Continuum Observations

Jim Condon

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

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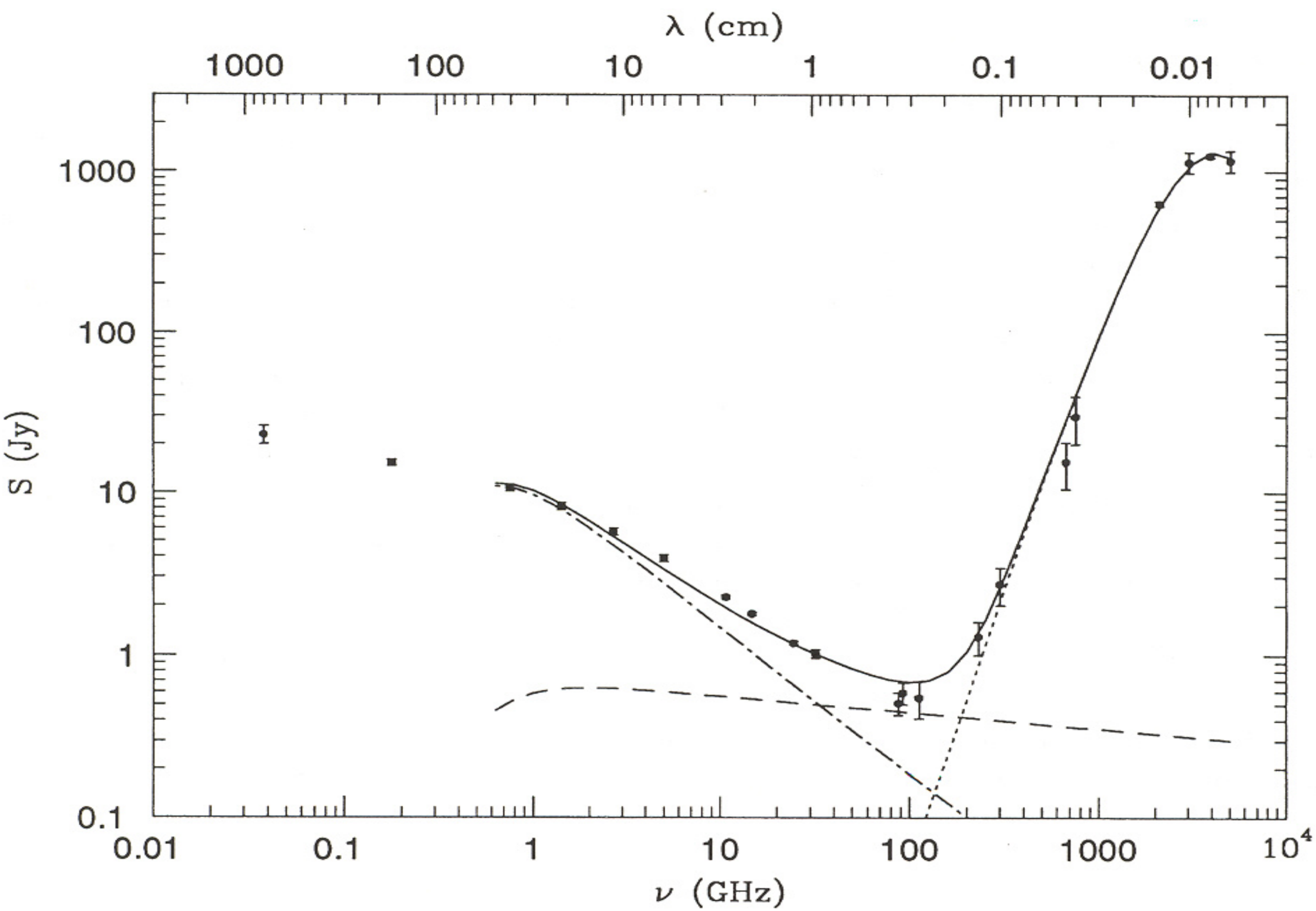
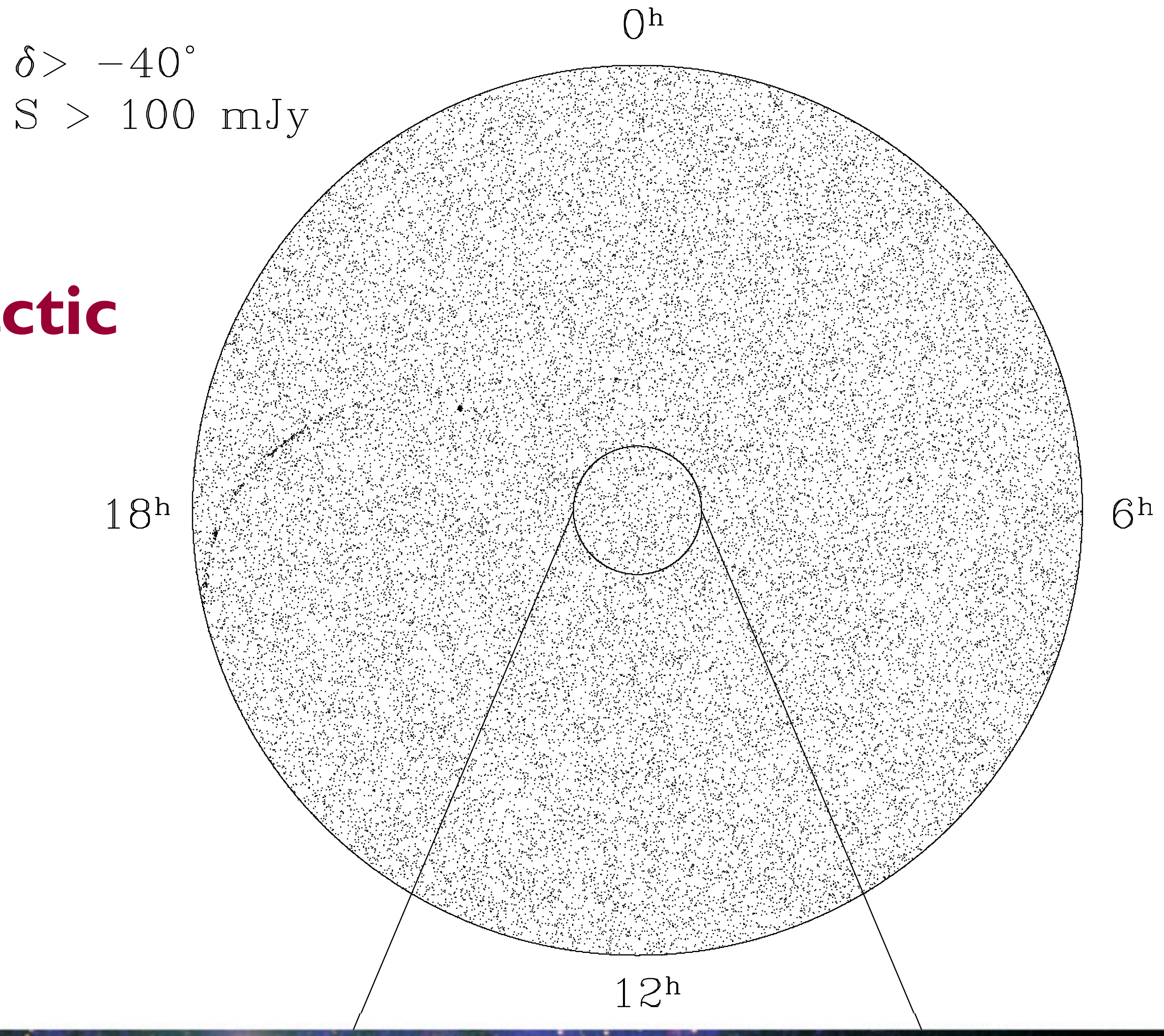
Astronomical Continuum Sources

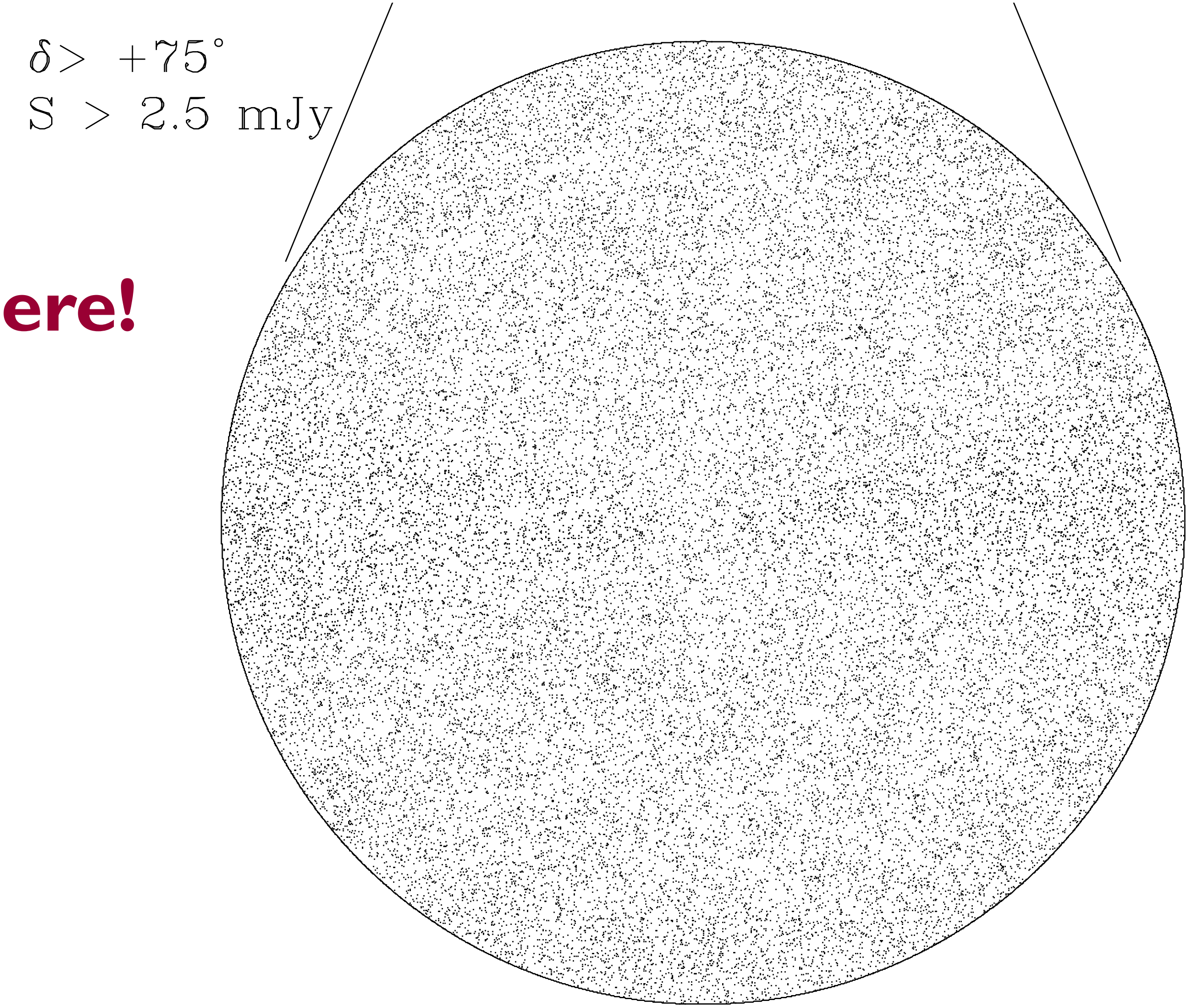


Synchrotron (dash-dot curve), free-free (dashes), and dust (dots) emission typical of spiral galaxies

Mostly extragalactic



Everywhere!

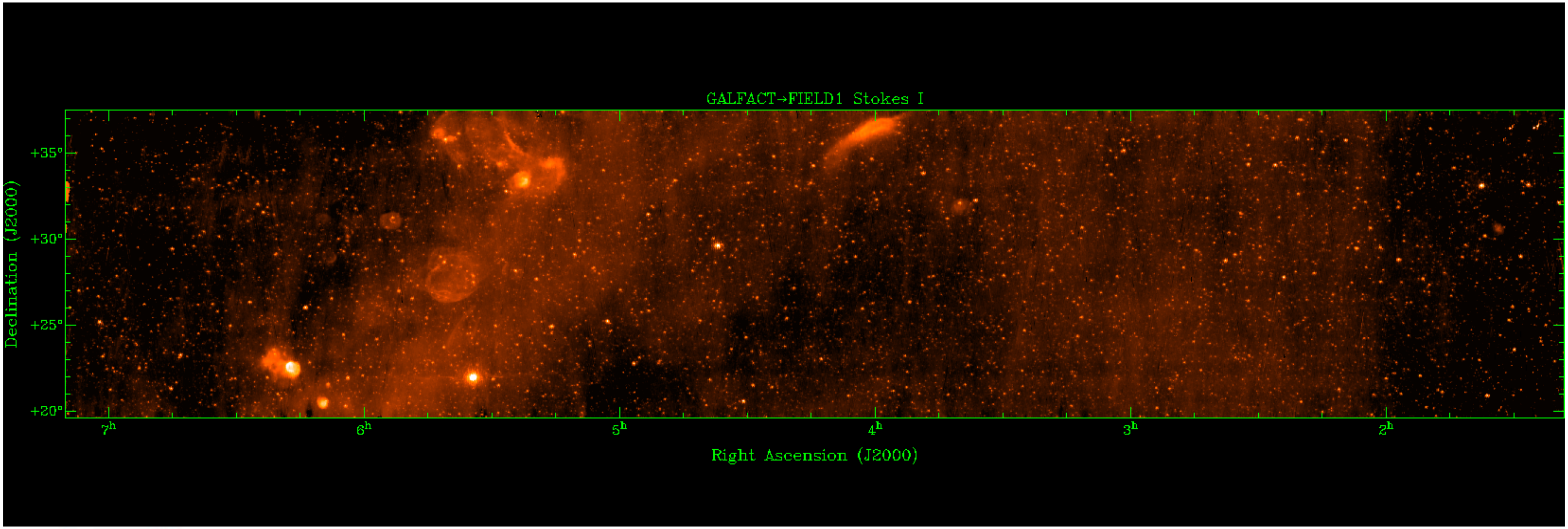


Continuum emission and single-dish telescopes

- Continuum sources produce steady, broadband noise
- So do receiver noise and drift, atmospheric emission, ground pickup, confusion by other astronomical sources in the beam, etc.
- Astronomical continuum sources are everywhere:
  Good: for telescope calibration and collimation
  Bad: for system noise, confusion, spectral baselines
- Single dishes can image large areas and smooth low-brightness sources to complement interferometric observations
- Single dishes can (more easily) use array feeds and wide bandwidths (but interferometers are catching up)

GALFACTS

- Full-Stokes, all-Arecibo-sky, 1.4 GHz continuum survey; 300 MHz bandwidth
- Science:
  - Free-free / synchrotoron separation of low-b Galactic continuum.
  - Discrete Galactic radio sources (e.g. SNRs, HII regions,PNe).
  - Galactic Loops.
  - Foreground removal for Planck (CMB intensity and polarization).



Single-dish continuum observations of faint or extended sources

- Pure thermal noise
- 1/f noise (receiver and atmosphere)
- Total-power baselines
- Confusion
- RFI

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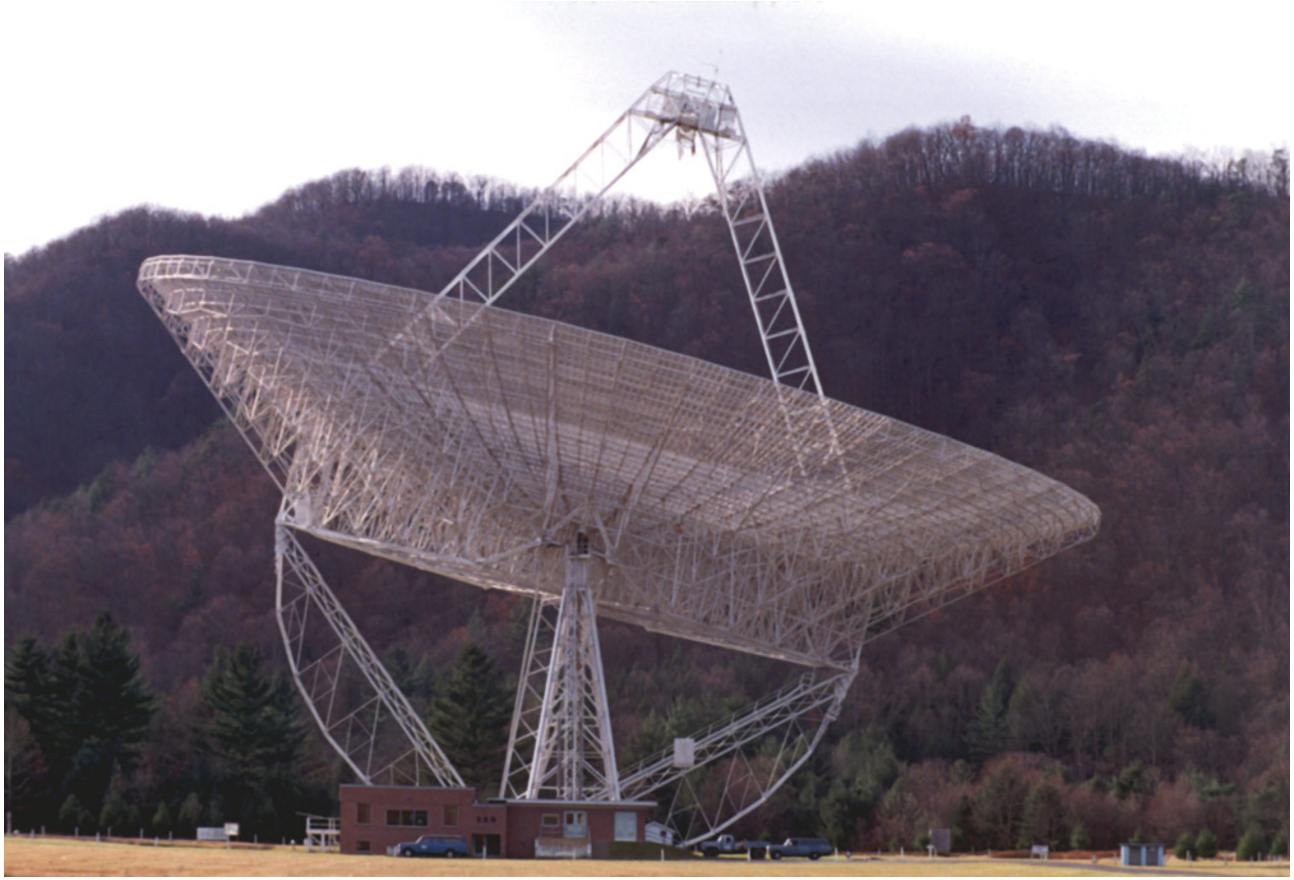
Example: Green Bank 300-foot telescope 7-beam total-power 4.85 GHz sky survey covering $+5^{o} < \delta < +75^{o}$



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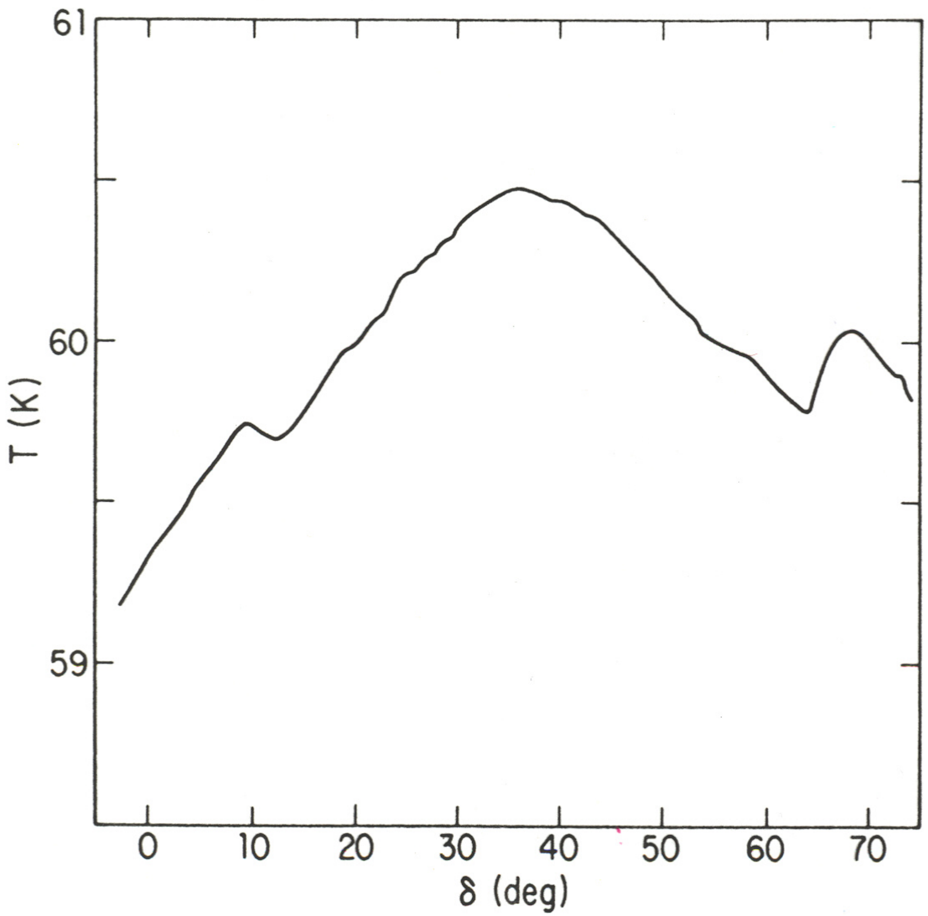
Continuum Baselines



The total-power output from one receiver channel during a 4.85 GHz scan. The system temperature T ≈ 60 K includes receiver noise, atmospheric emission, feed spillover, ground radiation leaking through the reflector mesh, etc.

The practical total-power radiometer equation

$$\sigma_{\mathrm{T}} \approx T_{\mathrm{sys}} \left[\frac{1}{\Delta\nu_{\mathrm{RF}}\tau} + \left(\frac{\Delta G}{G} \right)^2 \right]^{1/2} \quad \text{(3E4)}$$

Pure noise Gain changes

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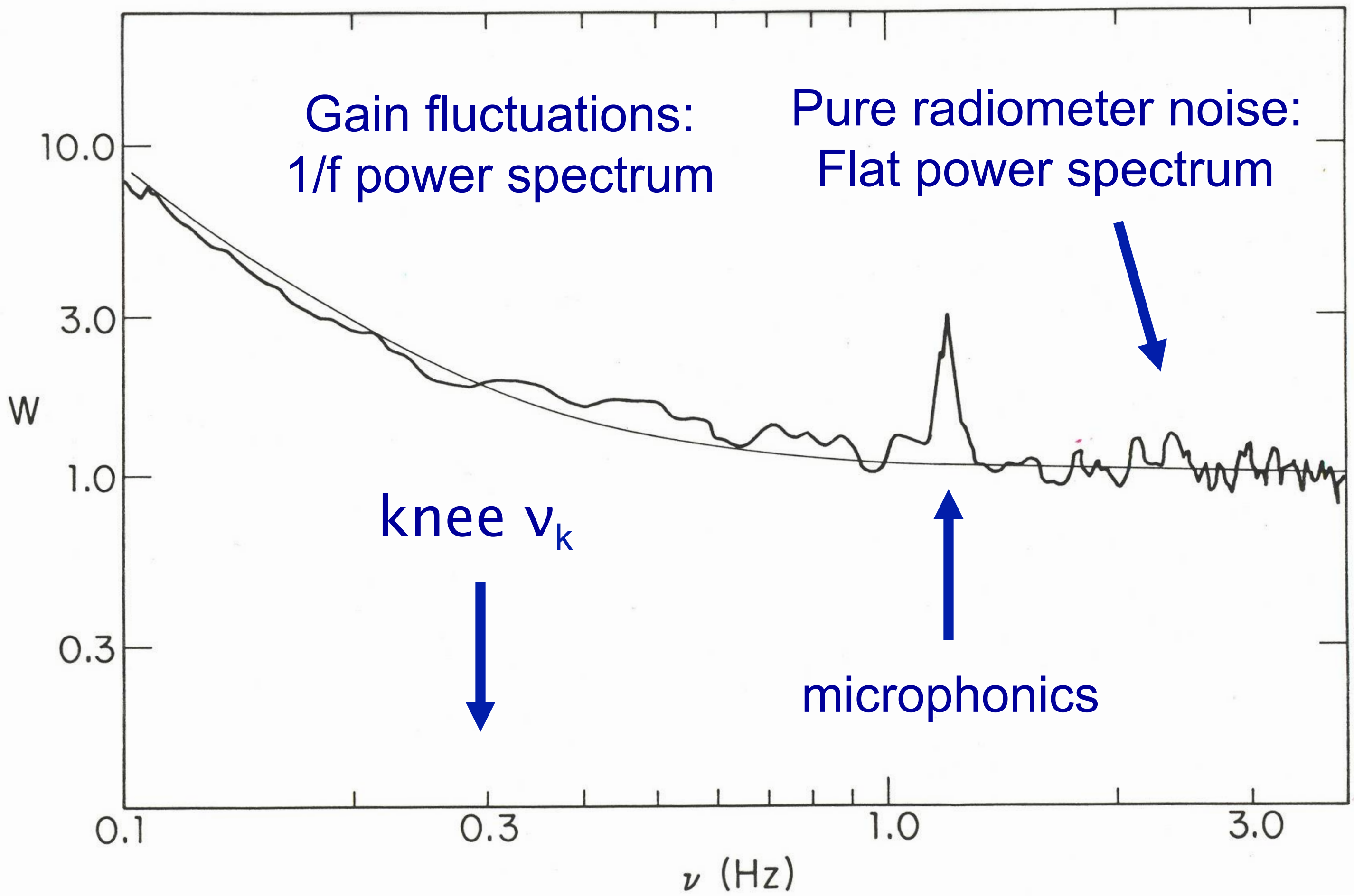
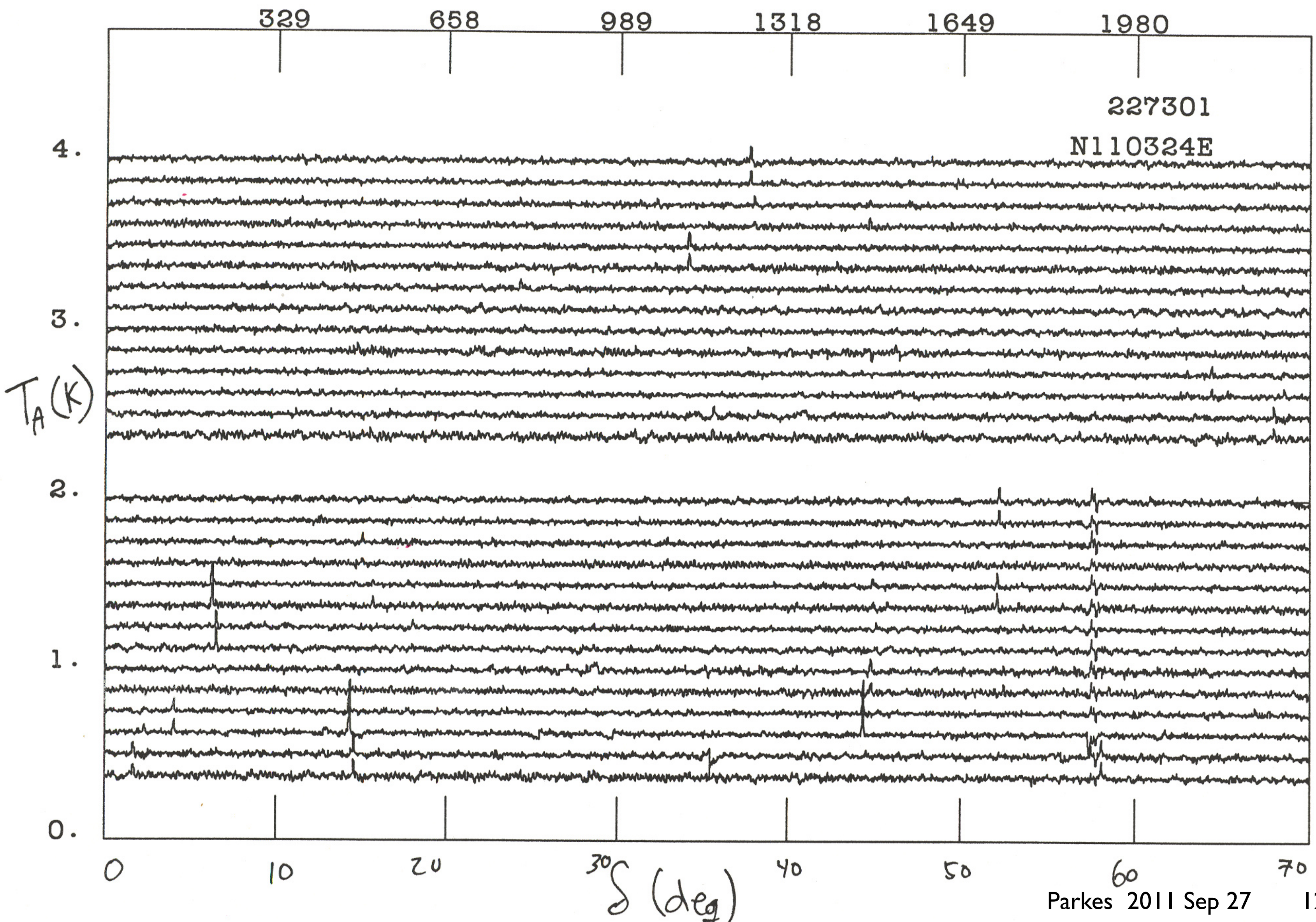
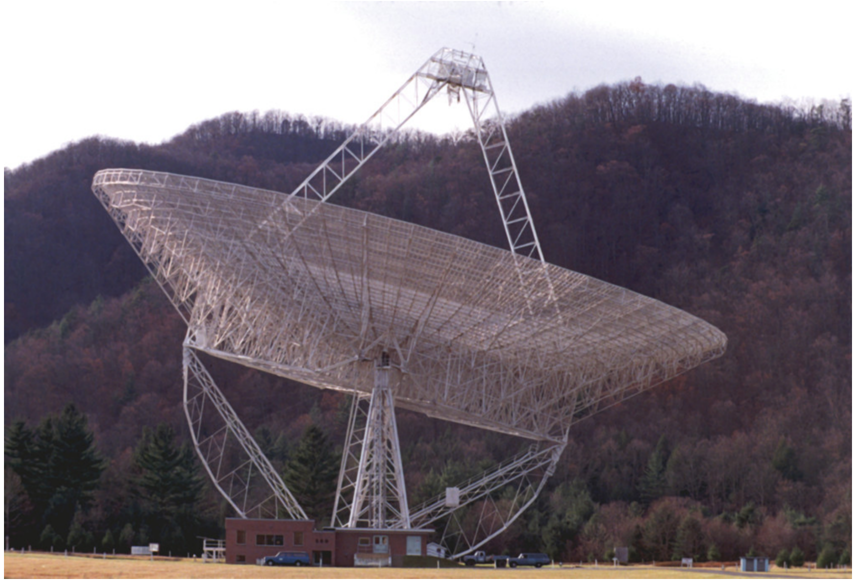
Postdetection power spectrum of total-power receiver output



Running-median baselines have removed atmospheric emission, spillover, 1/f noise, and extended sources.



300-foot telescope: RIP



Differential Radiometers

For $T_{SRC} << T_{SYS}$, gain fluctuations don't contribute significantly to the noise

$$G\{T_{SRC} + T_{RX} + T_{ATM}\}$$

$$G\{T_{RX} + T_{ATM}\}$$

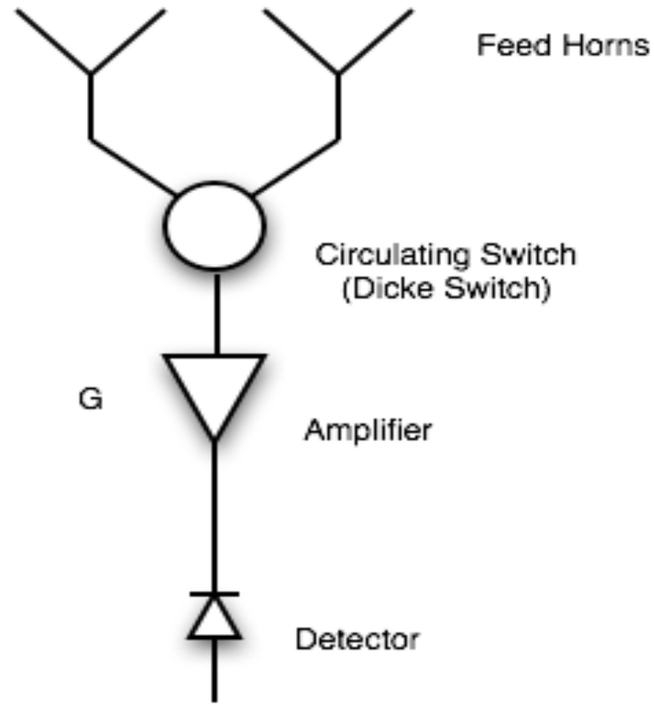
$$On - Off = GT_{SRC} + (\Delta G = 0)(T_{RX} + T_{SKY})$$

But: up to 2X higher noise

$$\Delta T = T_1 - T_2$$

$$RMS(\Delta T) = \sqrt{2} \times RMS(T_1)$$

$$= \sqrt{2}\frac{T_1}{\sqrt{\Delta\nu\tau_1}} = \frac{2T_1}{\sqrt{\Delta\nu\tau_{Tot}}}$$



G(t1) V1^2
G(t2) V2^2
G(t3) V1^2
.
.

$$\Delta P = G(V_1^2 - V_2^2)$$

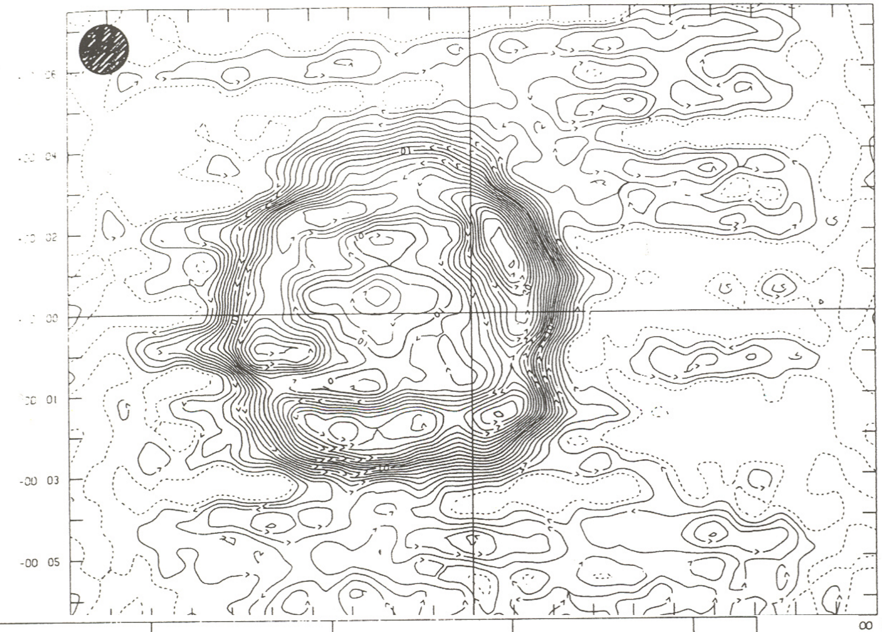
Beam switching and basketweaving

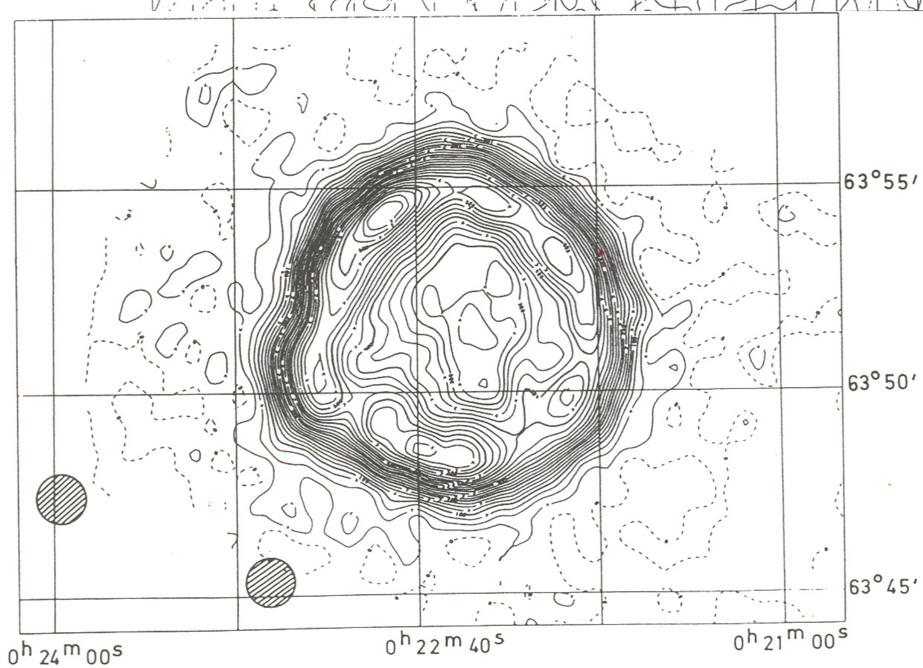
SNR 3C 10 imaged at 10.7 GHz by horizontal scans only (top) and by dual-beam basketweaving (bottom).

Basketweaving references:

Sieber et al. 1979, A&A, 74, 361

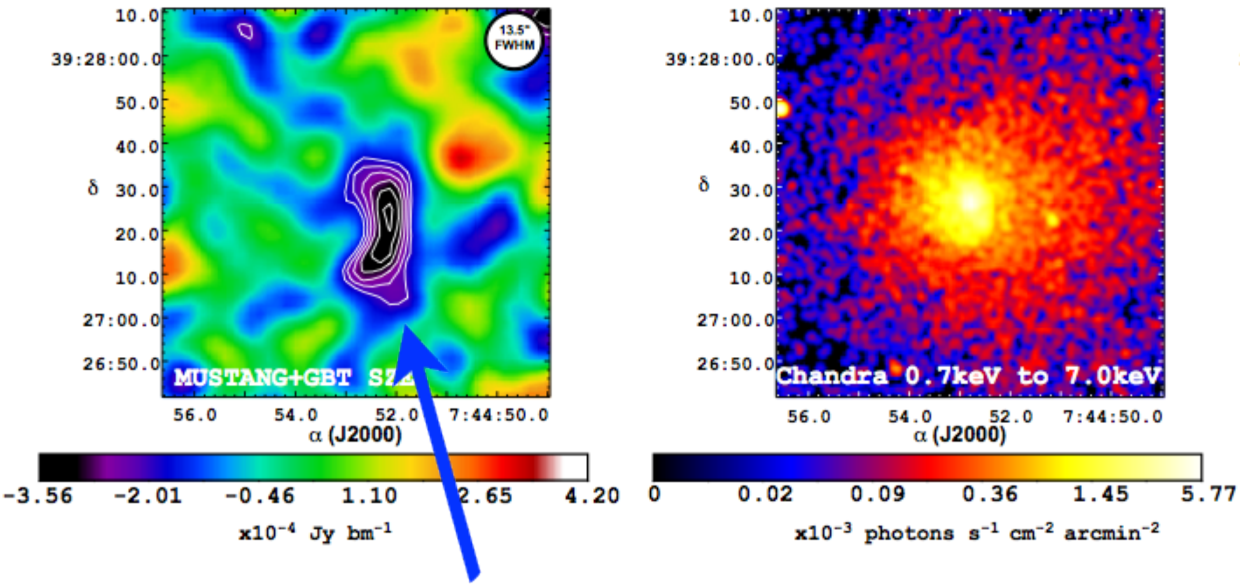
Emerson & Grave 1988, A&A, 190, 353





Sunyaev-Zel' dovich Effect

A spectral distortion in the CMB caused by scattering off of hot electrons in a cluster of galaxies



MACS0744+3927

GBT 90 GHz observations reveal a previously unknown & unexpected weak shock near the core of this cluster

Korngut et al. (2011)

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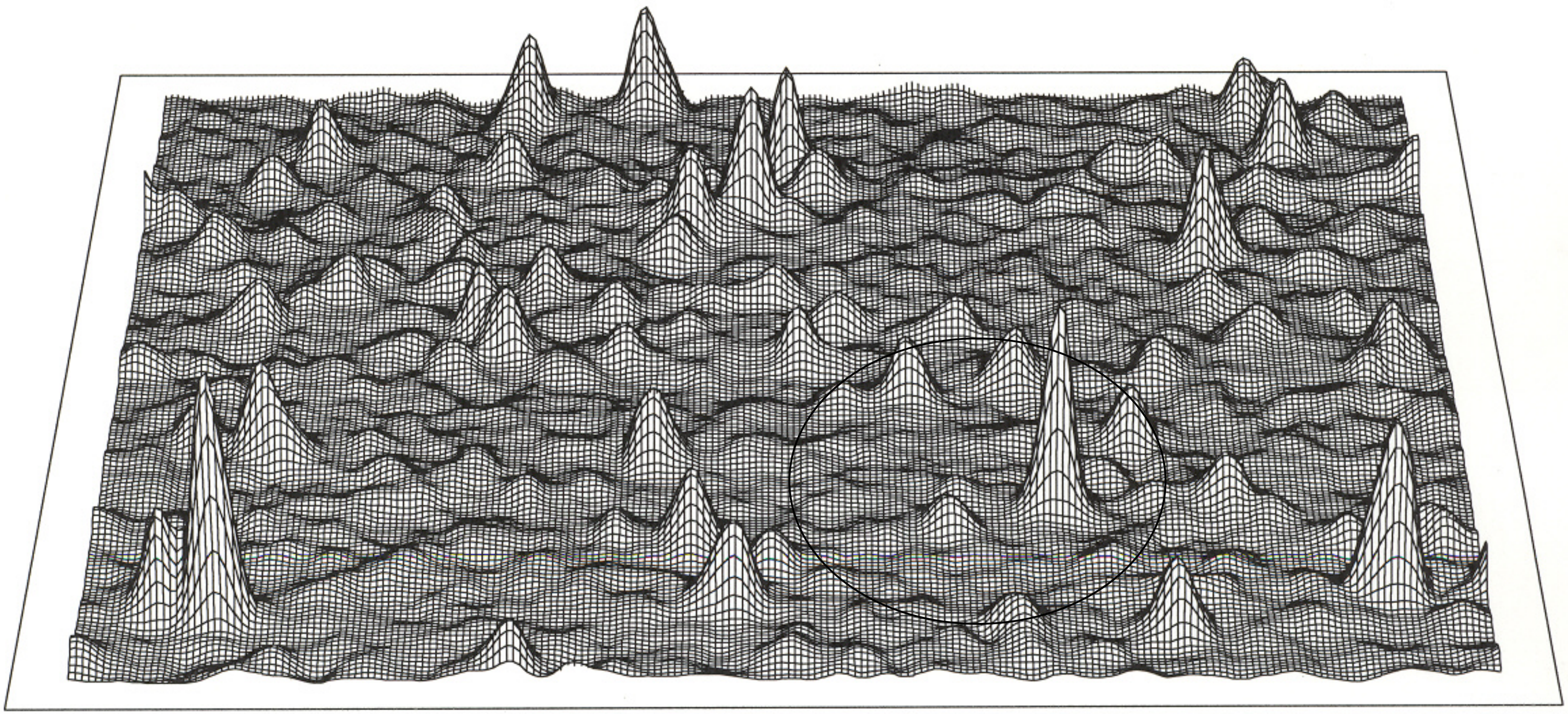
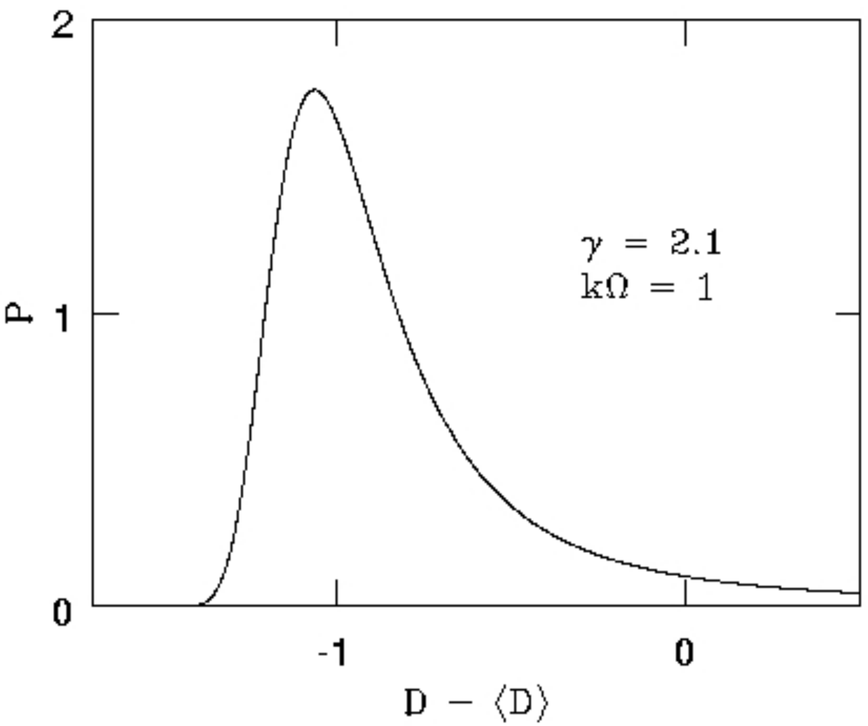
Confusion

Profile plot of 45 deg^2 near the NGP imaged with 12 arcmin resolution at 1.4 GHz. The strongest source has S ≈ 1.5 Jy.



The confusion amplitude distribution, a.k.a. P(D) distribution

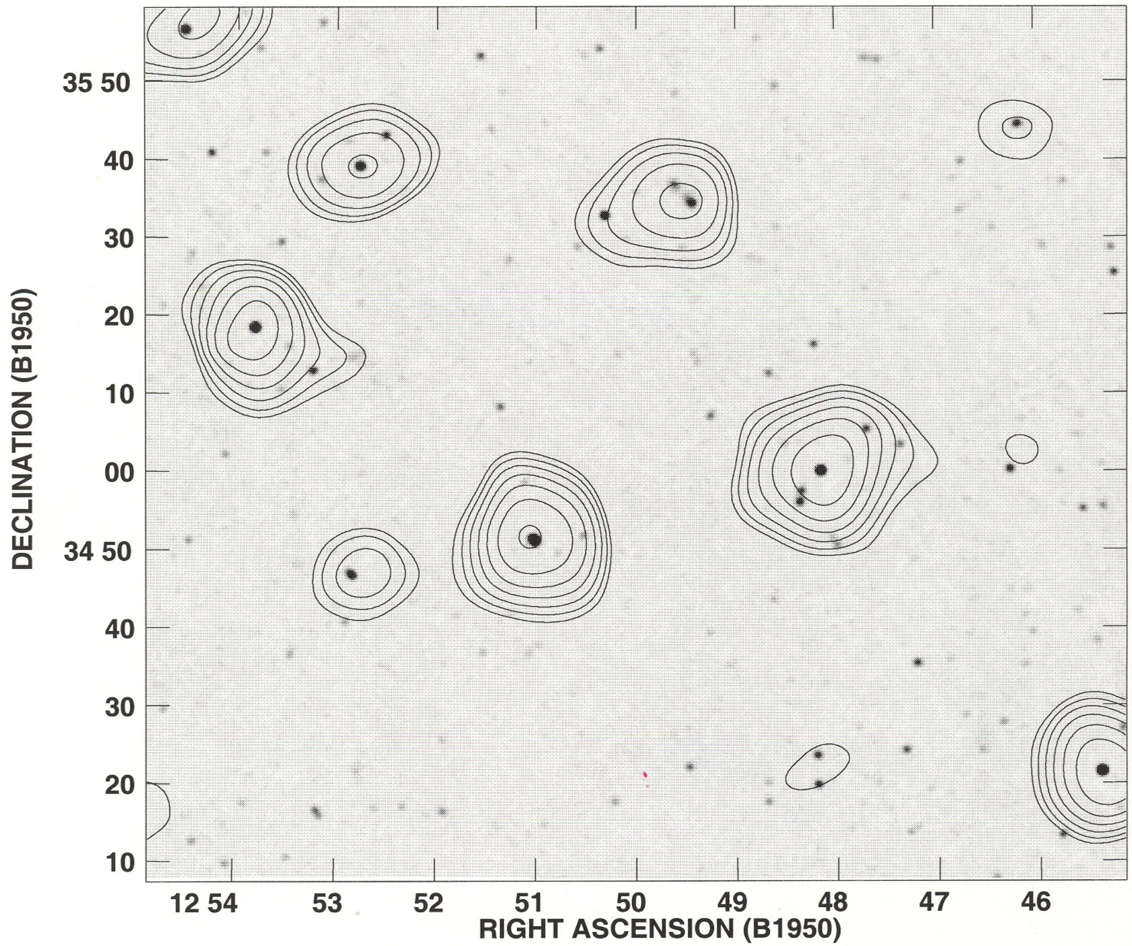


D = image brightness (e.g., Jy/beam)
D = 0 mean is not a good baseline

Confusion limit

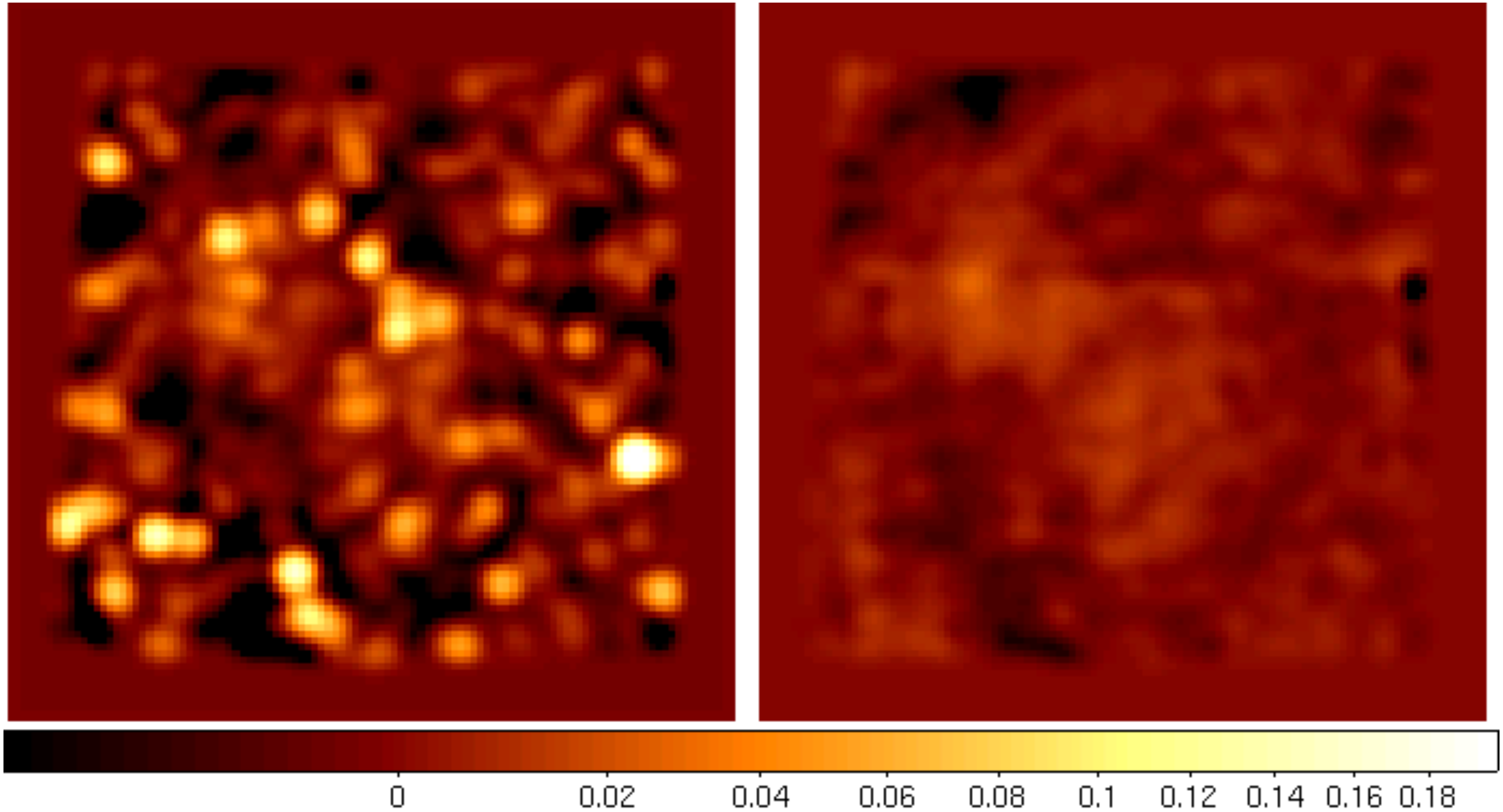
NVSS (45 arcsec FWHM) grayscale

GB6 300’ (12 arcmin FWHM) contours



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

$S_{min} \approx 5\sigma_c$



GBT 4 degree x 4 degree images (1.4 GHz, scale in Jy/beam)
Left: “raw” image Right: after NVSS sources subtracted

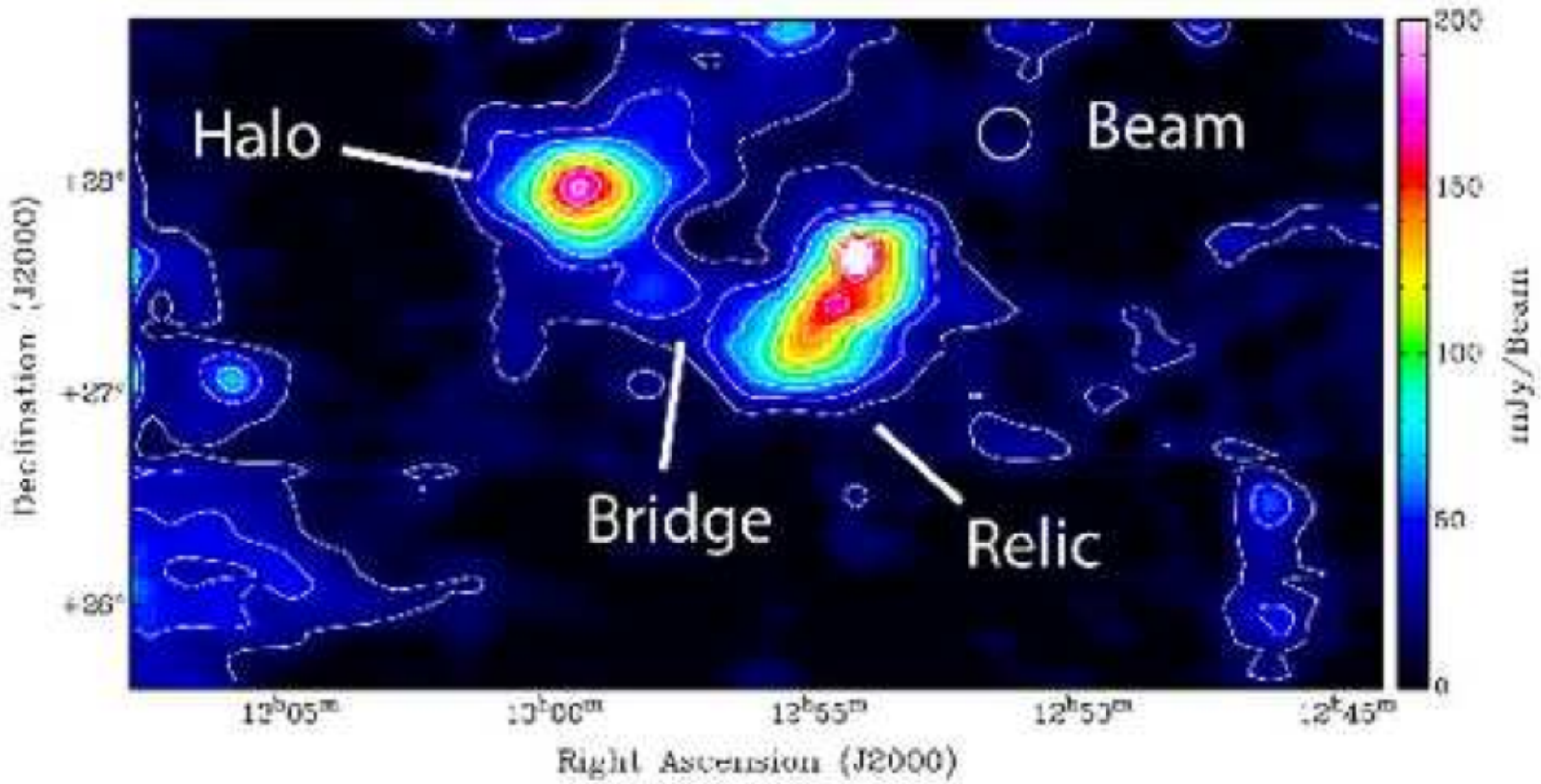


Figure 1. GBT total intensity image (using DEC scans only) with all NVSS emission subtracted out. ($14.25' \times 13'$ beam). Contours start at 20 mJy beam^{-1} (3σ) and increase in steps of 20 mJy beam^{-1}. The bright background source Coma A (3C 277.3) was fit and subtracted out by hand, although a small residual is still seen as the burnt out spot towards the northern part of the relic.

Brown & Rudnick 2011, MNRAS, 412, 2 1.4 GHz

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Strong continuum point sources as observing tools

- Sanity checks
- Offset pointing, focus, and surface setting
- Intensity (flux density), effective area, and polarization calibration

Effective collecting area and K/Jy

The Effective Area of a Receiving Antenna

How can we characterize antennas used for receiving, as in radio astronomy, rather than for transmitting? The receiving counterpart of transmitting power gain is the ***effective area*** or ***effective collecting area*** of an antenna.

Imagine an ideal antenna that collects all of the radiation falling on it from a distant point source and converts it to electrical power—a "rain gauge" for collecting photons. The total spectral power that it collects will be the product of its geometric area A and the incident spectral power per unit area, or flux density S. By analogy, if any real antenna collects spectral power P_ν, its *effective area* A_e is defined by

$$\boxed{A_e \equiv \frac{P_\nu}{S_{(\mathrm{matched})}}}, \quad (3A5)$$

where $S_{(\mathrm{matched})}$ is the flux density in the "matched" polarization.

What does ***matched polarization*** mean? Any electromagnetic wave can be decomposed into two orthogonal polarized components. For example, the transverse electric field can be resolved into horizontal and vertical components, or horizontal and vertical ***linear polarizations***. If the horizontal and vertical electric fields are equal in amplitude and 90° out of phase, the radiation is ***circularly polarized***. Any radio wave can also be decomposed into left- and right-circular polarizations. If the wave is essentially random (noise generated by blackbody radiation for example), the two orthogonal components will vary rapidly in intensity but have equal powers when averaged over long times. Such radiation is called ***unpolarized***. Thus for an *unpolarized* source,

$$S_{(\mathrm{matched})} = \frac{S}{2}\,.$$

Antenna Temperature

A convenient practical unit for the power output per unit frequency from a receiving antenna is the ***antenna temperature*** T_A. Antenna temperature has nothing to do with the physical temperature of the antenna as measured by a thermometer; it is only the temperature of a matched resistor whose thermally generated power per unit frequency equals that produced by the antenna. It is widely used because:

1. 1 K of antenna temperature is a conveniently small power. $T_A = 1$ K corresponds to $P_\nu = kT_A = 1.38 \times 10^{-23}\ \mathrm{J\,K^{-1}} \times 1\ \mathrm{K} = 1.38 \times 10^{-23}\ \mathrm{W\,Hz^{-1}}$.
2. It can be calibrated by a direct comparison with hot and cold *loads* (another word for matched resistors) connected to the receiver input.
3. The units of receiver noise are also K, so comparing the signal in K with the receiver noise in K makes it easy to decide if a signal will be detectable.

$$\boxed{T_A \equiv \frac{P_\nu}{k}} \qquad (3A9)$$

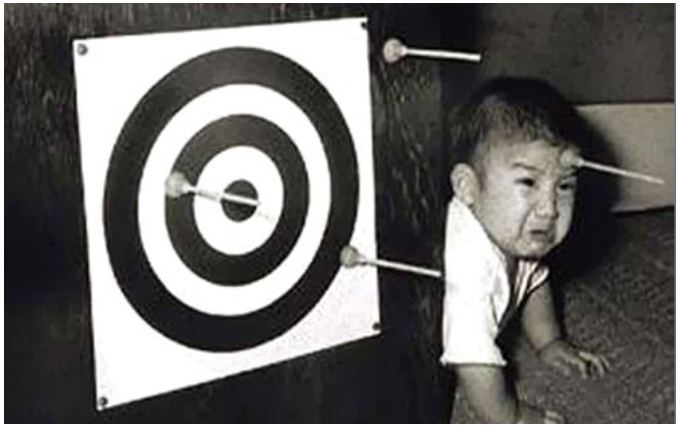
An unpolarized point source of flux density S increases the antenna temperature by

$$\boxed{T_A = \frac{P_\nu}{k} = \frac{A_e S}{2k}} \qquad (3A10)$$

where A_e is the effective collecting area. It is often convenient to express the point-source sensitivity of a radio telescope in units of "Kelvins per Jansky" rather than in units of area (m^2). The effective area corresponding to a sensitivity of $1\ \mathrm{K\,Jy^{-1}}$ is

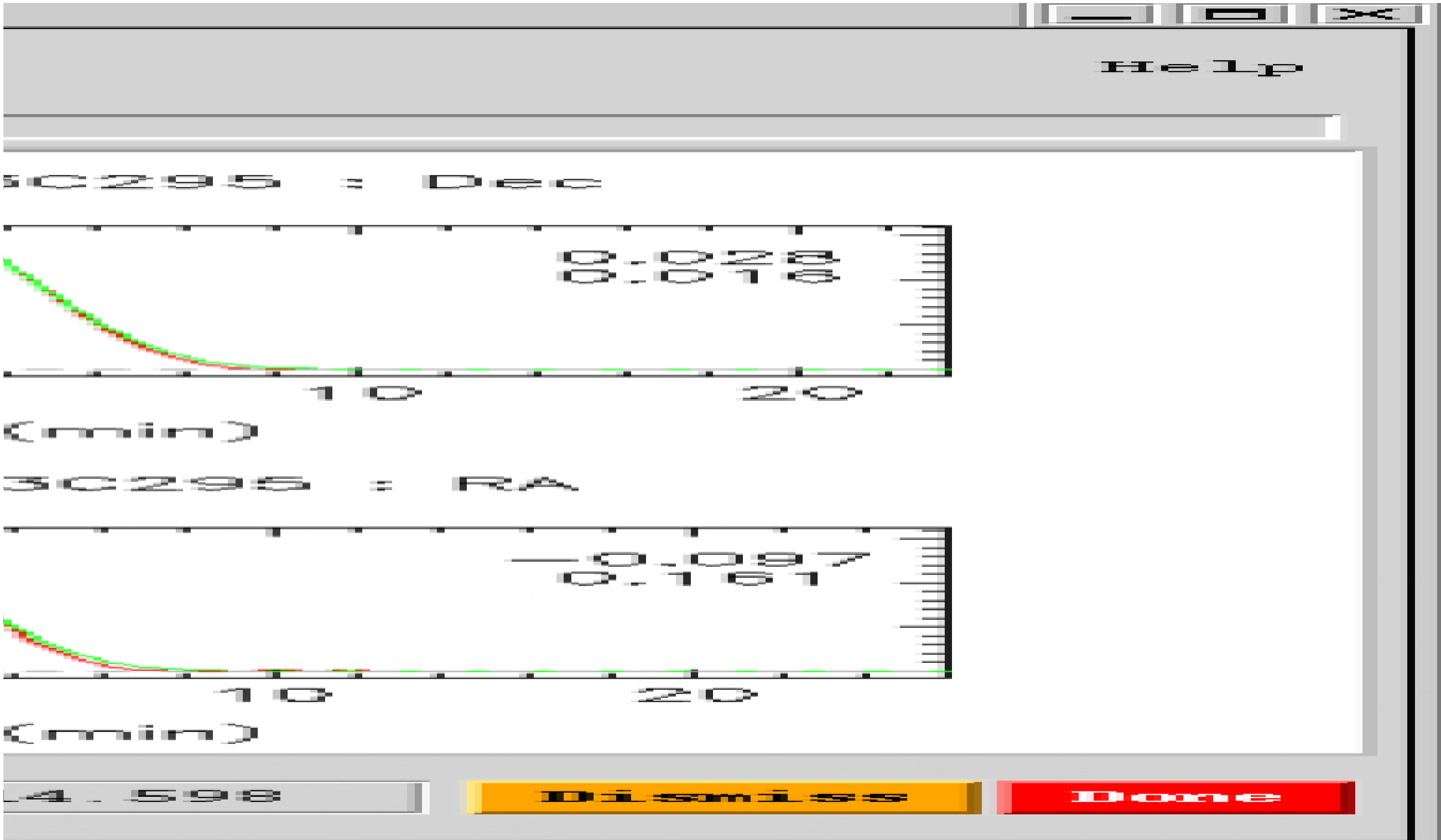
$$A_e = \frac{2kT}{S} = \frac{2 \cdot 1.38065 \times 10^{-23}\ \mathrm{J\,K^{-1}} \cdot 1\ \mathrm{K}}{10^{-26}\ \mathrm{W\,m^{-2}\,Hz^{-1}}} = 2761\ \mathrm{m}^2 .$$

Telescope pointing, focus, and surface accuracy



- Repeatable errors (e.g., gravitational deformations) can be modeled and corrected in the telescope pointing/focus/surface model.
- Non-repeatable errors
  - thermal: timescale ~1 hour (night vs day). Differentiate errors by monitoring a pointing/focus calibrator, correct surface with OOF holography
  - wind: timescale ~ 10 seconds. Optically monitor and correct telescope deformations

A cross scan yields the pointing offset, beamwidth, T_A (and T_A/S_{CAL})

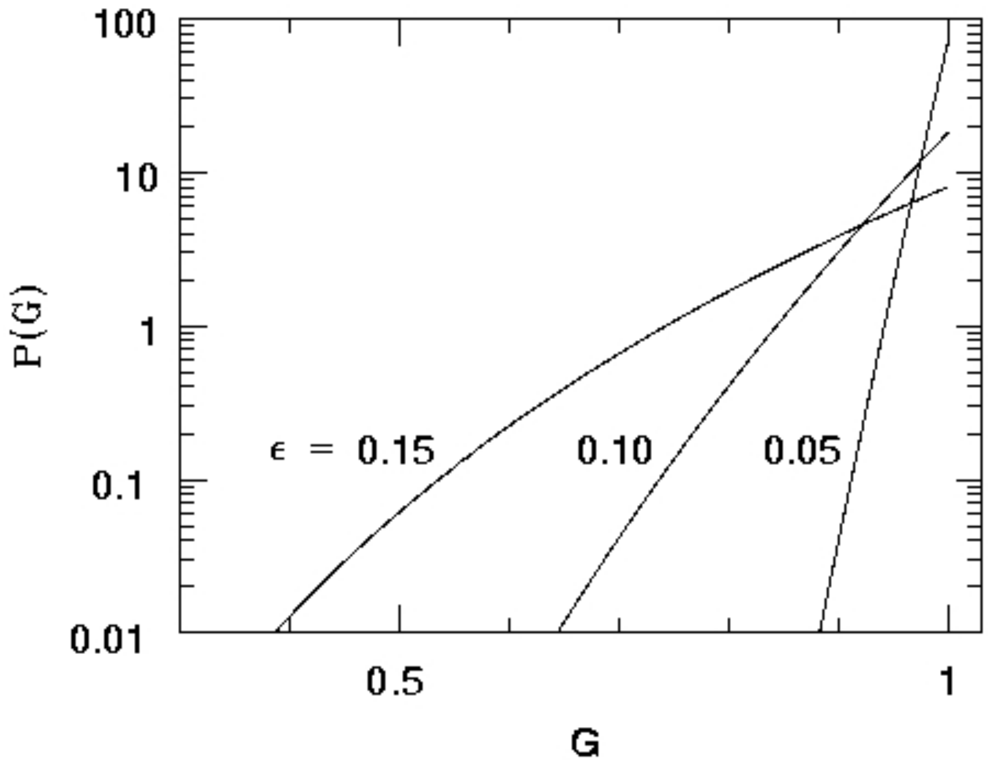


Distributions of normalized gain G resulting from Gaussian pointing errors with rms = ε × HPBW

$$P(G) = [(8 \ln 2)\epsilon^2 G]^{-1} \exp\left[\frac{\ln G}{(8 \ln 2)\epsilon^2}\right]$$

$$\langle G \rangle = [1 + (8 \ln 2)\epsilon^2]^{-1}$$

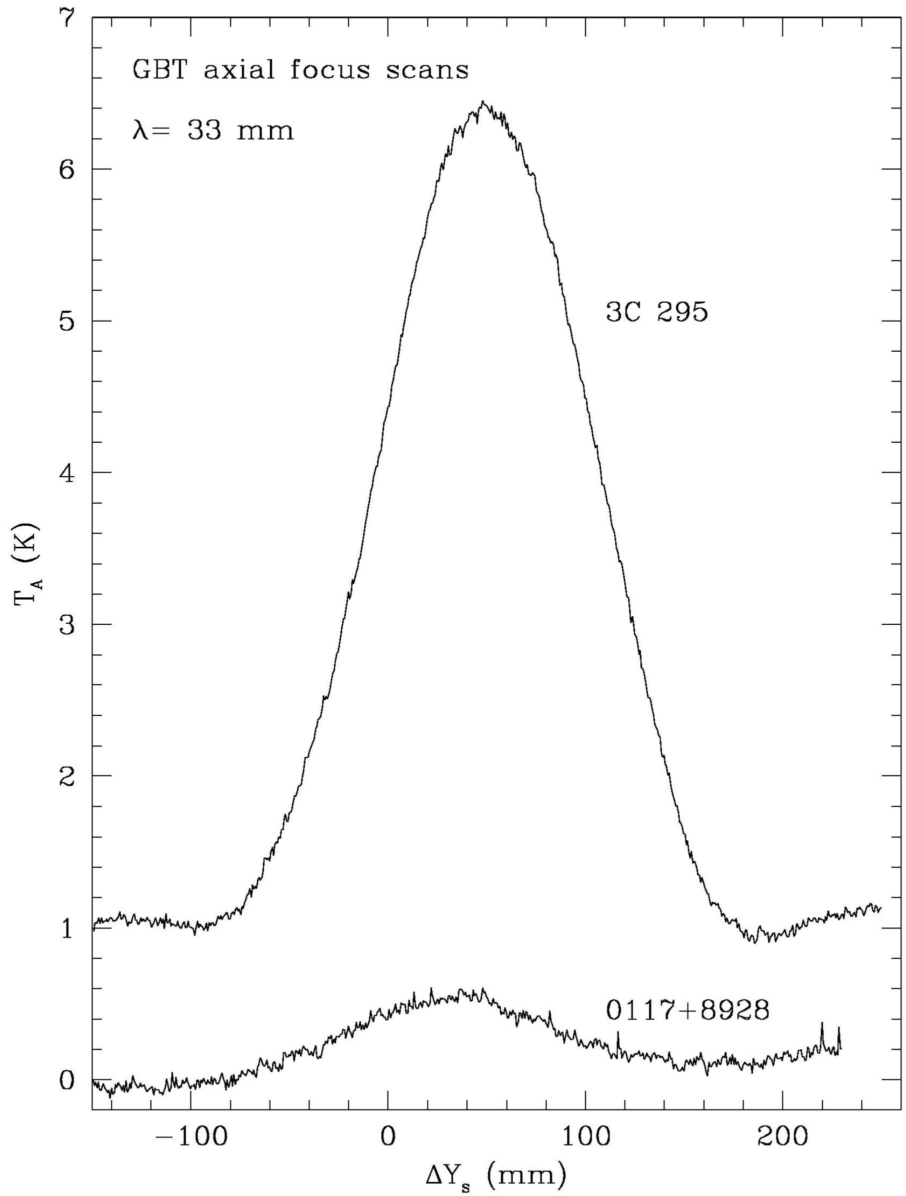
$$\frac{\sigma_{\rm G}}{\langle G \rangle} = (8 \ln 2)\epsilon^2 + [(8 \ln 2)\epsilon^2]^2$$



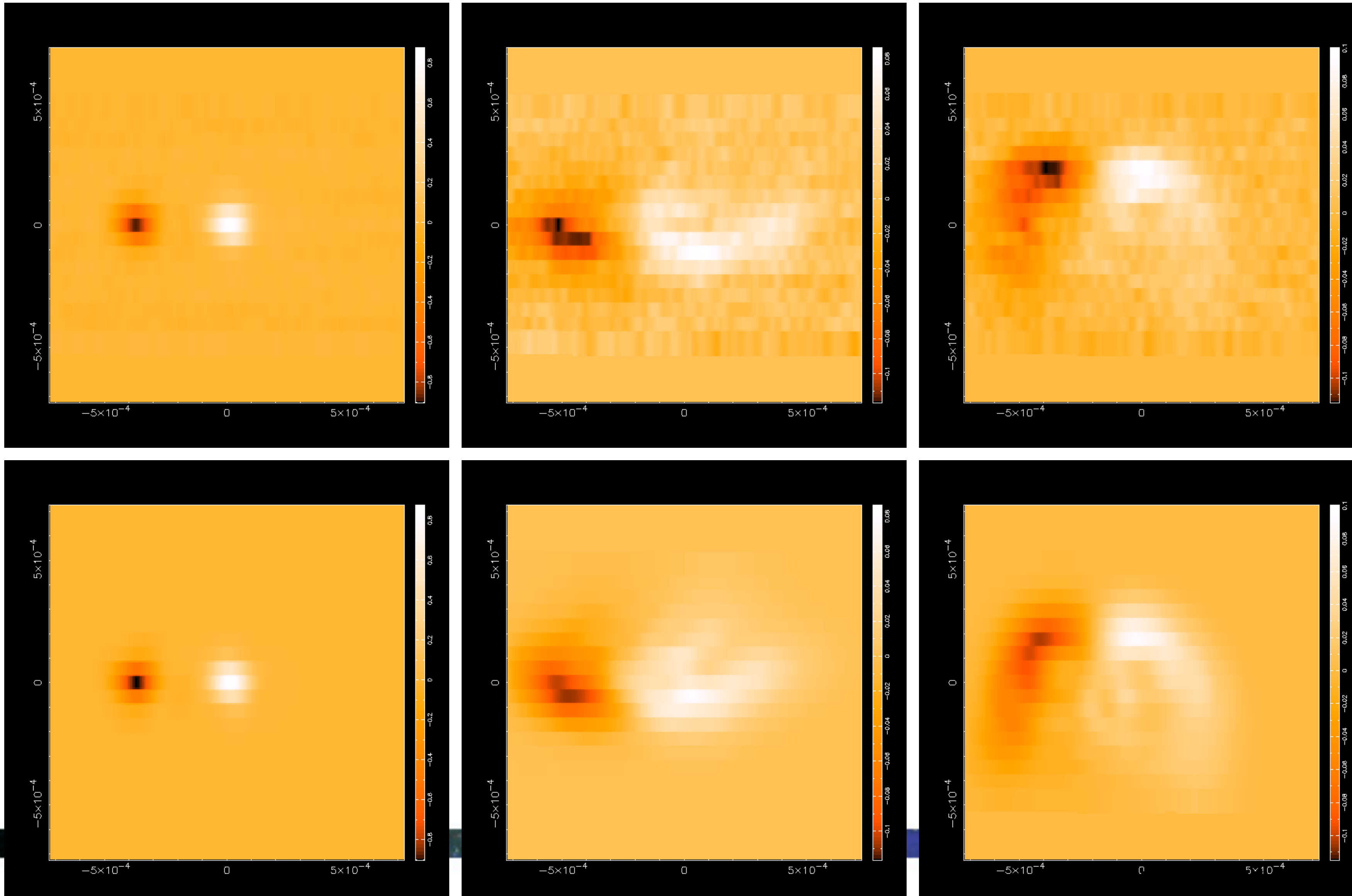
Axial Focus

GBT focal ellipsoid

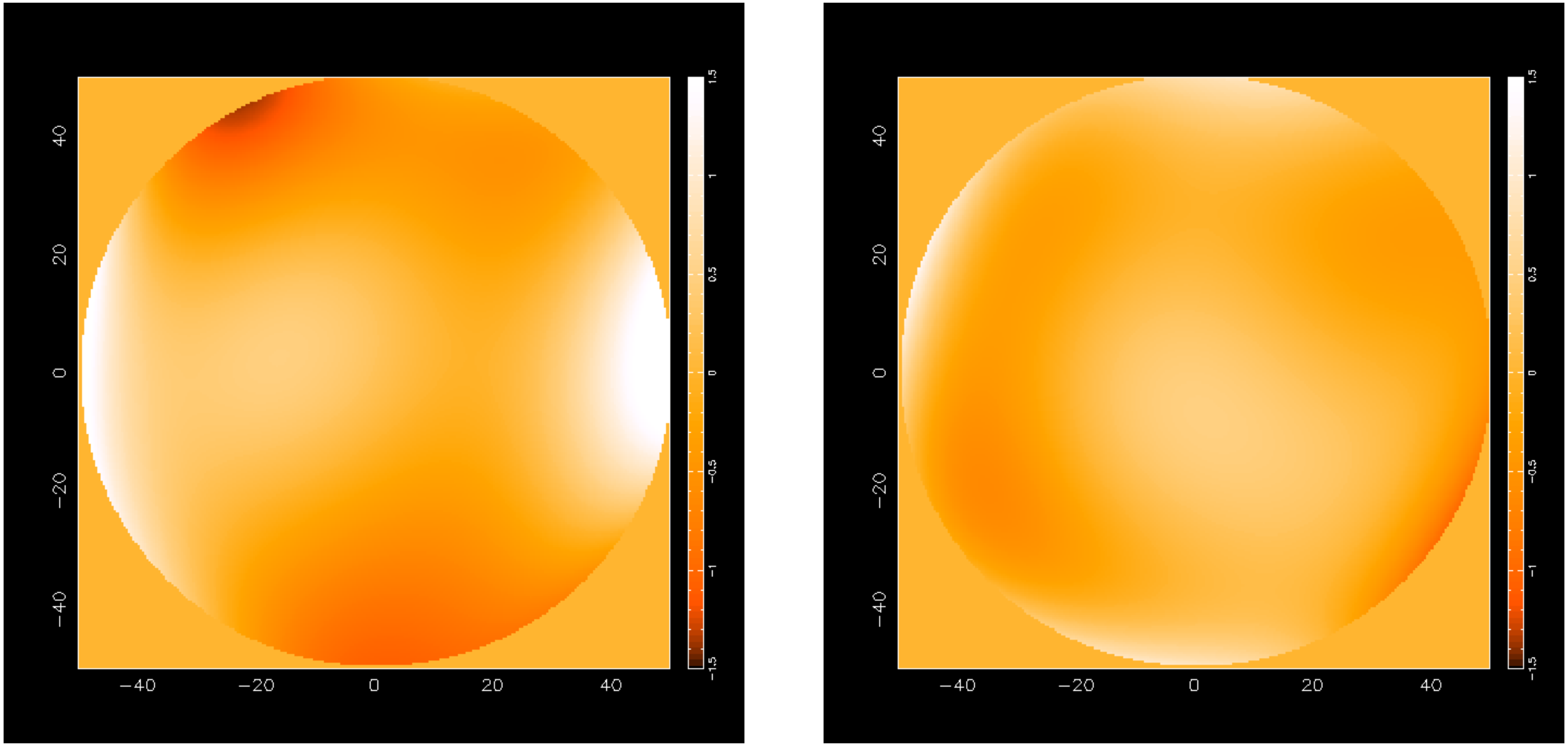
axial FWHM ≈ 4 λ



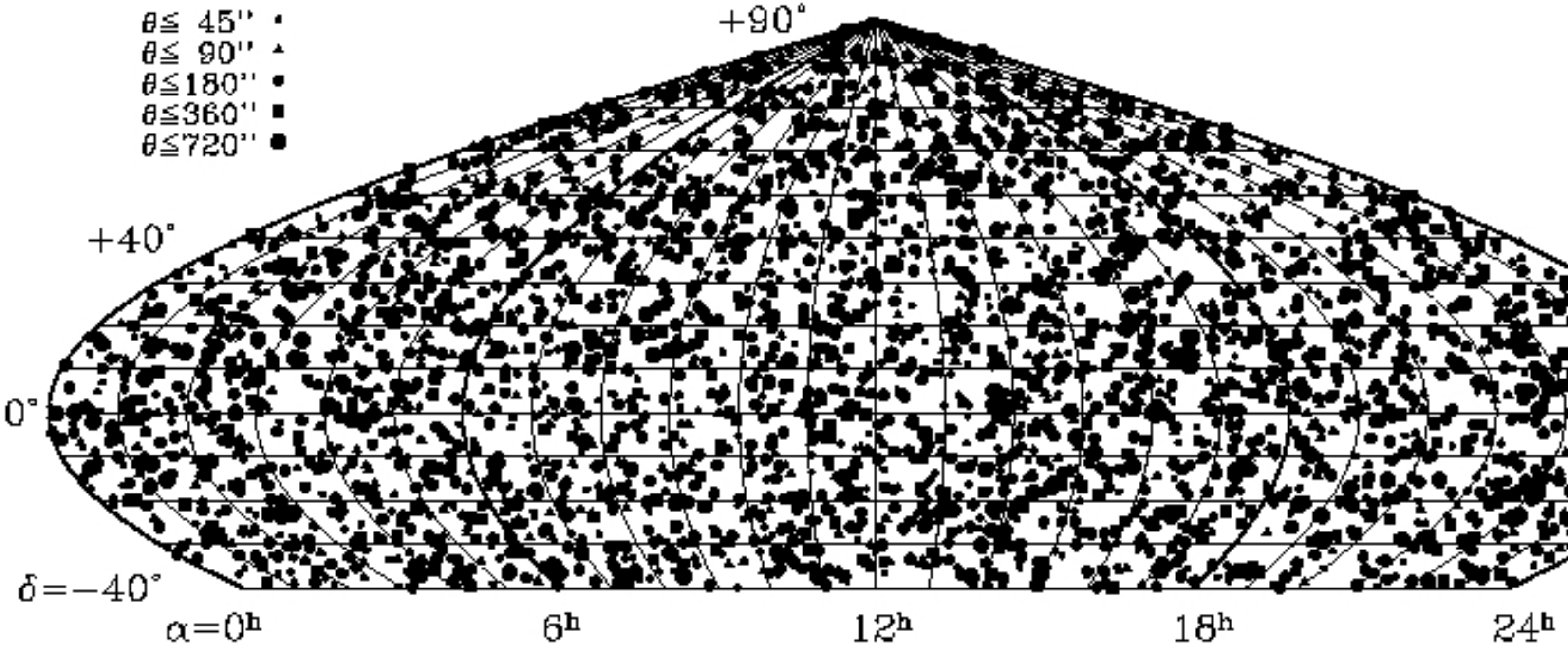
Telescope setting by OOF (out of focus) holography



GBT telescope surface-error maps: before: σ = 370 µm, after: σ = 210 µm



This grid calibrators is used to reduce GBT tracking errors north of δ = -40°.



Flux-density and polarization calibrators:
Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., & Witzel, A. 1977, A&A, 61, 99; Ott, M. et al. 1994, A&A, 284, 331
http://134.104.64.34/JN/effbg_rx/kalirie.htm
http://www.aoc.nrao.edu/~gtaylor/calib.html
http://www.aoc.nrao.edu/~gtaylor/calman/polcal.html
ftp://ftp.atnf.csiro.au/pub/atnfdocs/guides/at.cat

Single-dish position calibrators:
Condon, J. J., & Yin, Q. F. 2001, PASP, 113, 362
ftp://ftp.cv.nrao.edu/NRAO-staff/jcondon/PCALS4.4
http://wiki.gb.nrao.edu/bin/view/PTCS/PointingFocusCatalog

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