Principles of Single Dish Telescopes

John Reynolds

The “Dish” Advantage

Simplicity – cost effective for collecting area

Sensitivity – hard to beat

Versatility – imaging, spectral line, pulsars ….

Adaptability – still going strong after ~50 years!

Elegance!

The outline

- Some basics of dish antennas
  - Feeds, illumination
  - Sensitivity & noise

- Whistle-stop tour of a single-dish system
  - Principal components
  - Calibration basics

Dish technology: still relevant


64-metre
SRT
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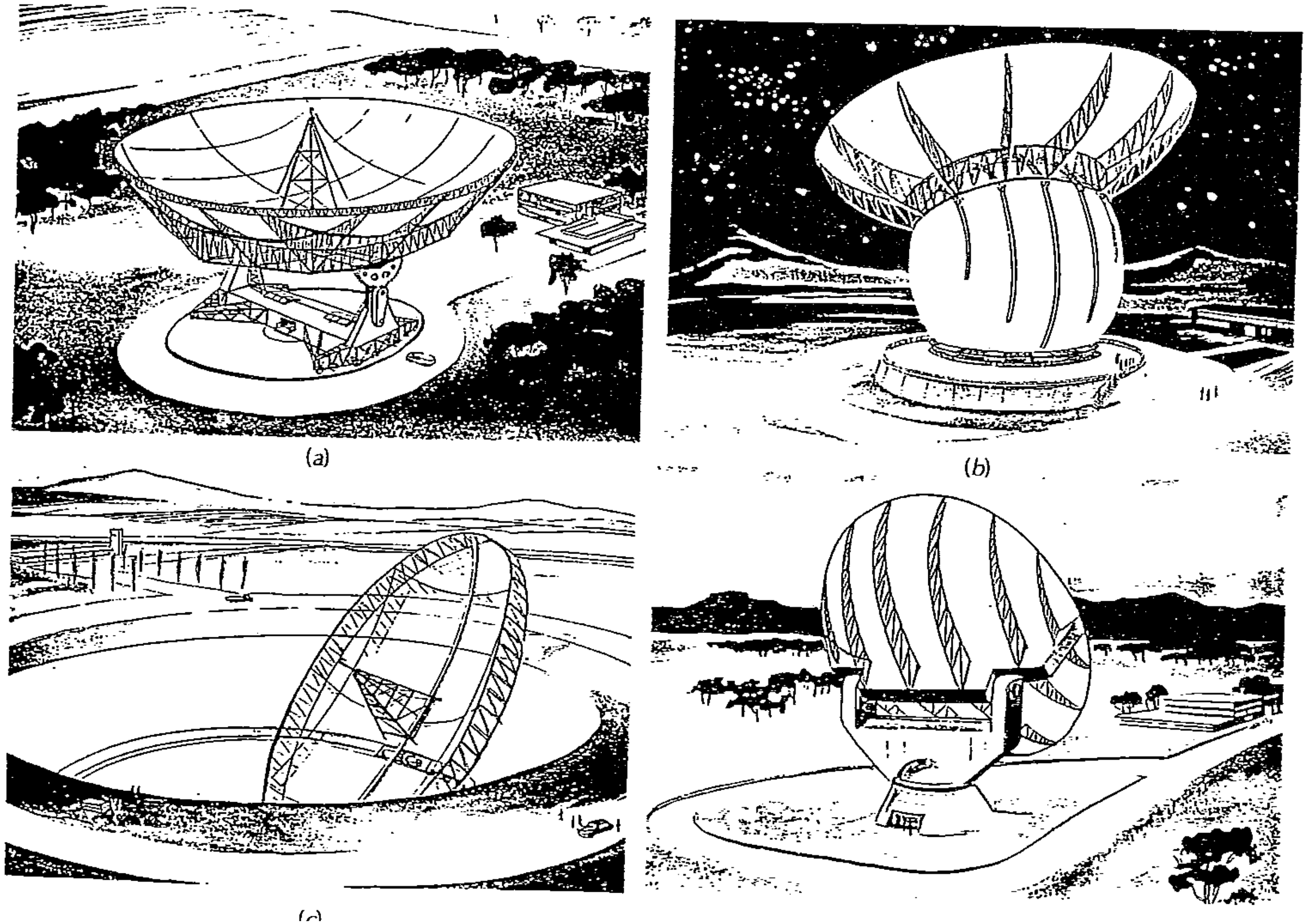
Early concepts for the “GRT”




The drawback:
cost ~$D^{2.8}$

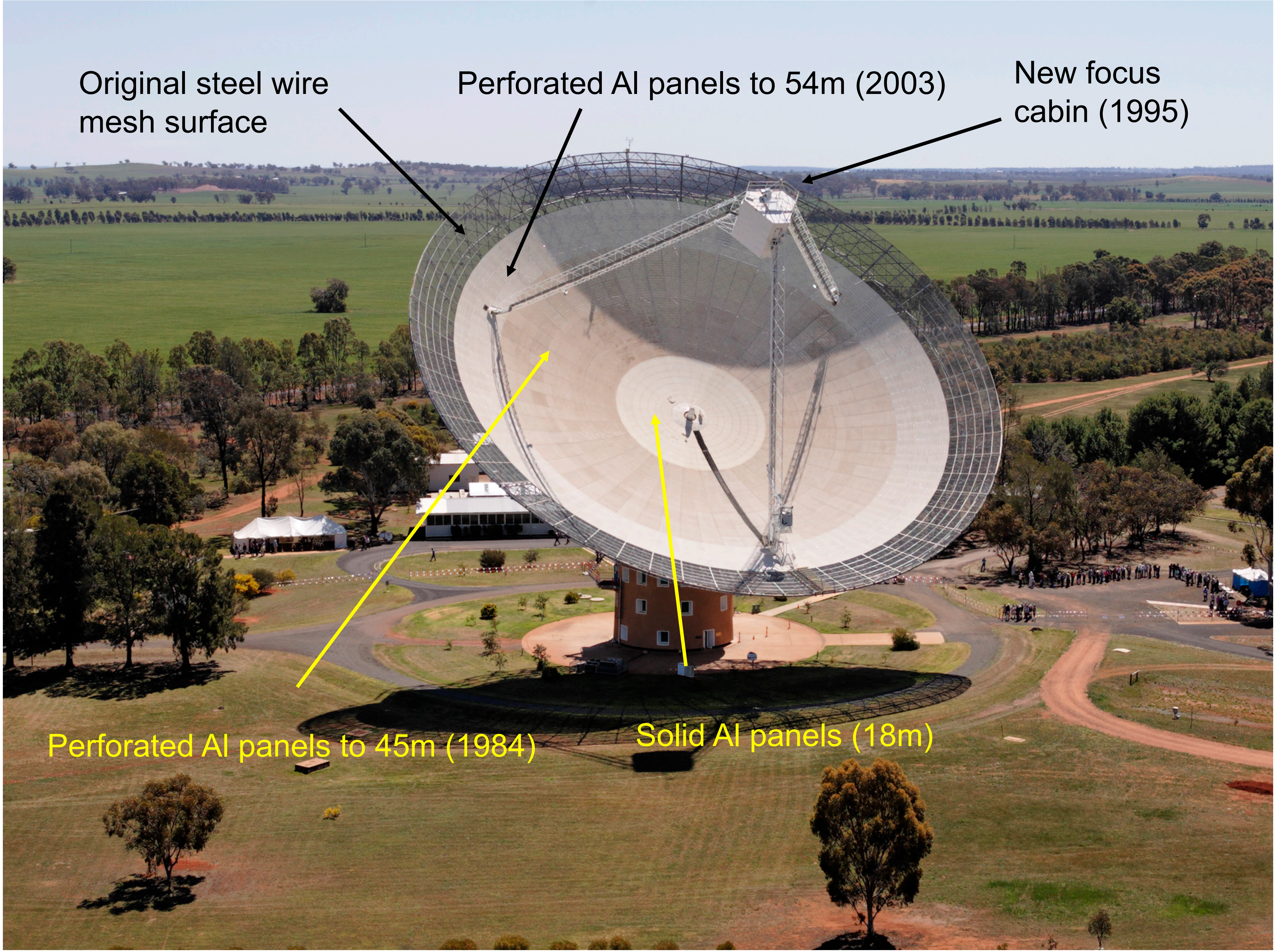
The parabolic reflector (“Dish”)

Parkes 64-metre

f/D ~ 0.4

74 MHz – 26 GHz
(2.5 decades)

Prime focus
vs
Secondary:
Cassegrain etc


Original steel wire
mesh surface
Perforated Al panels to 54m (2003)
New focus
cabin (1995)
Perforated Al panels to 45m (1984)
Solid Al panels (18m)

Multiple reflector systems

ATCA,
Tid 70m

SRT

aka
Beam-waveguide

e.g. GBT

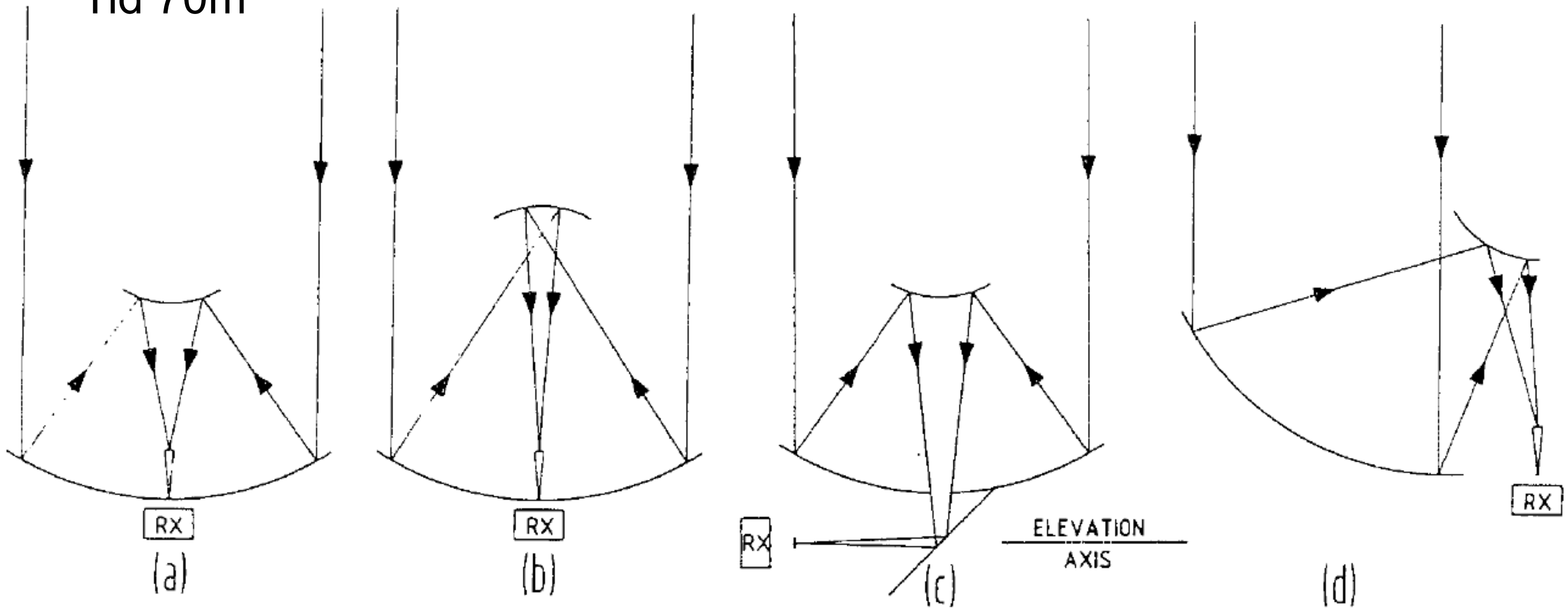


Fig. 6.7. The geometry of (**a**) Cassegrain, (**b**) Gregory, (**c**) Nasmyth and (**d**) offset Cassegrain systems

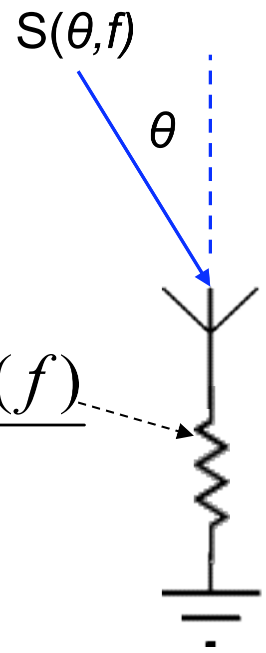
Antennas – the basic response

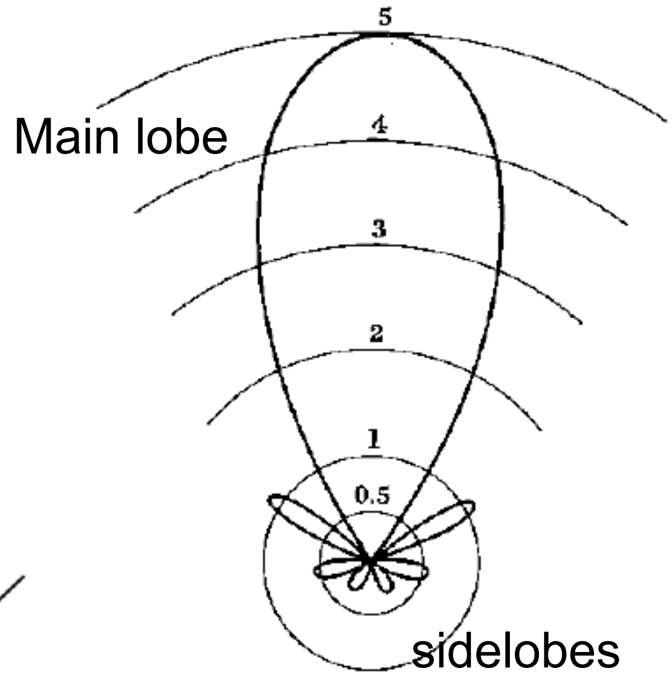
Recalling flux density:

1 Jy = 10^{-26} W / m^2 / Hz

Antenna Effective Area:

$$A_{eff}(\theta, f) = \frac{\text{Matched power density}(f)}{S(\theta, f)/2}$$





Single polarization

Two handy antenna facts

All-sky integral of A_{eff} depends only on wavelength:

$$\oint A_{eff}(\Omega).d\Omega = \lambda^2$$

"no high-gain isotropics"

$$A_{iso} = \lambda^2 / 4\pi$$

Reciprocity theorem;

transmit polar pattern = receive polar pattern

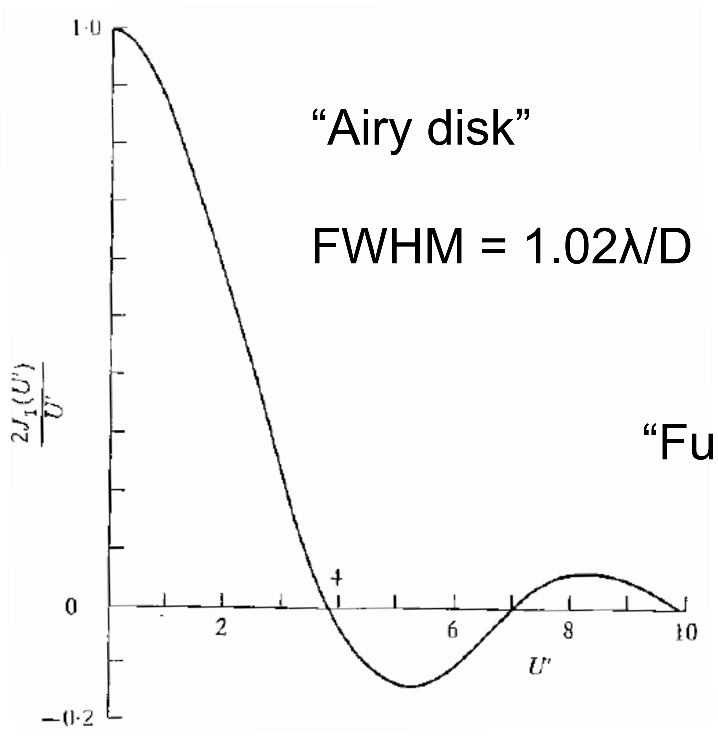
The pointy end: feeds & receivers

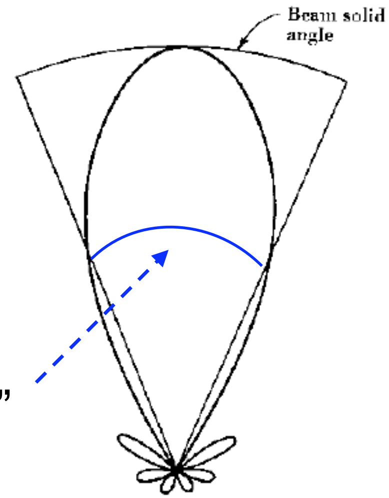
The feed

Illumination & Feeds

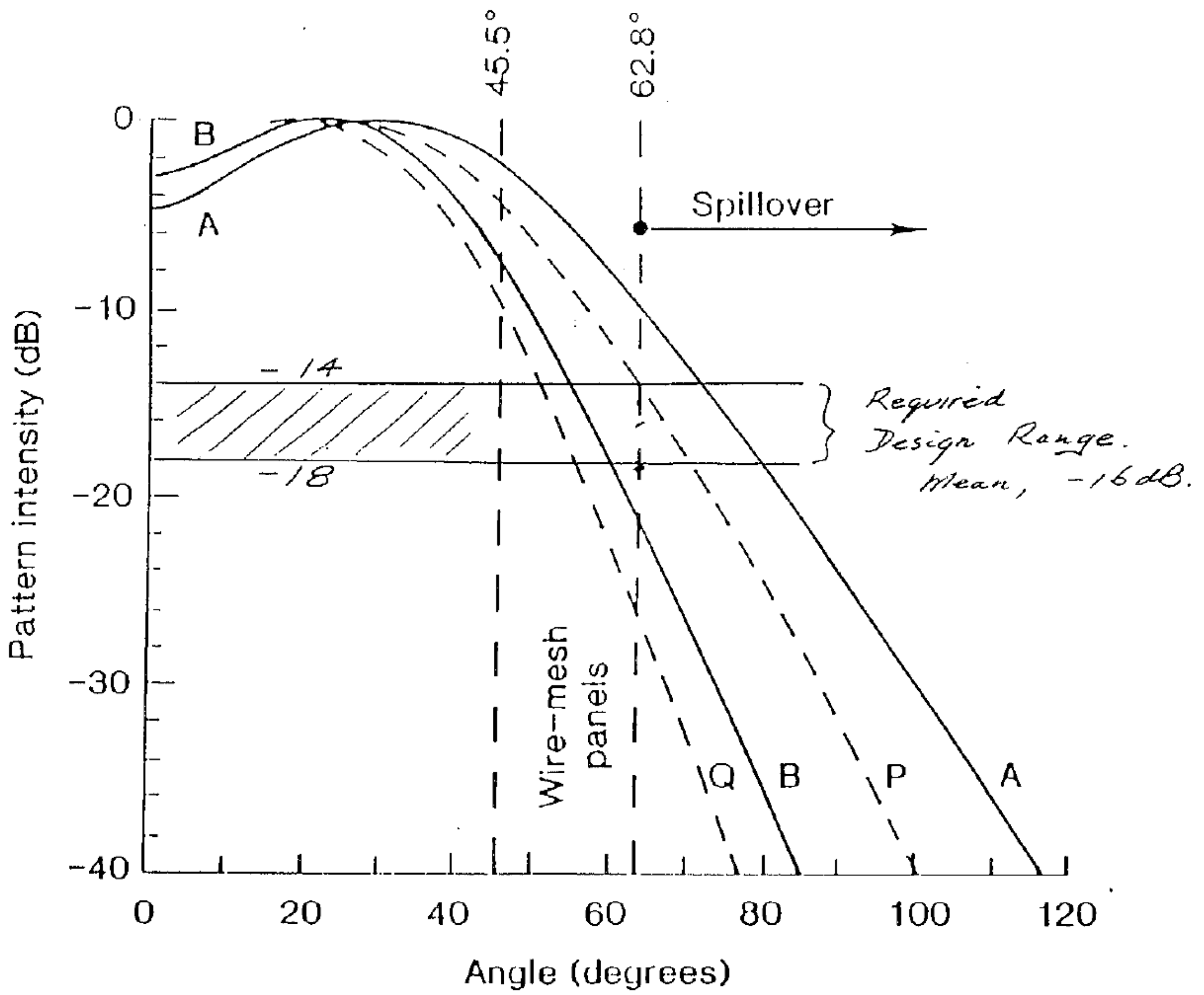
- For perfectly-illuminated circular aperture

$$A_{eff} = A_{physical} = \pi . r^2 \quad \text{(projected area)}$$

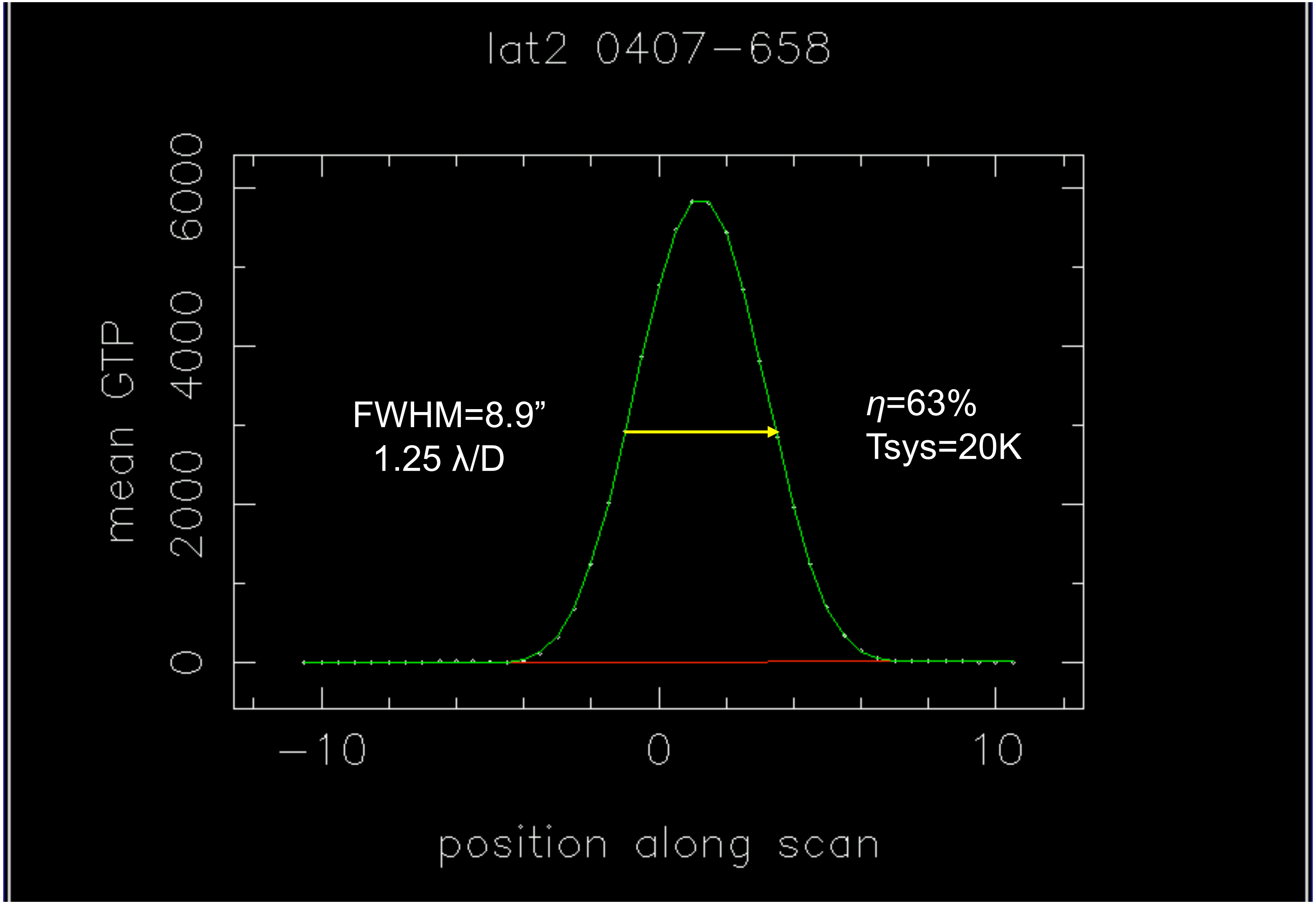




The real world – “Galileo Feed”



A real 64-metre beam – at 2.3GHz



Antenna/feed sensitivity

Signal vs *Signal-to-noise* (SNR)

Aliases for A_{eff} (effective area);

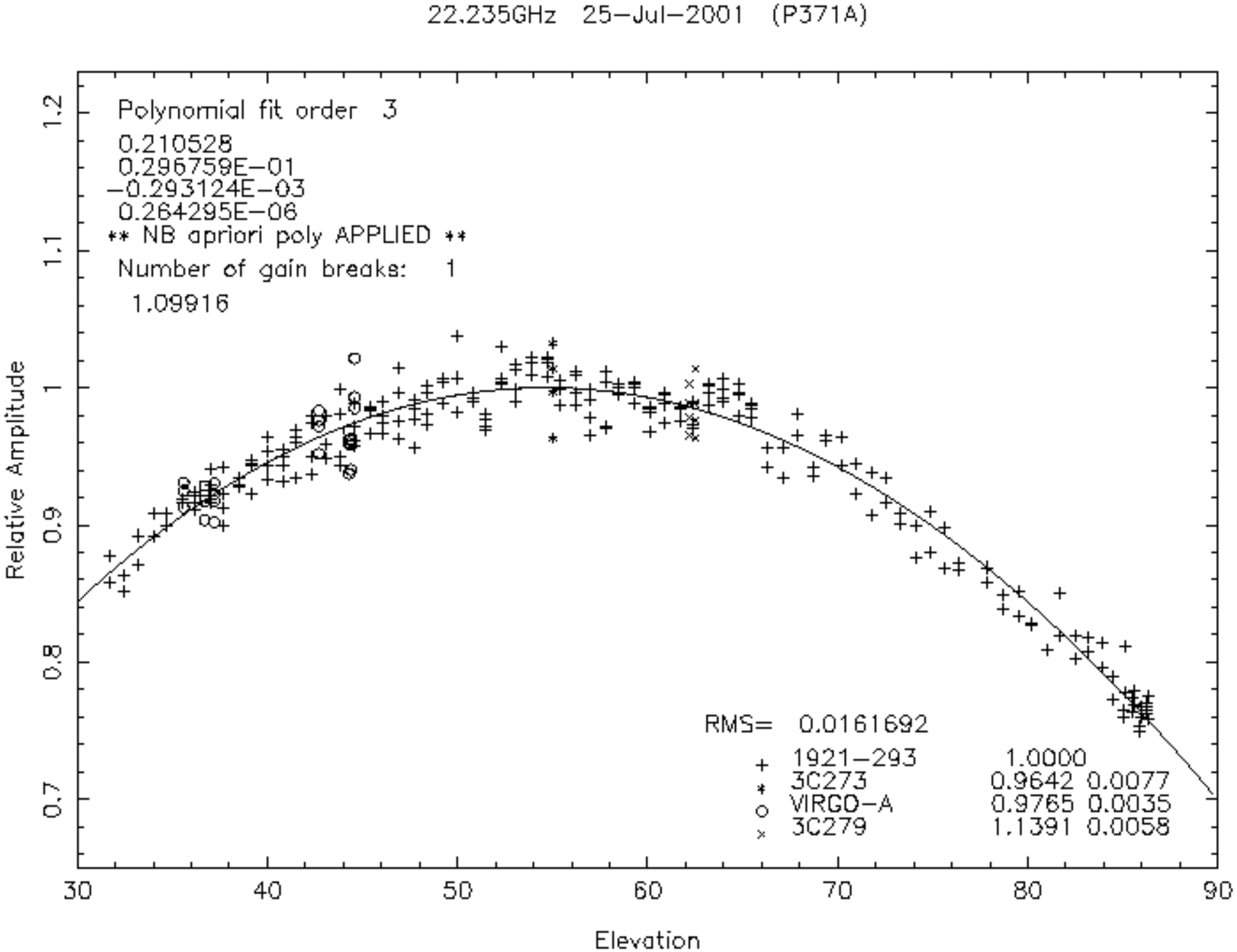
$\lambda^2/4\pi$

Forward gain (dB) := $10*\log(A_{eff}/A_{iso})$

Aperture efficiency := $A_{eff}/A_{physical}$

S/T ("Jy per Kelvin") := $2k/A_{eff} \, . \, 10^{26}$

Antenna gain



Equivalent temperature

Planck Law

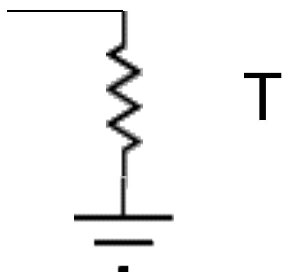
$$I(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}.$$

Rayleigh Jeans approximation;

$I(\lambda,T) = 2kT/\lambda^2$ ($Wm^{-2}Hz^{-1}sterad^{-1}$)

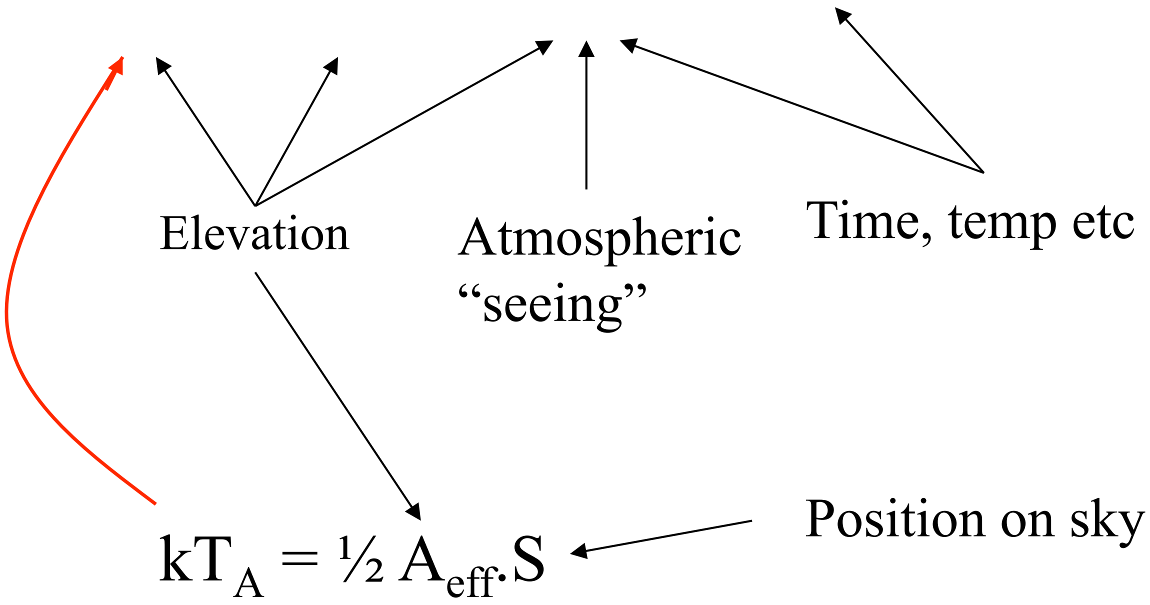
Power density W/Hz^{-1}

= kT



The noise equation

$$T_{sys} = T_A + T_{spill} + T_{sky} + T_{rx} + T_{2.7K}$$



Signal-to-Noise

Two extreme cases;

1. Large source, small beam: $\theta >> \theta_{FWHM}$
2. Point (unresolved) source: $\theta << \theta_{FWHM}$

1. Extended source: Tsky ~ Jy/sterad

   $T_{ANT} = T_{Sky}$

   For SNR=1, $T_{Sky} = T_{sys0}$

   (independent of antenna size/gain)

Small (unresolved) sources

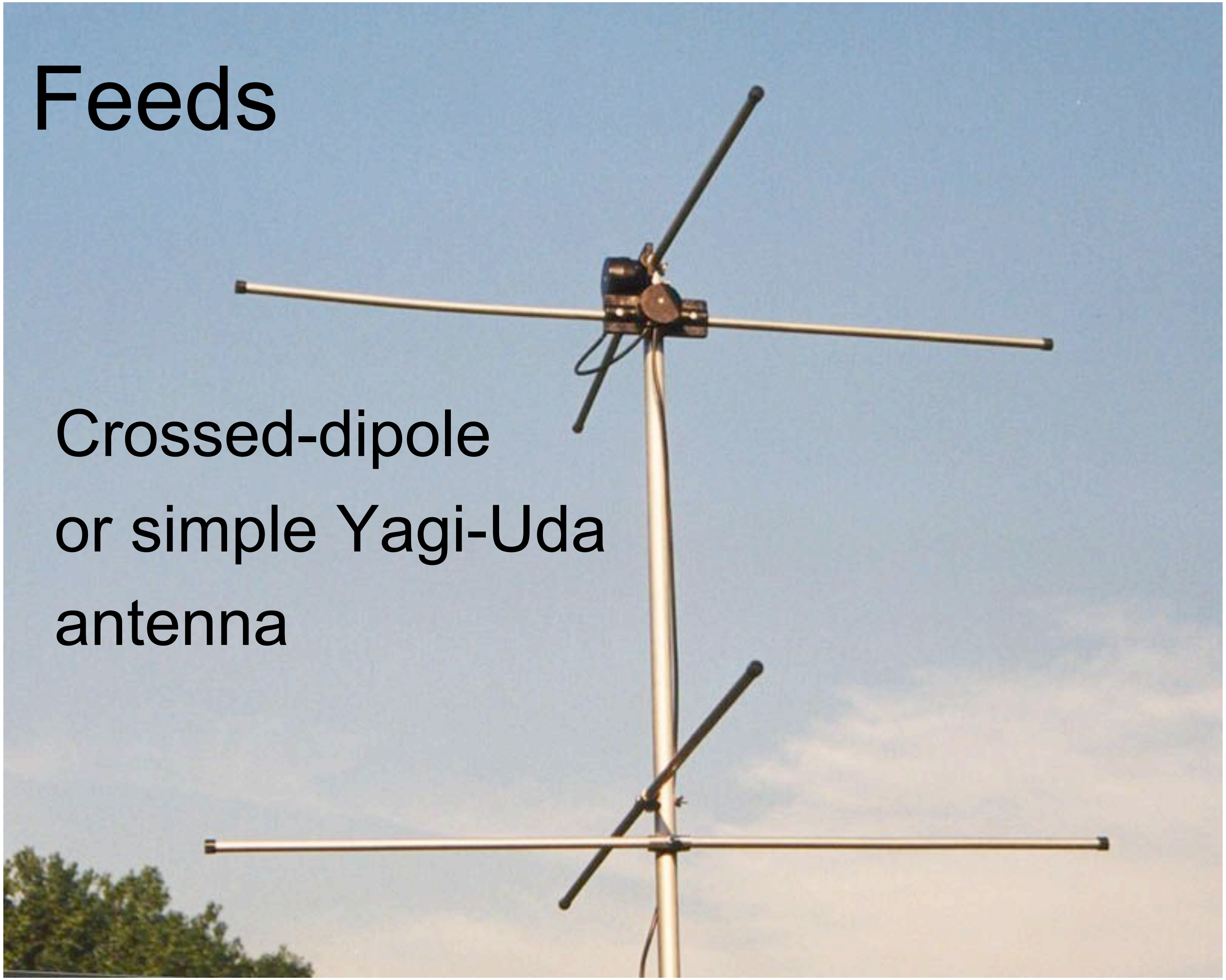
Point sources (S_{source} , $\theta << \theta_{FWHM}$)

$$T_{ANT} = S_{source} / (S/T)$$

For SNR=1, → SEFD = T_{sys0} * (S/T)

SEFD = System equivalent flux density

Feeds

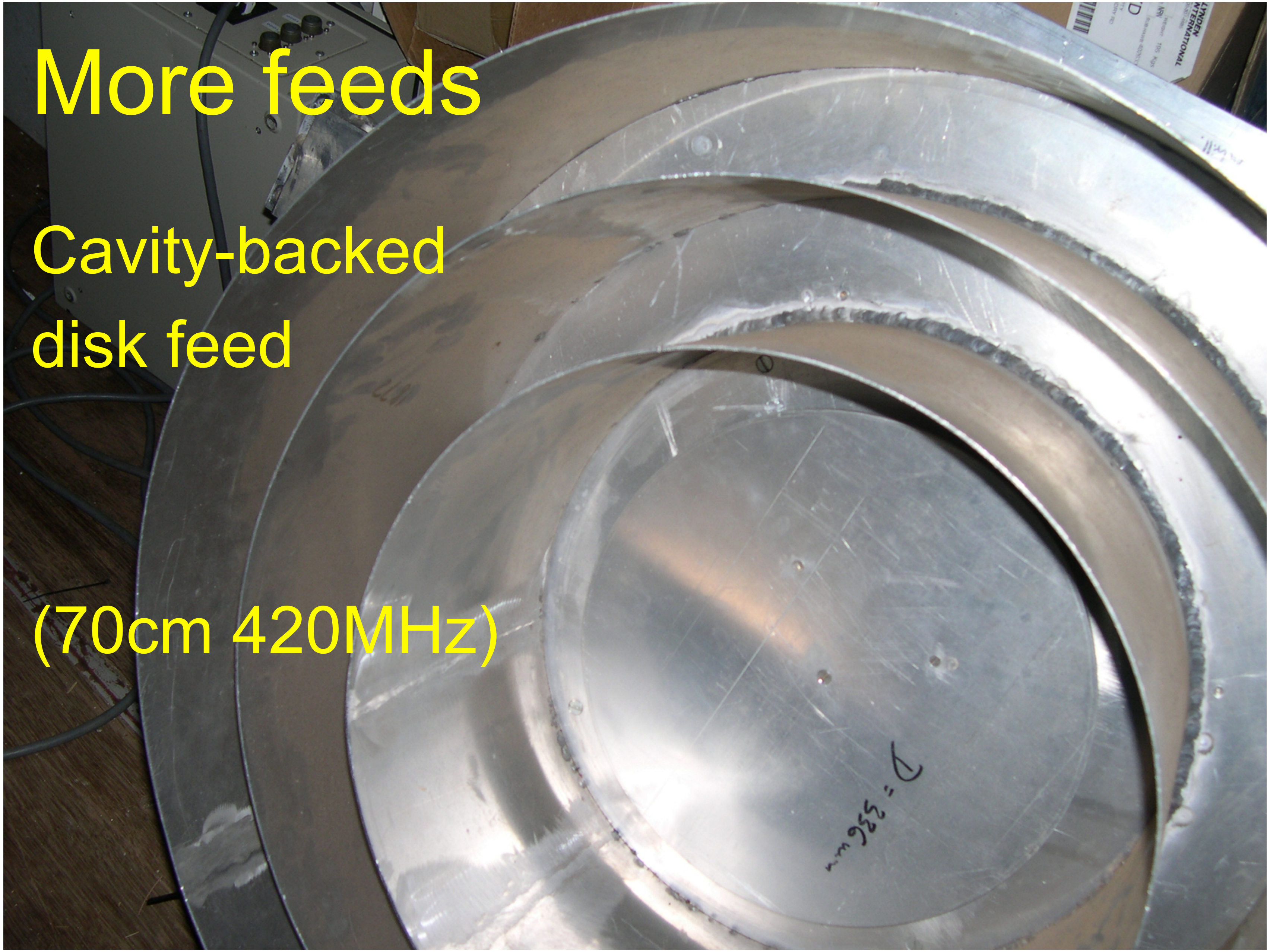


Crossed-dipole
or simple Yagi-Uda
antenna

More feeds

Cavity-backed
disk feed

(70cm 420MHz)




DRAO “boxing ring” feed
300-900MHz

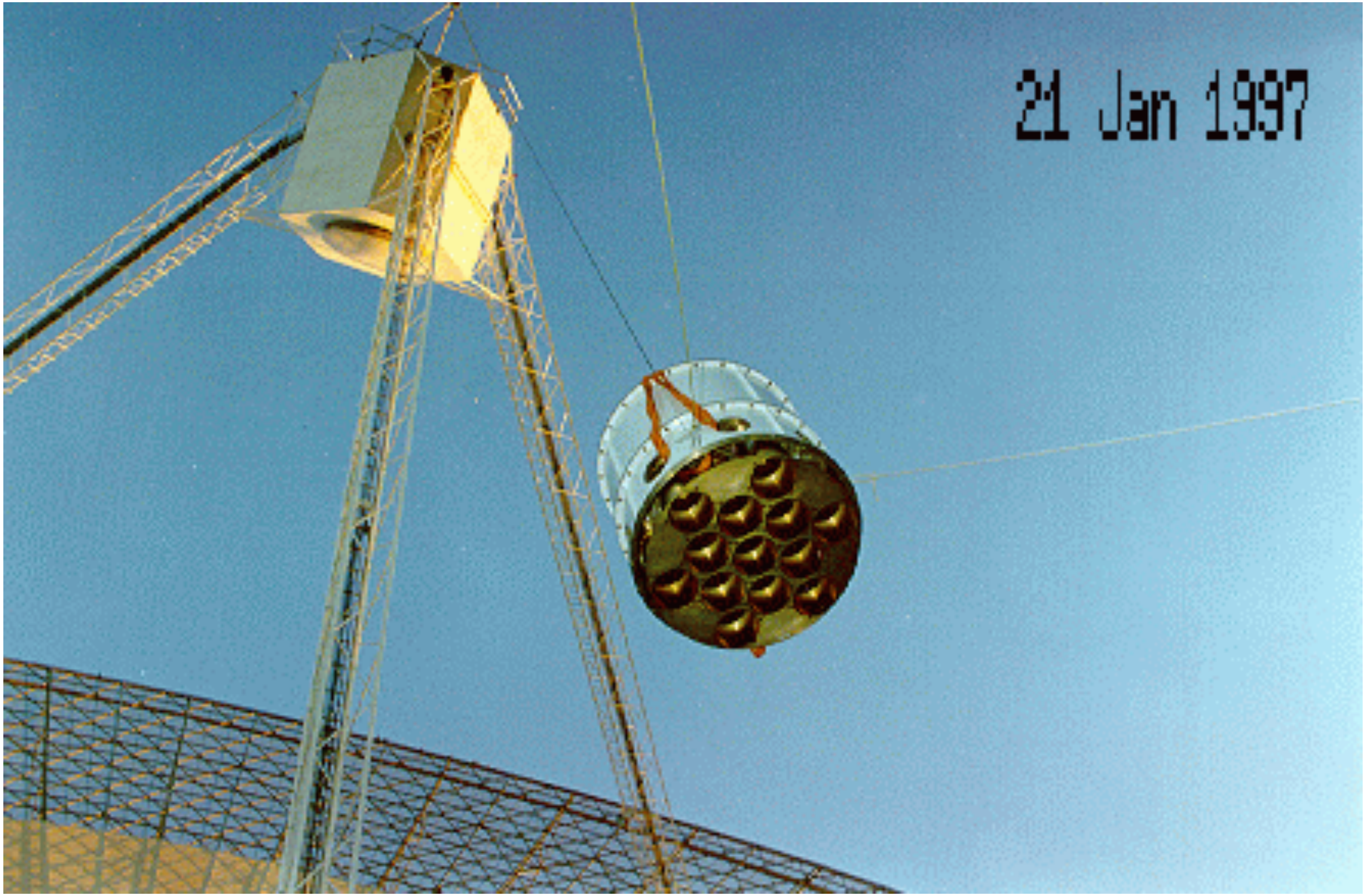
Multibeam Feeds

Why stop at one?

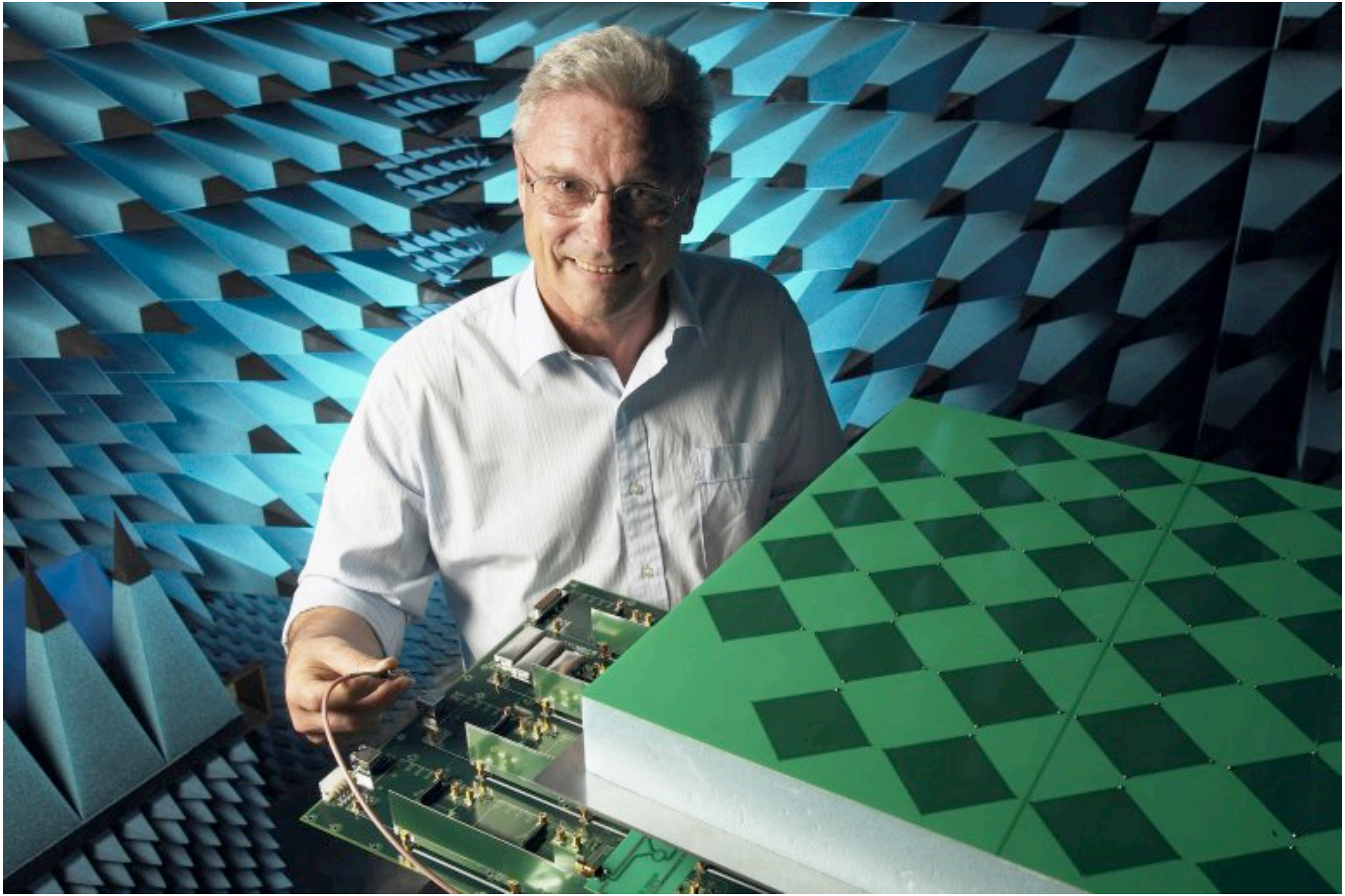
The simple parabolic reflector is best.

Shaped reflectors and Cassegrains can't compete

Transforming technology



The new frontier: PAF=FPA



Parkes X-band feed design

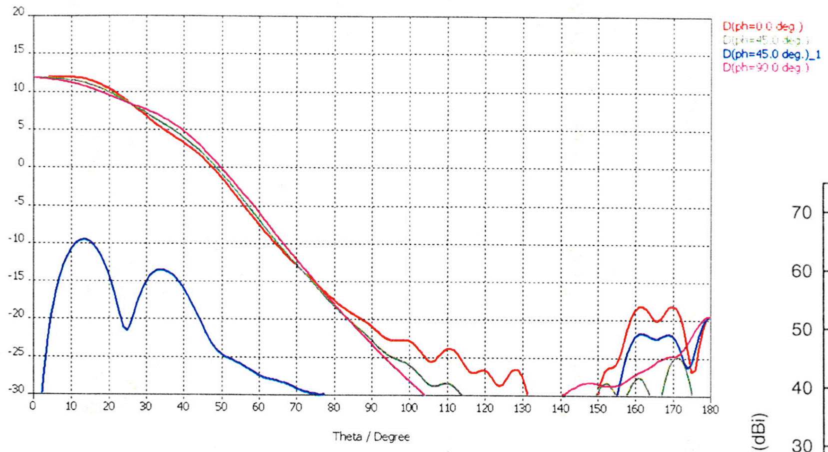


Figure 14: Radiation pattern at 8.30 GHz.

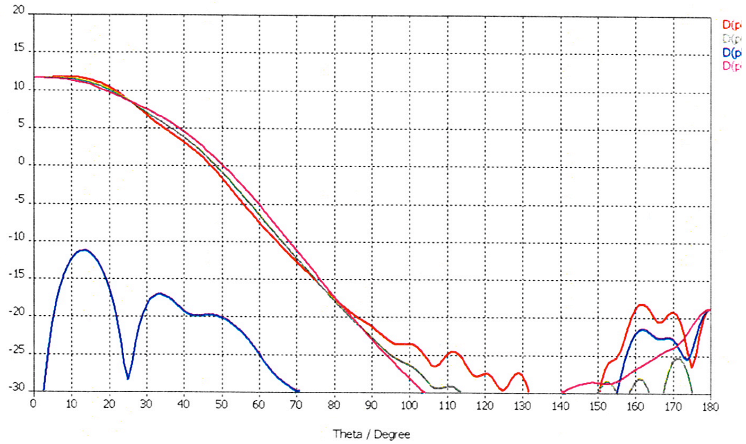


Figure 15: Radiation pattern at 8.40 GHz.

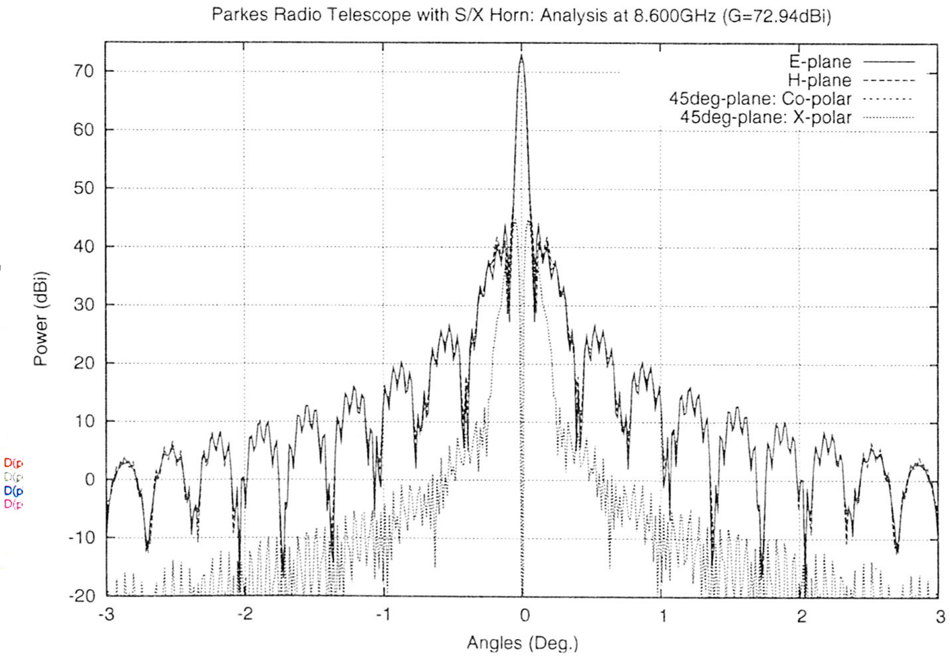


Figure 29: Radiation pattern at 8.60 GHz of the Parkes radio telescope with the new S/X feed system (linear-polarization).

Radiometer Equation

$$SE(T_{sys}) = \alpha \, . T_{sys} / \sqrt{t \, . \Delta f}$$

where;

t = integration time (seconds)

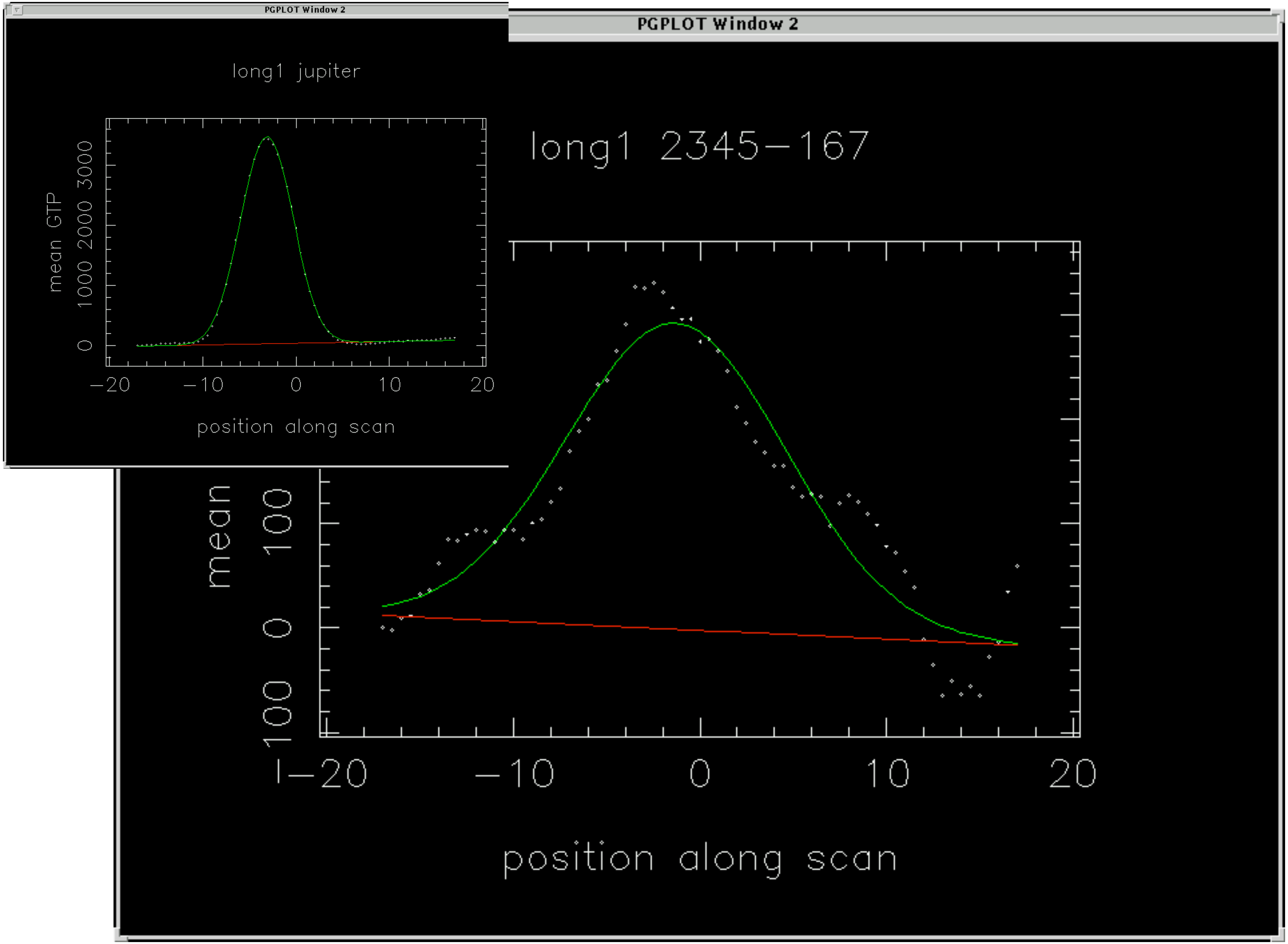
Δf = detector bandwidth (Hz)

α = factor of order unity (system dependent)

1 sigma (SE) not usually enough → 3 or 5 sigma

There's noise and there's noise:

above does not include "flicker" noise



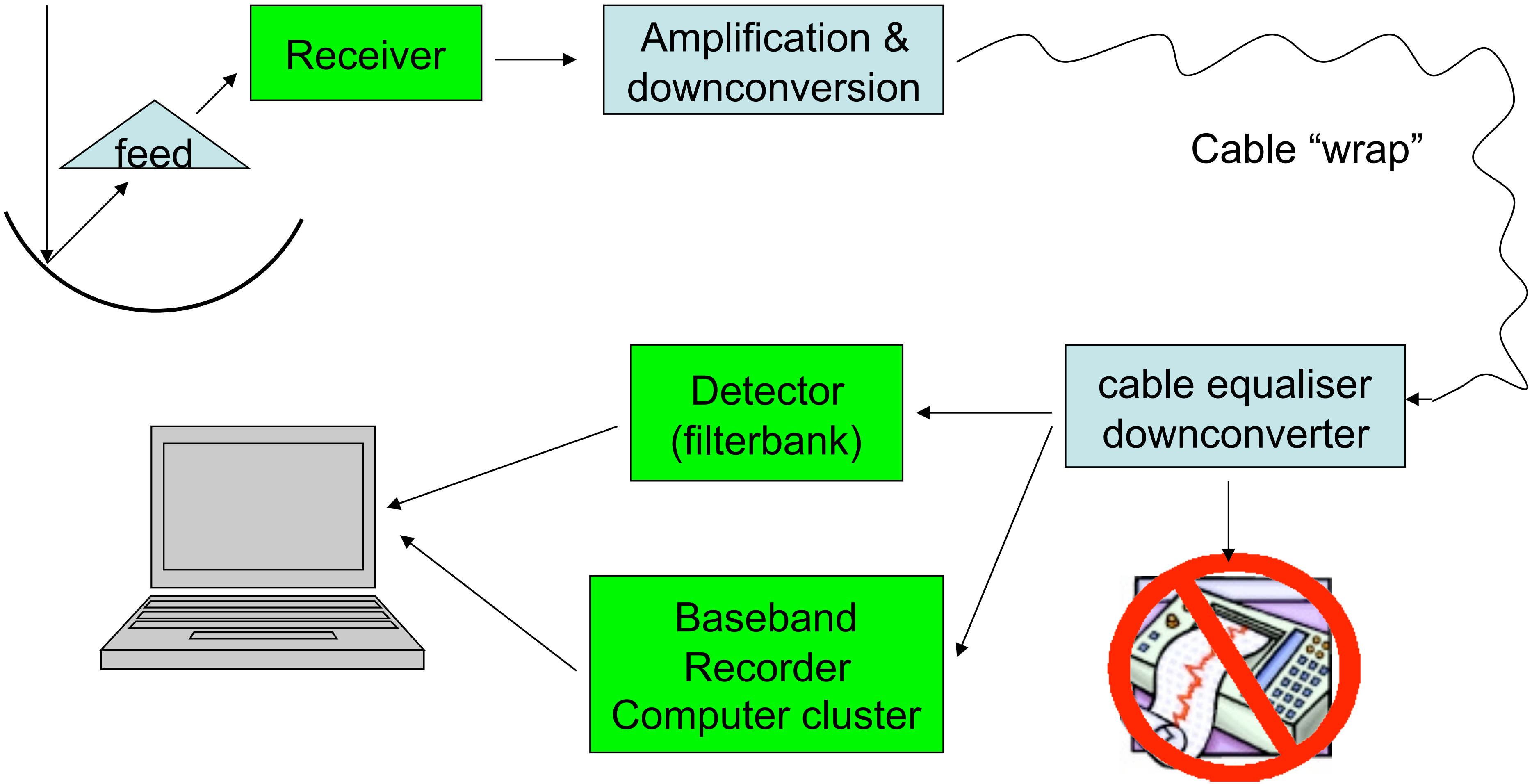
PGPLOT Window 2
long1 jupiter
mean GTP
0 1000 2000 3000
−20 −10 0 10 20
position along scan
PGPLOT Window 2
long1 2345−167
mean
100 0 100
−20 −10 0 10 20
position along scan

Out of scope

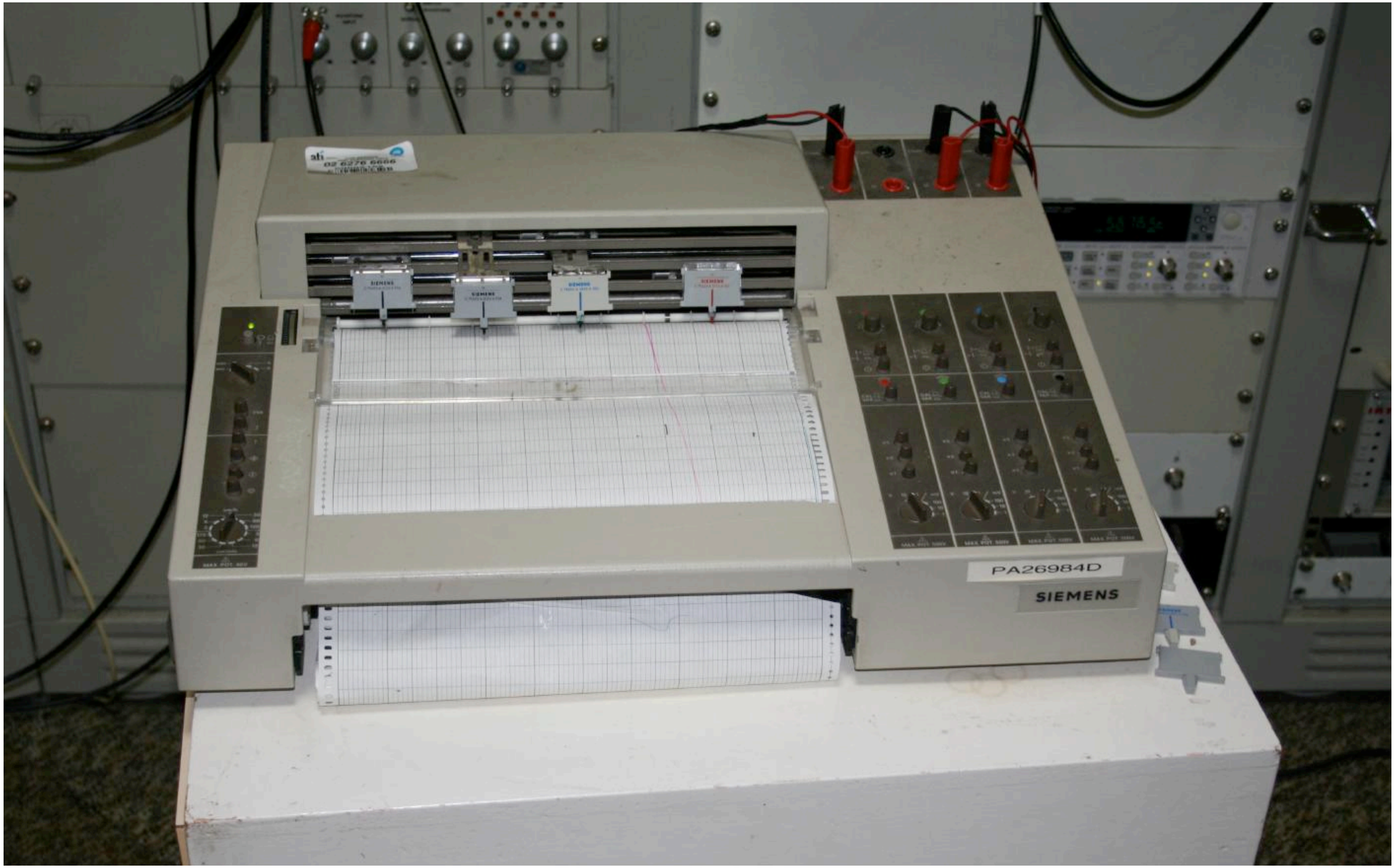
- Secondary reflector systems
- Surface accuracy deformations
- Fourier theory
- Aperture blockage
- Holography
- Pointing models
- ….

See e.g. “Radiotelescopes”, Christiansen & Hogbom
“Radio Astronomy”, Kraus

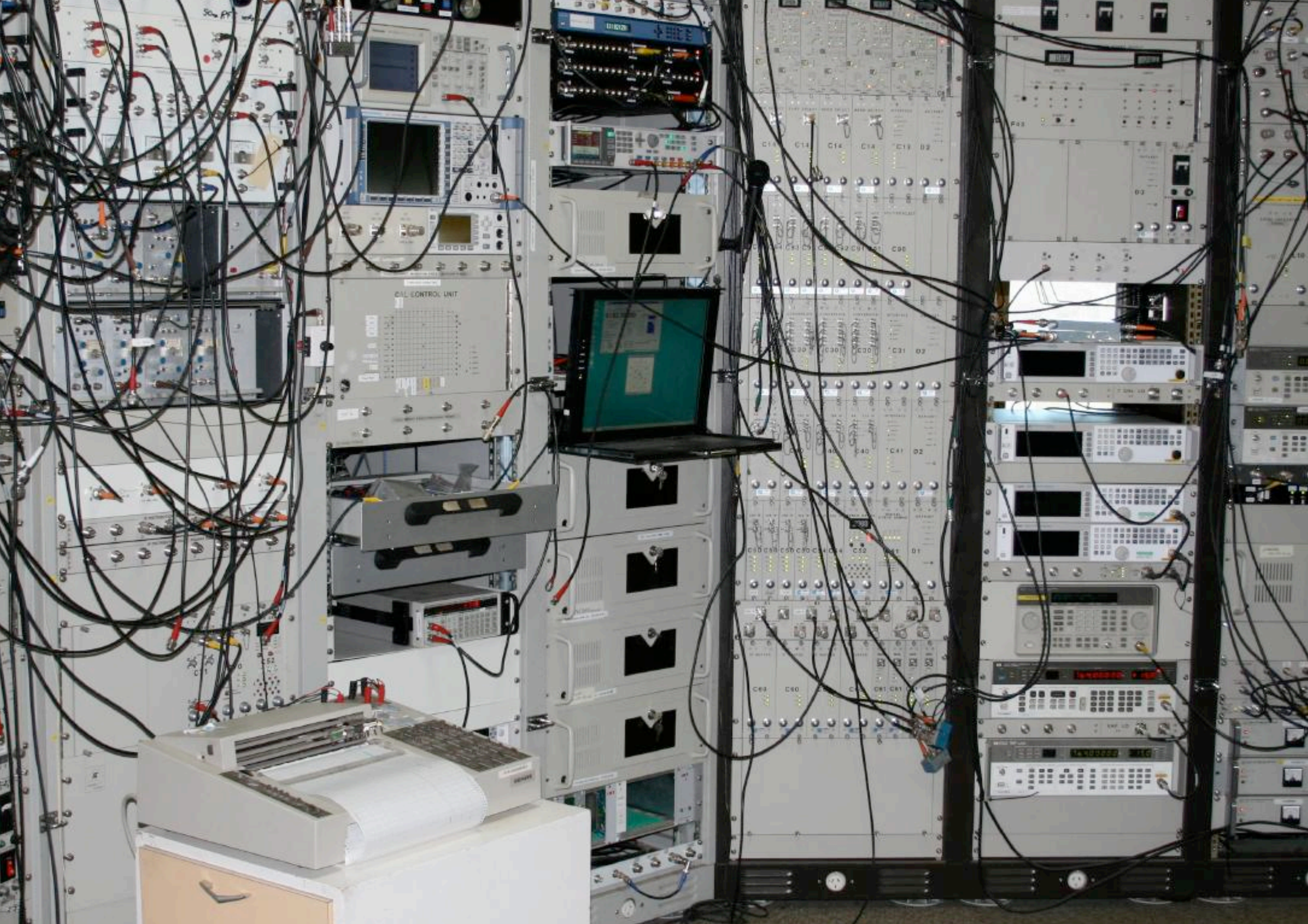
Single-dish system – the basics



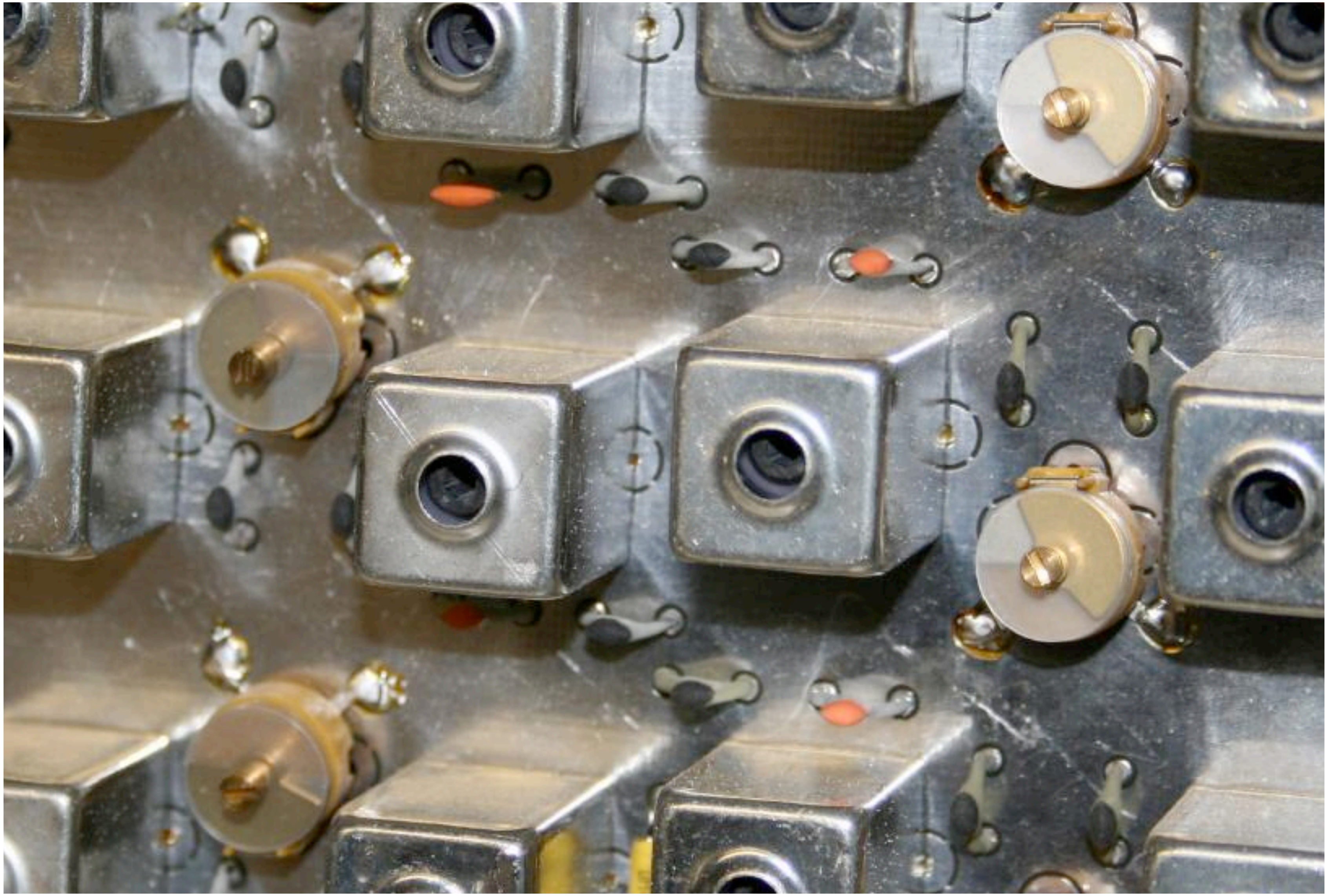
Data recording across the ages
Part 1.



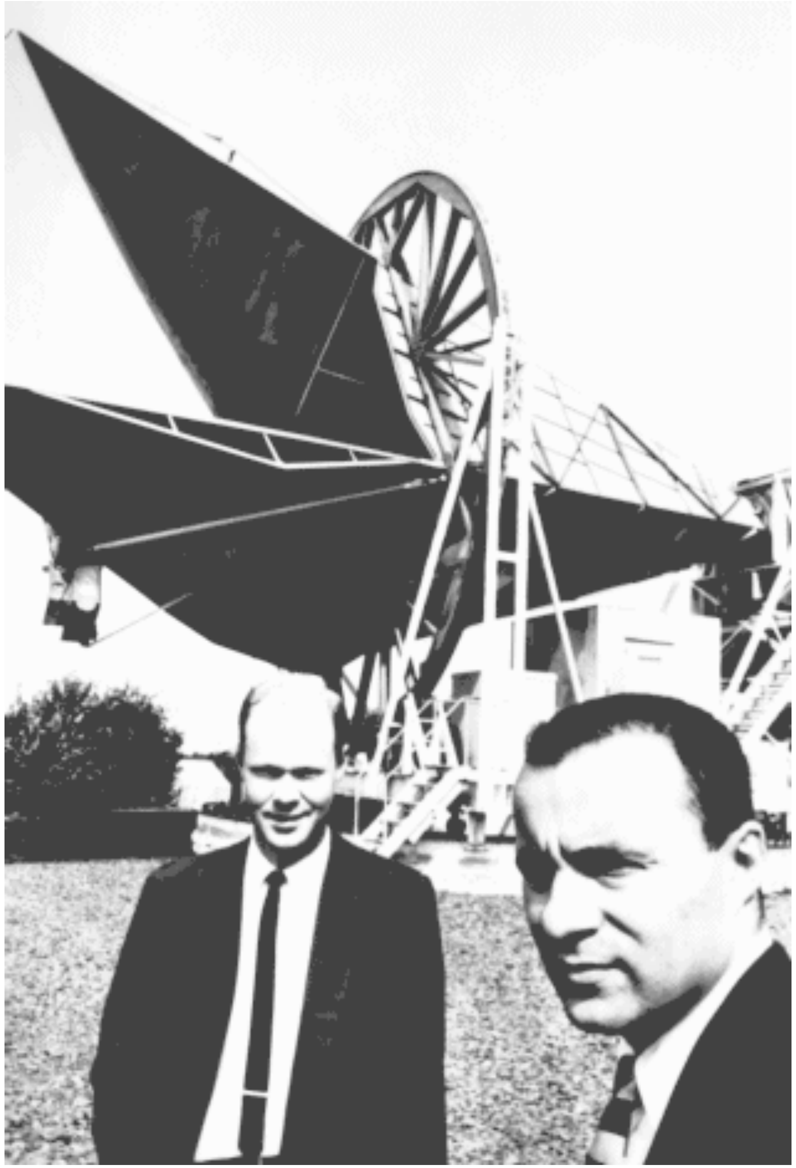
8GHz
receiver
package


CAL-CONTROL UNIT

The last great analogue filterbank?



Calibration You never know – it might be important.



Single-dish calibration

Pointing (at higher frequencies)

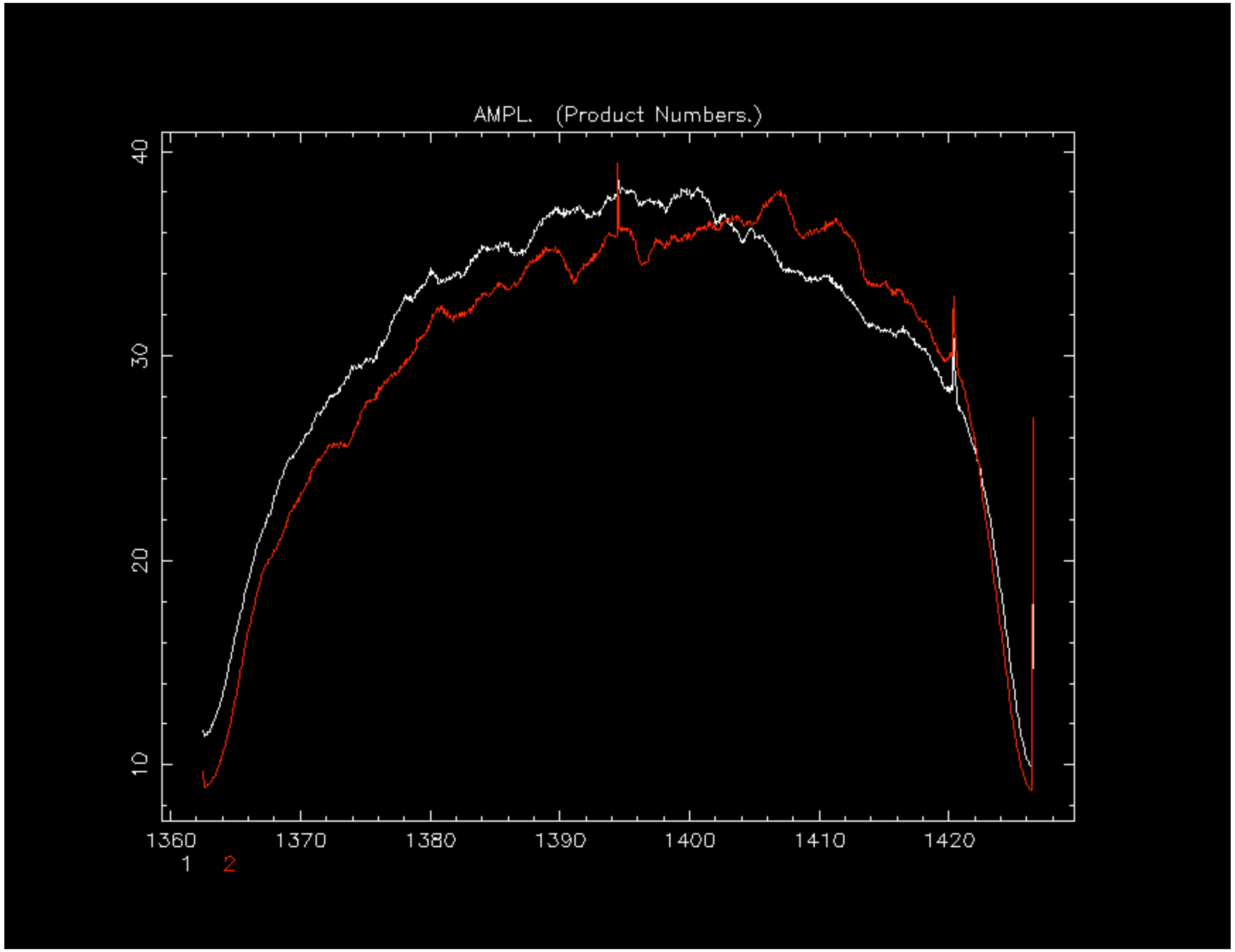
Gain vs Elevation

Tsys vs time

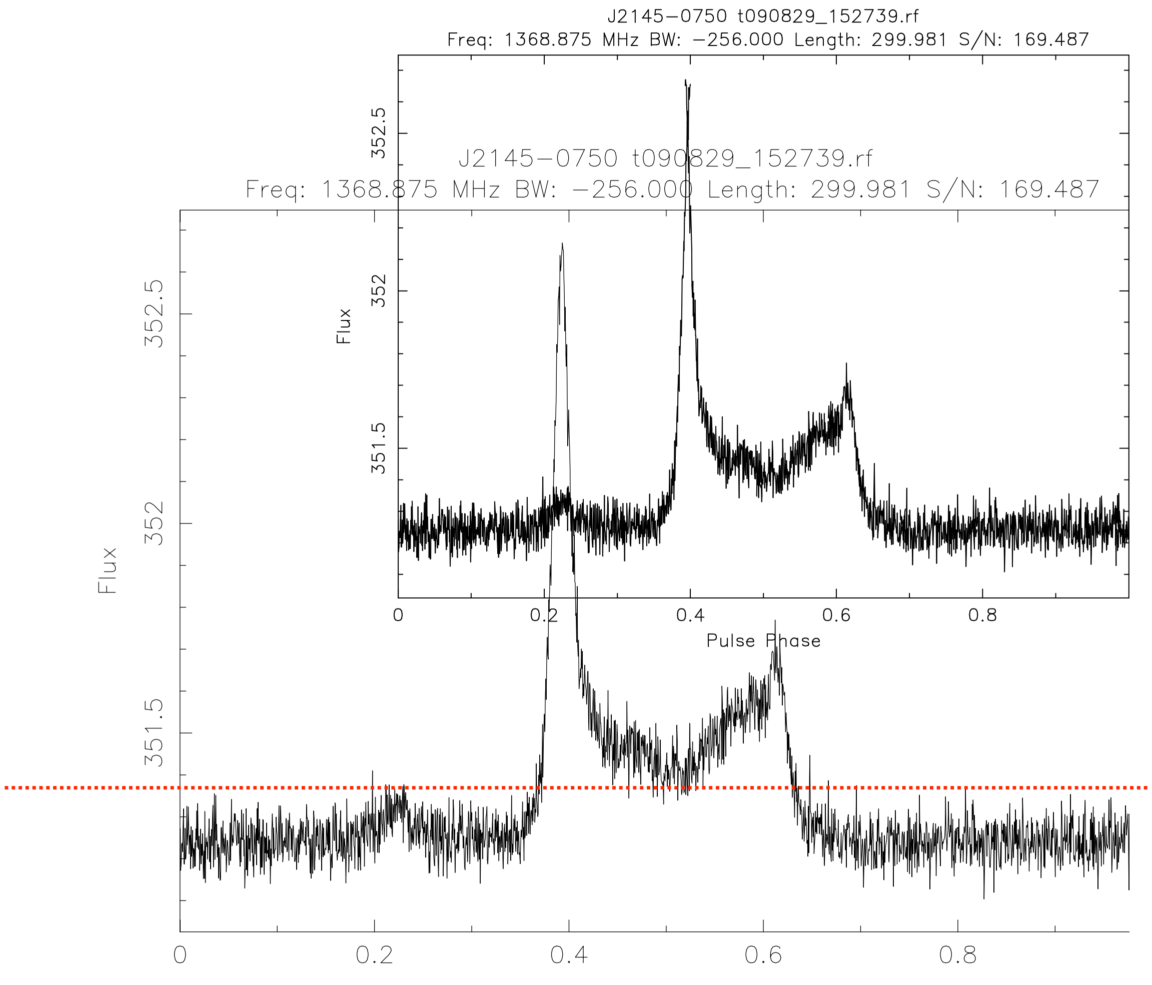
Remove the noise pedestal!

The single-dish millstone

Large and quasi~constant “DC” noise pedestal floor –
Small fluctuations with time/frequency are important!



Pulsars: average "off pulse" noise;



Spectral-line / continuum

- On source – Off source

  Switch between on and off-source, subtract/divide

  "MX" mode on Multibeam receivers

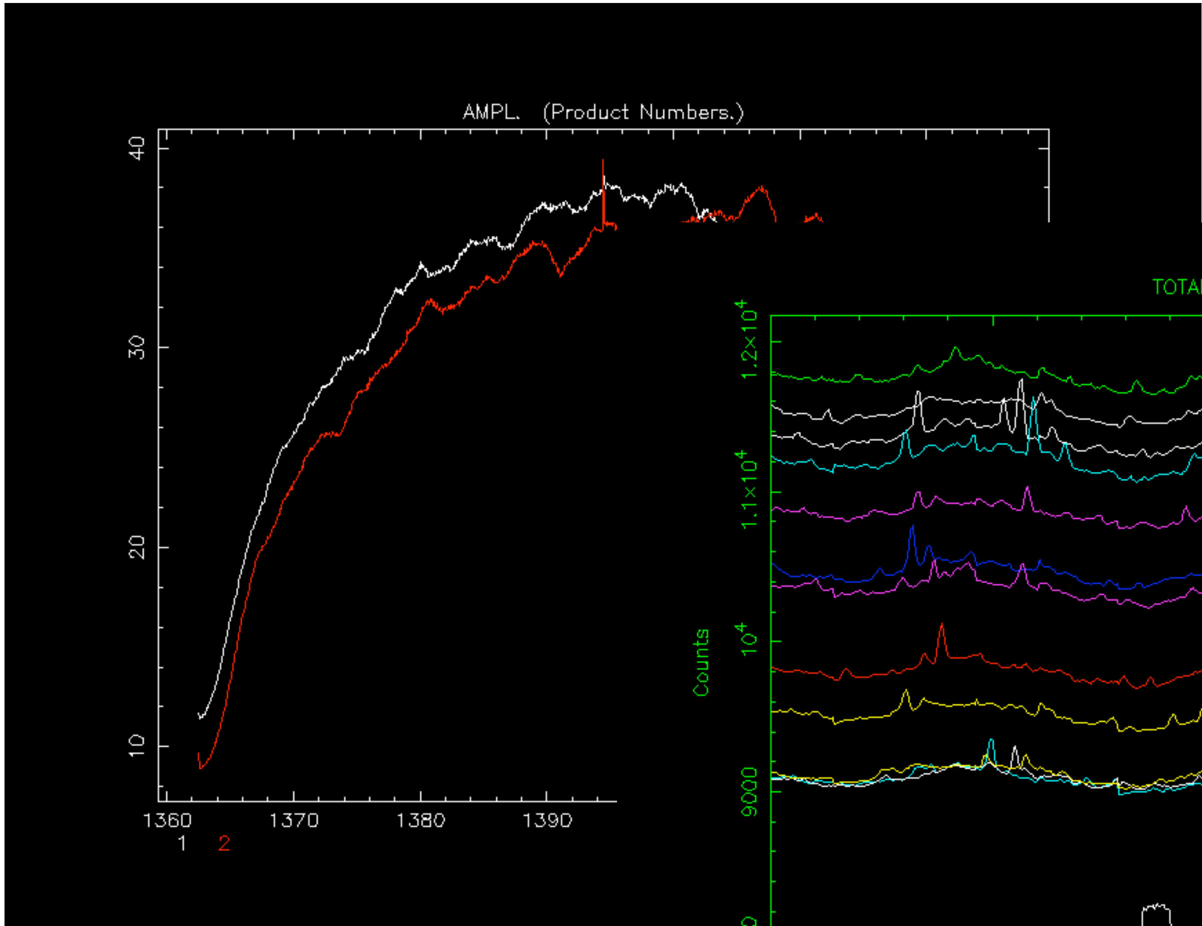
- Frequency shift

  Switch between two adjacent frequencies, divide

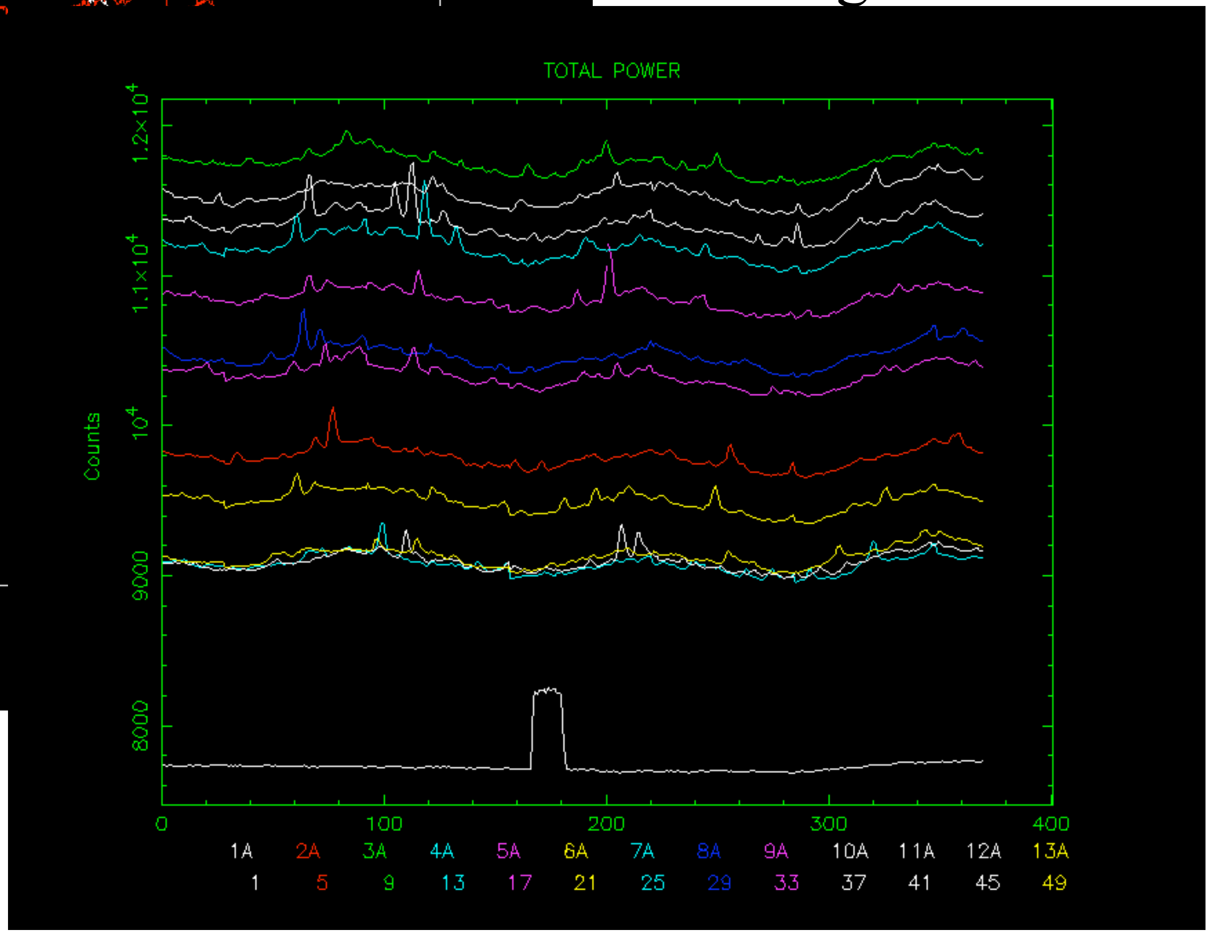
- Scan and average

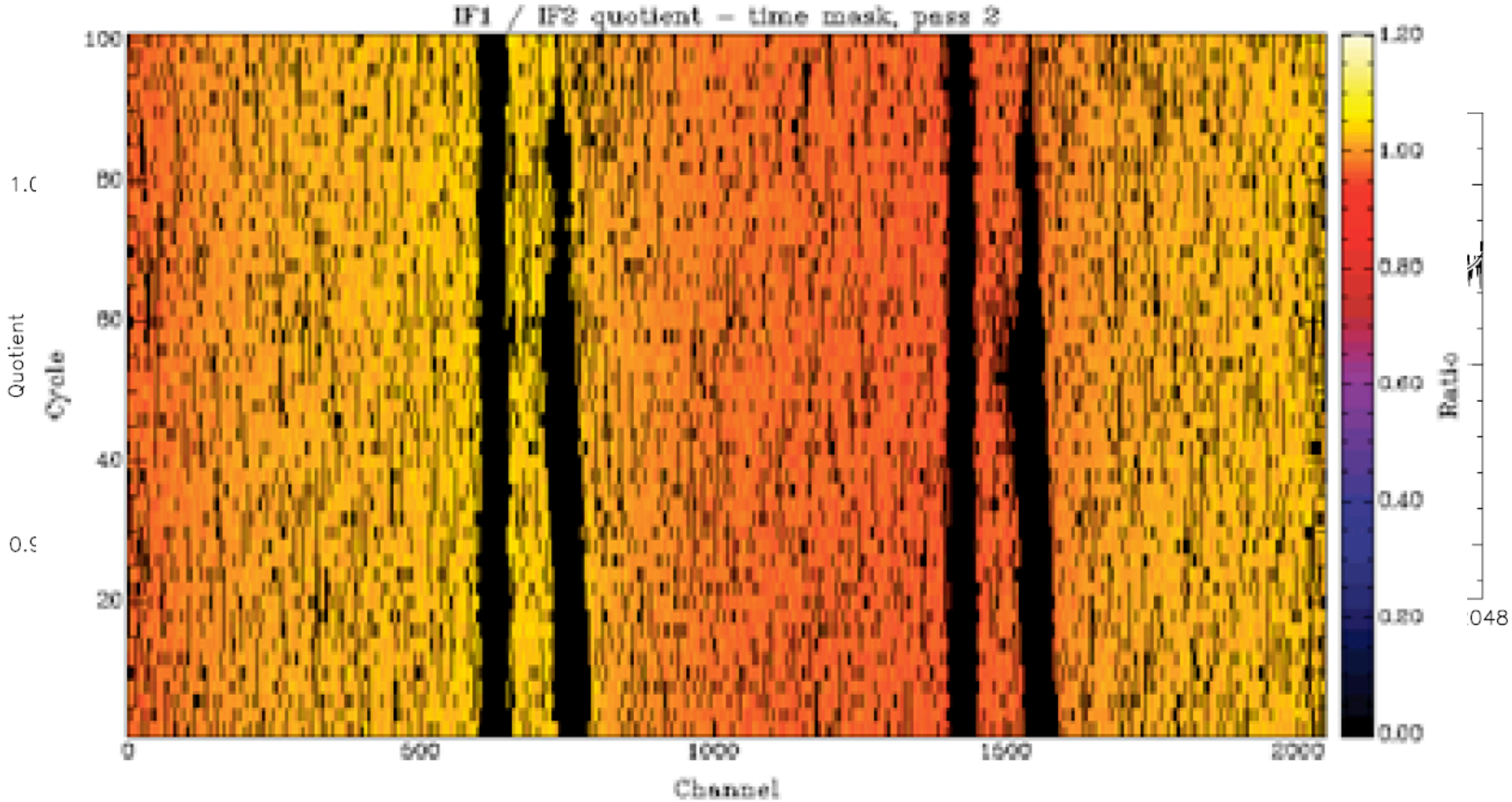
  Subtract mean (median) of entire scan

Bandpass calibration

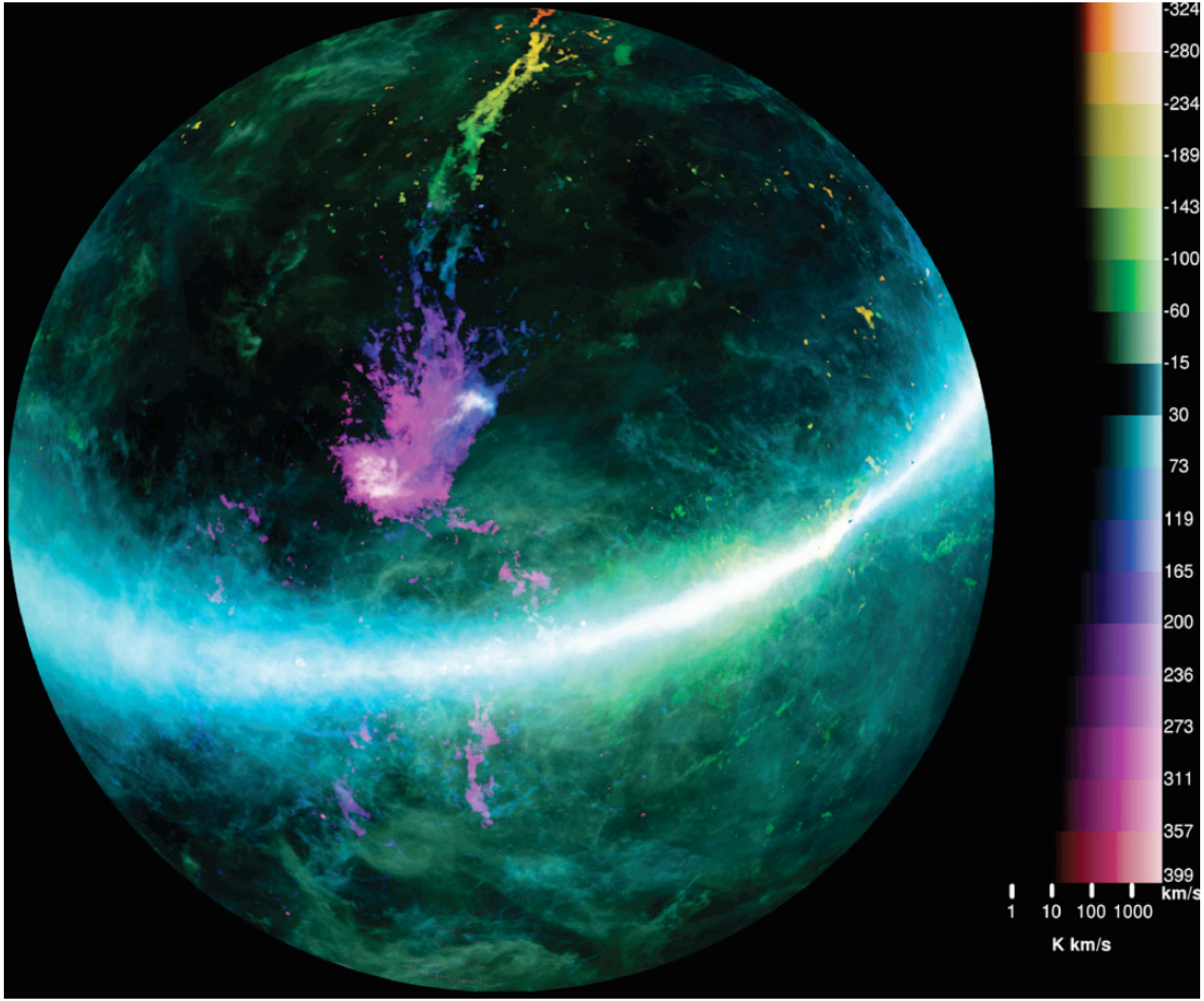


Calibrate bandpass by observing “off source”





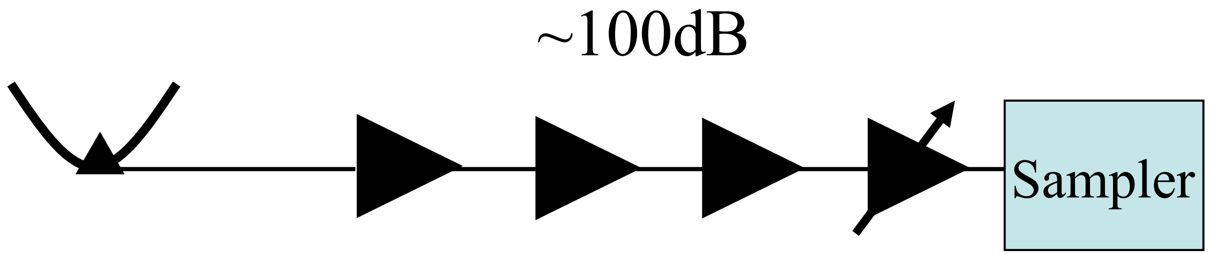
IF1 / IF2 quotient - time mask, pass 2
Cycle
Channel
Ratio
0
500
1000
1500
2000
20
40
60
80
100
0.00
0.20
0.40
0.60
0.80
1.00
1.20
Quotient
1.0
0.9
048


-324
-280
-234
-189
-143
-100
-60
-15
30
73
119
165
200
236
273
311
357
399
km/s
1
10
100
1000
K km/s

What are we measuring?

- Typical receiver systems have large gain which varies with time.

  Abandon detected power for calibration: use only equivalent noise temperatures.



NAR –
noise-adding radiometer

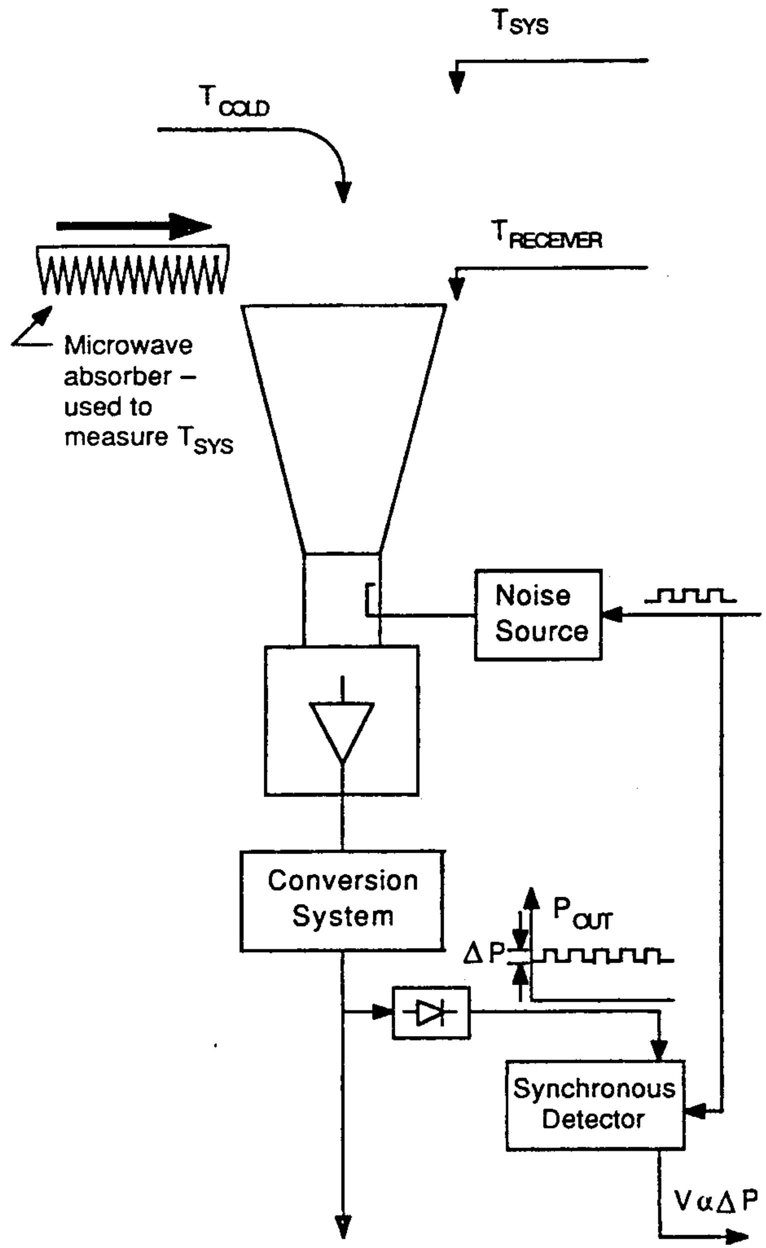
In the jargon:

"noise tube"

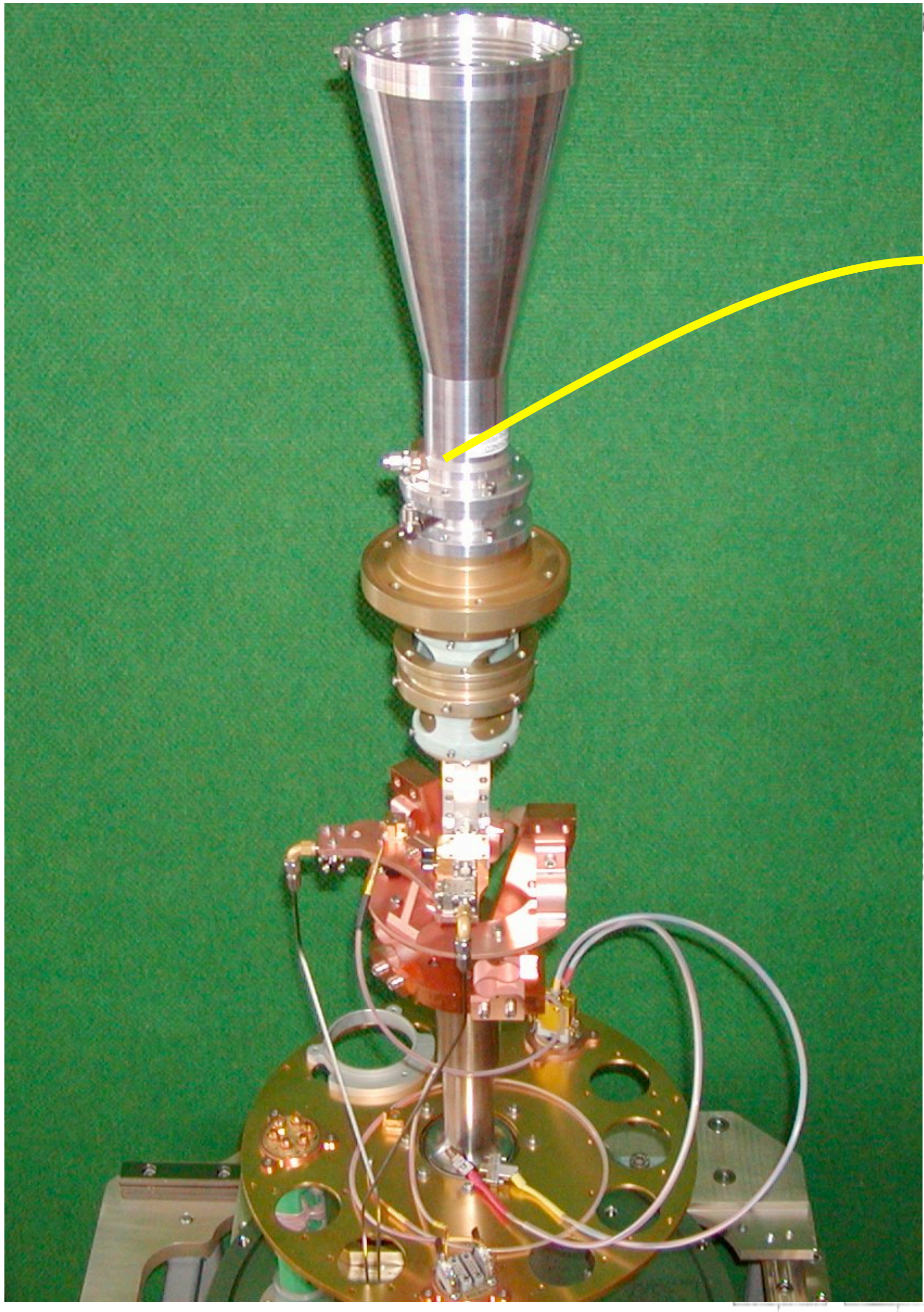
"noise diode"

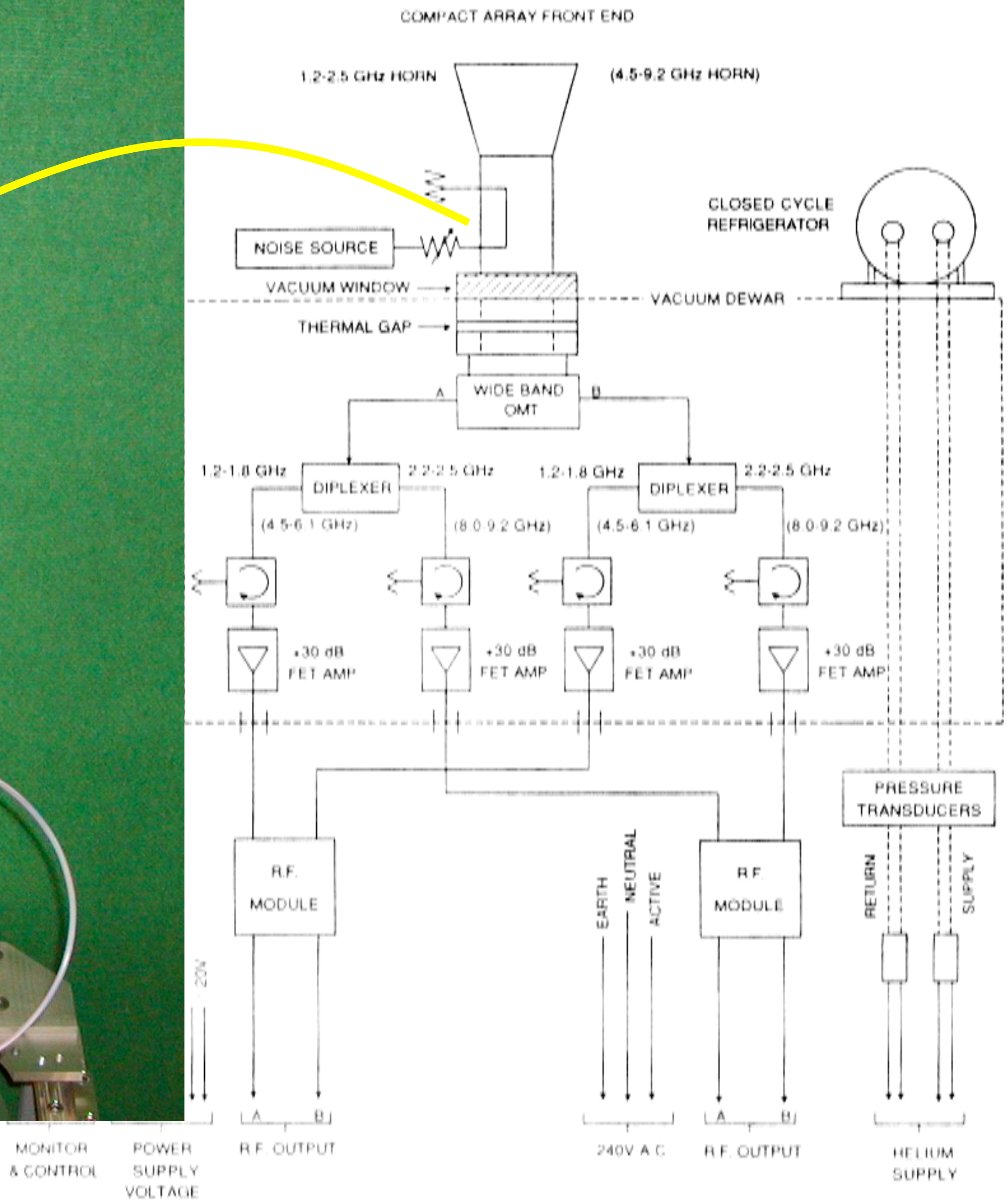
"noise source"

"cal"



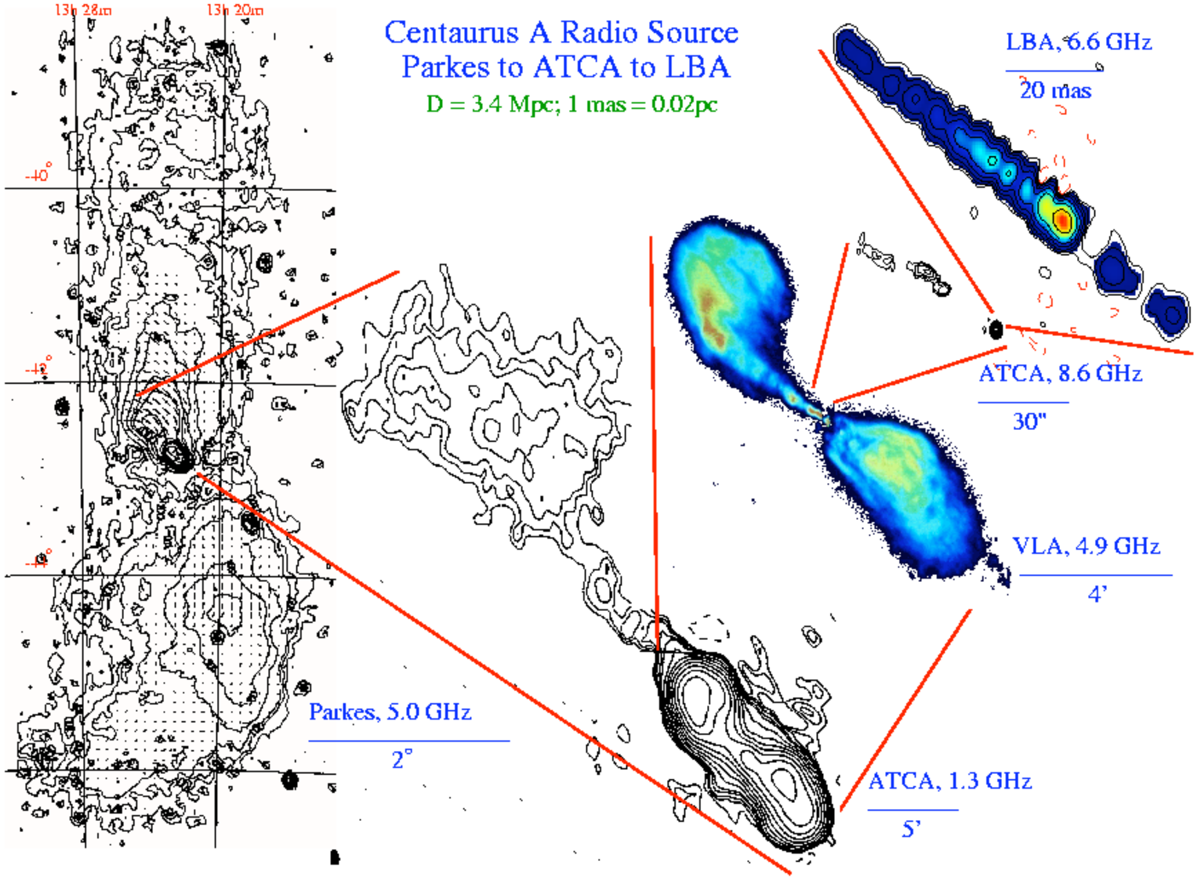
NAL PATH - THE RECEIVER SYSTEM - *Sinclair, et al*





The end!

Basic imaging



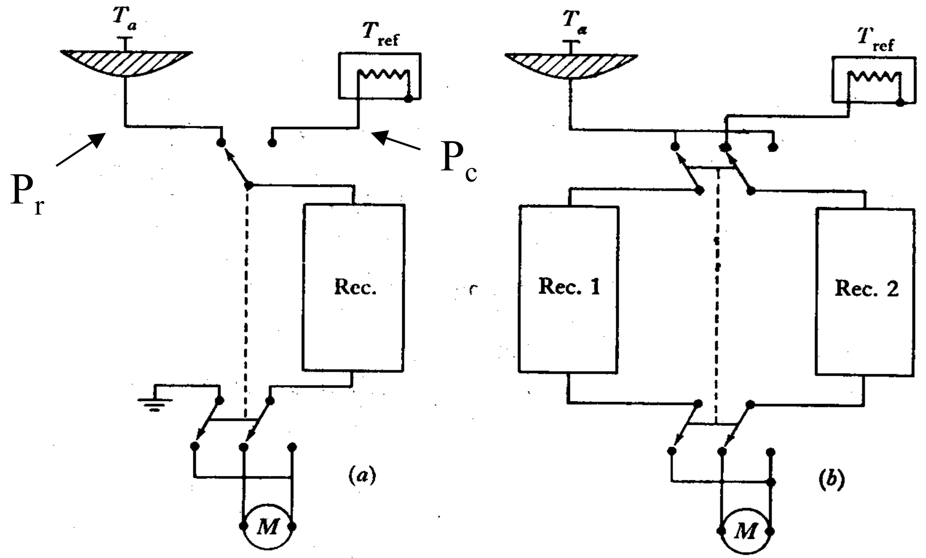
Equivalent noise temperature

Flux density : 1 Jansky = 10^{-26} W/m^2/Hz

$P_r = ½ A_{eff} S d\nu$ (A_{eff}:= collecting area, S:=flux density)

$P_c = kT_{ref} d\nu$

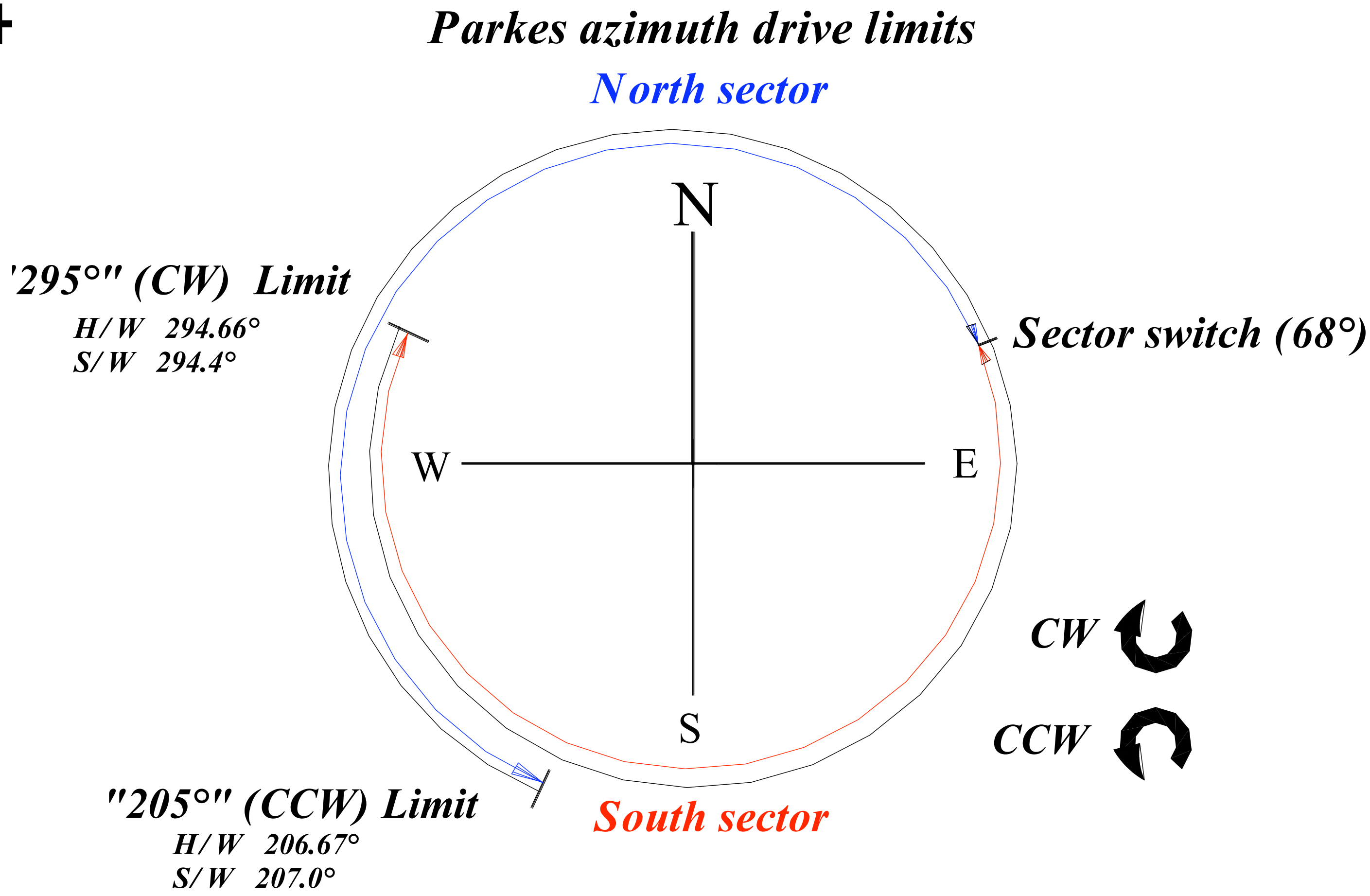
$kT_A = ½ A_{eff}.S$

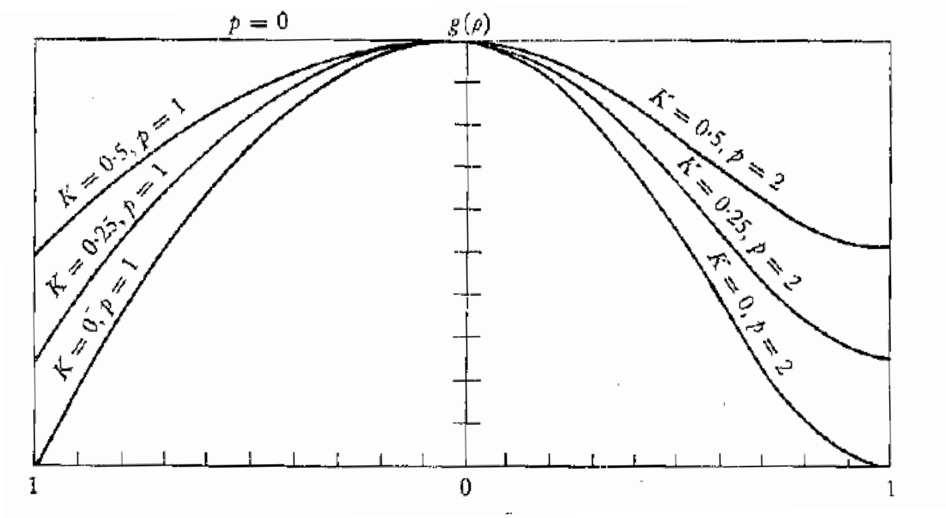


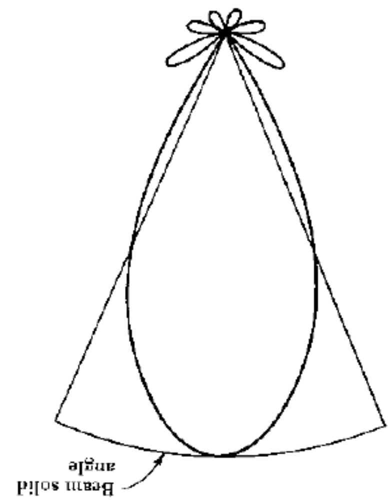
$T_{sys} = T_A + T_{spill} + T_{sky} + T_{rx}$

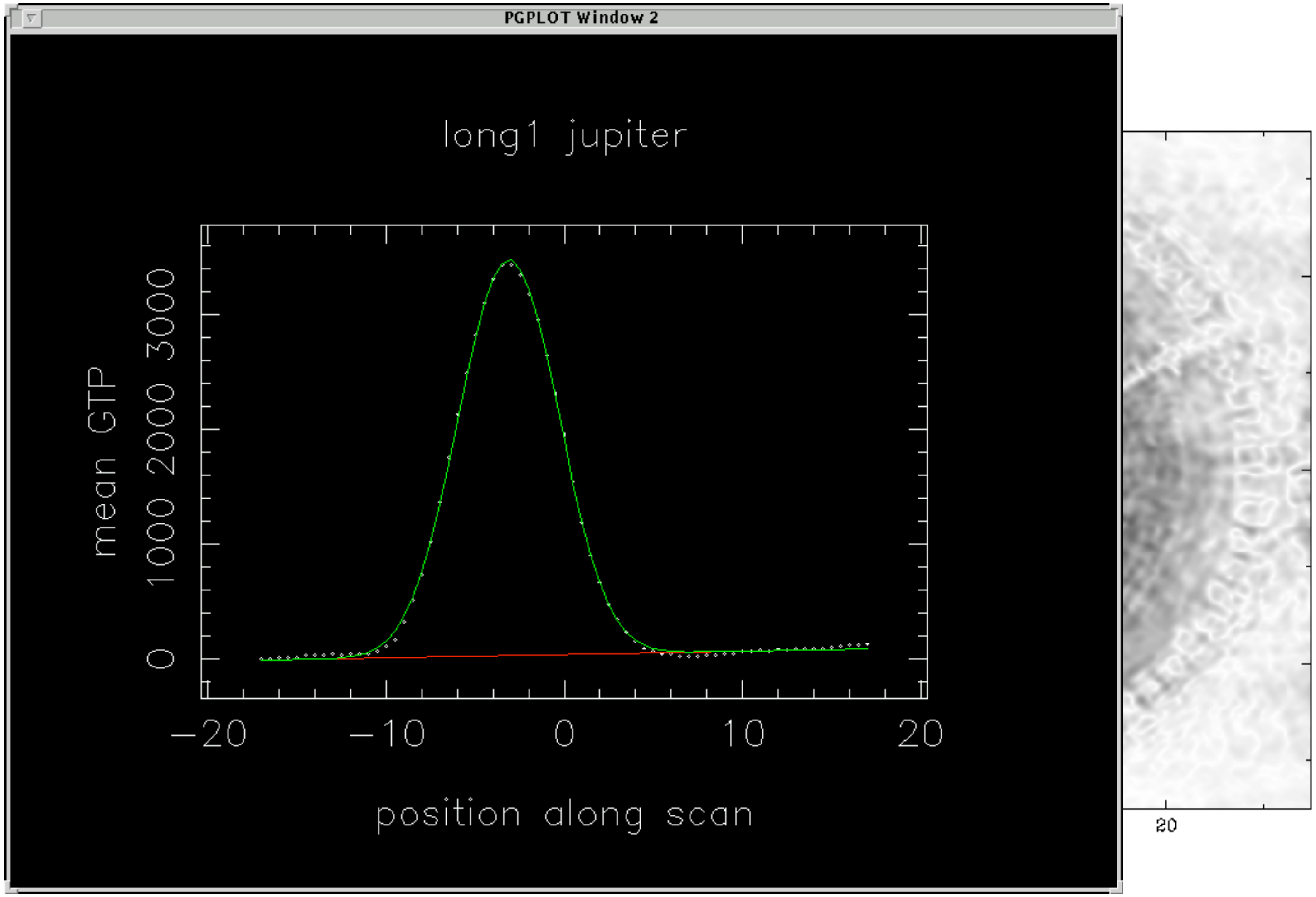
Az “wrap”

- 360+


Parkes azimuth drive limits
North sector
N
W
E
S
'295°" (CW) Limit
H/W 294.66°
S/W 294.4°
Sector switch (68°)
"205°" (CCW) Limit
H/W 206.67°
S/W 207.0°
South sector
CW
CCW


p = 0
g(ρ)
K = 0·5, p = 1
K = 0·25, p = 1
K = 0, p = 1
K = 0·5, p = 2
K = 0·25, p = 2
K = 0, p = 2
1
0
1


Beam solid angle


PGPLOT Window 2
long1 jupiter
mean GTP
0
1000
2000
3000
−20
−10
0
10
20
position along scan
20

Antenna effective area

S(f) : flux density

1 Jy = 10^{-26} W / Hz / m^2

P(f) : received power density (W / Hz)

A_{eff} : effective area of aperture

$$P(f) = A(f) \, . \, S(f)$$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