
Side lobes
Beam solid angle
dB (deciBels)
Main beam efficiency
Effective aperture

Aperture efficiency
Antenna Temperature
Aperture illumination function
Spillover
Gain
System temperature
Receiver temperature
convolution

# Text books on Radio Astronomy

- Essential Radio Astronomy
- https://science.nrao.edu/opportunities/courses/era

## Essential Radio Astronomy


James J. Condon, Scott M. Ransom

Princeton University Press, Apr 5, 2016 - Science - 376 pages

*Essential Radio Astronomy* is the only textbook on the subject specifically designed for a one-semester introductory course for advanced undergraduates or graduate students in
More »

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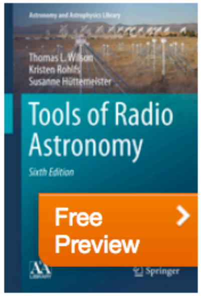


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## Tools of Radio Astronomy

Authors: **Wilson**, Thomas, **Rohlfs**, Kristen, **Huettemeister**, Susanne

Presents the 6th edition of a leading textbook on radio astronomy to include state-of-the-art descriptions of instrumentation and new observations

# Pioneers of Radio Astronomy

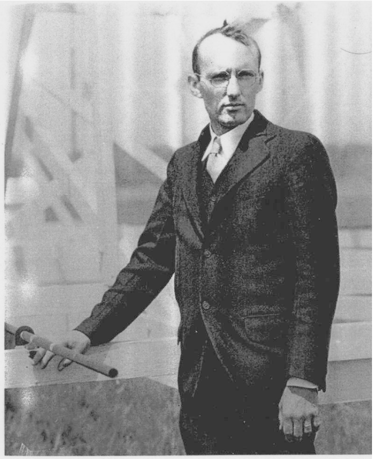
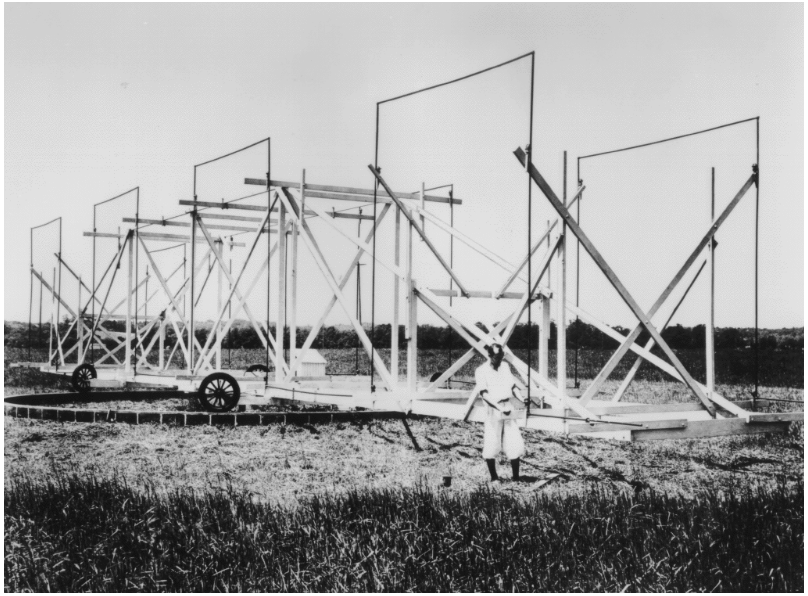


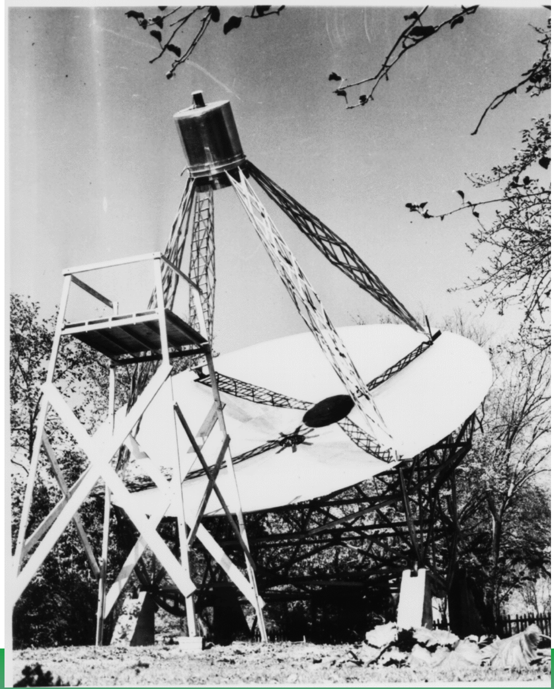
Fig. 1—Karl Guthe Jansky, about 1933.

Karl Jansky
1932

Grote Reber
1938

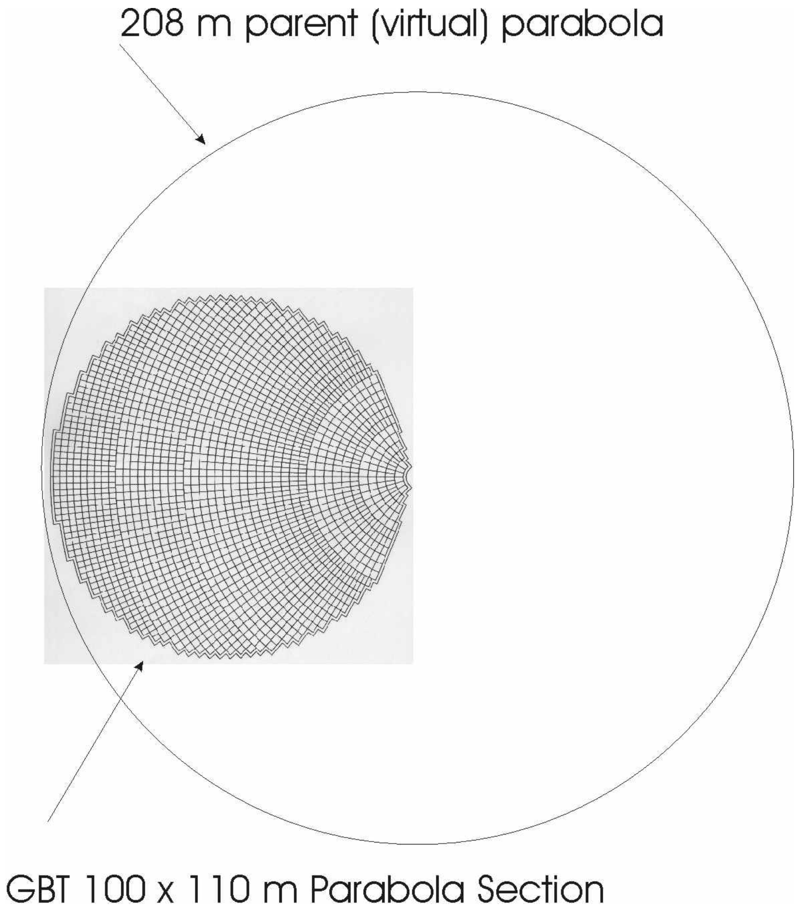
–Grote Reber, about 1937.

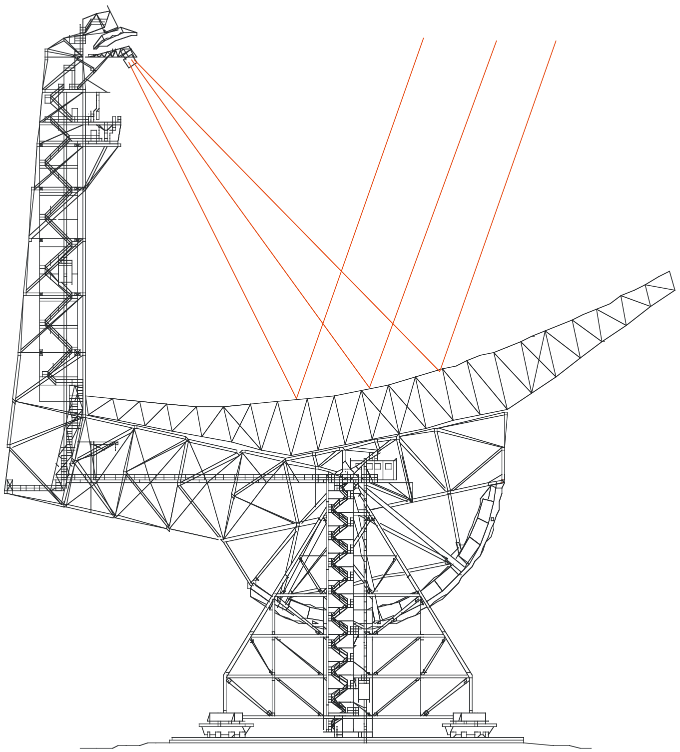


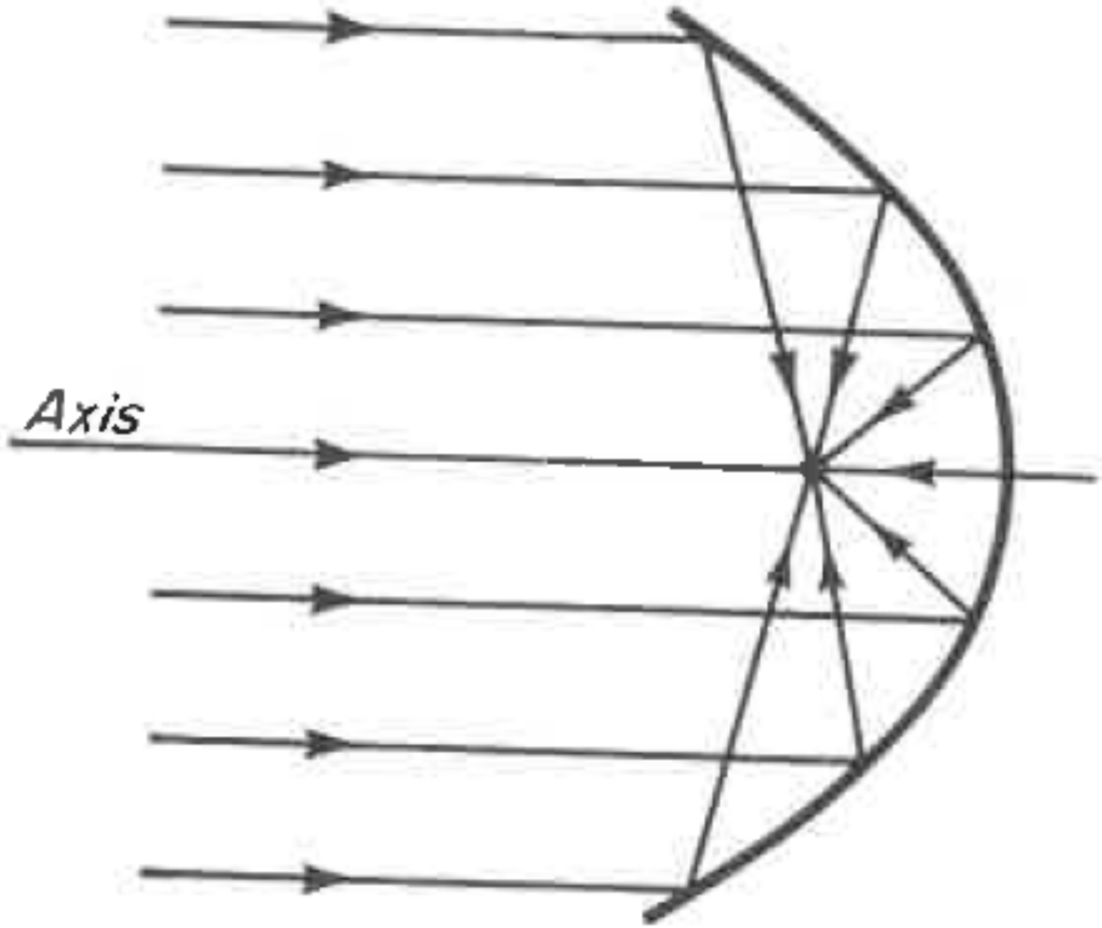


# Unblocked Aperture

- 100 x 110 m section of a parent parabola 208 m in diameter
- Cantilevered feed arm is at focus of the parent parabola





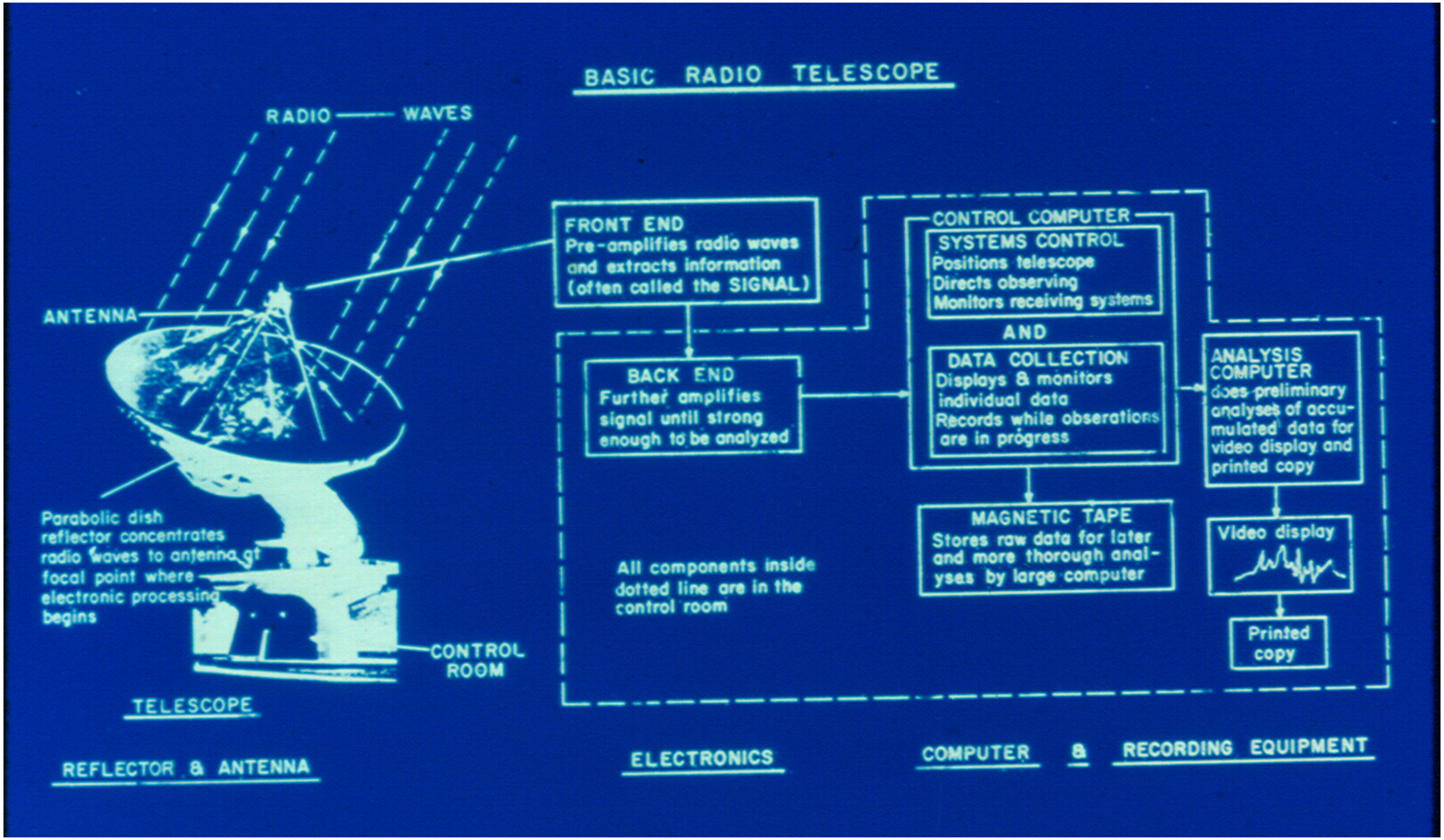

Paraboloidal mirror

Spherical reflector :Arecibo telescope

# Subreflector and receiver room

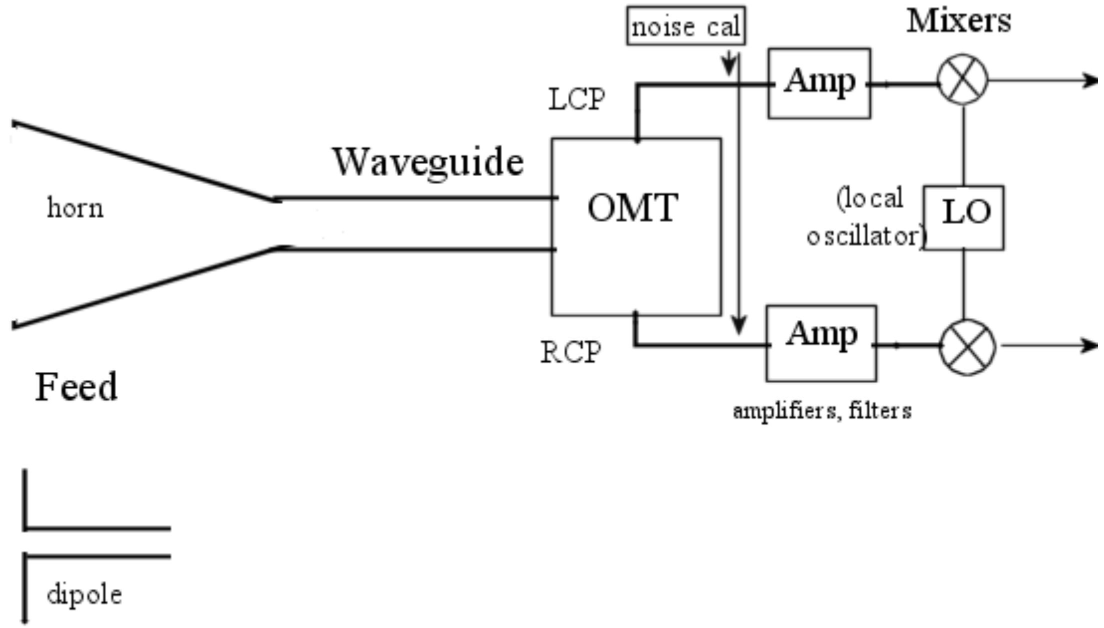
# On the receiver turret

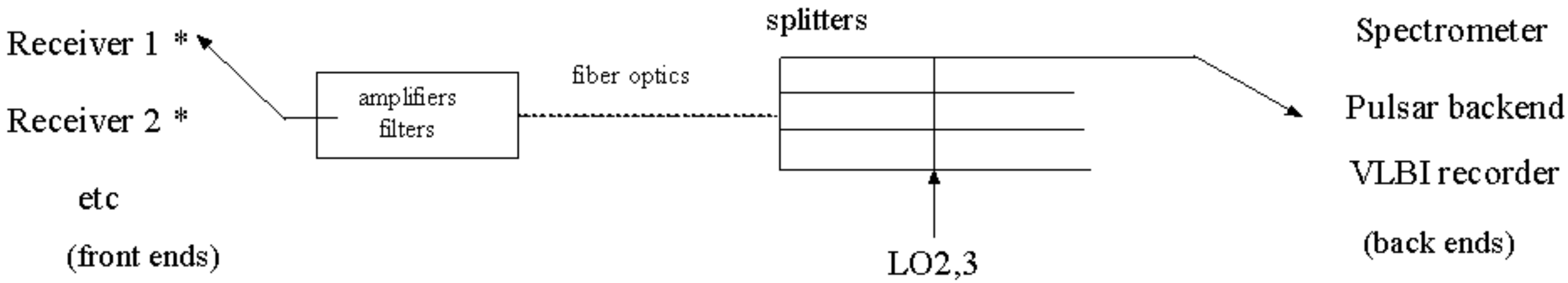
# Basic Radio Telescopes




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

# Signal paths



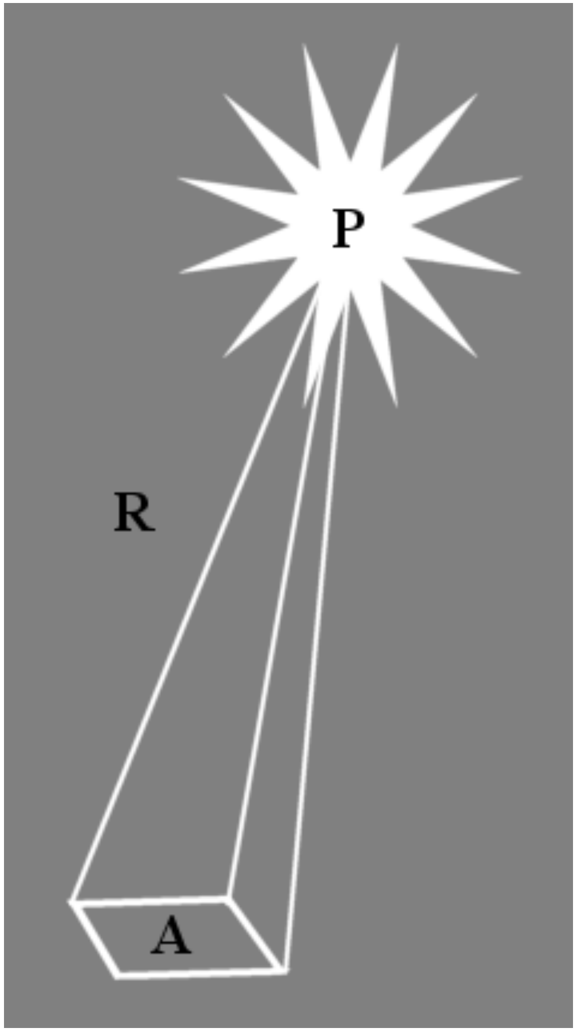
Intrinsic Power P (Watts)
Distance R (meters)
Aperture A (sq.m.)

Flux = Power/Area
Flux Density (S) =
Power/Area/bandwidth
Bandwidth (β)

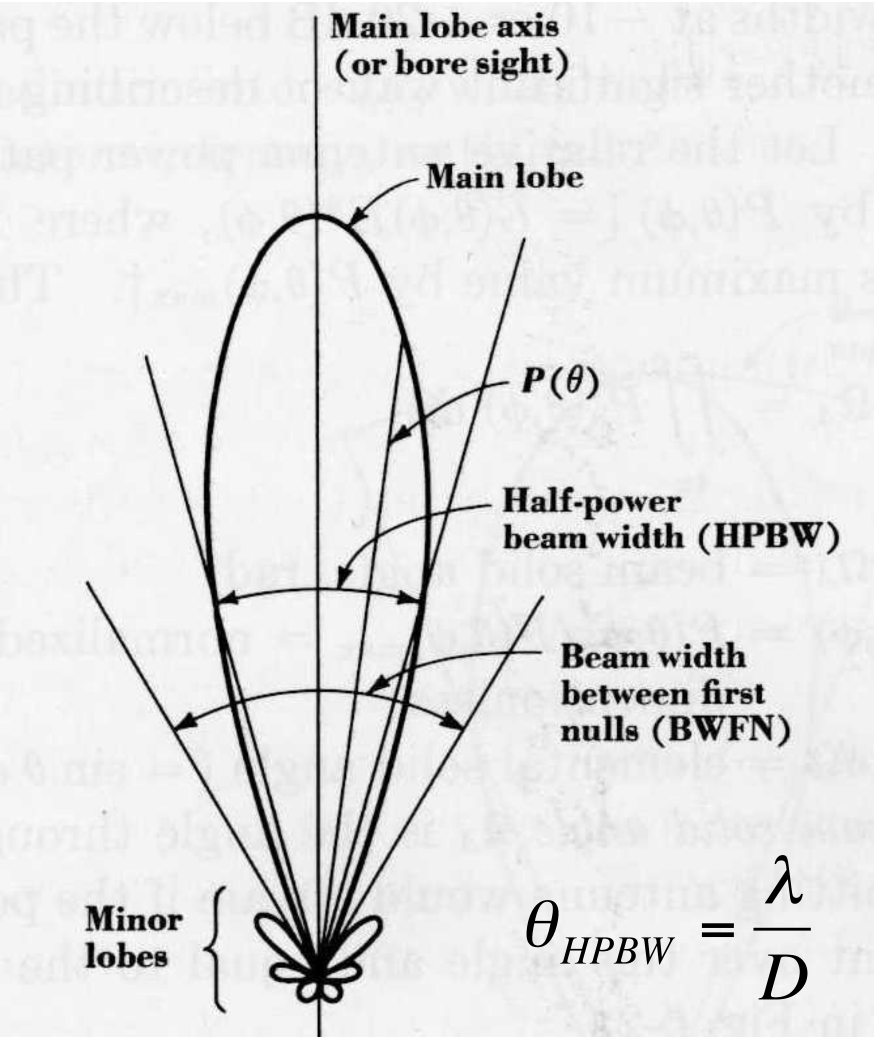
A "Jansky" is a unit of flux density

$$10^{-26} Watts / m^2 / Hz$$

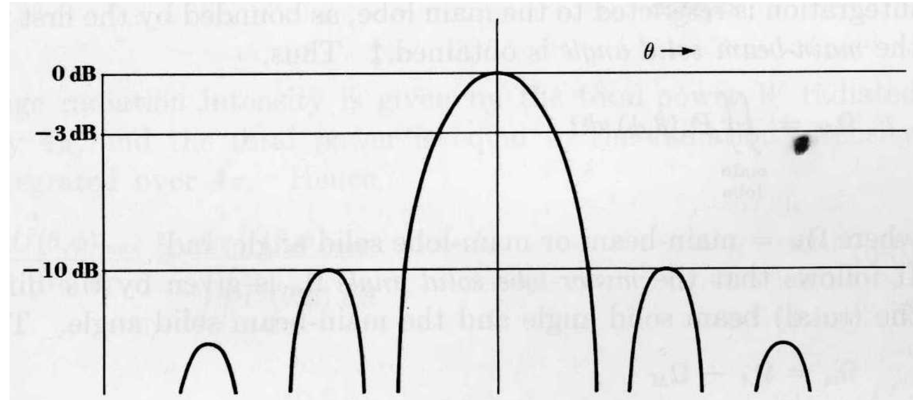
$$P = 10^{-26} 4\pi R^2 S\beta$$



# Antenna Beam Pattern (power pattern)




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




Beam Solid Angle (steradians)

$$\Omega_A = \iint_{4\pi} P_n(\theta,\phi)\,d\Omega$$

Main Beam Solid Angle

$$\Omega_M = \iint_{main\ lobe} P_n(\theta,\phi)\,d\Omega$$

$P_n$ = normalized power pattern

Kraus, 1966. Fig.6-1, p. 153.

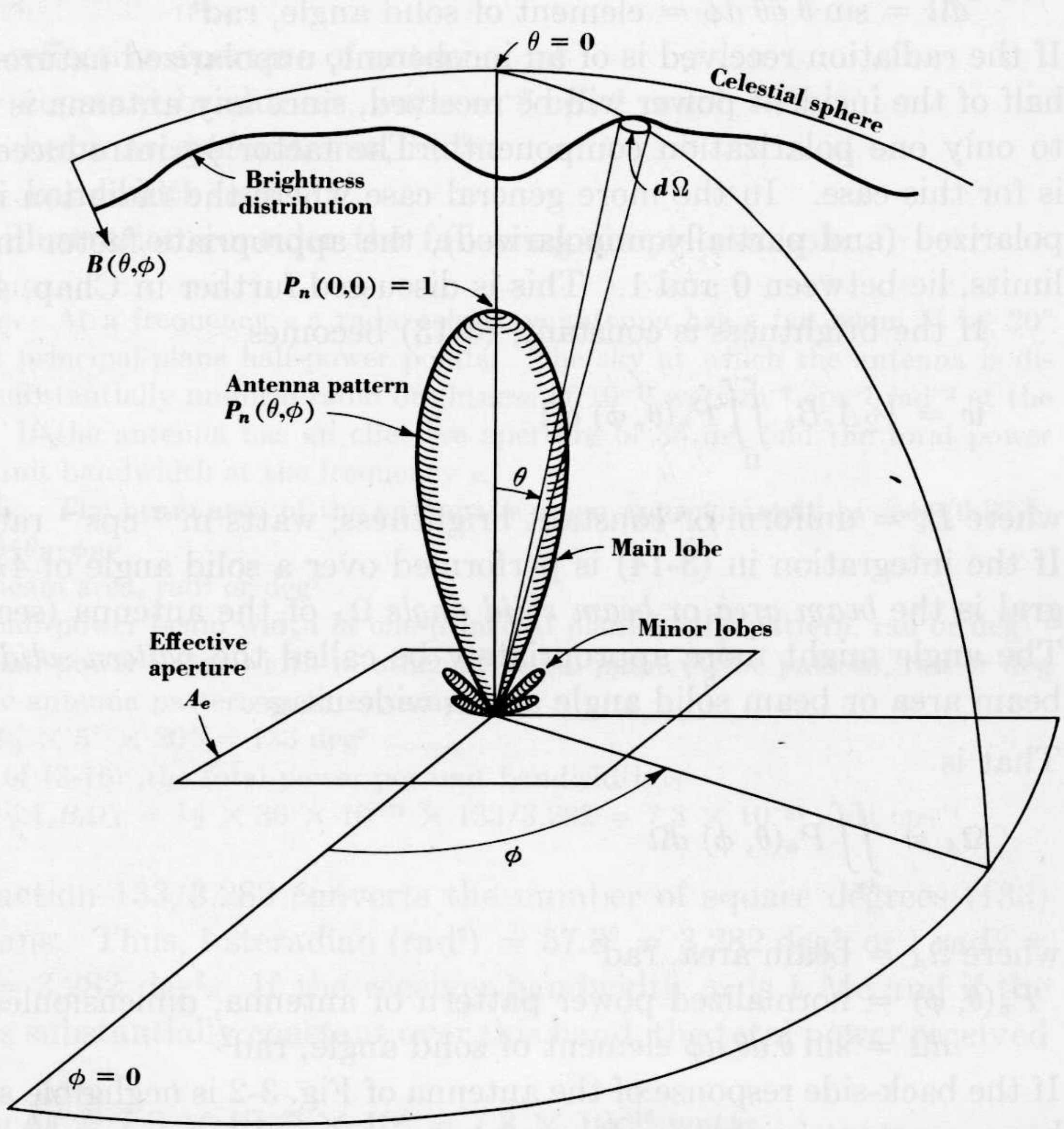



*Fig. 3-2.* Relation of antenna pattern to celestial sphere with associated coordinates.

# dB ??

$$\Delta p(dB) = 10\log_{10}(\frac{P_1}{P_2})$$

| P1/P2 | Δp(dB) |
|---|---|
| 1 | 0 |
| 2 | 3 |
| 10 | 10 |
| 100 | 20 |
| 1000 | 30 |

# Convolution relation for observed brightness distribution

$$S(\theta) \propto \int_{source} A(\theta'-\theta) I(\theta') d\theta'$$

(Note: A is antenna pattern,
Means the same as P in
Previous slides.)

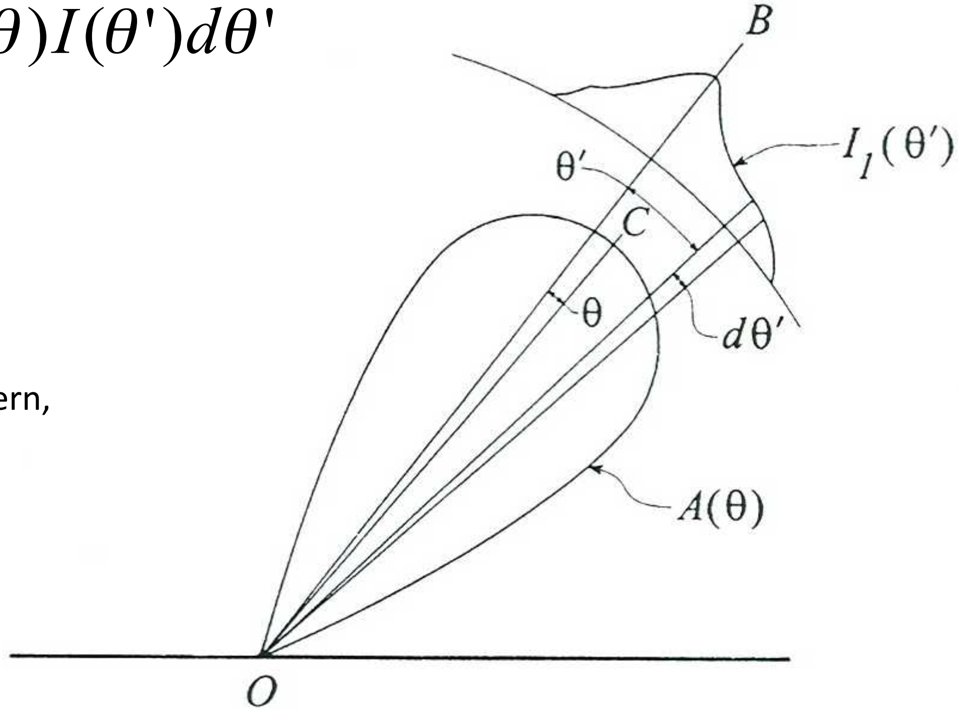



**Figure 2.5** The power pattern of an antenna $A(\theta)$ and the intensity profile of a source $I_1(\theta')$ used to illustrate the convolution relationship. The angle $\theta$ is measured with respect to the beam center $OC$ and $\theta'$ is measured with respect to the direction of the nominal position of the source $OB$.



Thompson, Moran, Swenson, 2001. Fig 2.5, p. 58.

# Smoothing by the beam

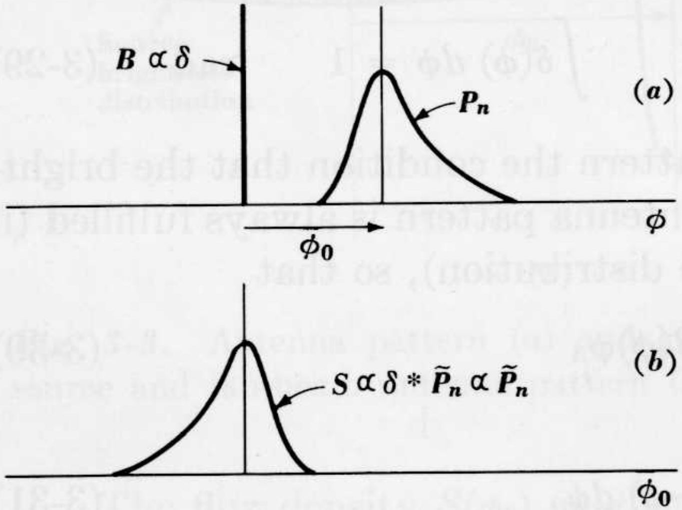



***Fig. 3-6.*** For a point source the observed distribution is the same as the mirror image of the antenna pattern.

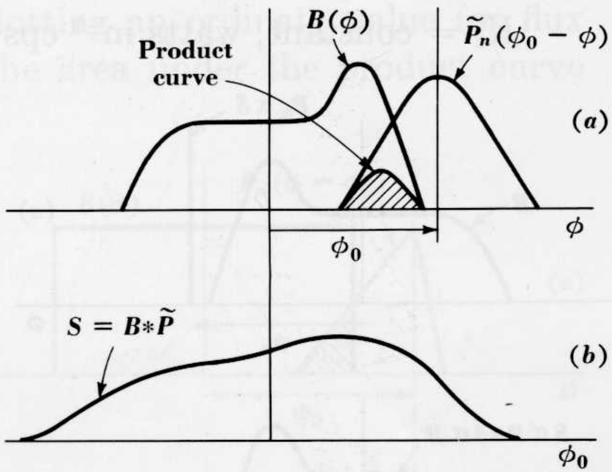



***Fig. 3-4.*** The true brightness distribution $B$ scanned by, or convolved with, the antenna pattern $\tilde{P}$, as in (a) yields the observed flux-density distribution $S$, as in (b).

# Some definitions and relations

Main beam efficiency, $\varepsilon_M$

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

Antenna theorem

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

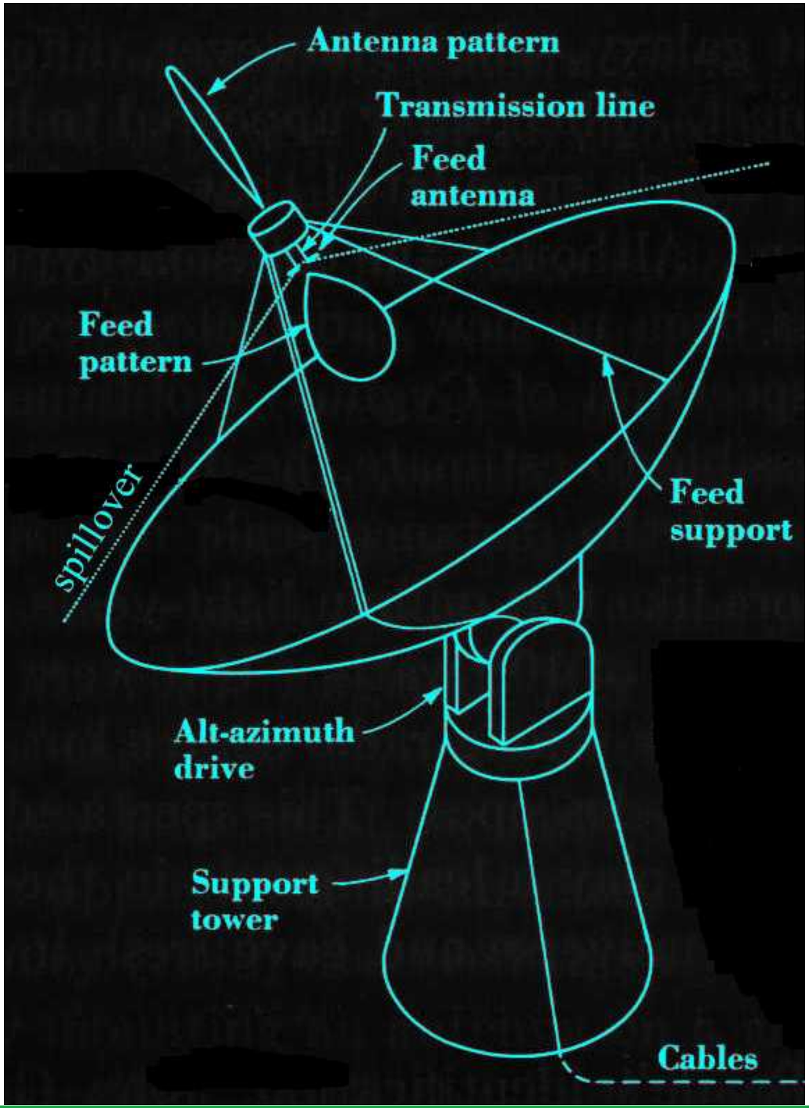
Aperture efficiency, $\varepsilon_{ap}$
Effective aperture, $A_e$
Geometric aperture, $A_g$

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

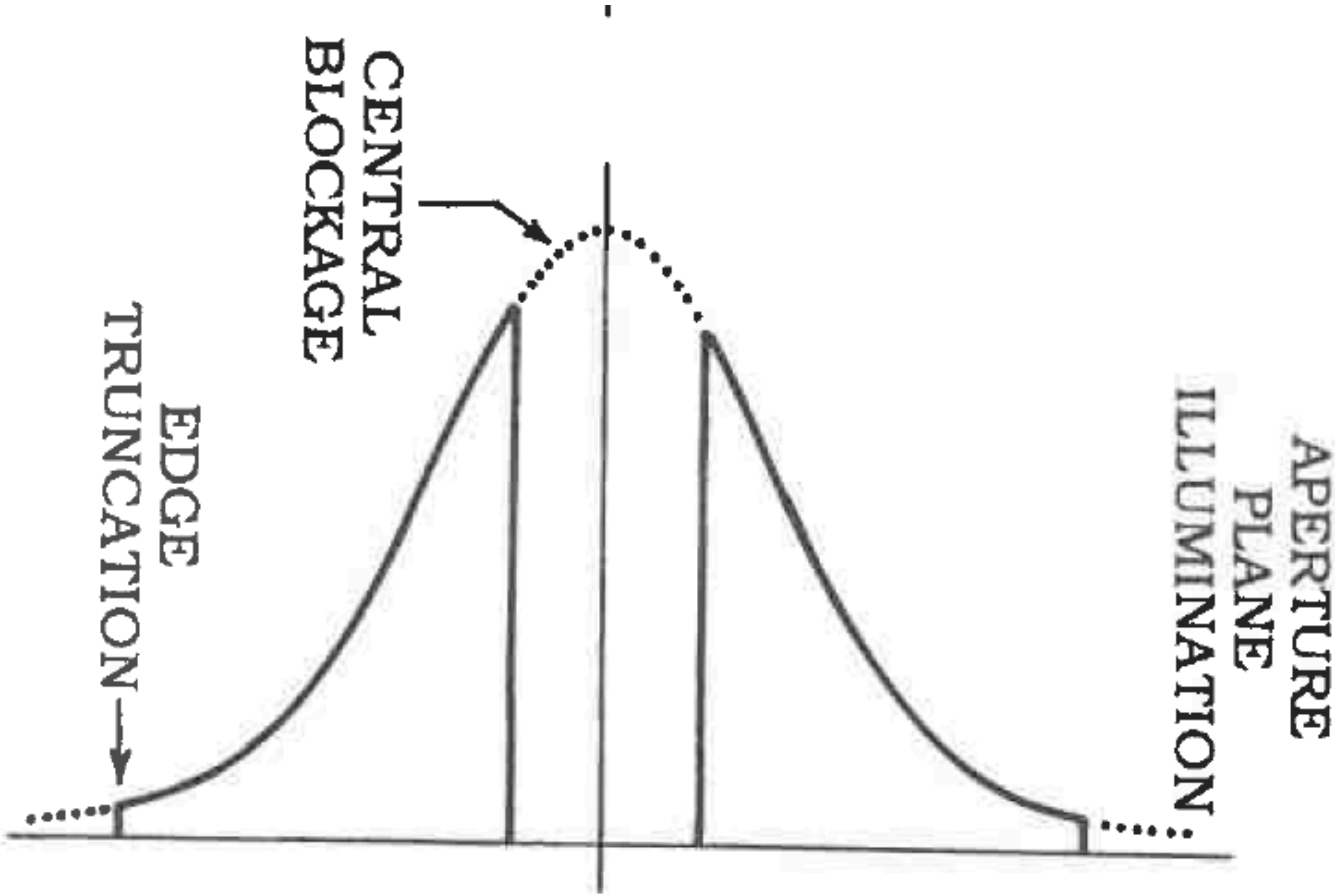
$$A_g(GBT) = \pi \left\{ \frac{1}{2}(100m) \right\}^2 = 7854m^2$$

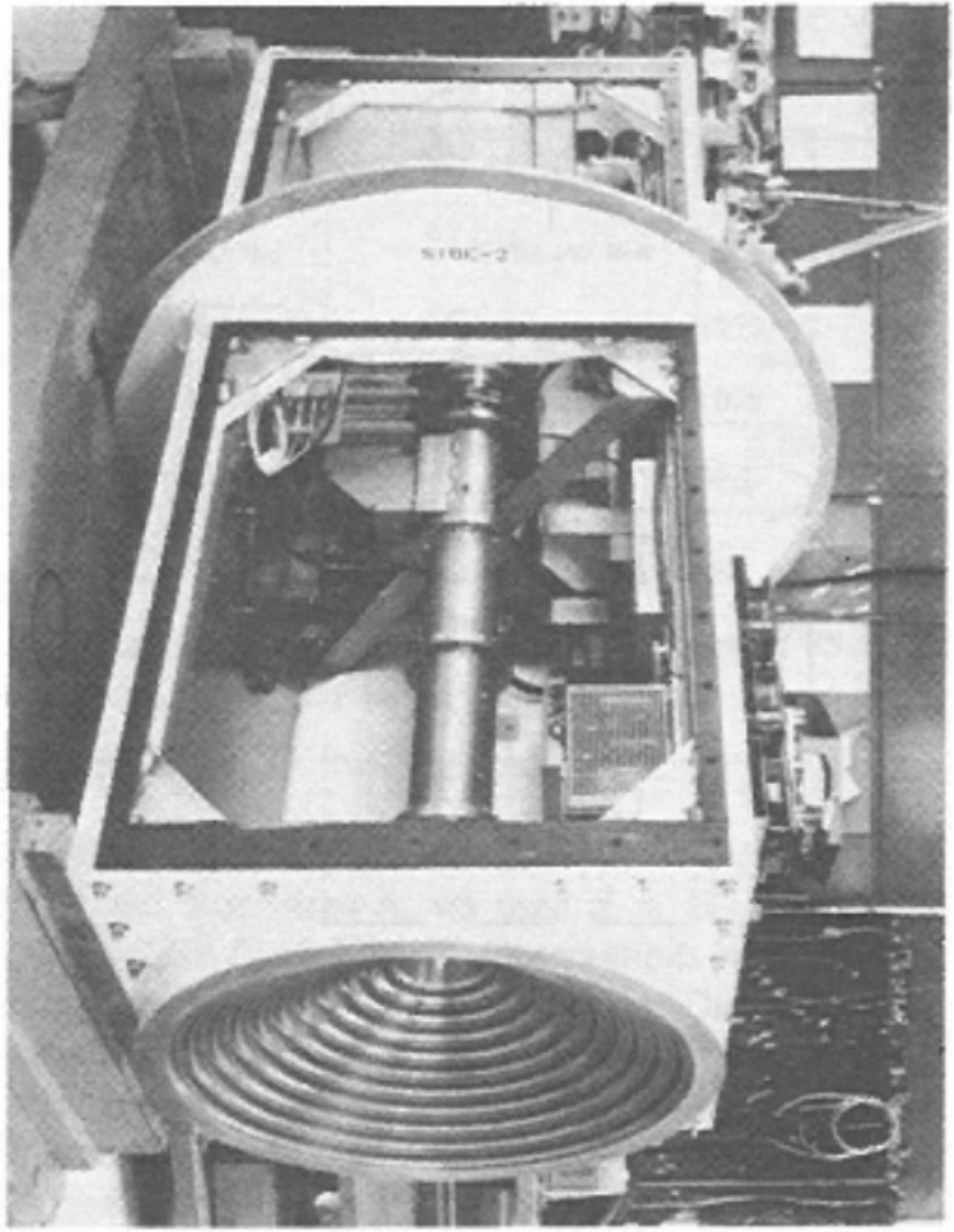
$$\varepsilon_{ap} = \varepsilon_{pat}\varepsilon_{surf}\varepsilon_{block}\varepsilon_{ohmic}\cdots$$

# another Basic Radio Telescope




Kraus, 1966. Fig.1-6, p. 14.

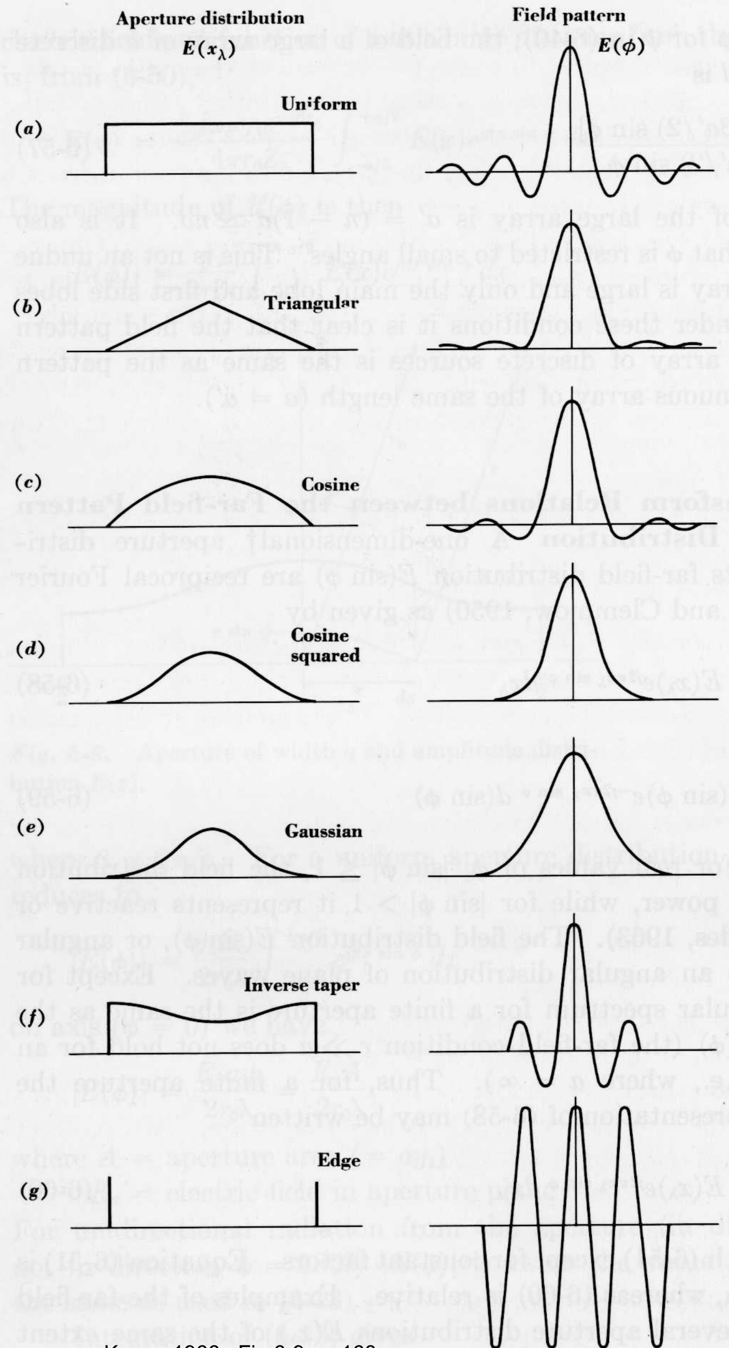

CENTRAL BLOCKAGE
EDGE TRUNCATION
APERTURE PLANE ILLUMINATION



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.

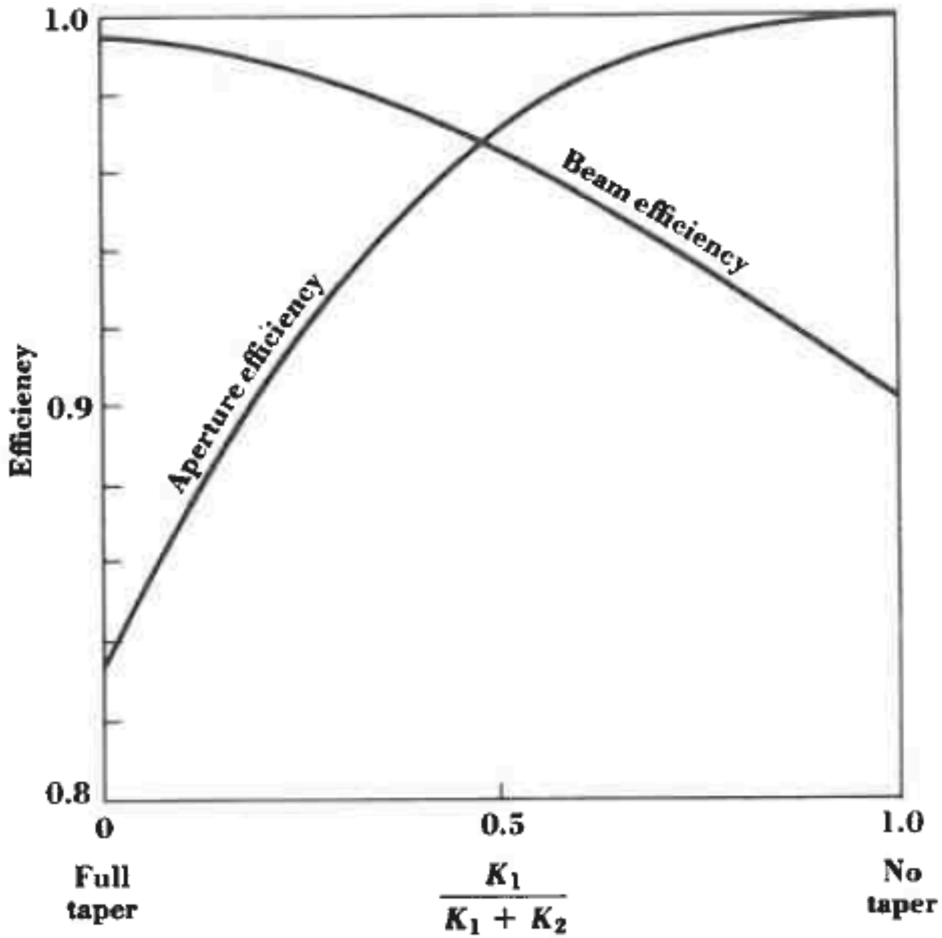
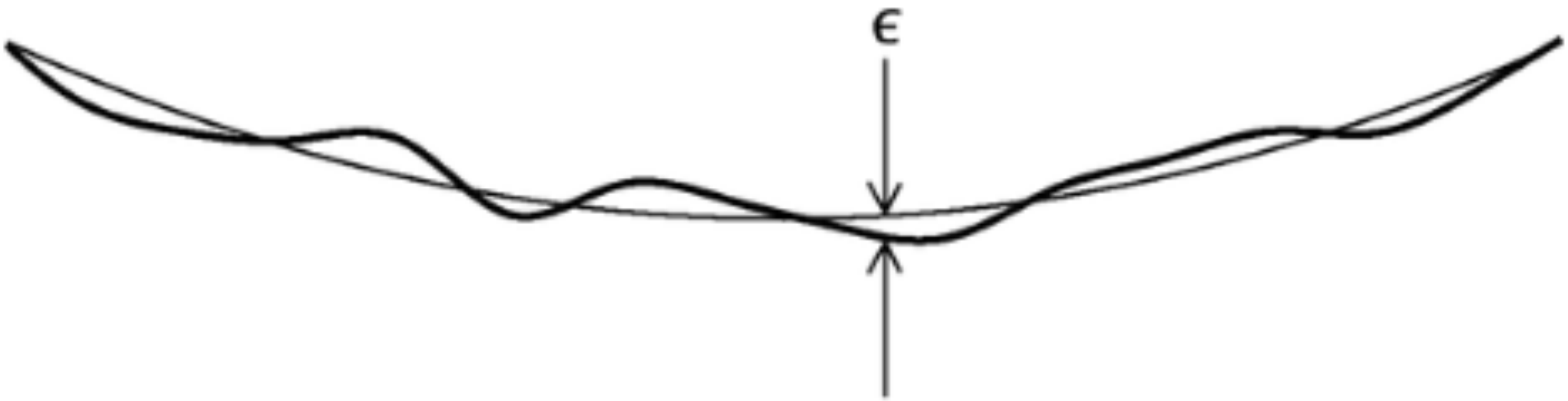



Fig. 6–104 Beam and aperture efficiencies for a one-dimensional aperture as a function of taper. (*After Nash*, 1964.) The aperture efficiency is a maximum with no taper, while the beam efficiency is a maximum with full taper.




Not-quite-perfect parabola

σ = rms surface error

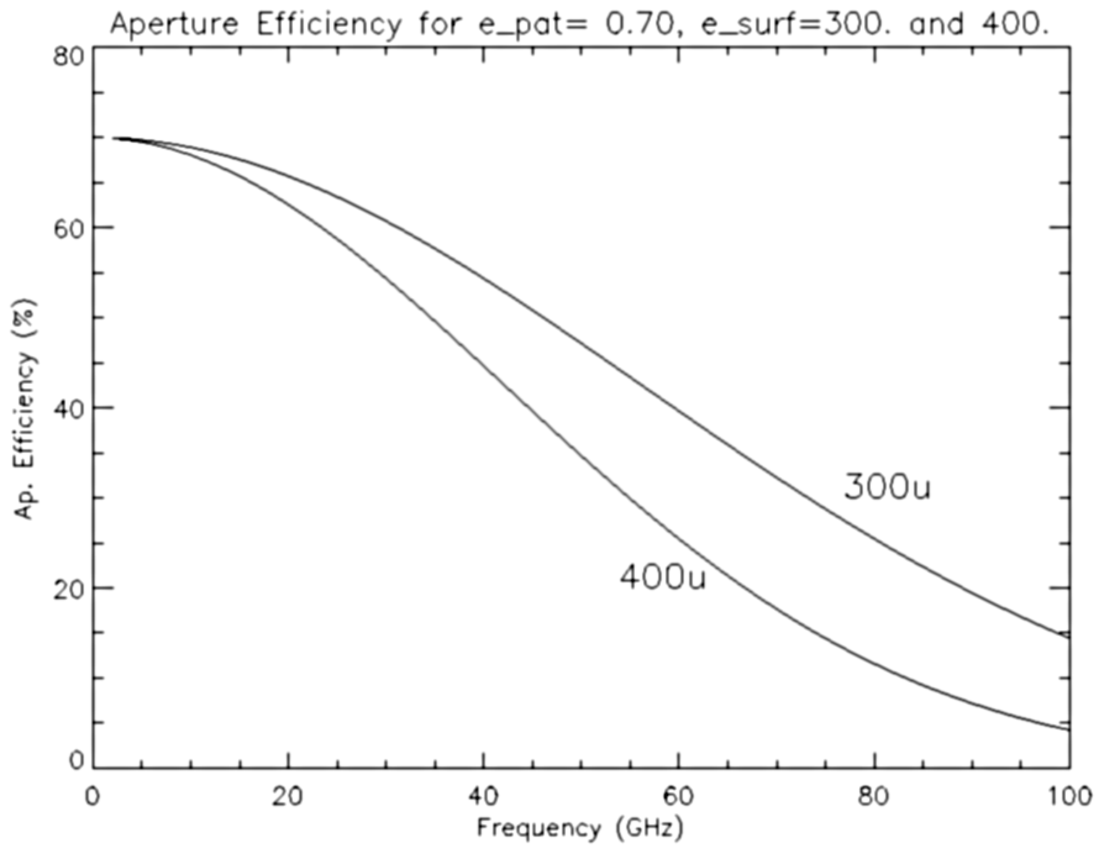
# Surface efficiency -- Ruze formula

$$\varepsilon_{surf} = e^{-(4\pi\sigma/\lambda)^2}$$

$\sigma$ = rms surface error

Effect of surface efficiency

$$\varepsilon_{ap} = \varepsilon_{pat}\varepsilon_{surf}\cdots$$




John Ruze of MIT -- Proc. IEEE vol 54, no. 4, p.633, April 1966.

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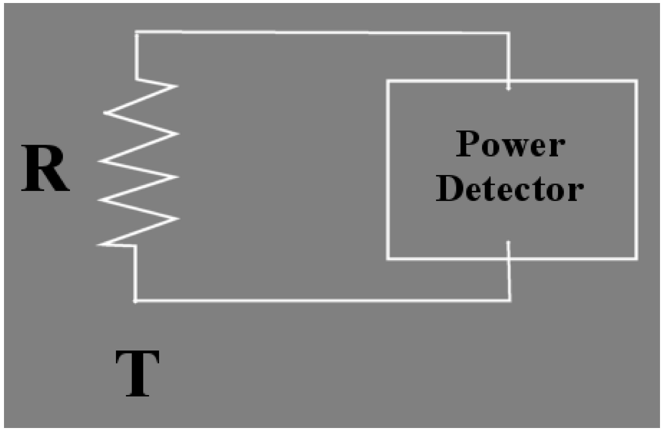
Detected power (P, watts) from a resistor R
at temperature T (kelvin) over bandwidth β(Hz)




$$P = kT\beta$$

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

$$P_A = \tfrac{1}{2} AS\beta$$

power as equivalent temperature.
Antenna Temperature $T_A$
Effective Aperture $A_e$

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

# System Temperature

= total noise power detected, a result of many contributions

$$T_{sys} = T_{ant} + T_{rcvr} + T_{atm}(1 - e^{-\tau a}) + T_{spill} + T_{CMB} + \cdots$$

Thermal noise $\Delta$T

= minimum detectable signal

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

The Radiometer Equation

# Gain(K/Jy) for the GBT

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

Including atmospheric absorption:

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

$$G = \frac{T_A}{S} = \frac{\varepsilon_{ap} A_g}{2k}$$

$$G(K / Jy) = 2.84 \cdot \varepsilon_{ap}$$

# Physical temperature vs antenna temperature

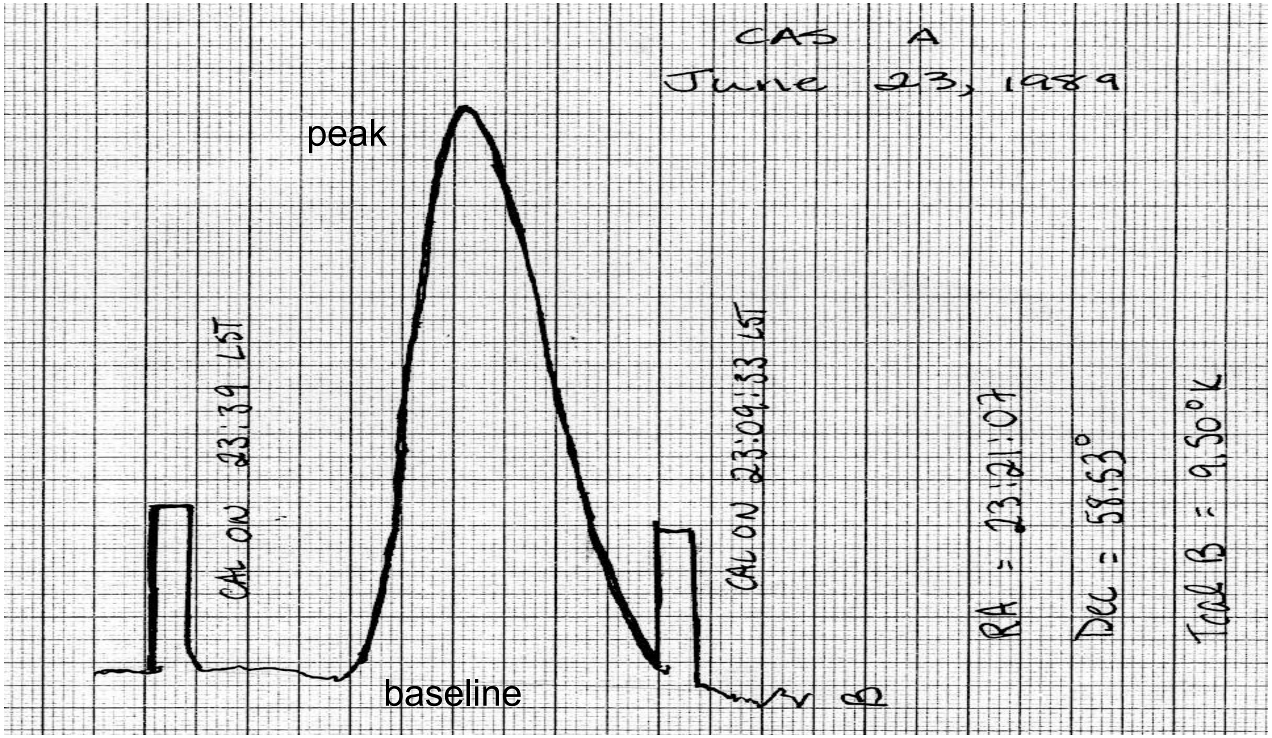
For an extended object with source solid angle $\Omega_s$,
And physical temperature $T_s$, then

for $\Omega_s < \Omega_A$ $$T_A = \frac{\Omega_s}{\Omega_A} T_s$$

for $\Omega_s > \Omega_A$ $$T_A = T_s$$

In general : $$T_A = \frac{1}{\Omega_A} \iint_{source} P_n(\theta,\phi) T_s(\theta,\phi) d\Omega$$

# Calibration:  Scan of Cass A with the 40-Foot



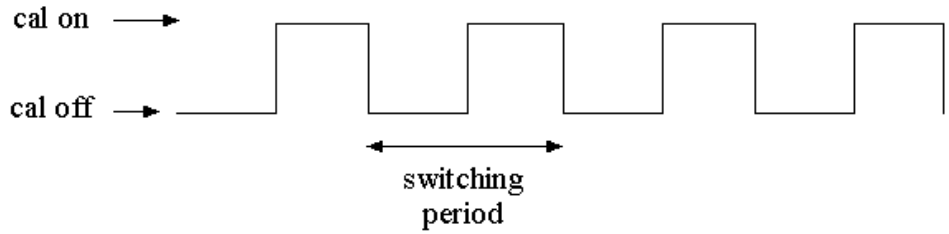

Tant = Tcal * (peak-baseline)/(cal – baseline)

(Tcal is known)

# More Calibration : GBT

Convert counts to T

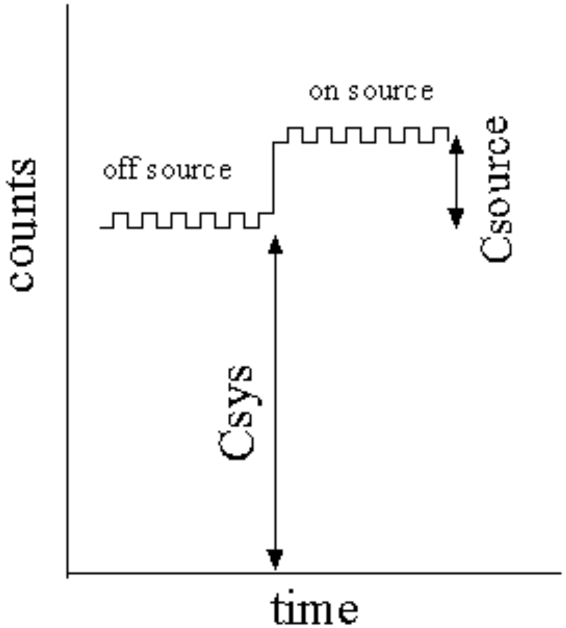
$$K = \frac{T_{cal}}{\left\langle C_{cal-on} - C_{cal-off} \right\rangle}$$



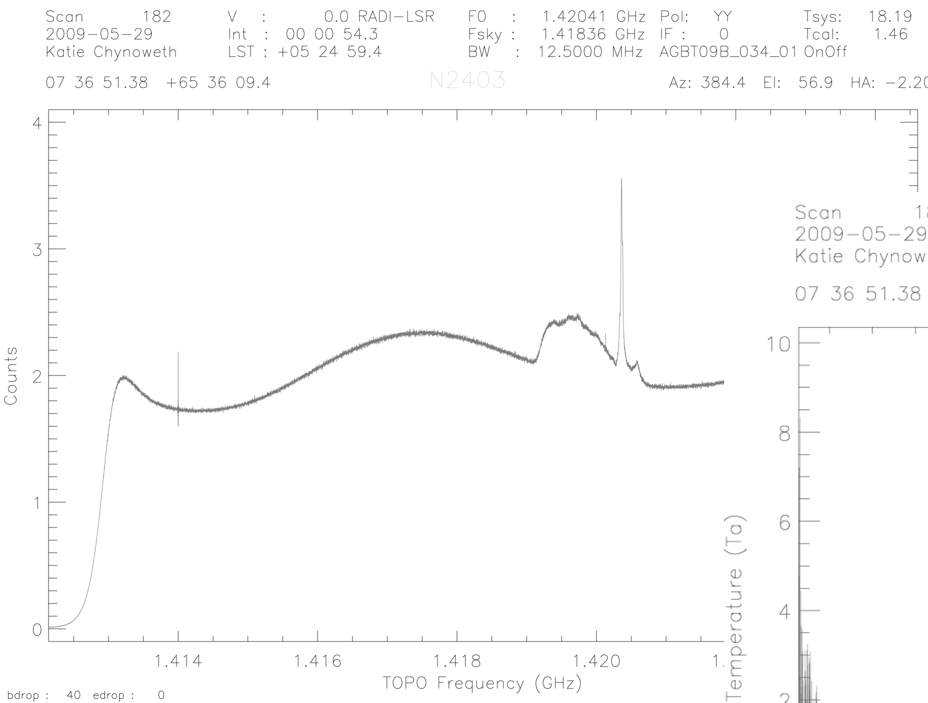

$$T_{sys} = K \cdot C_{sys}$$

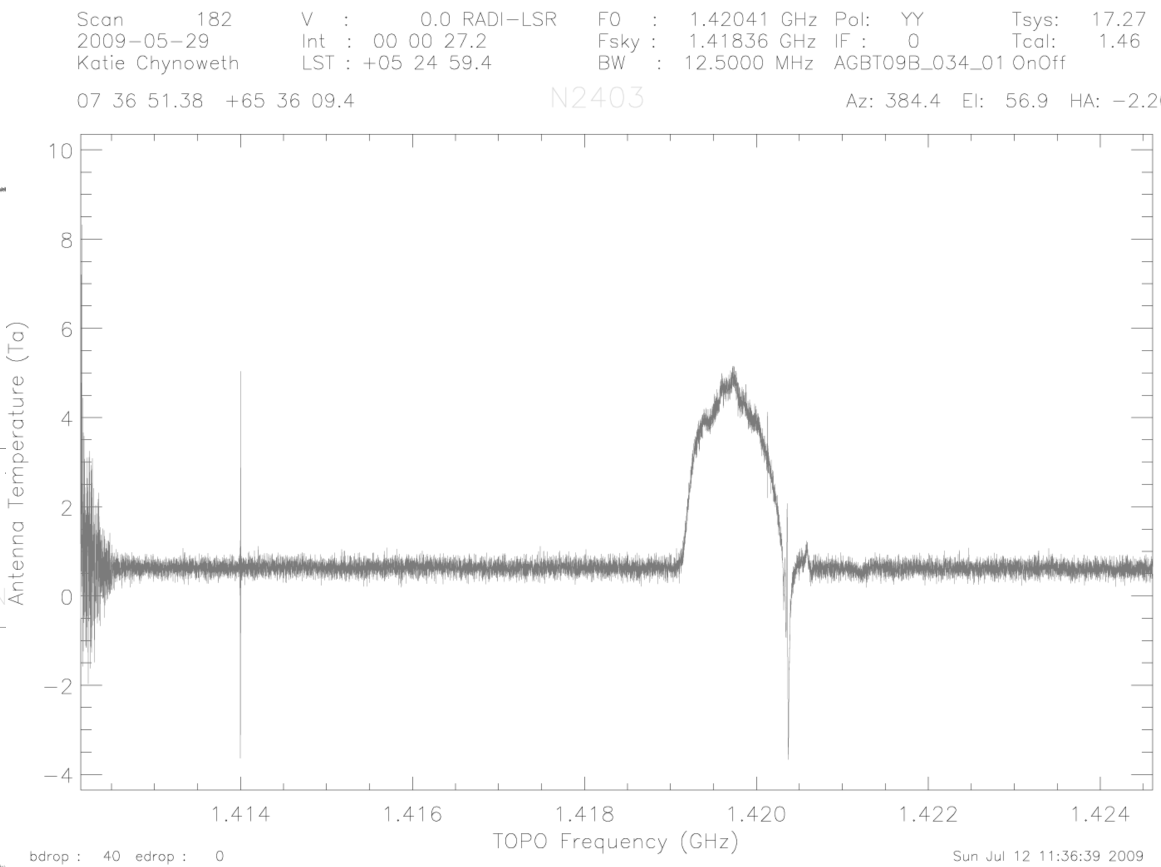
$$= \frac{1}{2} K \cdot (C_{offsource,calon} + C_{offsource,caloff}) - \frac{1}{2} T_{cal}$$

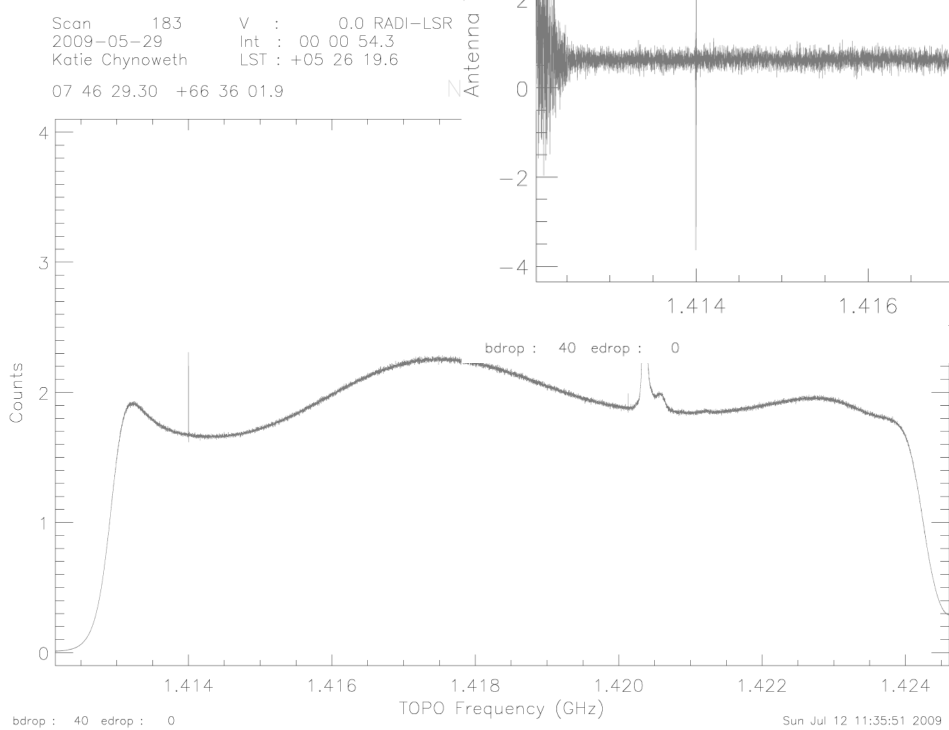
$$T_{ant} = K \cdot C_{source}$$



# Position switching



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