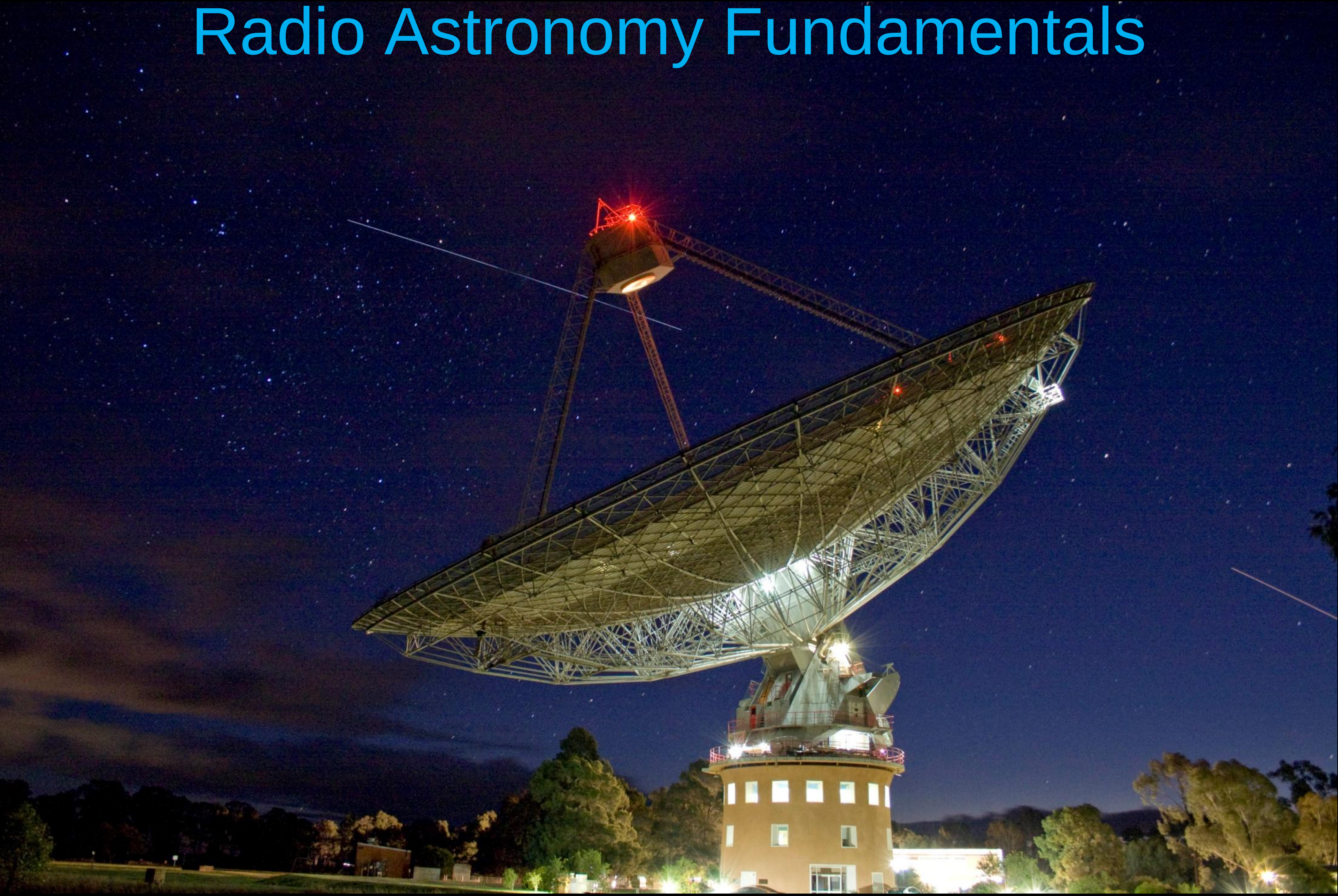
Radio Astronomy Fundamentals



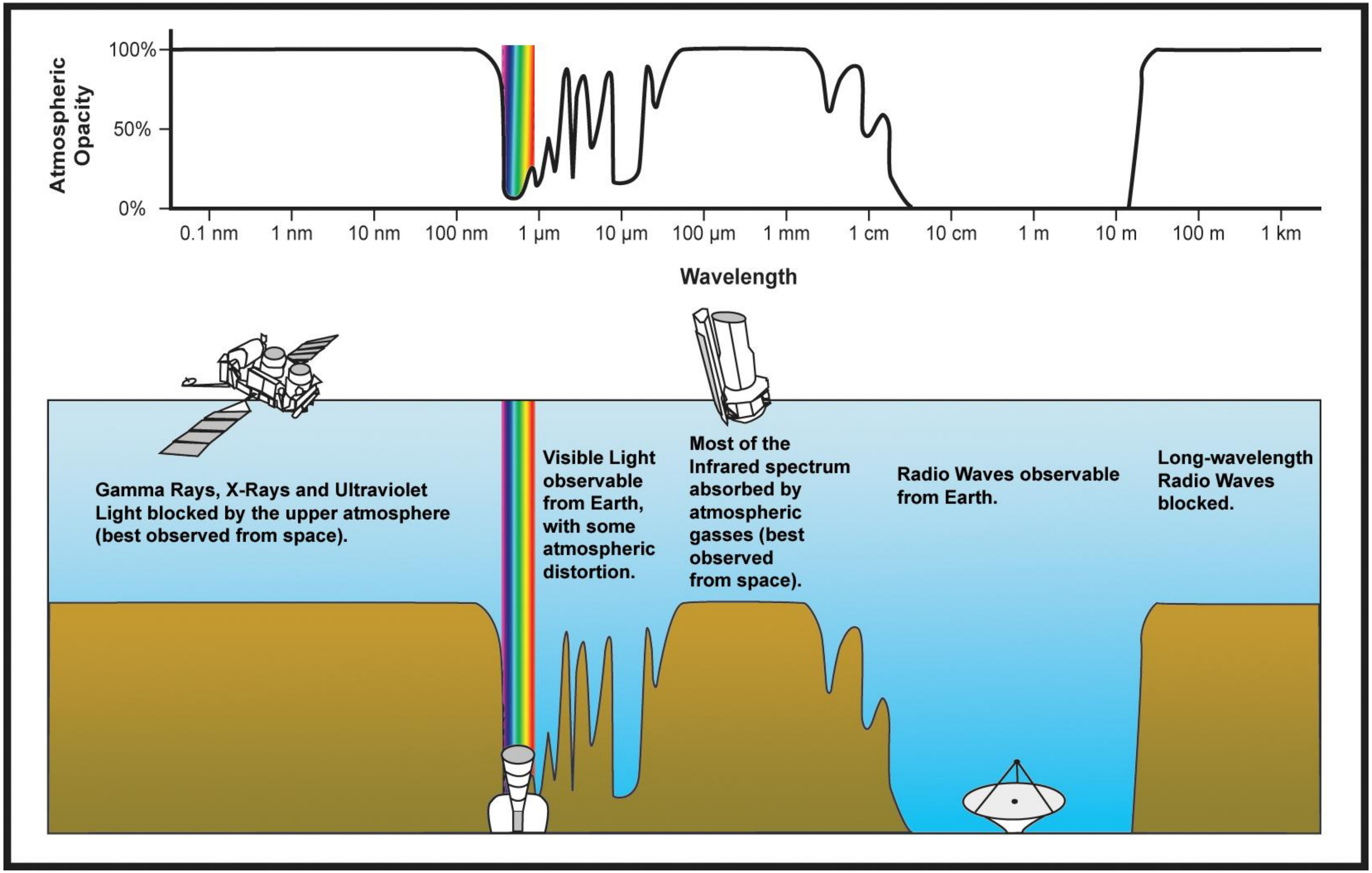
John Reynolds

RAS 2015, Narrabri

Talk outline

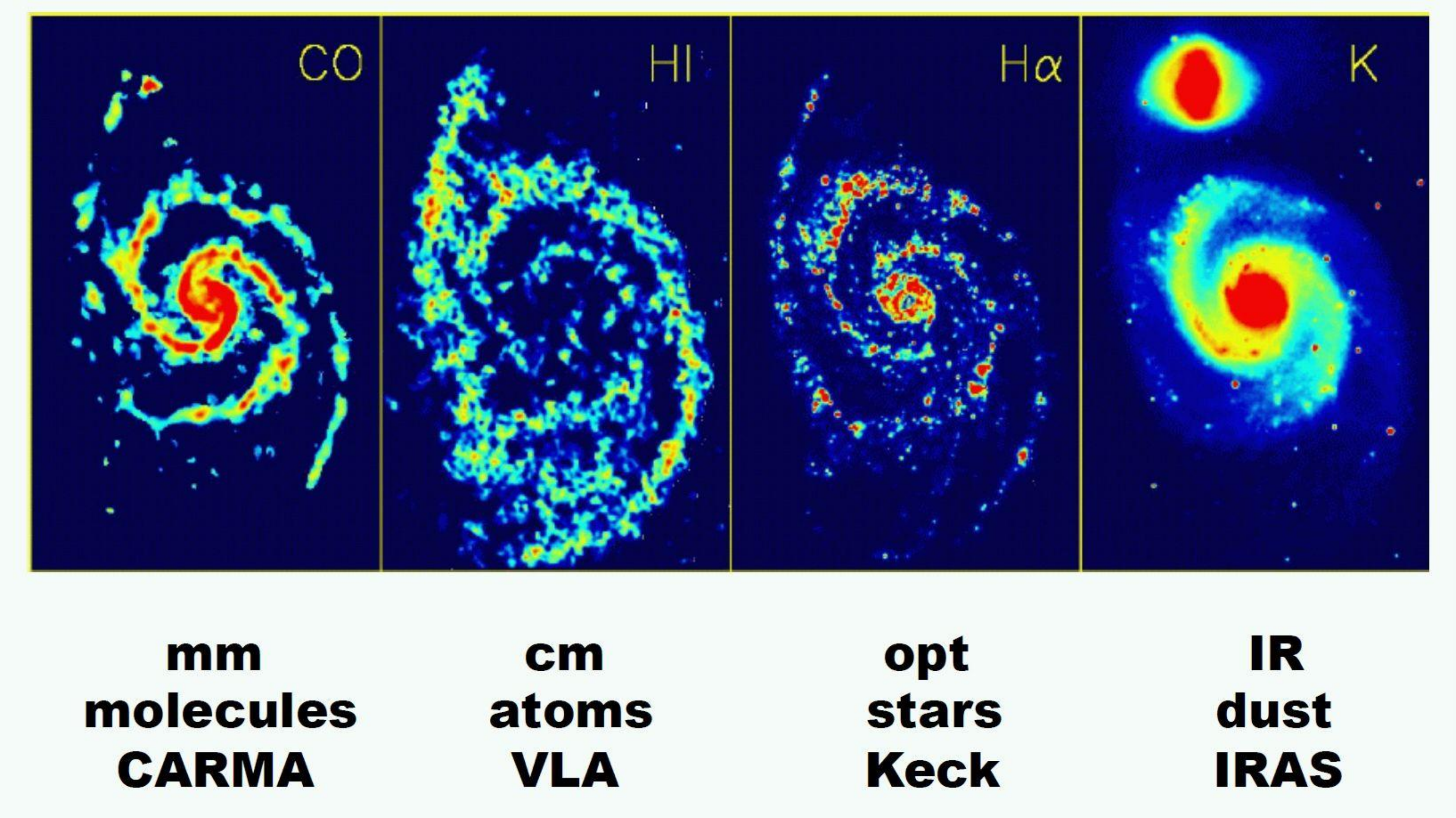
- The radio window
  - Basic emission mechanisms
- Some basics of radio telescopes
  - Feeds, illumination
  - Sensitivity & noise
- Whistle-stop tour of a single-dish system
  - Principal components
  - Example observation

The electromagnetic windows



The Night Sky in Radio

Multi-wavelength astronomy



Radiation mechanisms
(the quite short version)

- Thermal radiation
  - aka “free-free” or “bremsstrahlung” emission - electrons

- Non-thermal emission
  - Synchrotron emission
  - Atomic and molecular spectral lines
  - masers
  - gyrotron / synchro-gyrotron
  - Cerenkov
- Absorption and radiative transfer

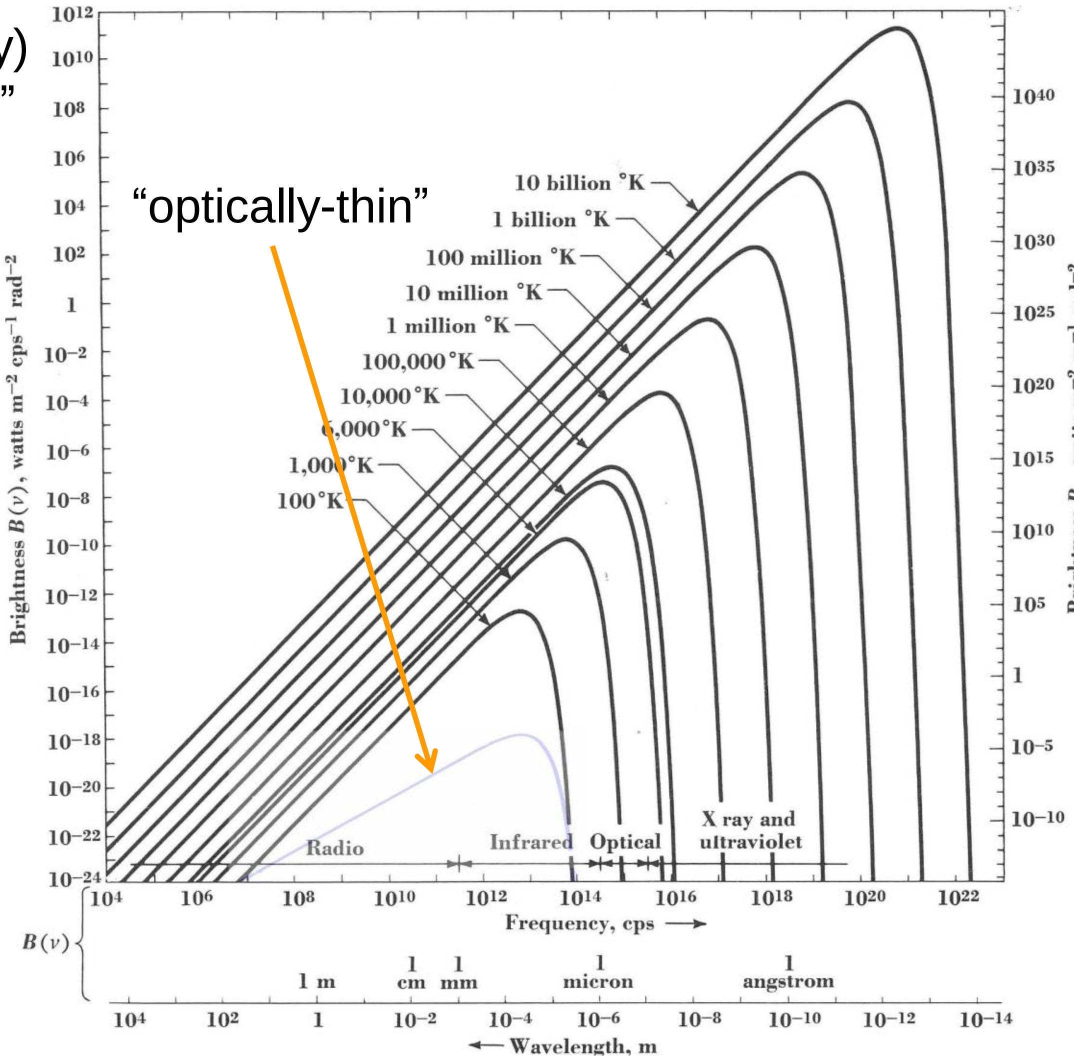
Thermal radiation

Radio astronomy we're (nearly) always in the "Rayleigh-Jeans" regime;

$$B(\nu) = 2kT / \lambda^2$$

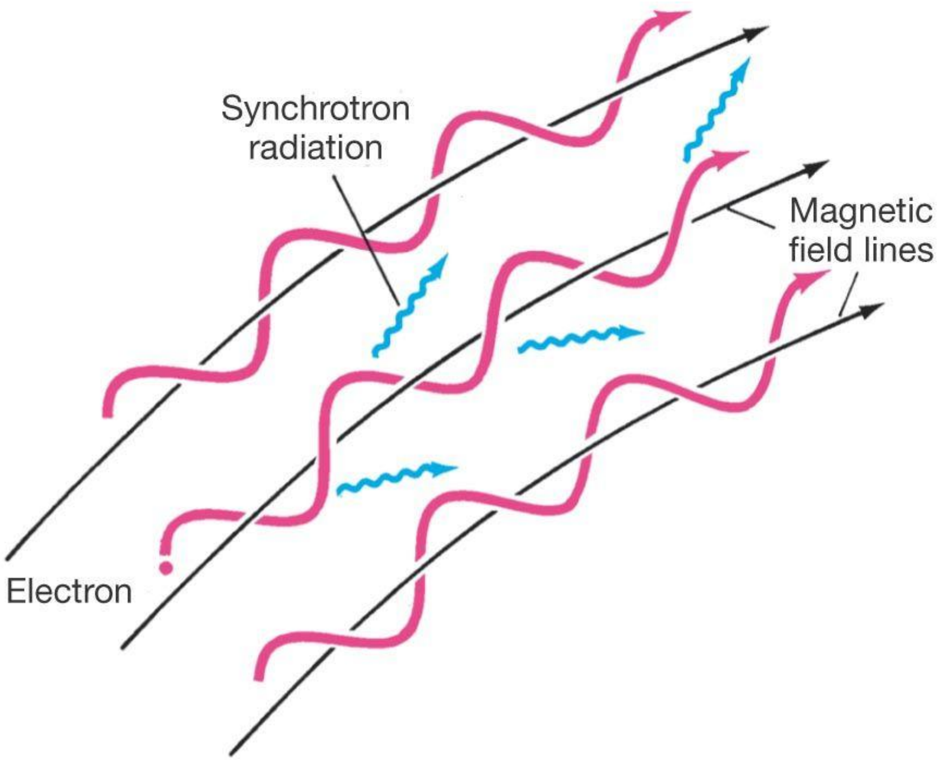
units: Watt/m^2/Hz/sterad

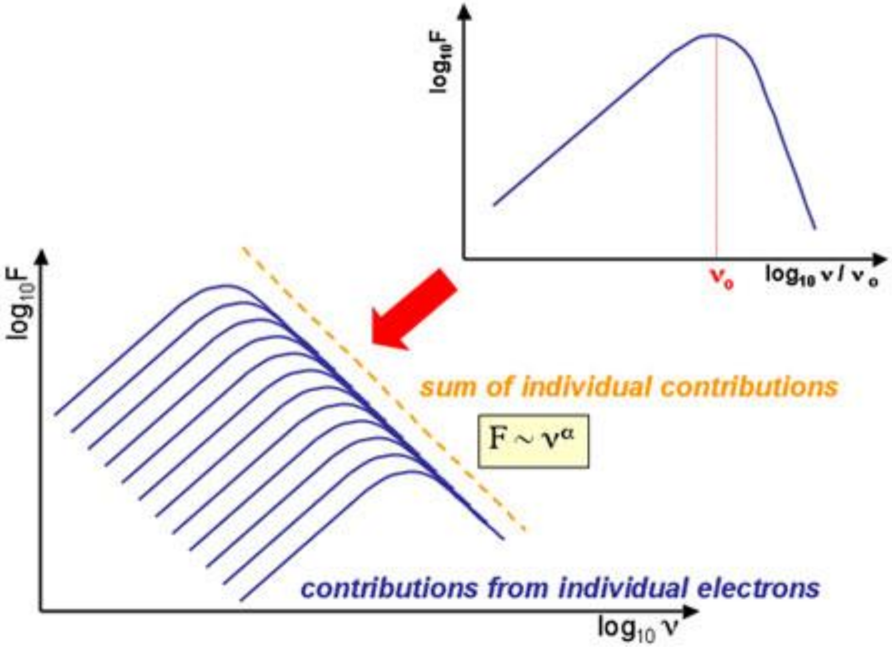
short-hand: refer instead to "brightness temperature" T



"optically-thin"

Synchrotron or “non-thermal” radiation

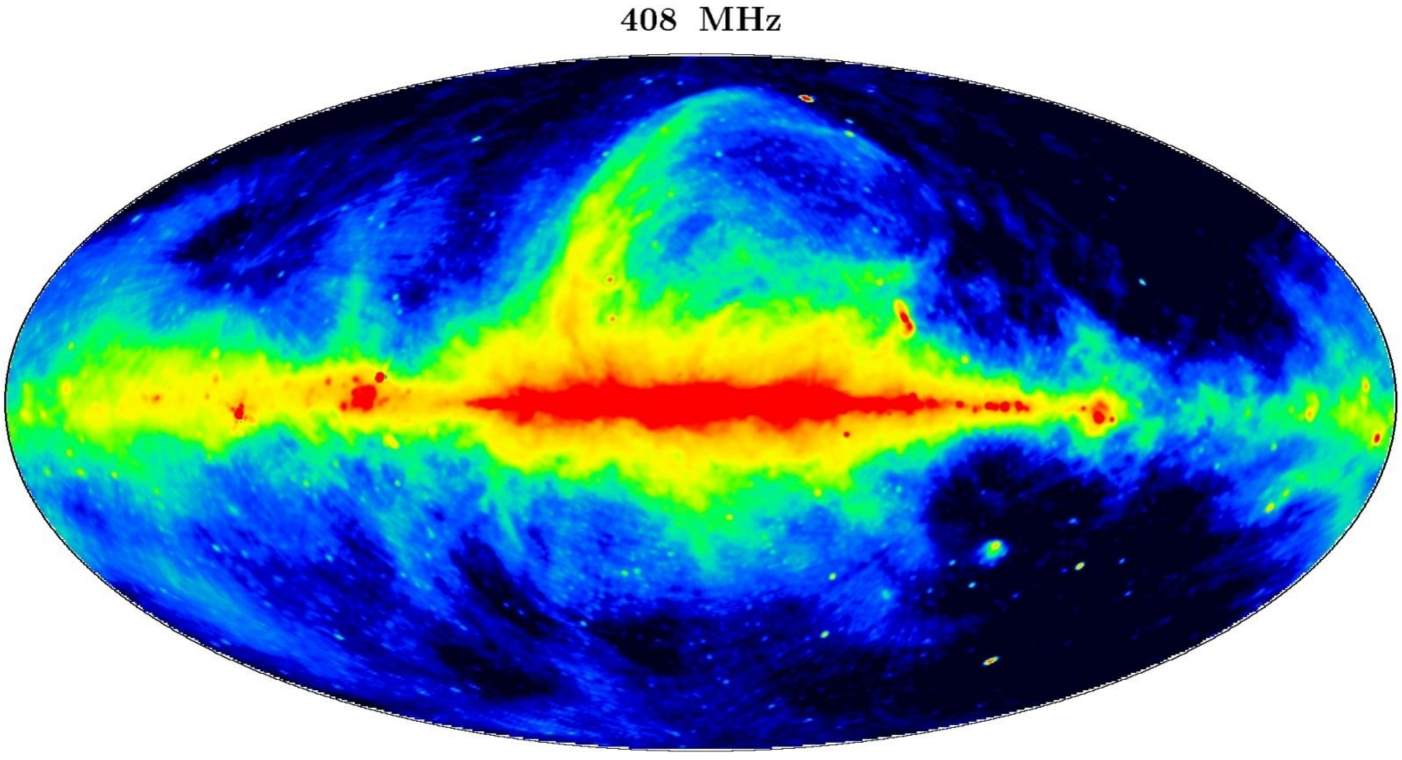




F = ν^{α} : “power-law” spectrum
α : spectral index

$\alpha \sim 0$ to -0.5 “flat spectrum”
$\alpha < -1$ “steep spectrum”
$\alpha > 0$: “inverted spectrum”
GPS : “GHz Peaked spectrum”

The radio sky at 408MHz (70cm)

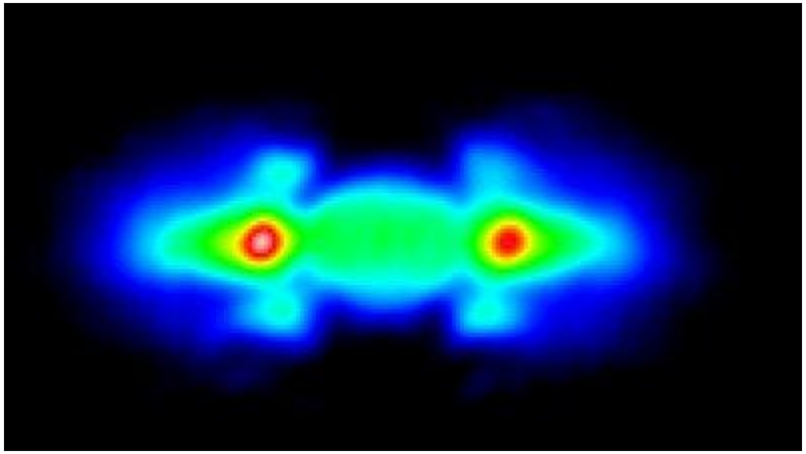


Jodrell-Bank 250-feet + Effelsberg 100-m + Parkes 64-m

Jupiter in the radio

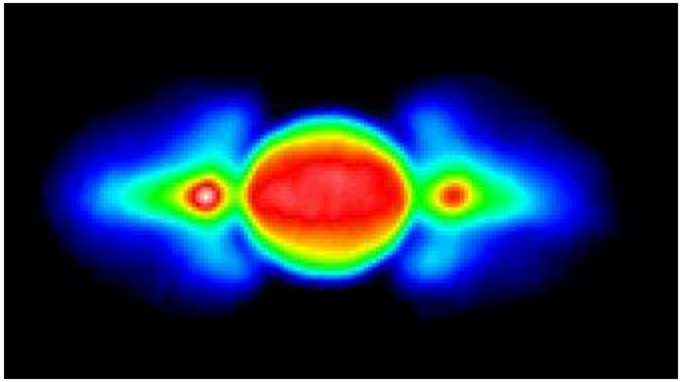
22cm = 1.3GHz

Synchrotron emission from electrons trapped in Jovian magnetic field



13cm = 2.4GHz

Thermal emission from Jupiter’s atmosphere much more prominent



ATCA images by Dulk, Leblanc, Sault & Hunstead

Spectral lines – cosmic “tuning forks”

1958

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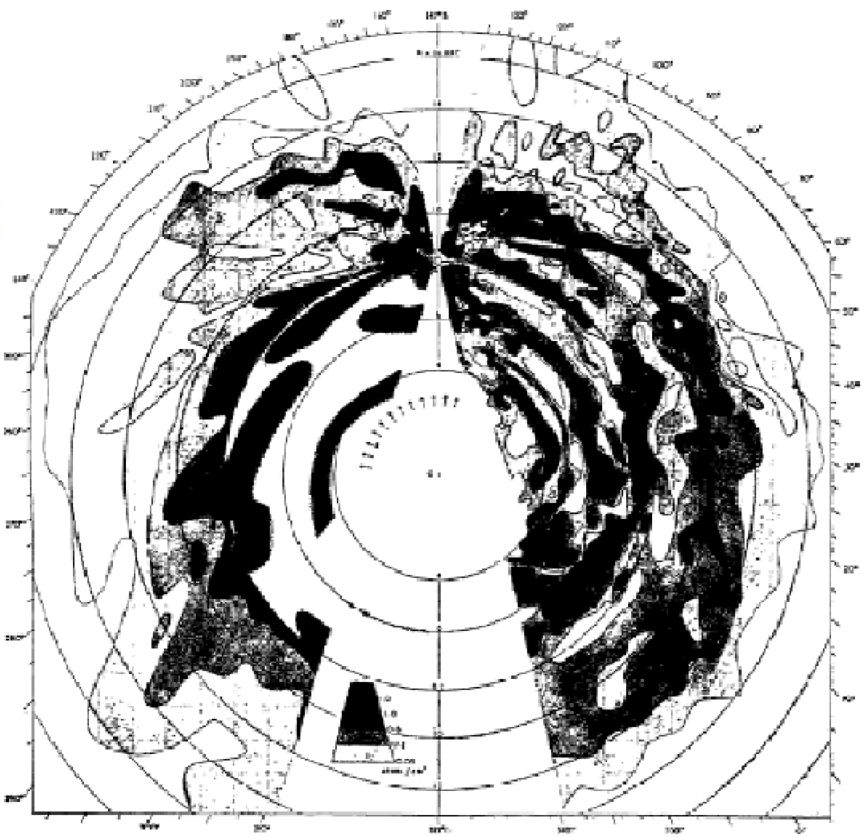


Fig. 1. Distribution of neutral hydrogen in the galactic system.

Neutral atomic Hydrogen – HI

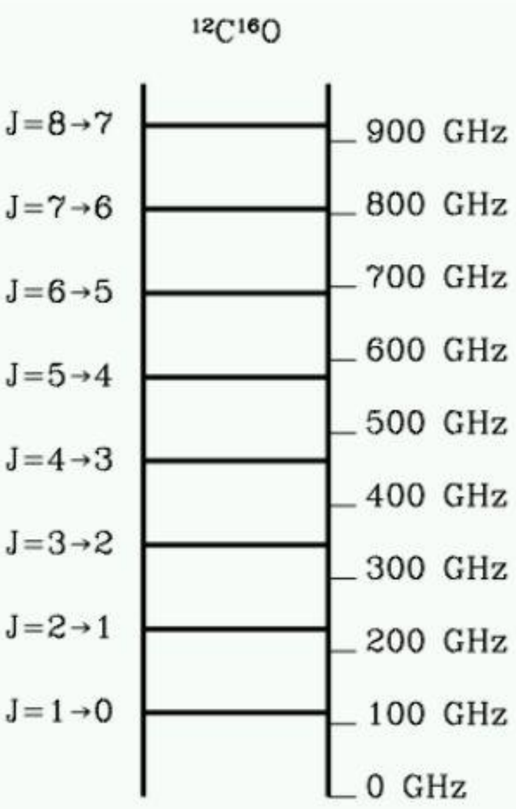
the “spin-flip” hyperfine transition

produces photons at λ = 21cm or

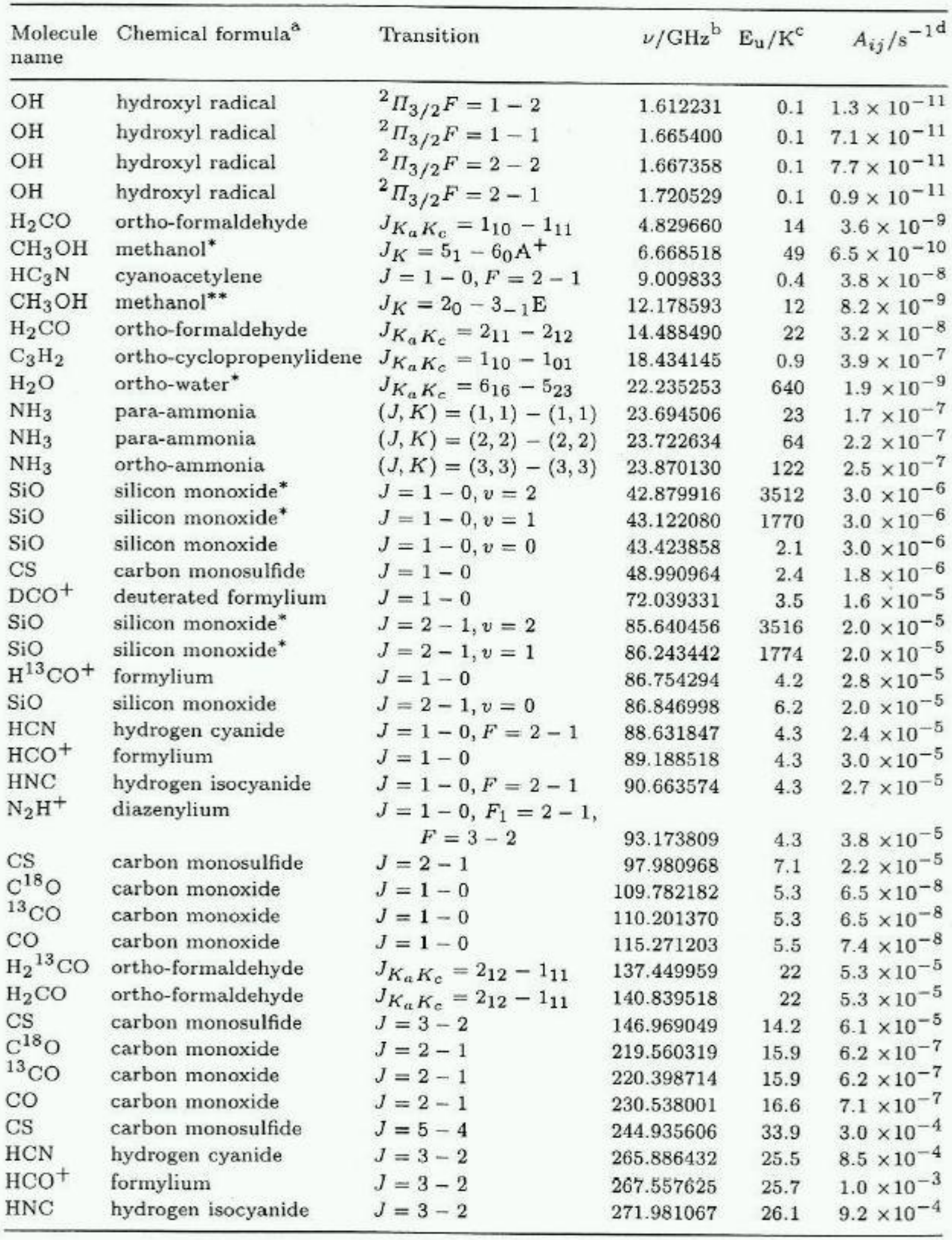
1420.40575177 MHz

(same transition as used by
Hydrogen maser atomic clocks)

Molecular Lines

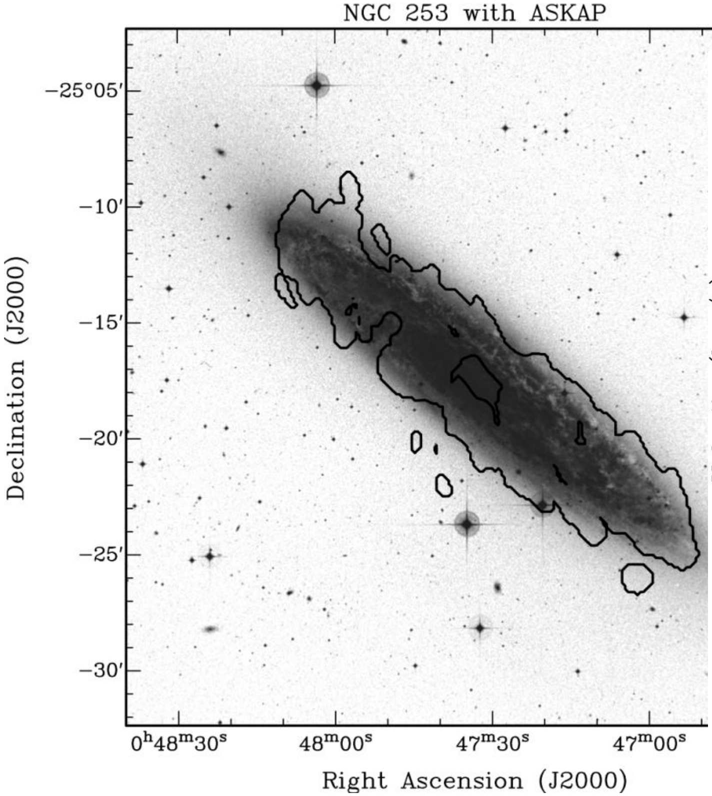


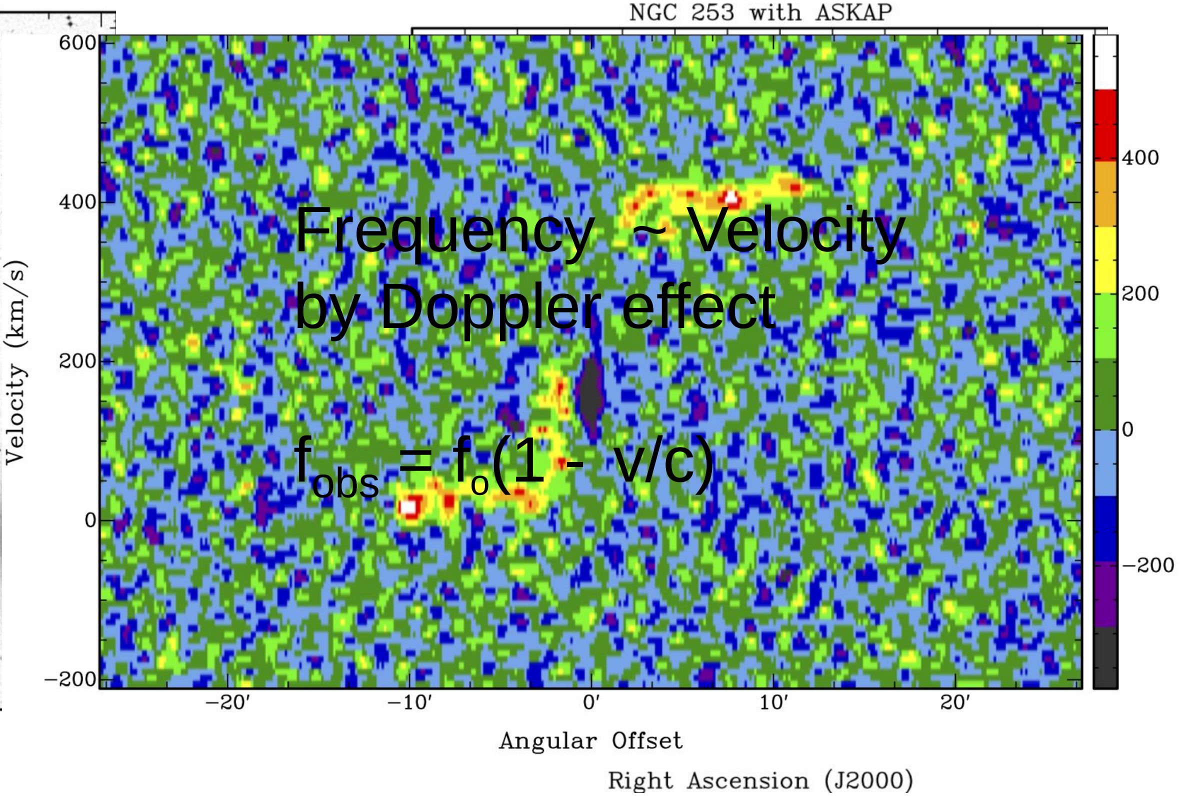
(Rohlfs & Wilson 1996)



Molecule name	Chemical formula[a]	Transition	ν/GHz[b]	E_u/K[c]	A_{ij}/s^{-1}[d]
OH	hydroxyl radical	$^2\Pi_{3/2}F = 1-2$	1.612231	0.1	1.3×10^{-11}
OH	hydroxyl radical	$^2\Pi_{3/2}F = 1-1$	1.665400	0.1	7.1×10^{-11}
OH	hydroxyl radical	$^2\Pi_{3/2}F = 2-2$	1.667358	0.1	7.7×10^{-11}
OH	hydroxyl radical	$^2\Pi_{3/2}F = 2-1$	1.720529	0.1	0.9×10^{-11}
H_2CO	ortho-formaldehyde	$J_{K_aK_c} = 1_{10} - 1_{11}$	4.829660	14	3.6×10^{-9}
CH_3OH	methanol*	$J_K = 5_1 - 6_0A^+$	6.668518	49	6.5×10^{-10}
HC_3N	cyanoacetylene	$J = 1-0, F = 2-1$	9.009833	0.4	3.8×10^{-8}
CH_3OH	methanol**	$J_K = 2_0 - 3_{-1}E$	12.178593	12	8.2×10^{-9}
H_2CO	ortho-formaldehyde	$J_{K_aK_c} = 2_{11} - 2_{12}$	14.488490	22	3.2×10^{-8}
C_3H_2	ortho-cyclopropenylidene	$J_{K_aK_c} = 1_{10} - 1_{01}$	18.434145	0.9	3.9×10^{-7}
H_2O	ortho-water*	$J_{K_aK_c} = 6_{16} - 5_{23}$	22.235253	640	1.9×10^{-9}
NH_3	para-ammonia	$(J,K) = (1,1) - (1,1)$	23.694506	23	1.7×10^{-7}
NH_3	para-ammonia	$(J,K) = (2,2) - (2,2)$	23.722634	64	2.2×10^{-7}
NH_3	ortho-ammonia	$(J,K) = (3,3) - (3,3)$	23.870130	122	2.5×10^{-7}
SiO	silicon monoxide*	$J = 1-0, v = 2$	42.879916	3512	3.0×10^{-6}
SiO	silicon monoxide*	$J = 1-0, v = 1$	43.122080	1770	3.0×10^{-6}
SiO	silicon monoxide	$J = 1-0, v = 0$	43.423858	2.1	3.0×10^{-6}
CS	carbon monosulfide	$J = 1-0$	48.990964	2.4	1.8×10^{-6}
DCO^+	deuterated formylium	$J = 1-0$	72.039331	3.5	1.6×10^{-5}
SiO	silicon monoxide*	$J = 2-1, v = 2$	85.640456	3516	2.0×10^{-5}
SiO	silicon monoxide*	$J = 2-1, v = 1$	86.243442	1774	2.0×10^{-5}
$H^{13}CO^+$	formylium	$J = 1-0$	86.754294	4.2	2.8×10^{-5}
SiO	silicon monoxide	$J = 2-1, v = 0$	86.846998	6.2	2.0×10^{-5}
HCN	hydrogen cyanide	$J = 1-0, F = 2-1$	88.631847	4.3	2.4×10^{-5}
HCO^+	formylium	$J = 1-0$	89.188518	4.3	3.0×10^{-5}
HNC	hydrogen isocyanide	$J = 1-0, F = 2-1$	90.663574	4.3	2.7×10^{-5}
N_2H^+	diazenylium	$J = 1-0,\ F_1 = 2-1,\ F = 3-2$	93.173809	4.3	3.8×10^{-5}
CS	carbon monosulfide	$J = 2-1$	97.980968	7.1	2.2×10^{-5}
$C^{18}O$	carbon monoxide	$J = 1-0$	109.782182	5.3	6.5×10^{-8}
^{13}CO	carbon monoxide	$J = 1-0$	110.201370	5.3	6.5×10^{-8}
CO	carbon monoxide	$J = 1-0$	115.271203	5.5	7.4×10^{-8}
$H_2{}^{13}CO$	ortho-formaldehyde	$J_{K_aK_c} = 2_{12} - 1_{11}$	137.449959	22	5.3×10^{-5}
H_2CO	ortho-formaldehyde	$J_{K_aK_c} = 2_{12} - 1_{11}$	140.839518	22	5.3×10^{-5}
CS	carbon monosulfide	$J = 3-2$	146.969049	14.2	6.1×10^{-5}
$C^{18}O$	carbon monoxide	$J = 2-1$	219.560319	15.9	6.2×10^{-7}
^{13}CO	carbon monoxide	$J = 2-1$	220.398714	15.9	6.2×10^{-7}
CO	carbon monoxide	$J = 2-1$	230.538001	16.6	7.1×10^{-7}
CS	carbon monosulfide	$J = 5-4$	244.935606	33.9	3.0×10^{-4}
HCN	hydrogen cyanide	$J = 3-2$	265.886432	25.5	8.5×10^{-4}
HCO^+	formylium	$J = 3-2$	267.557625	25.7	1.0×10^{-3}
HNC	hydrogen isocyanide	$J = 3-2$	271.981067	26.1	9.2×10^{-4}

Spectral lines – a new dimension





Frequency ~ Velocity
by Doppler effect

$$f_{obs} = f_o(1 - v/c)$$

Images: Paolo Serra

You’ll need a telescope

The two main functions;

- Sensitivity (collecting area)

  Area ~ Diameter^2

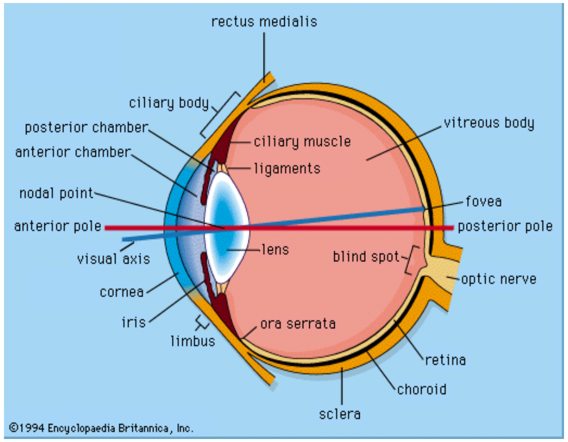
- Magnification, angular resolution

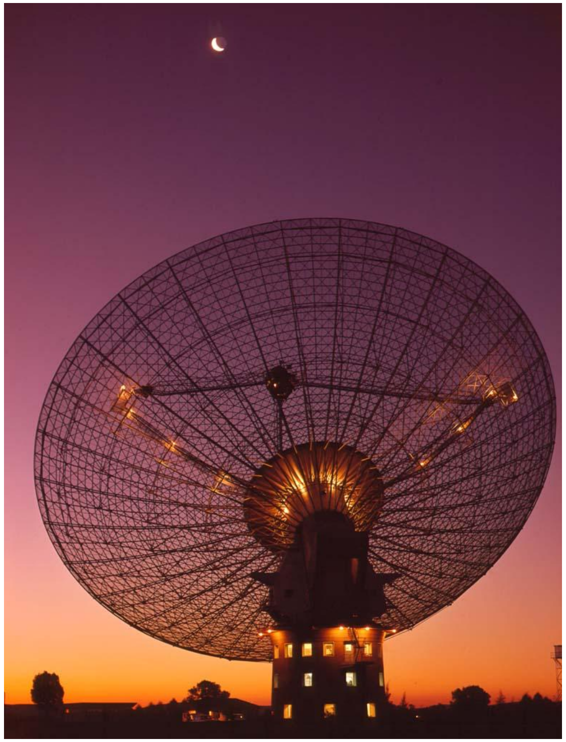
  ~Diameter (largest dimension)

  $\theta \sim \lambda/D$

Some well known telescopes

$\Delta\theta$ $1'$ $2''$ $10'$





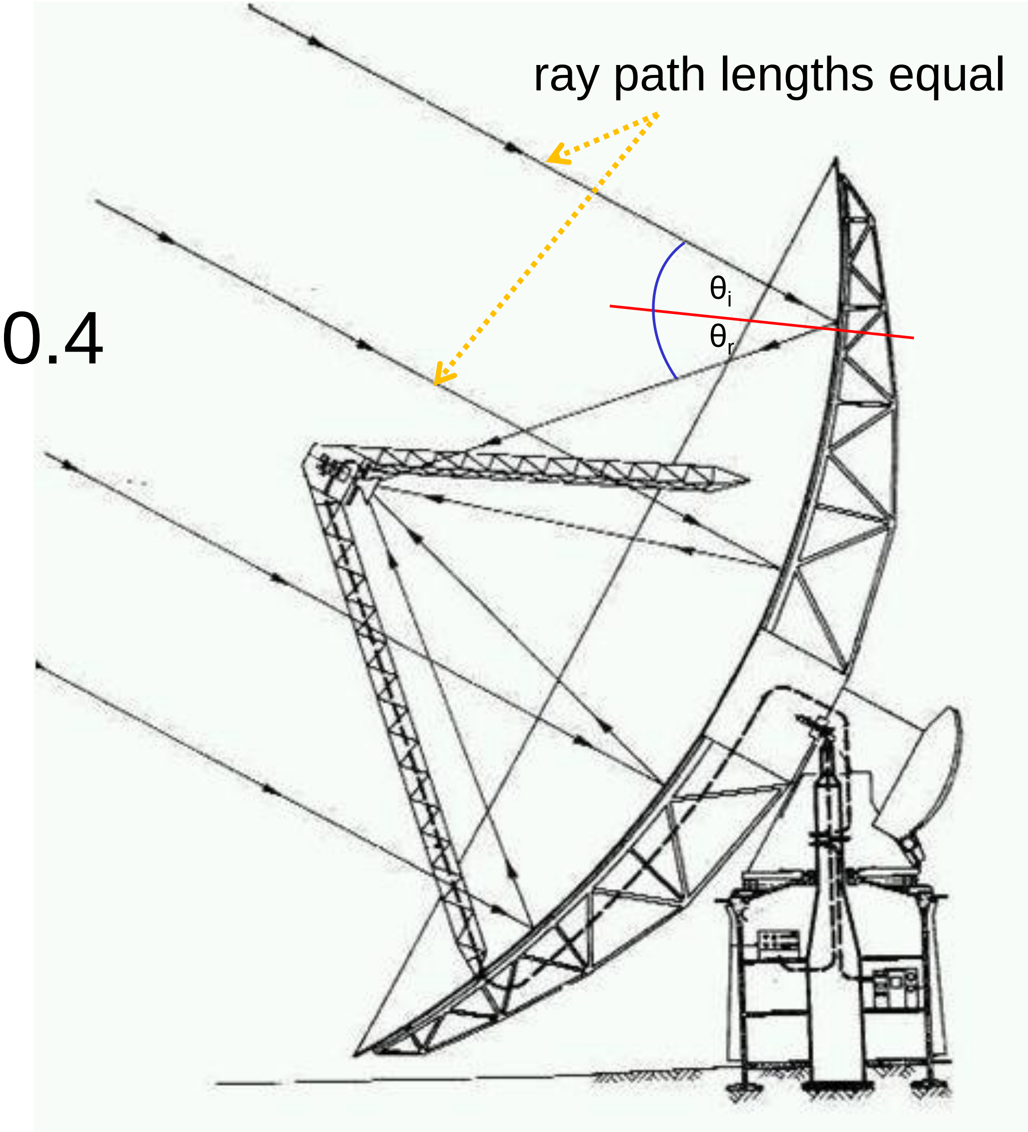
The parabolic reflector (“Dish”)

Parkes 64-metre

Prime-focus: f/D ~ 0.4

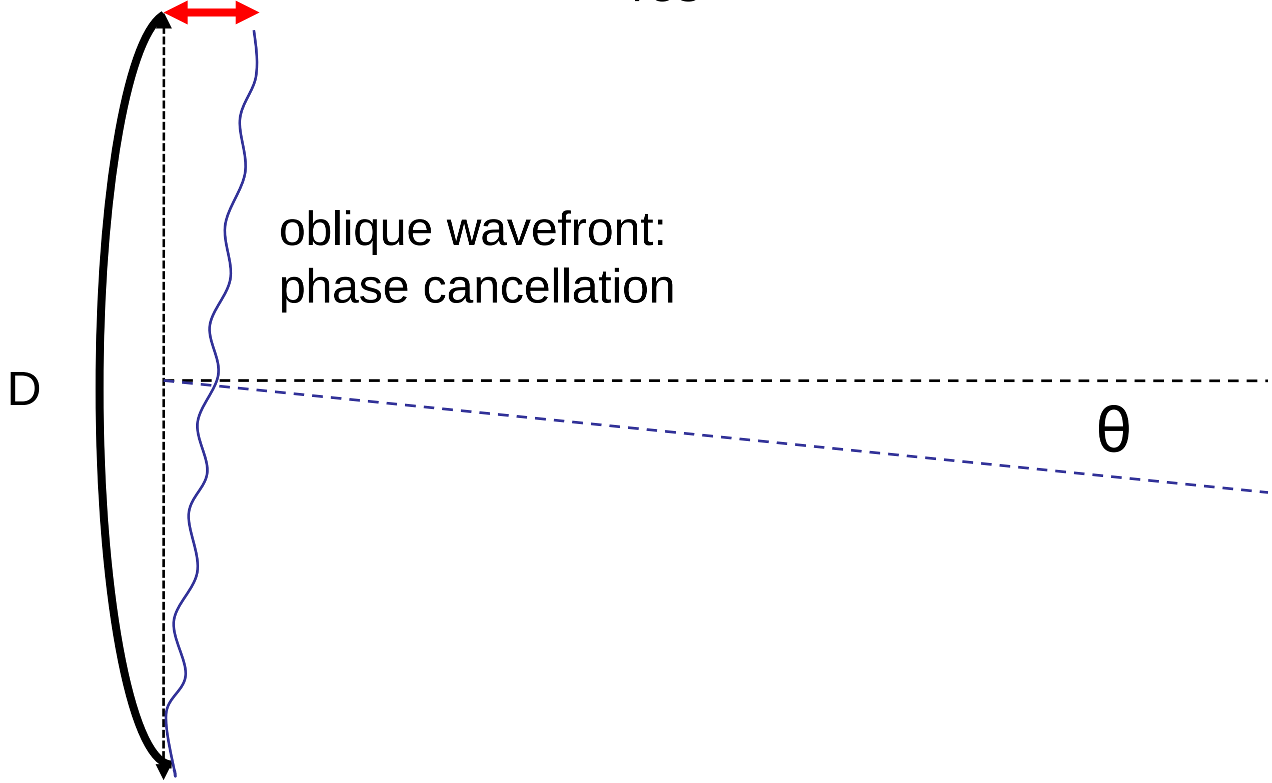
74 MHz – 26 GHz
(2.5 decades)

Prime focus
vs
Secondary;
Cassegrain etc


ray path lengths equal

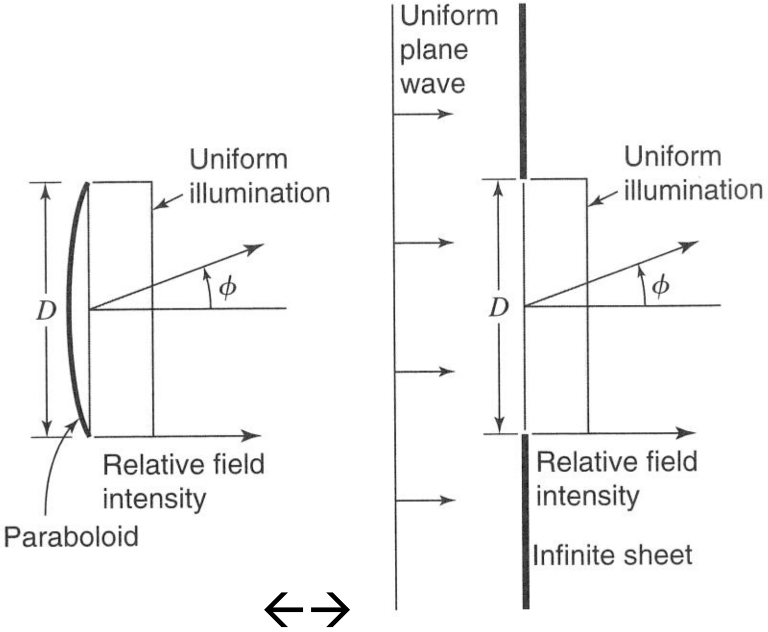
Diffraction limit – simplified

$\theta D = \lambda \quad \rightarrow \quad \theta_{res} = \lambda / D$

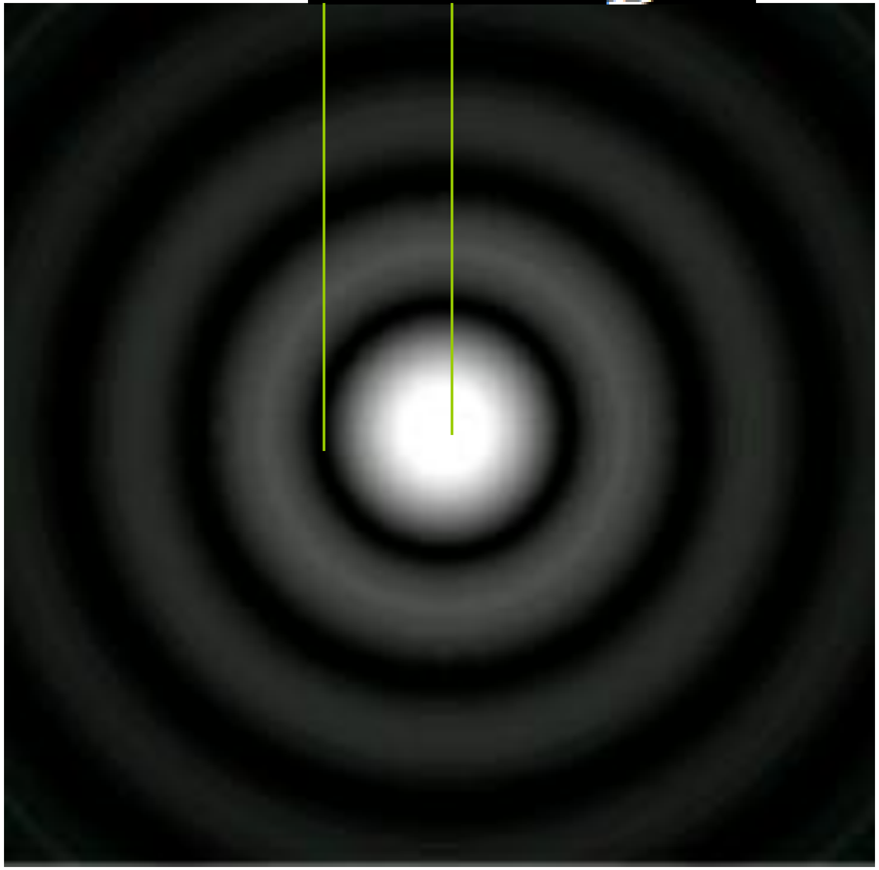


oblique wavefront:
phase cancellation

Diffraction limit

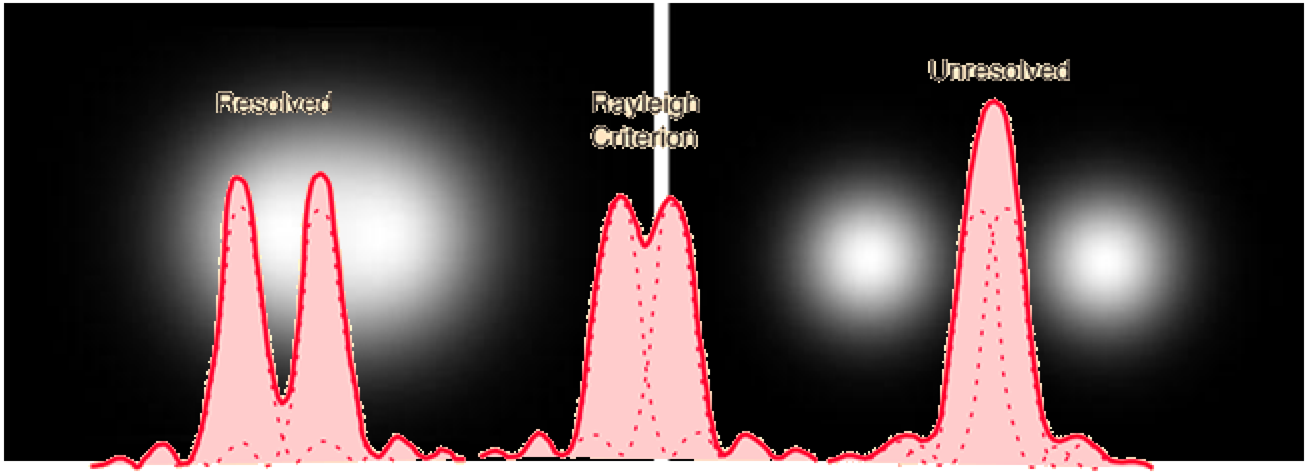


$$\Delta\theta \approx \frac{1.22\lambda}{D}$$



Diffraction theory
Airy pattern →

Angular resolution: the Rayleigh criterion



Rayleigh criterion to resolve two point sources:

peak of first source lies on first null of second source

$$d\theta = 1.22\lambda / D$$

Multiple reflector systems

ATCA,
Tid 70m

SRT 64m

“Beam-waveguide”
DSS34,35 … at Tid

GBT
MeerKAT

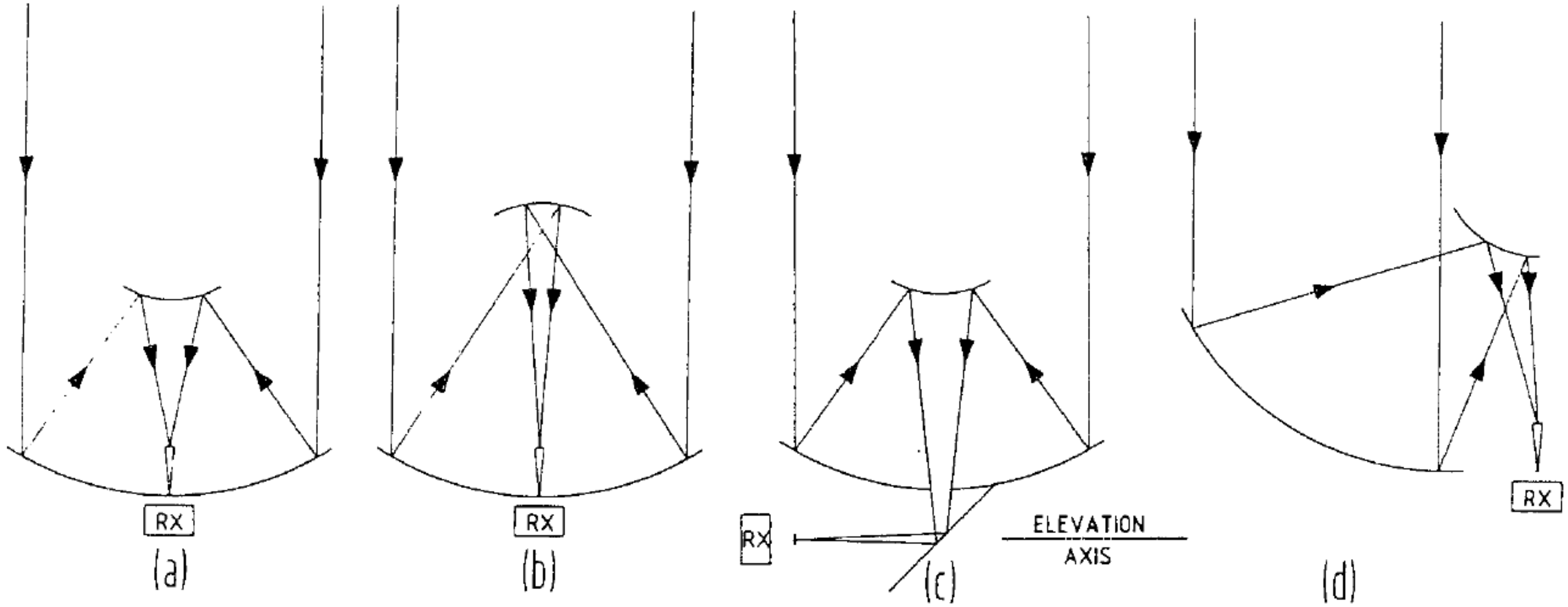
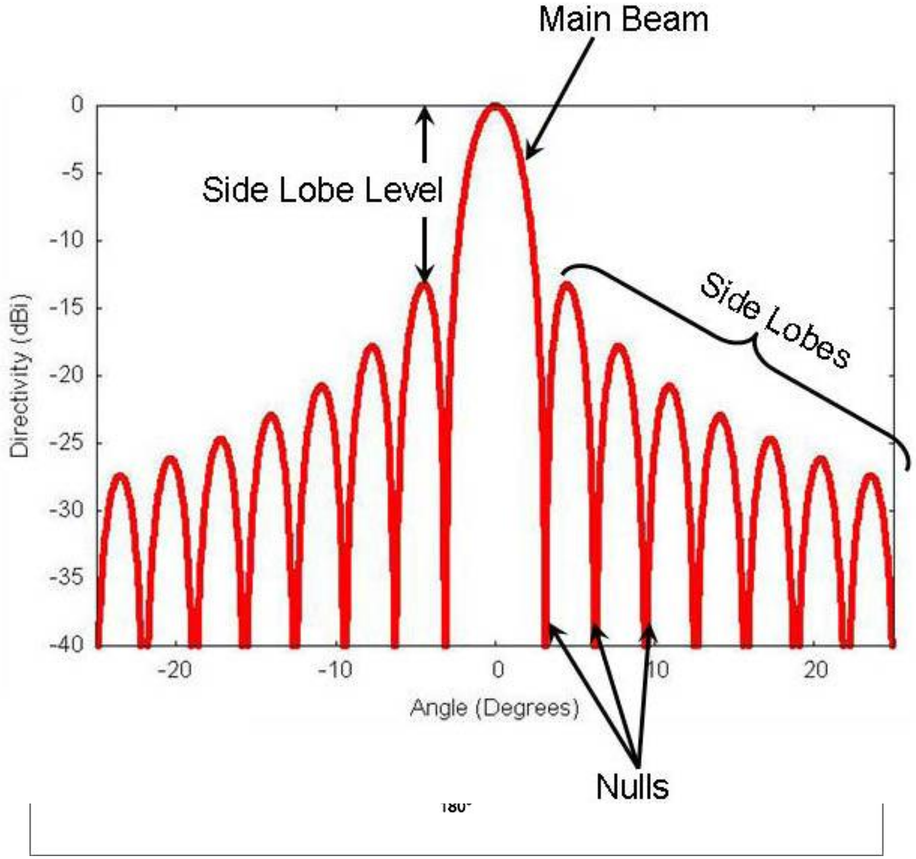
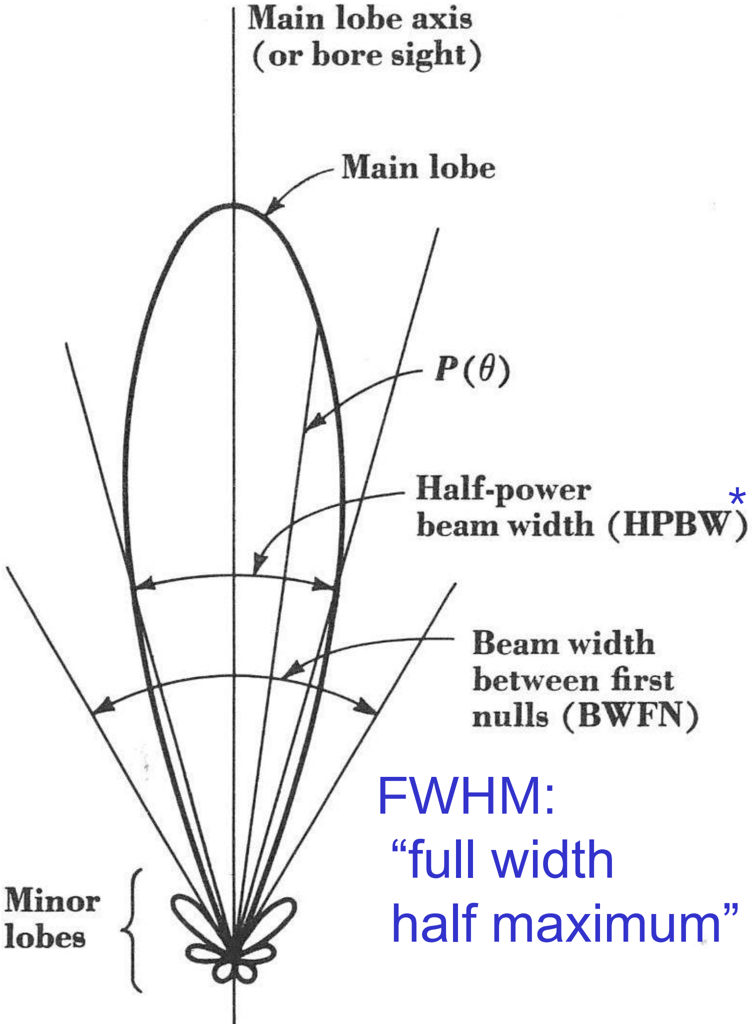


Fig. 6.7. The geometry of (**a**) Cassegrain, (**b**) Gregory, (**c**) Nasmyth and (**d**) offset Cassegrain systems

Telescope beams





*

FWHM:
“full width
half maximum”

Antenna effective area

S(ν) : flux density (W/m^2/Hz) – discrete sources

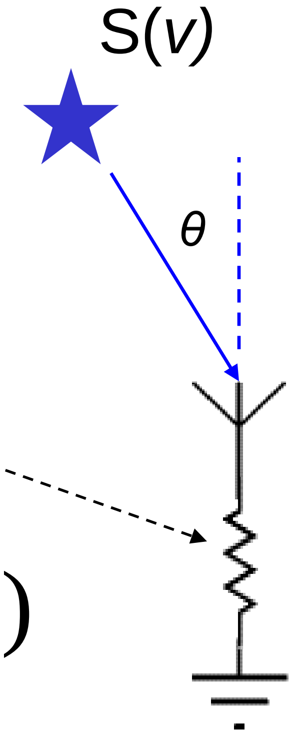
Jansky: 1Jy = 10^{-26} W/m^2/Hz

Antenna Effective Area:
how much flux is collected?

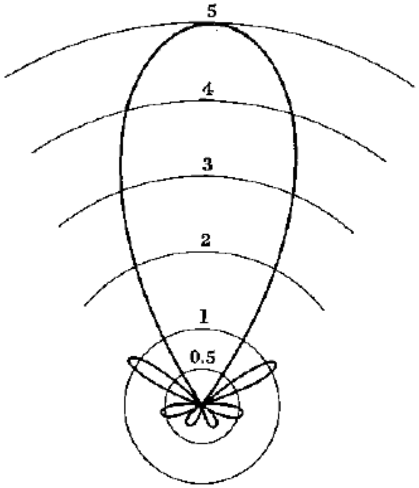
matched power density, pol i

$$P_i(\theta,\nu) = S_i(\nu)\mathrm{A}_{\mathrm{eff}}(\theta,\nu)$$

$S_i(\nu) = \frac{1}{2}S(\nu)$ for unpolarized source



Main lobe



sidelobes

A$_{\mathrm{eff}}$ (θ) : the beamshape

Two handy antenna facts

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

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

high gain = small beam area

“no high-gain isotropics”

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

Reciprocity theorem;

transmit beamshape = receive beamshape

Antenna response

$B(v,\mathbf{n})$: Brightness - Watts/Hz/m^2/sterad

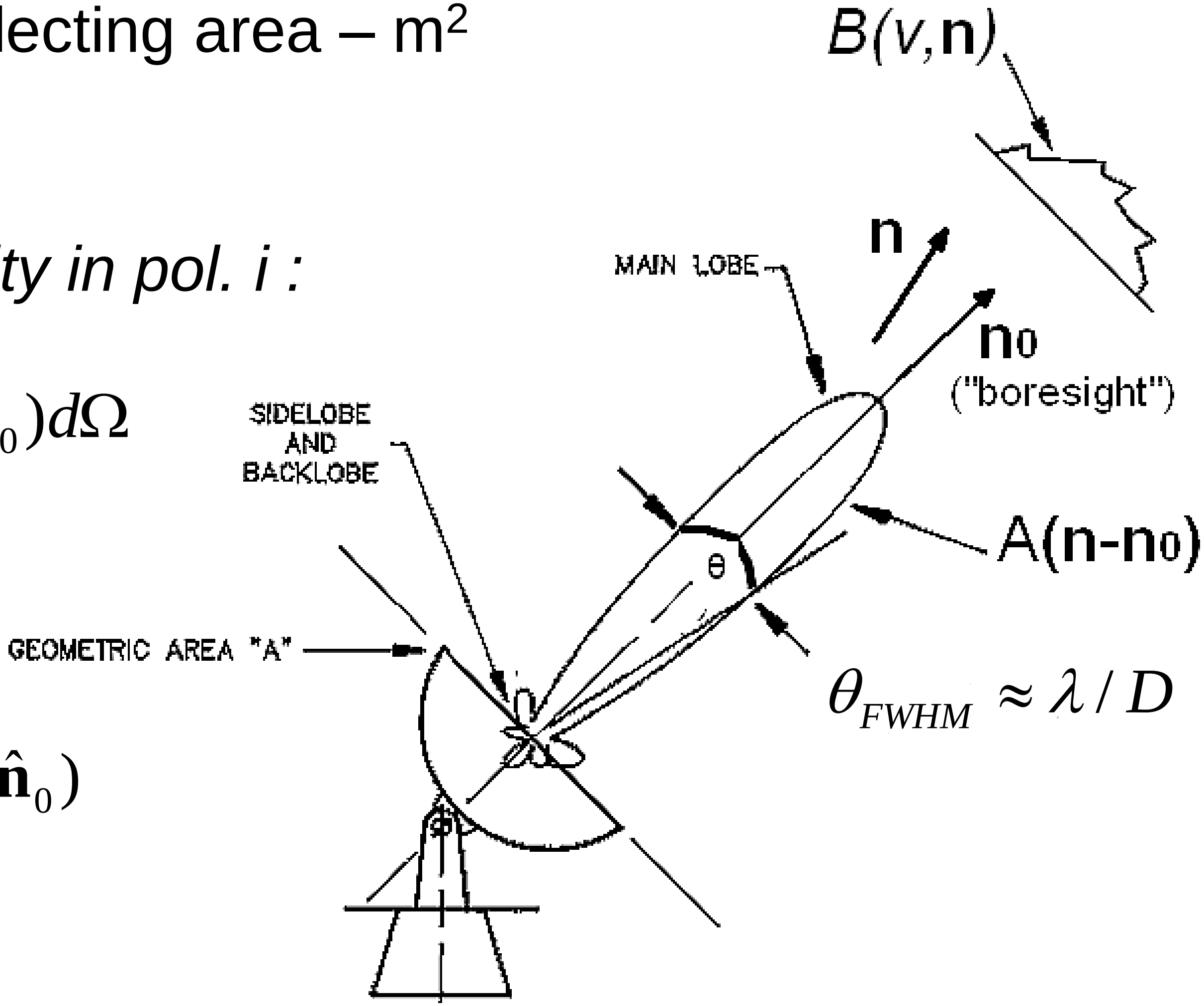
$A(v,\mathbf{n}_0)$: Effective collecting area – m^2

Received power density in pol. i :

$$P_i(\hat{\mathbf{n}}_0) = \oint B_i(\hat{\mathbf{n}}) A_{eff}(\hat{\mathbf{n}} - \hat{\mathbf{n}}_0) d\Omega$$

For “broad” sources;

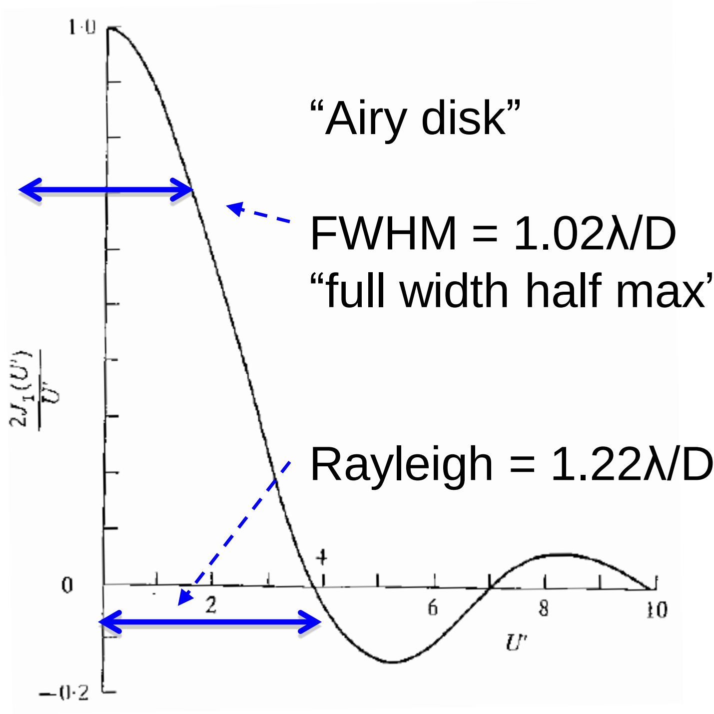
$$P_i(\hat{\mathbf{n}}_0) = \lambda^2 B_i(\hat{\mathbf{n}}_0) = kT_B(\hat{\mathbf{n}}_0)$$



$$\theta_{FWHM} \approx \lambda / D$$

Perfectly-illuminated circular aperture

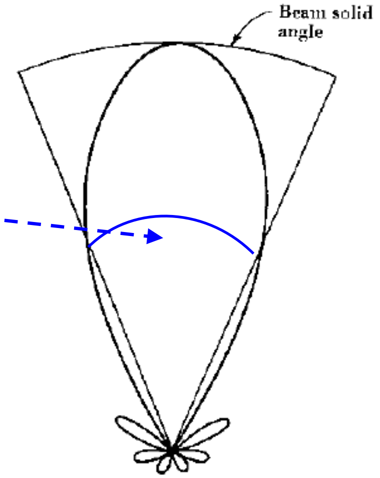
$A_{eff}(0) = A_{physical} = \pi . r^2$ (projected area)



“Airy disk”

FWHM = 1.02λ/D
“full width half max”

Rayleigh = 1.22λ/D



The “Dish” Advantage

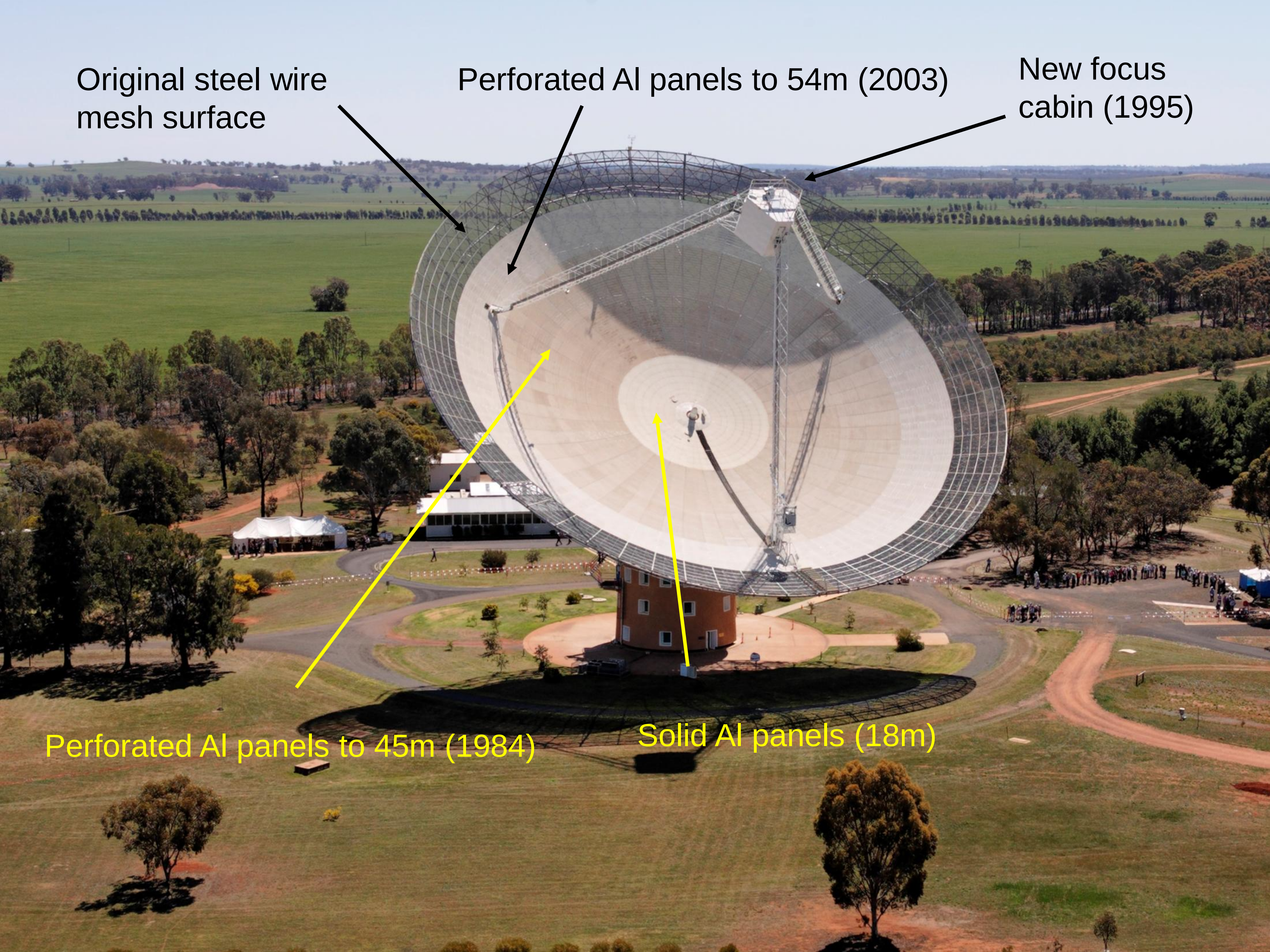
Simplicity – cost effective for collecting area

Sensitivity – hard to beat

Versatility – imaging, spectral line, pulsars ….

Adaptability – still going strong after ~50 years!

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



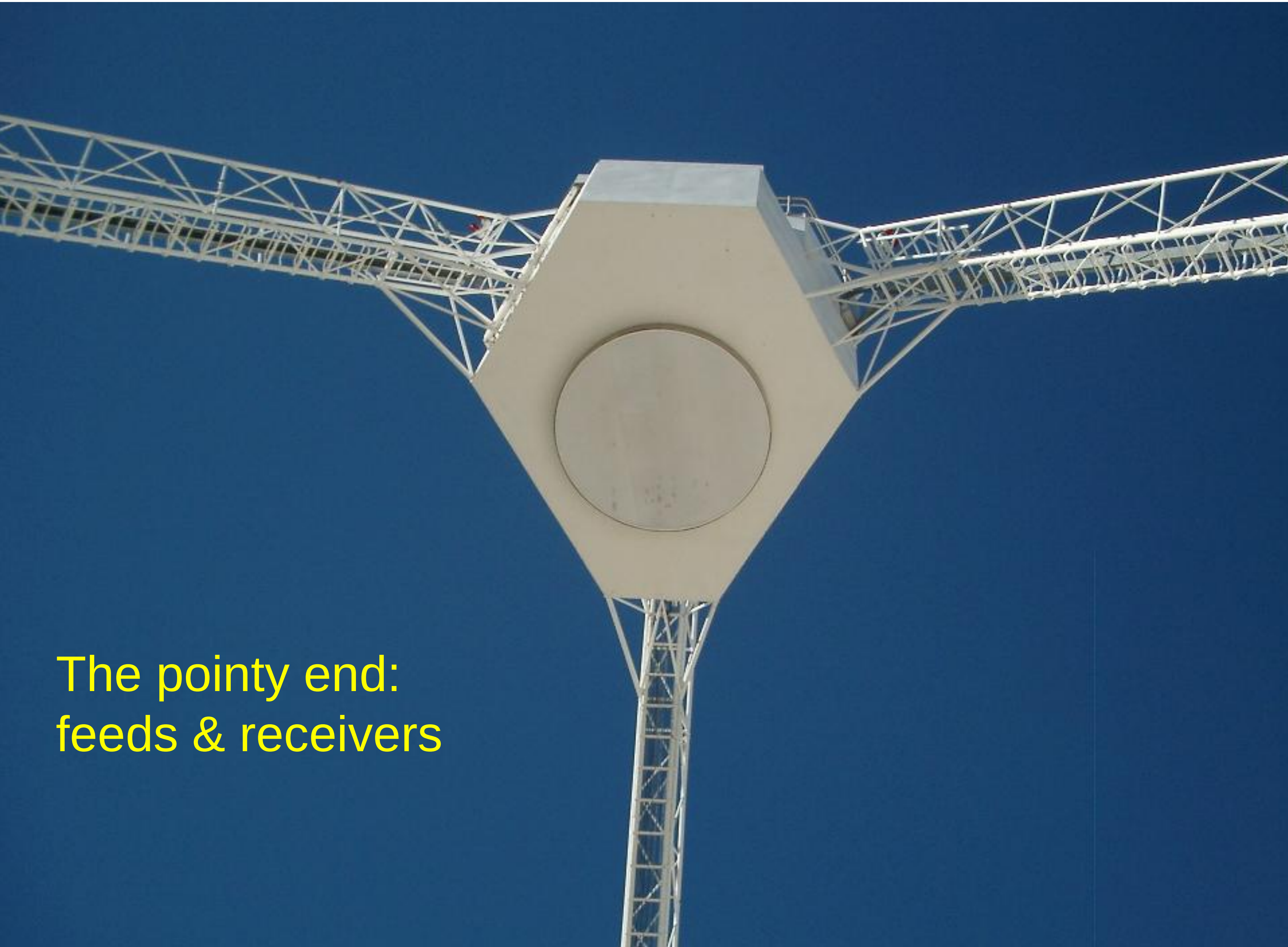
Original steel wire mesh surface

Perforated Al panels to 54m (2003)

New focus cabin (1995)

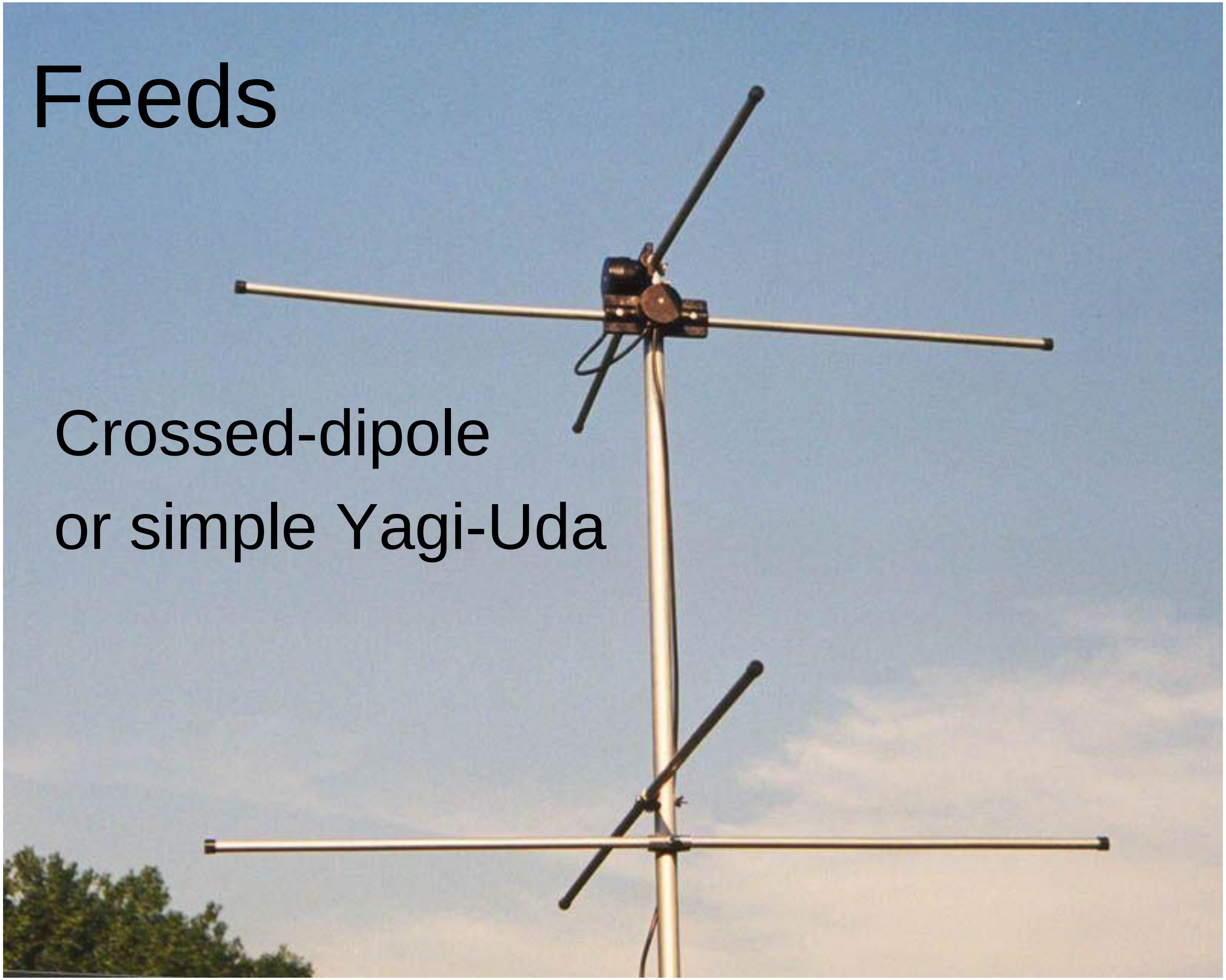
Perforated Al panels to 45m (1984)

Solid Al panels (18m)



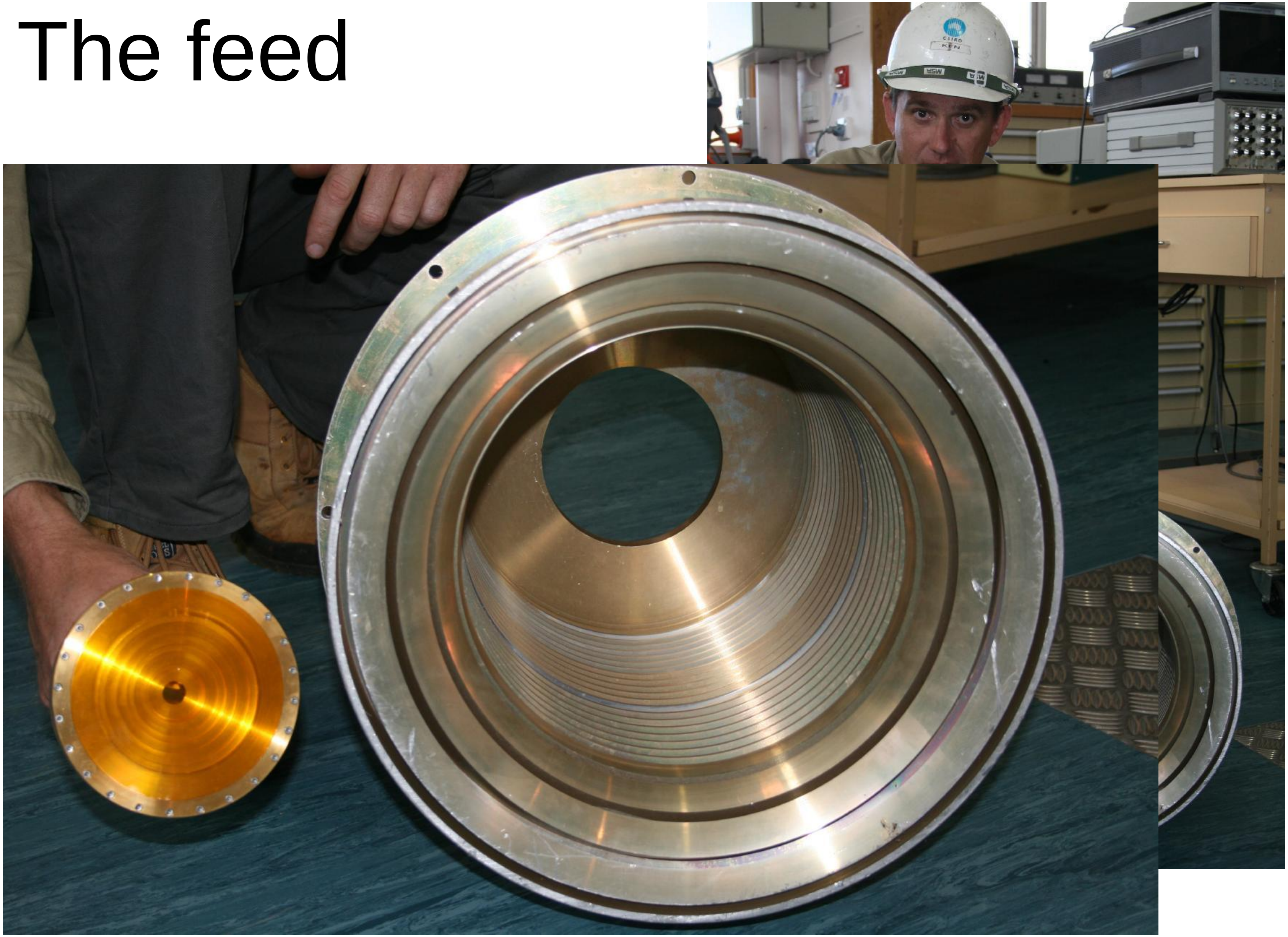
The pointy end:
feeds & receivers

Feeds

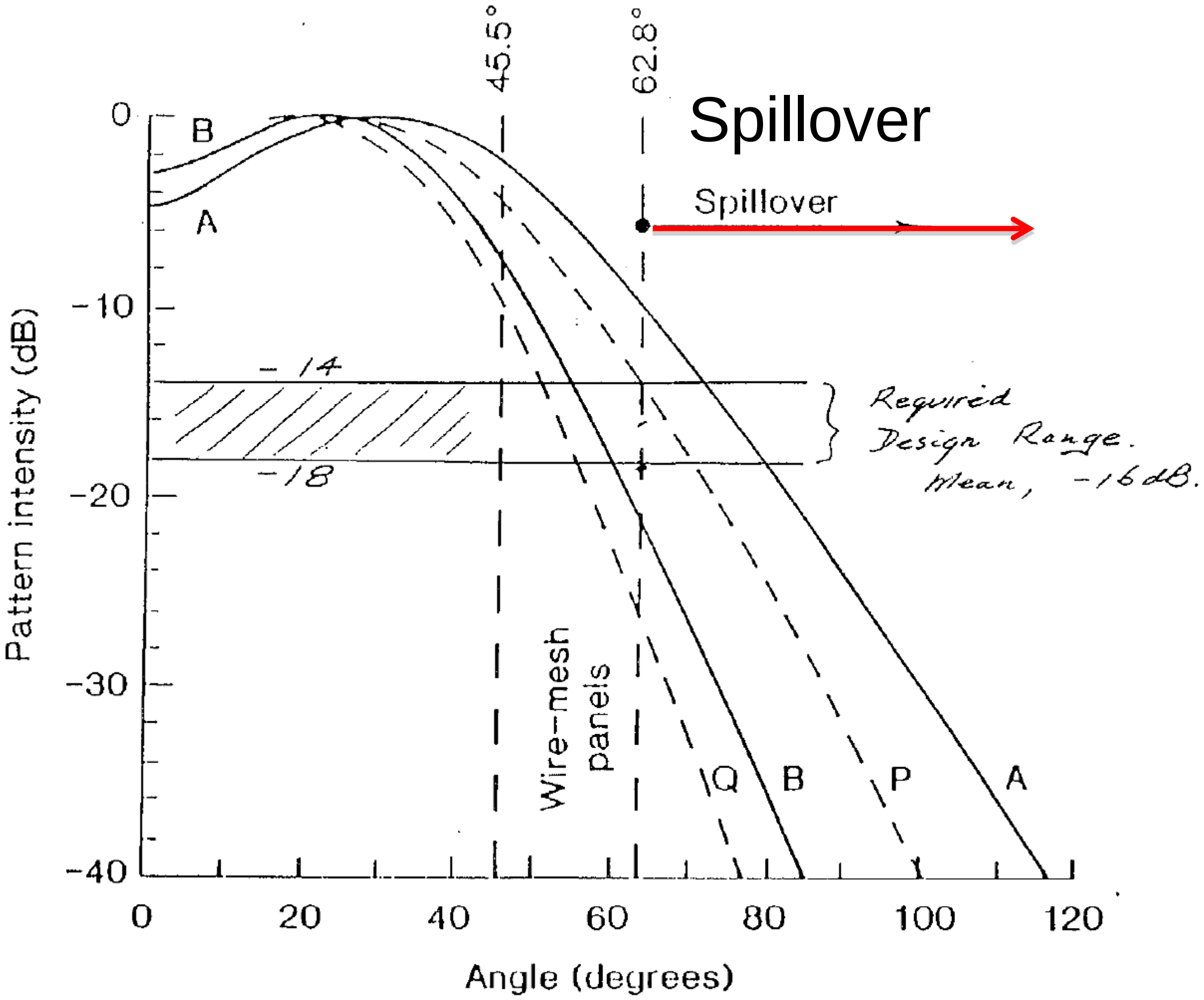


Crossed-dipole
or simple Yagi-Uda

The feed

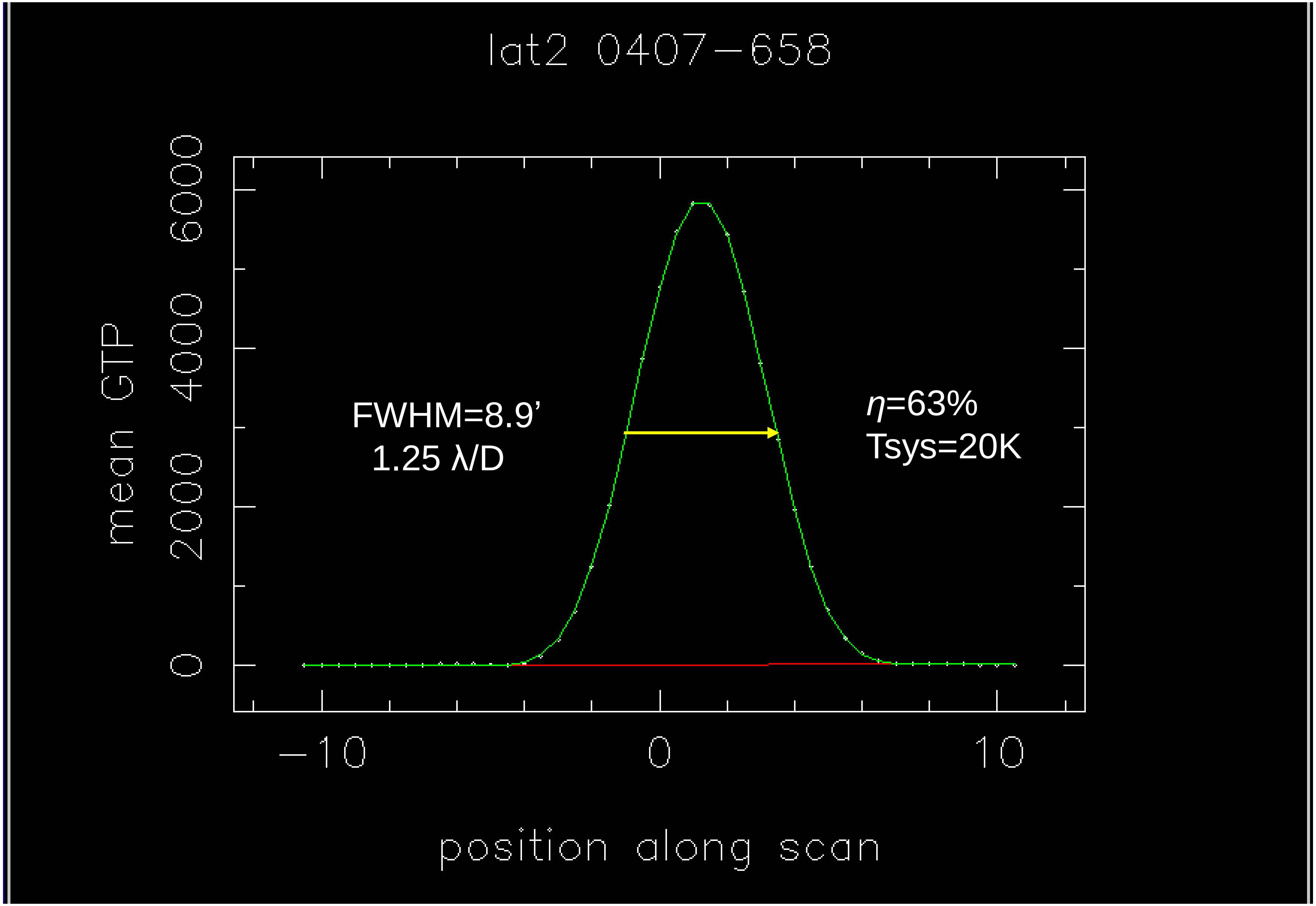


The real world – “Galileo” Feed



Spillover

A real 64-metre beam – at 2.3GHz



FWHM=8.9'
1.25 λ/D

η=63%
Tsys=20K

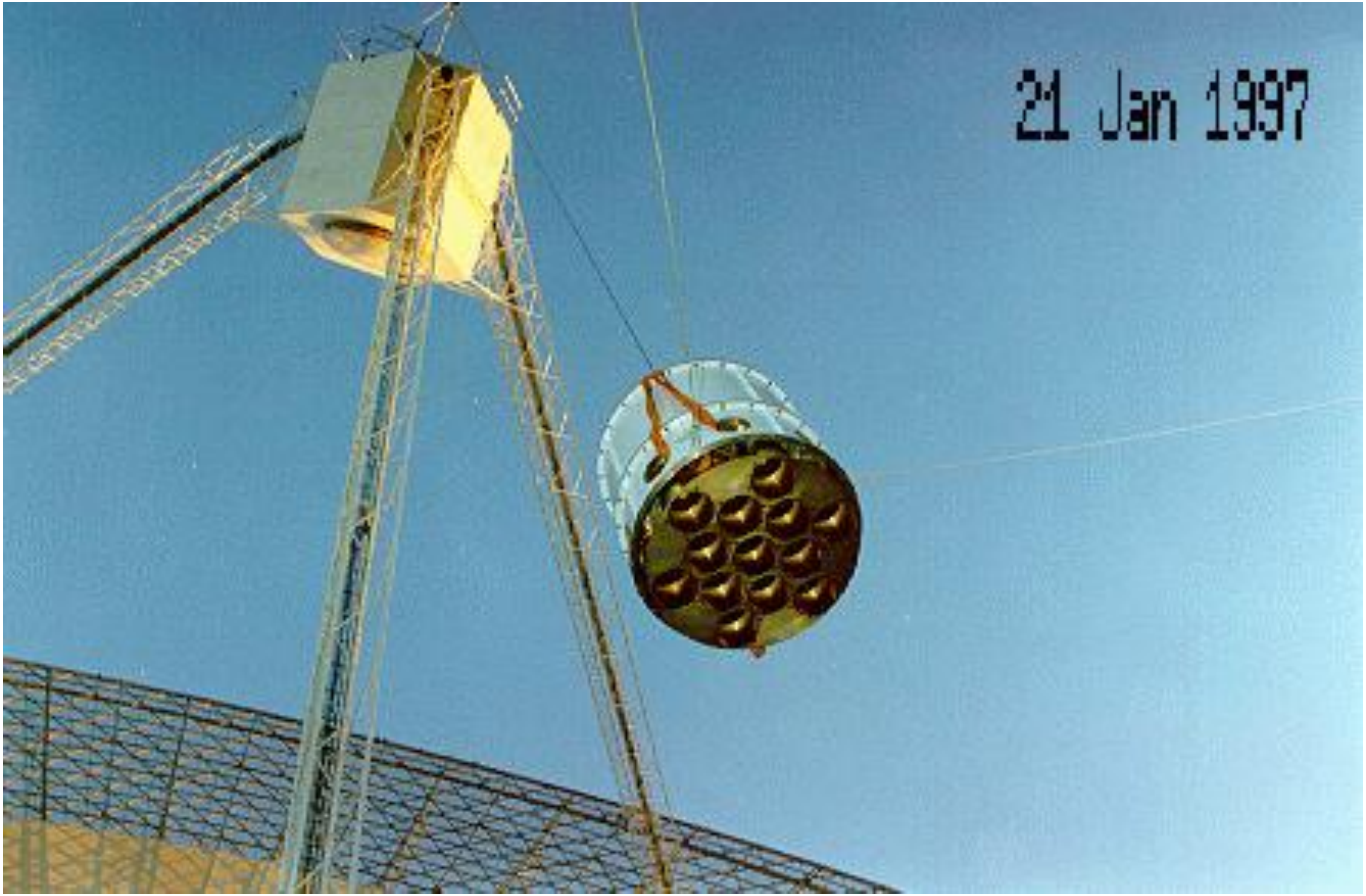
Multibeam Feeds

Why stop at one?

The simple parabolic reflector is best.

Shaped reflectors and Cassegrains can't compete

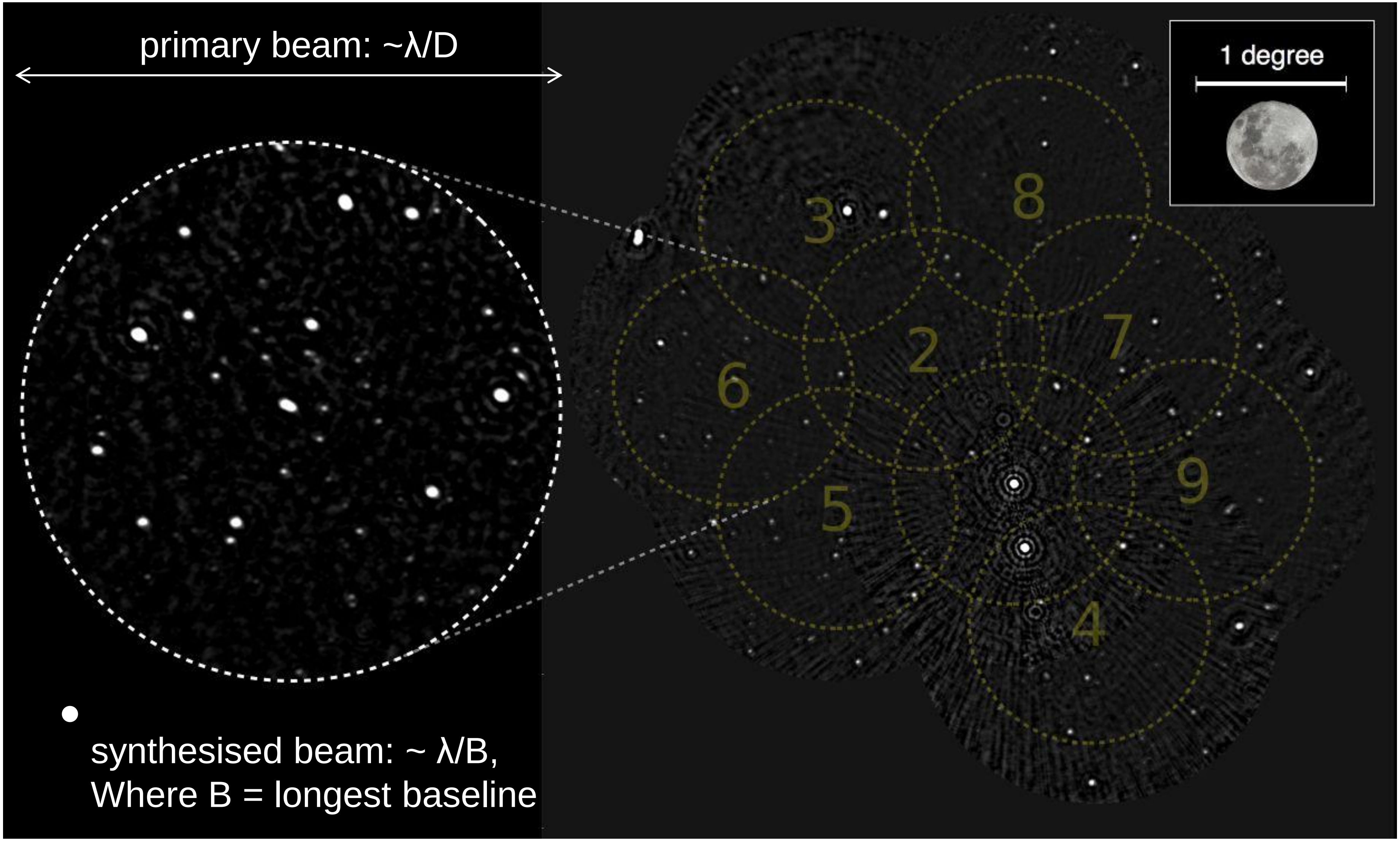
Transforming technology



Phased Array Feed

each pair of neighbouring
dipoles is effectively a pixel

BETA – a PAF interferometer



primary beam: ~λ/D

- synthesised beam: ~ λ/B,
  Where B = longest baseline

Image: Ian Heywood

Mills Cross: phased-array feed

Antenna/feed sensitivity

Aliases for A_{eff} (effective area);

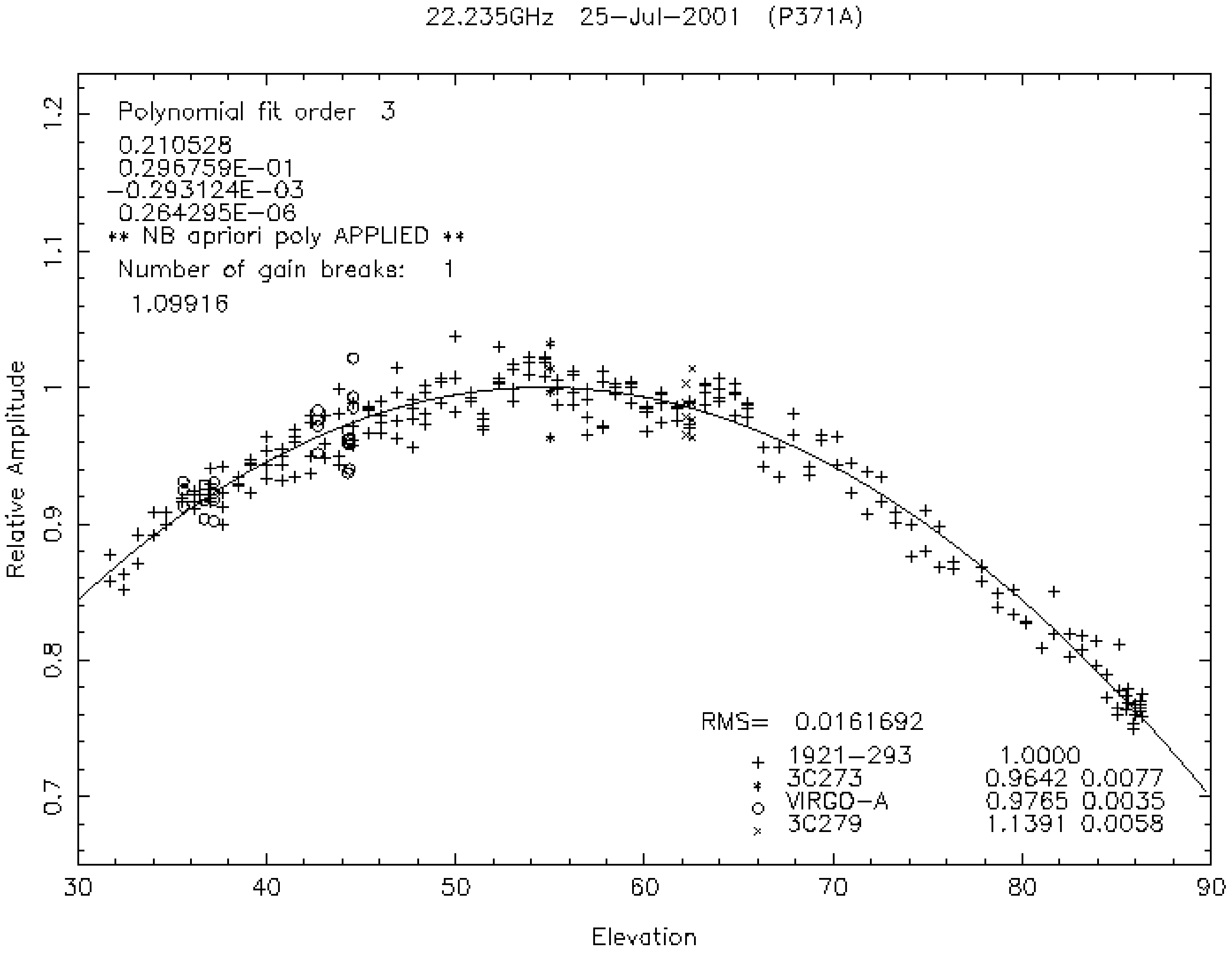
$\lambda^2/4\pi$

Aperture efficiency $\eta = A_{eff}/A_{physical}$

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

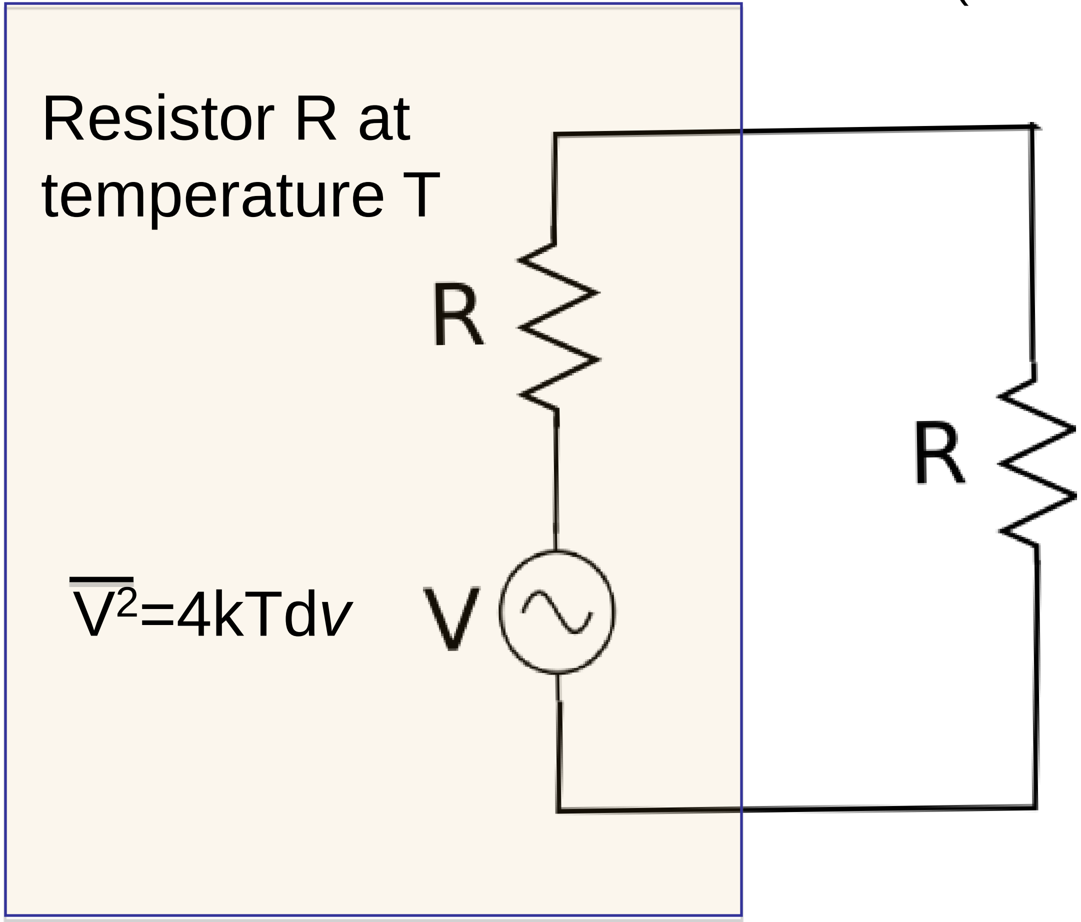
S/T (“Jy per Kelvin”) $:= 2k/A_{eff} . 10^{26}$

Antenna gain (A_{eff}) vs elevation



Nyquist noise theorem

(Thompson-Nyquist Theorem)



Resistor R at temperature T

$\overline{V}^2=4kTd\nu$

white noise power

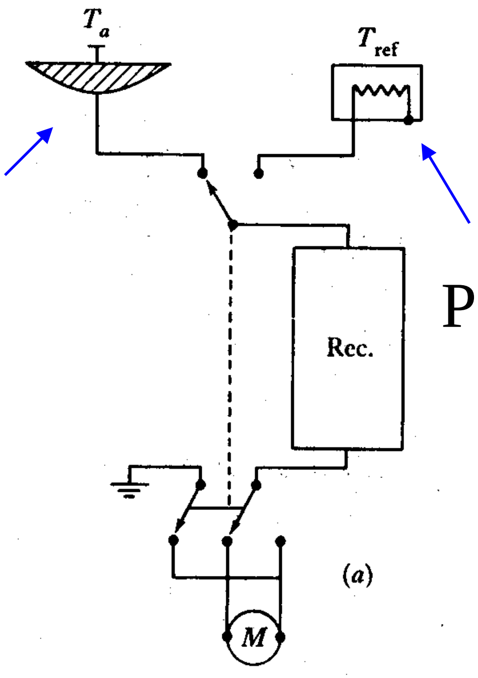
$P = kTd\nu$

Antenna noise temperature: T_A

T_A : temperature of a resistor producing the same power density in the receiver;

$P_i = kT_A dv = kT_{ref} dv \rightarrow \quad T_A := T_{ref}$

The Dicke switch



P_i

$P_c = kT_{ref} dv$

Alternatively for uniform T_B;

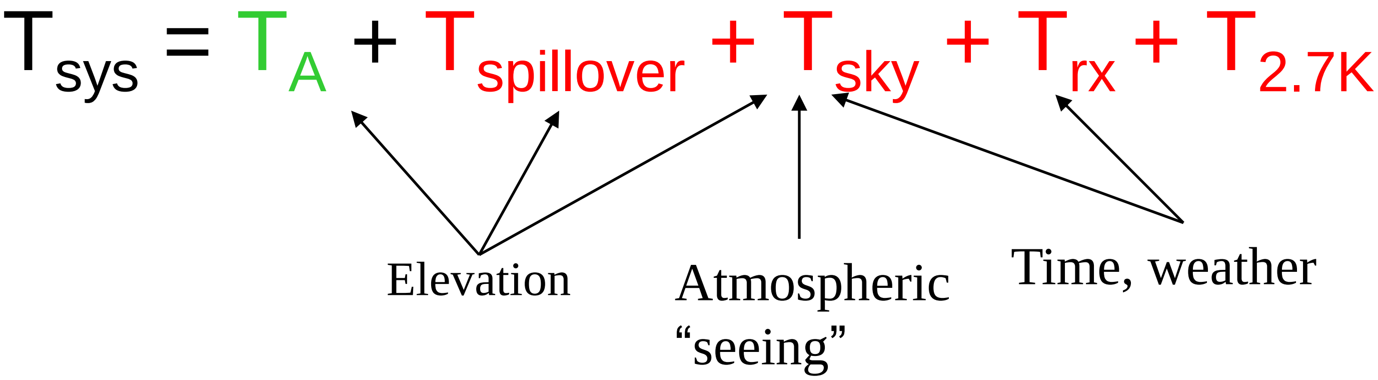
$$P_i(\hat{\mathbf{n}}_0) = \lambda^2 B_i(\hat{\mathbf{n}}_0) = kT_B(\hat{\mathbf{n}}_0)$$

$\rightarrow \quad T_A := T_B$

T_A : temperature of an equivalent uniform black-body radiation giving same power density

The noise equation

T_{sys} = total receiver power expressed as a temperature



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

Elevation

Atmospheric
“seeing”

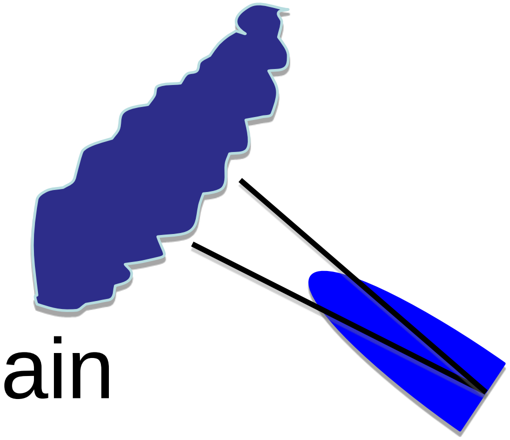
Time, weather

Typically, T_A < Tsys in radio astronomy !

Signal-to-Noise: extended source

Large source, small beam: $\theta_{src} >> \theta_{FWHM}$

Equivalent black-body at T_B



then $T_A = T_B$

independent of antenna size,gain

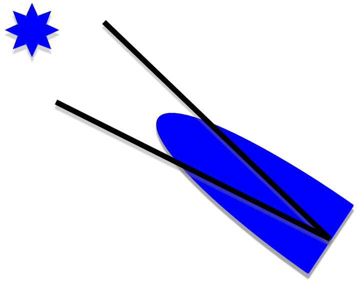
SNR = T_B / T_{sys}

T_{sys} is figure of (de)merit for extended sources

SNR small (unresolved) sources

Point source, unpol. flux density S, $\theta_{src} << \theta_{FWHM}$

$kT_A = ½*S*A_{eff}(0)$



$SNR = T_A / T_{sys} = SA_{eff}(0) / kT_{sys}$

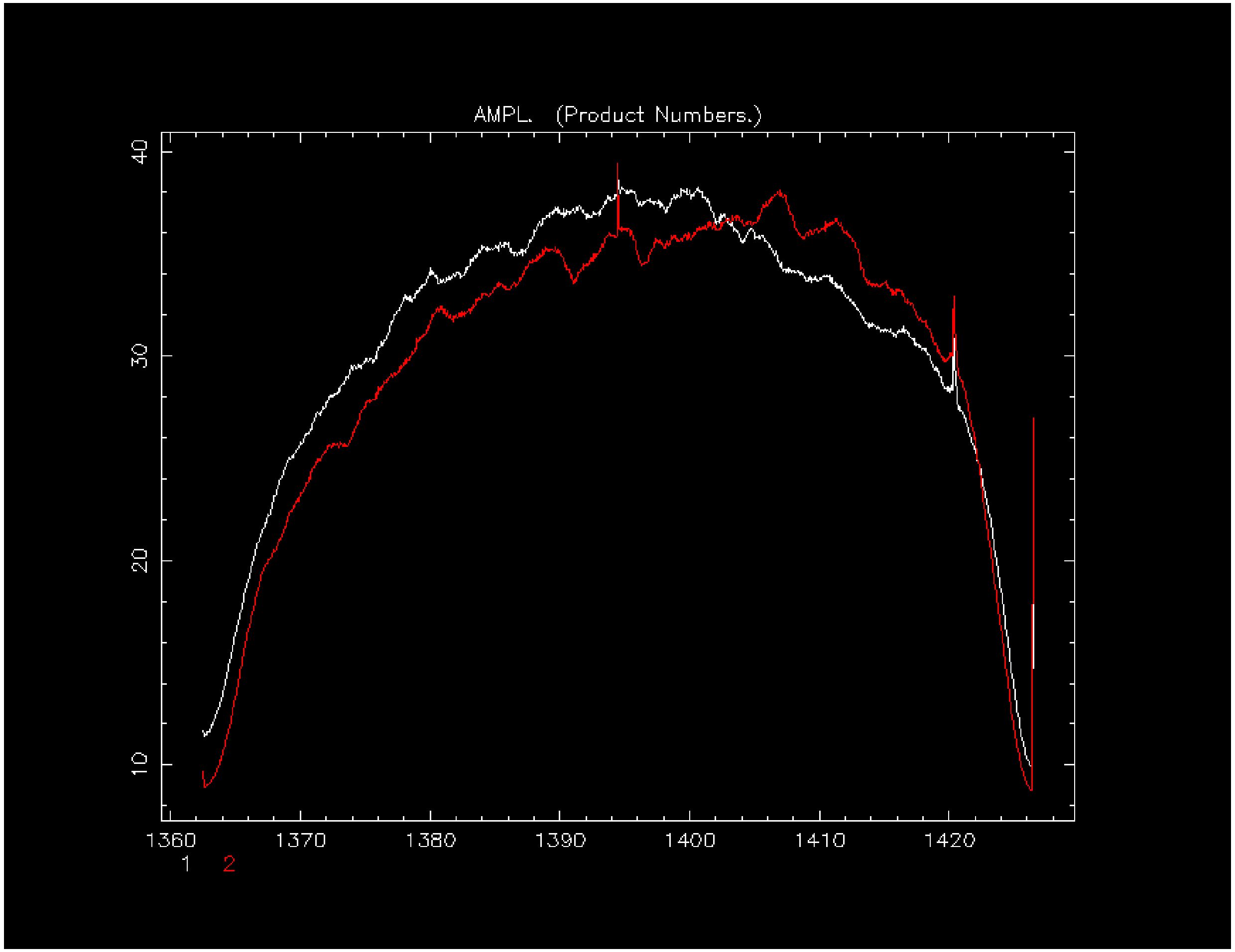
Figure of merit: $A_{eff}(0) / T_{sys}$

SEFD = System equivalent flux density:

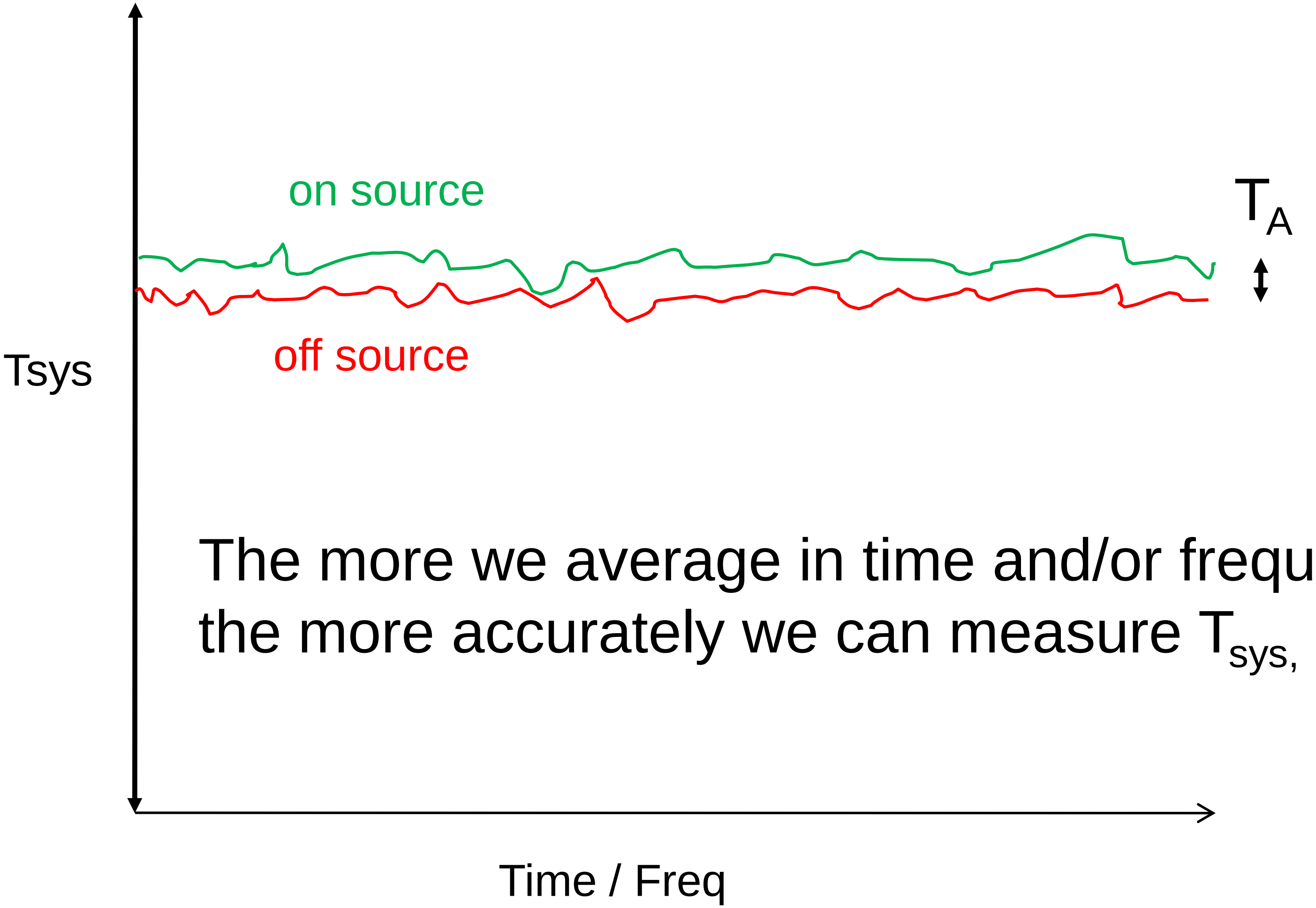
$= 2k*T_{sys}/A_{eff}(0)$

The single-dish millstone

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



Averaging to measure T_A



The more we average in time and/or frequency the more accurately we can measure T_{sys}, T_A

Radiometer Equation

Basic problem: want $T_A = T_{sys}$ (on source) – T_{sys}(off source)

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

where;

t = integration time (seconds)

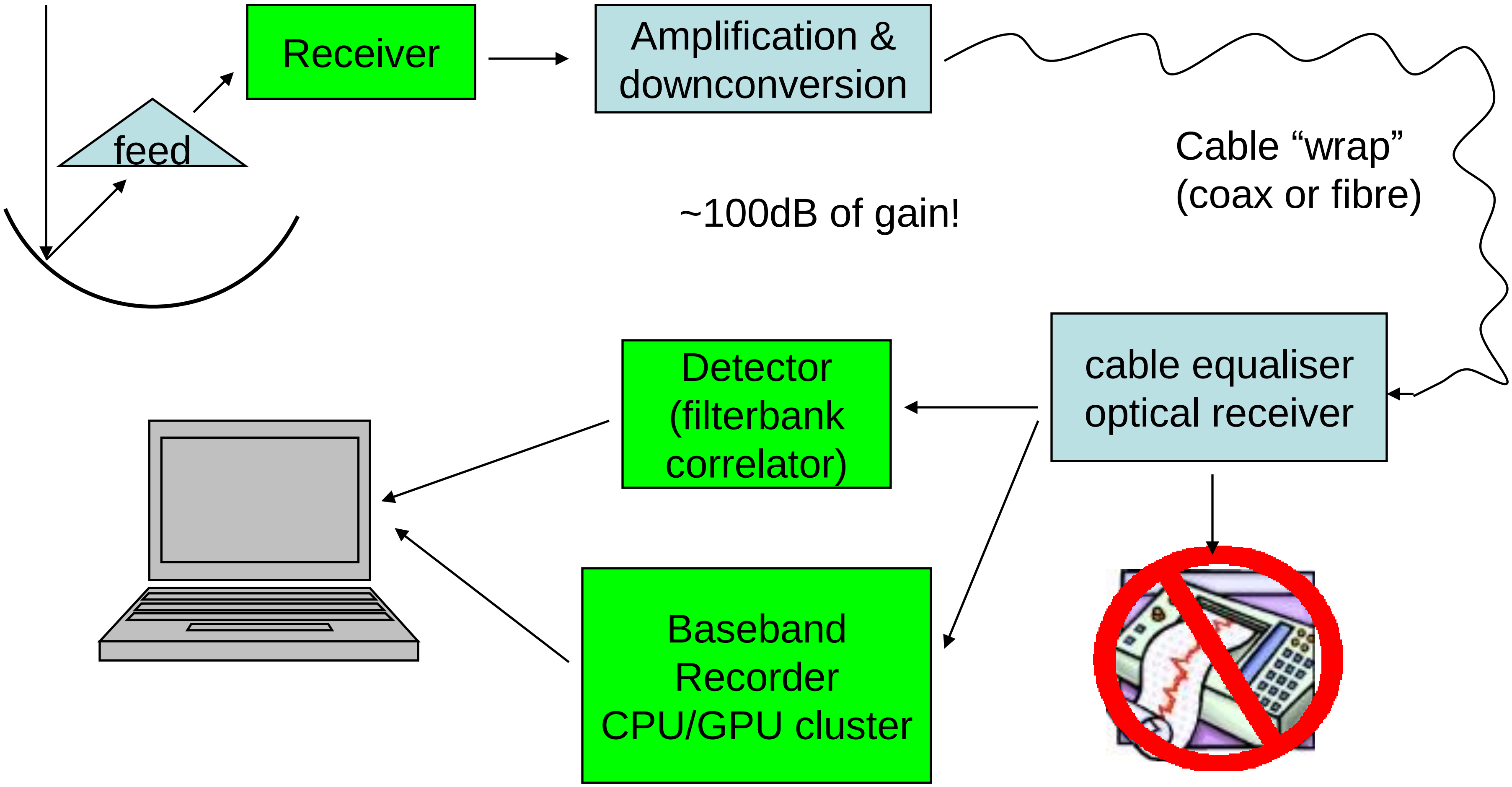
Δf = detector bandwidth (Hz)

α = factor of order unity (system dependent)

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

NB: only valid for “white noise”, not “1/f” noise etc.

Single-dish system – the basics



feed

Receiver

Amplification &
downconversion

Cable “wrap”
(coax or fibre)

~100dB of gain!

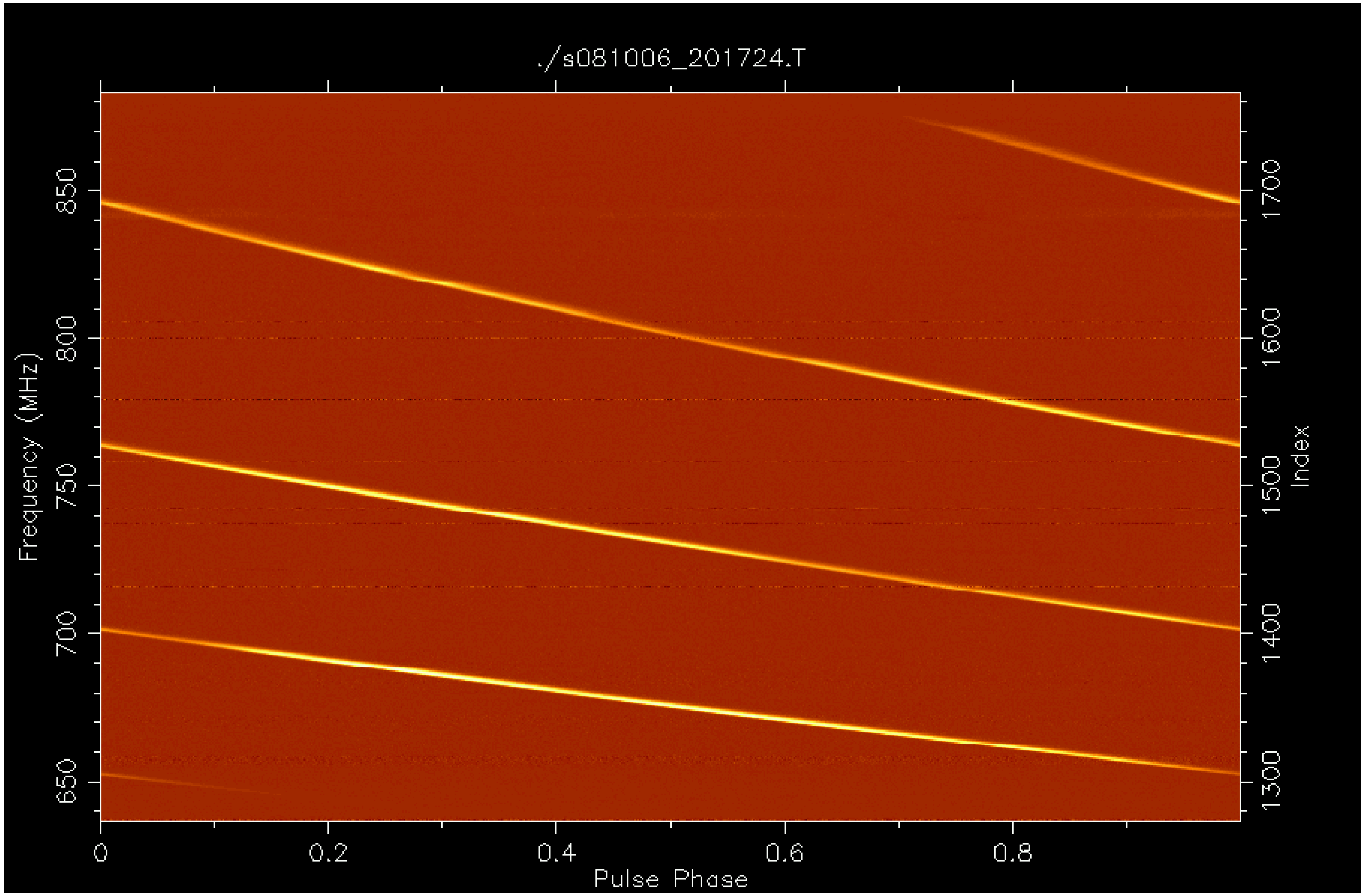
cable equaliser
optical receiver

Detector
(filterbank
correlator)

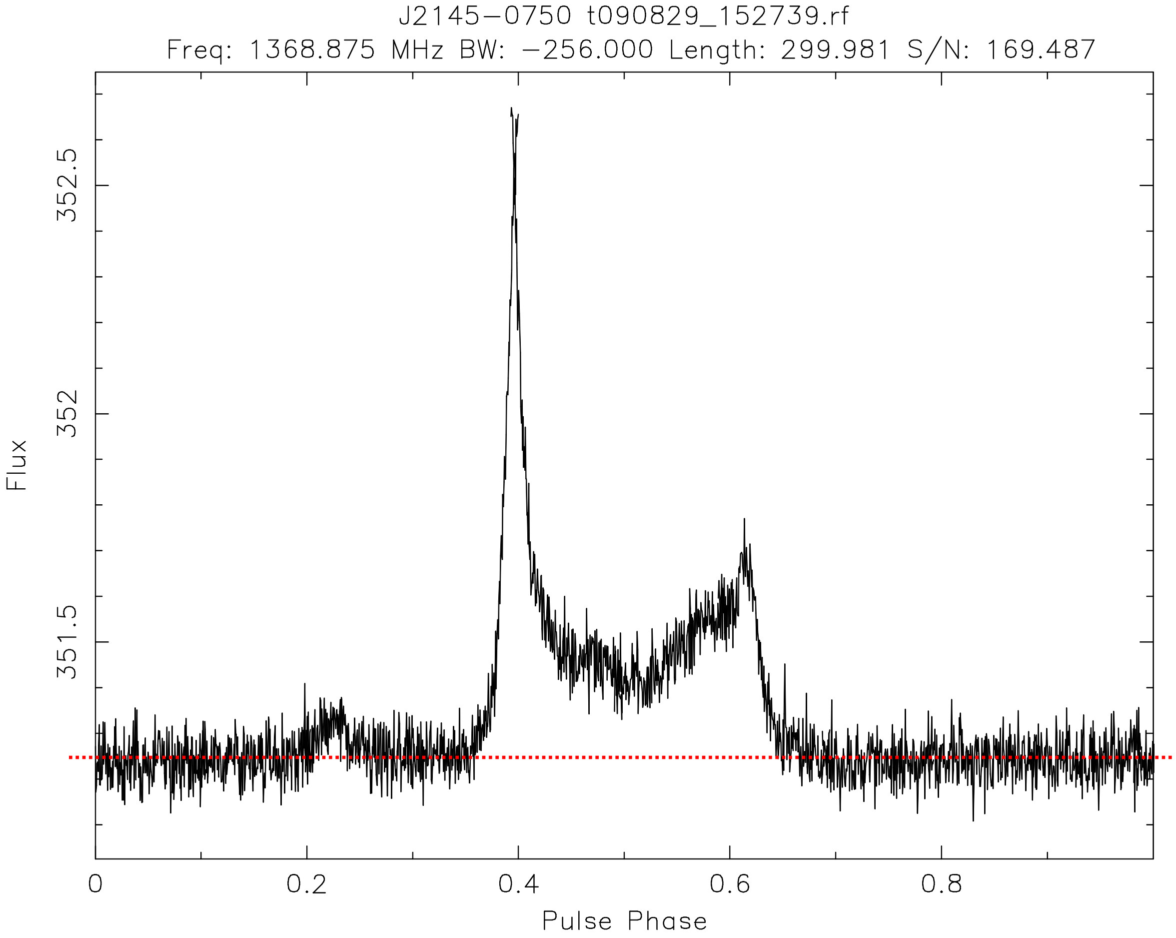
Baseband
Recorder
CPU/GPU cluster

Why we use filterbanks

Frequency dispersion of Vela pulsar, folded observation



Pulsars: average “off pulse” noise;



Out of scope

- Secondary reflector systems
- Surface accuracy deformations
- Holography
- Pointing models
- Fourier theory (aperture ←→ beams)
- Aperture blockage
- Polarization
- ….

Further reading: the classics

“Radiotelescopes” – Christiansen & Hogbom

“Radio Astronomy” – Kraus

“Interferometry and Synthesis in Radio Astronomy” - Thompson Moran & Swenson

This talk terminates here!

Stop!

Talk limits exceeded