

Radio Astronomy Fundamentals

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CSIRO ASTRONOMY AND SPACE SCIENCE – AUSTRALIA TELESCOPE NATIONAL FACILITY

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Radio Astronomy Fundamentals

1. What do we learn from radio astronomy (why do we do it?)

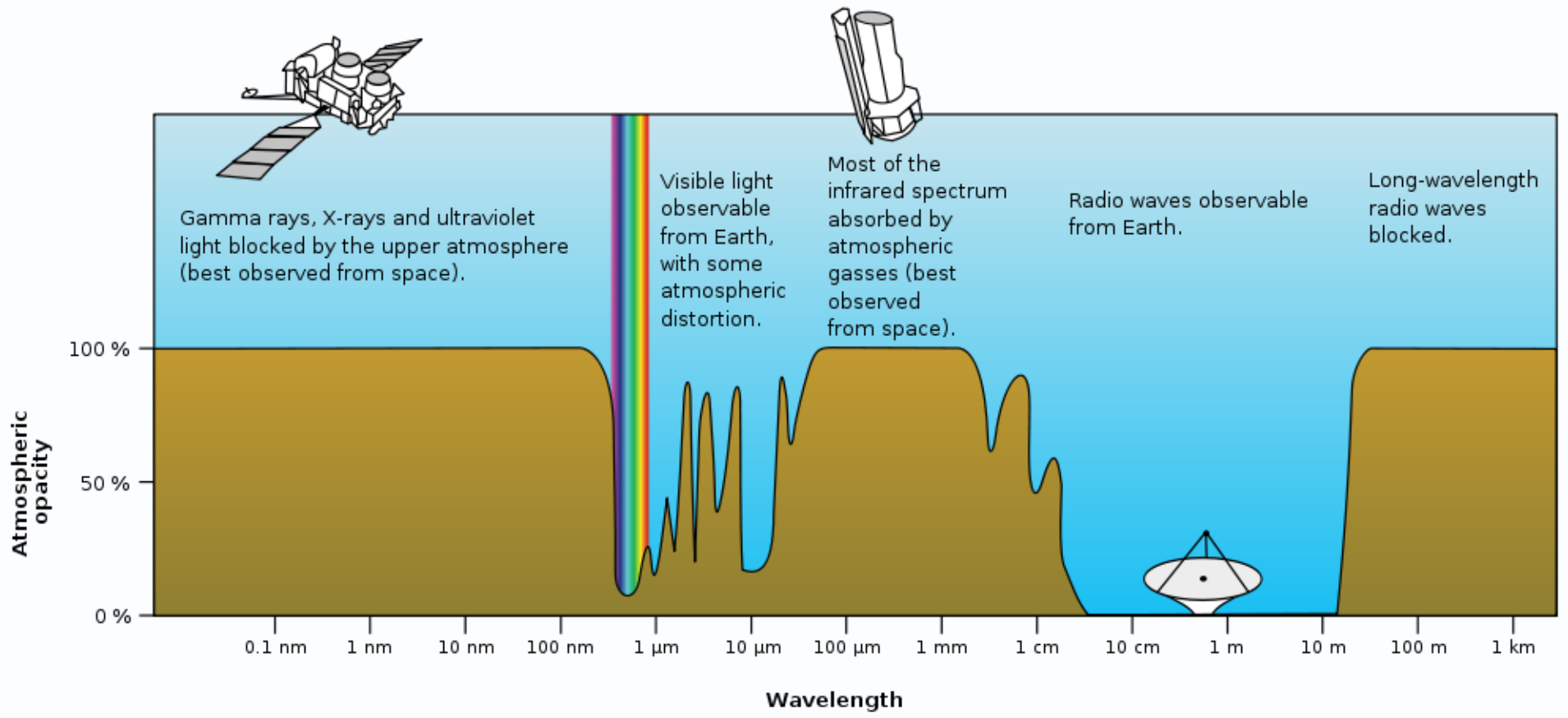
- Atmospheric window
- Radiation mechanisms
- Science examples

2. How do we measure radio waves

- Brightness and flux density
- Antenna temperature
- Antennas, feeds, and single-dish radio telescopes

3. Further key concepts

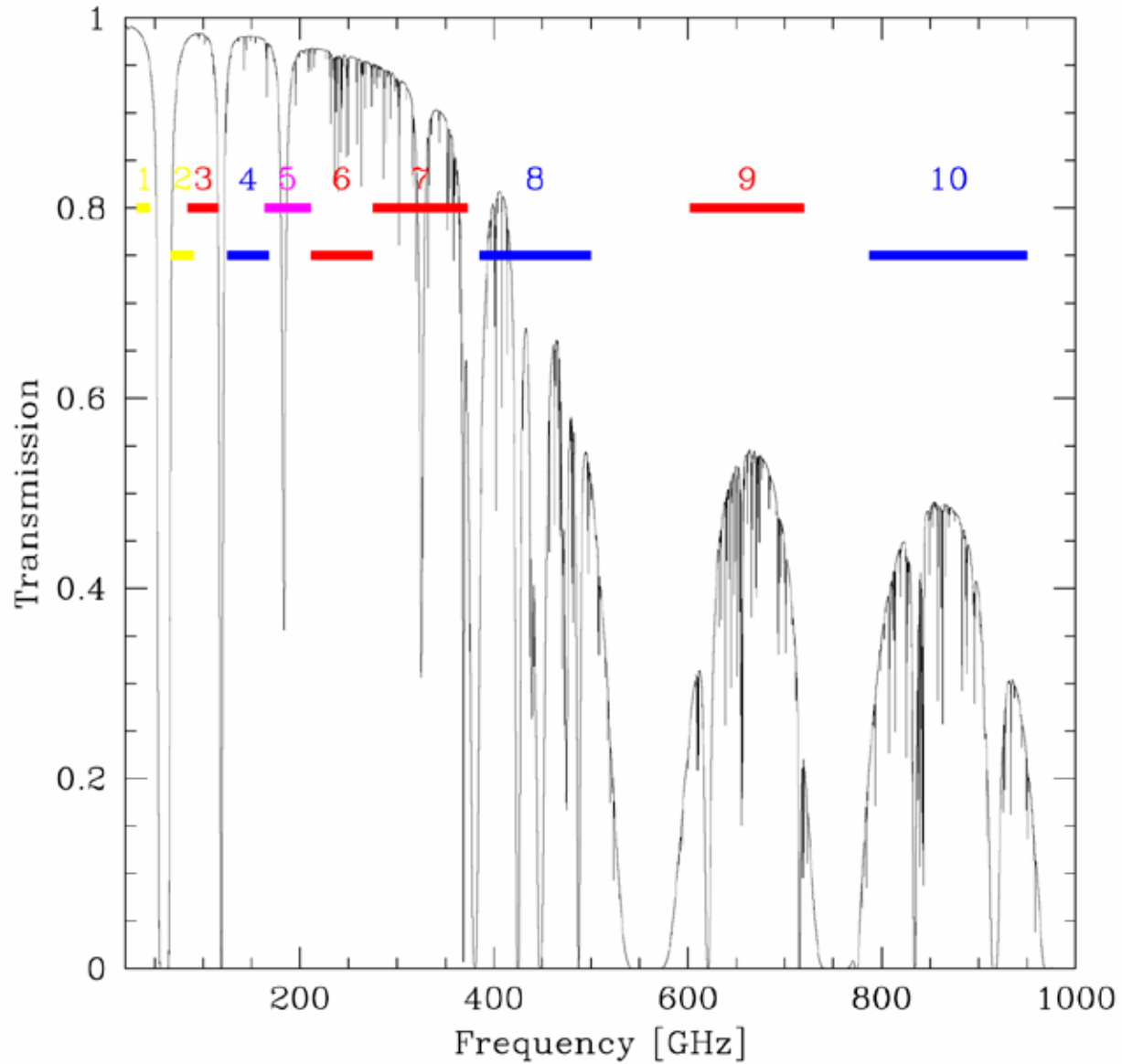
- Principle of reciprocity
- Contributions of receiver noise
- Radio-frequency interference



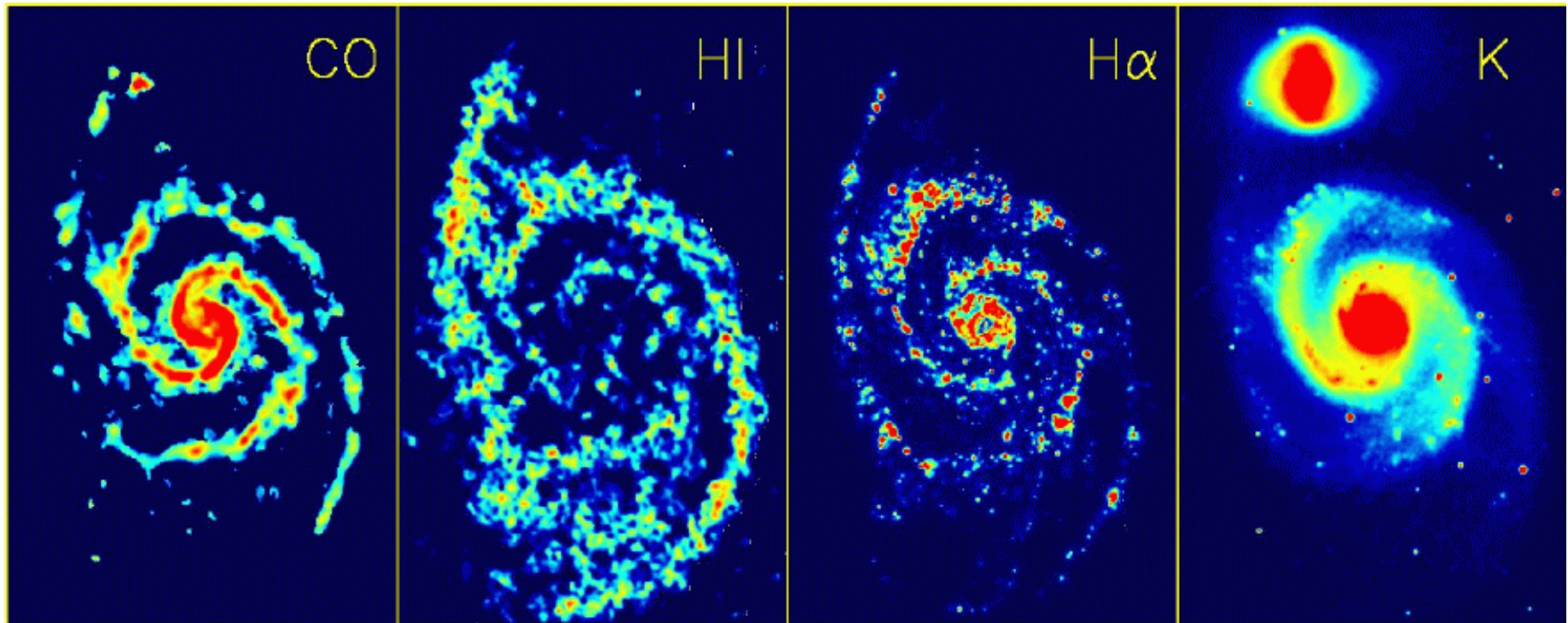
(NASA)

Millimetre windows

Atmospheric transmission at Chajnantor, pwv = 0.5 mm



(ALMA)



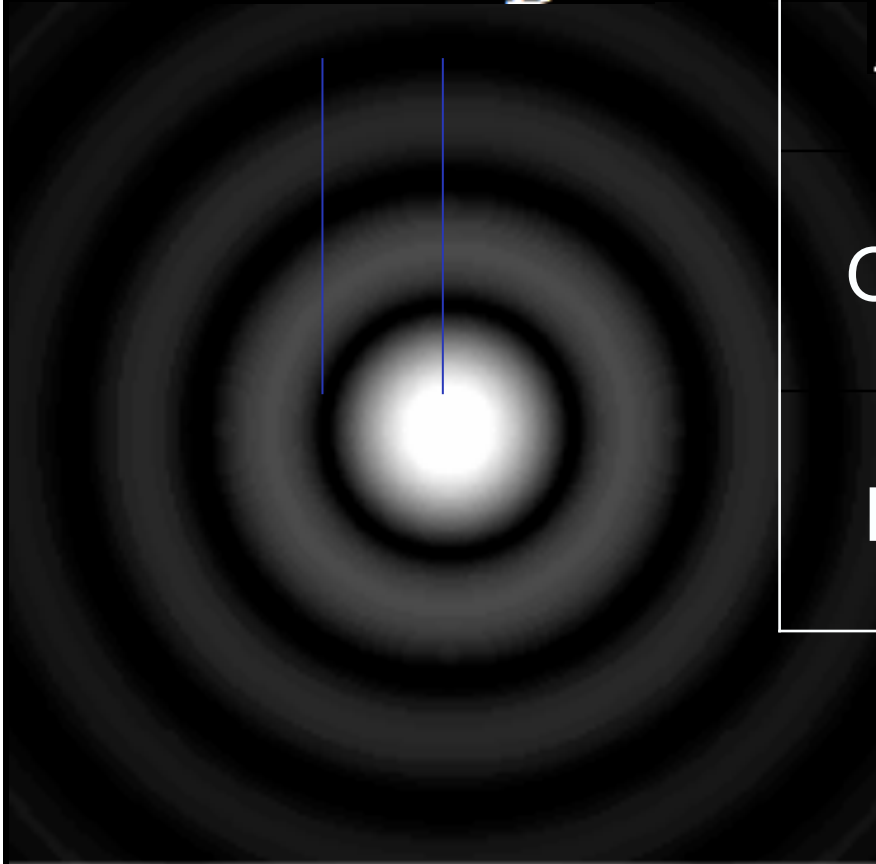
mm
molecules
CARMA

cm
atoms
VLA

opt
stars
Keck

IR
dust
IRAS

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



$\Delta\theta = 1''$	λ	D
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Optical	500 nm	125 mm
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Radio	20 cm	50 km
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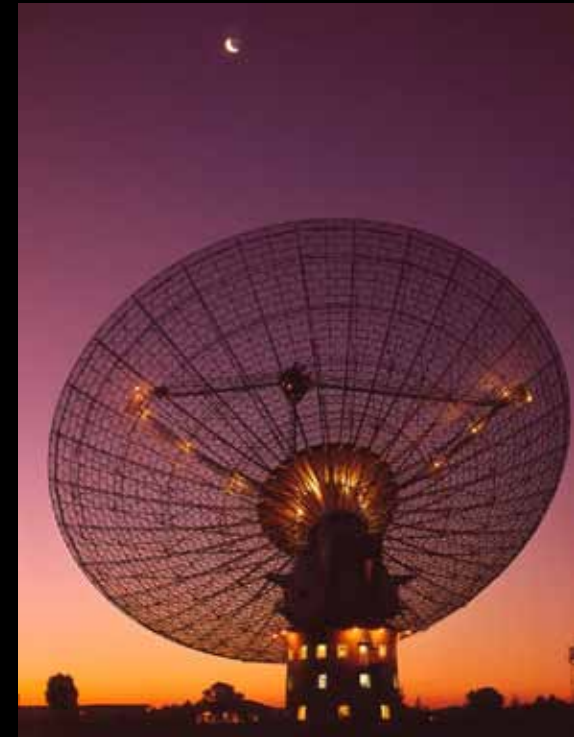
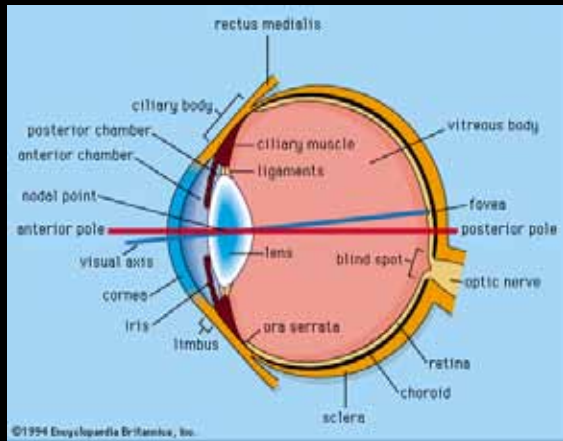
Direct imaging onto a focal plane

$\Delta\theta$

1'

2''

10'

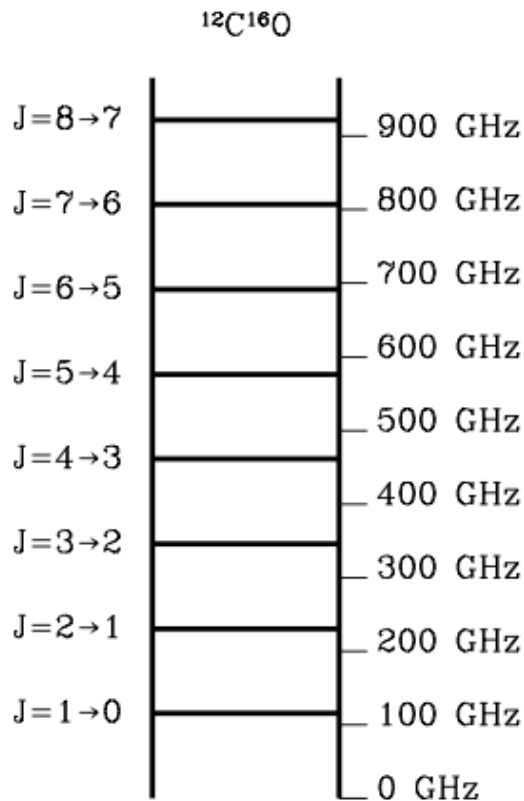


Gargantuan telescopes



Indirect imaging

Molecular Lines



(Rohlfs & Wilson 1996)

Molecule name	Chemical formula ^a	Transition	ν/GHz^b	E_u/K^c	A_{ij}/s^{-1d}
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 ₂ CO	ortho-formaldehyde	$J_{K_a K_c} = 1_{10} - 1_{11}$	4.829660	14	3.6×10^{-9}
CH ₃ OH	methanol*	$J_K = 5_1 - 6_0 A^+$	6.668518	49	6.5×10^{-10}
HC ₃ N	cyanoacetylene	$J = 1 - 0, F = 2 - 1$	9.009833	0.4	3.8×10^{-8}
CH ₃ OH	methanol**	$J_K = 2_0 - 3_{-1} E$	12.178593	12	8.2×10^{-9}
H ₂ CO	ortho-formaldehyde	$J_{K_a K_c} = 2_{11} - 2_{12}$	14.488490	22	3.2×10^{-8}
C ₃ H ₂	ortho-cyclopropenylidene	$J_{K_a K_c} = 1_{10} - 1_{01}$	18.434145	0.9	3.9×10^{-7}
H ₂ O	ortho-water*	$J_{K_a K_c} = 6_{16} - 5_{23}$	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 ₂ H ⁺	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	$J_{K_a K_c} = 2_{12} - 1_{11}$	137.449959	22	5.3×10^{-5}
H ₂ CO	ortho-formaldehyde	$J_{K_a K_c} = 2_{12} - 1_{11}$	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}

DUST AND
MOLECULAR GAS CLOUD

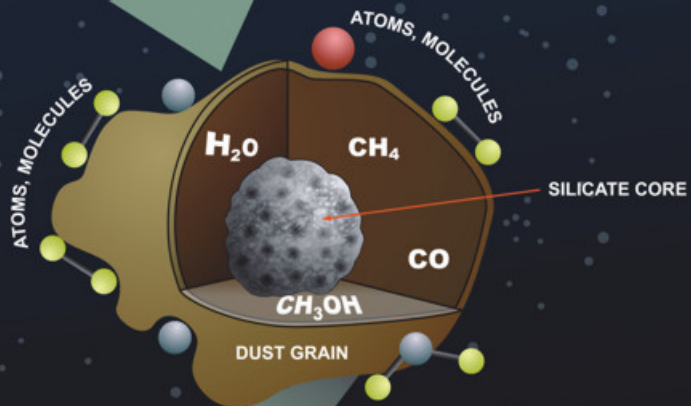
1 Material driven out from an active star-forming region collides with a nearby interstellar cloud, causing a shock front.

SHOCK
WAVE

SHOCKED
MATERIAL

YOUNG
STARS

2 Atoms and small molecules coat the surfaces and are embedded in the interiors of tiny dust grains in interstellar clouds. The energy of a shock powers chemical reactions that produce larger molecules such as glycolaldehyde.

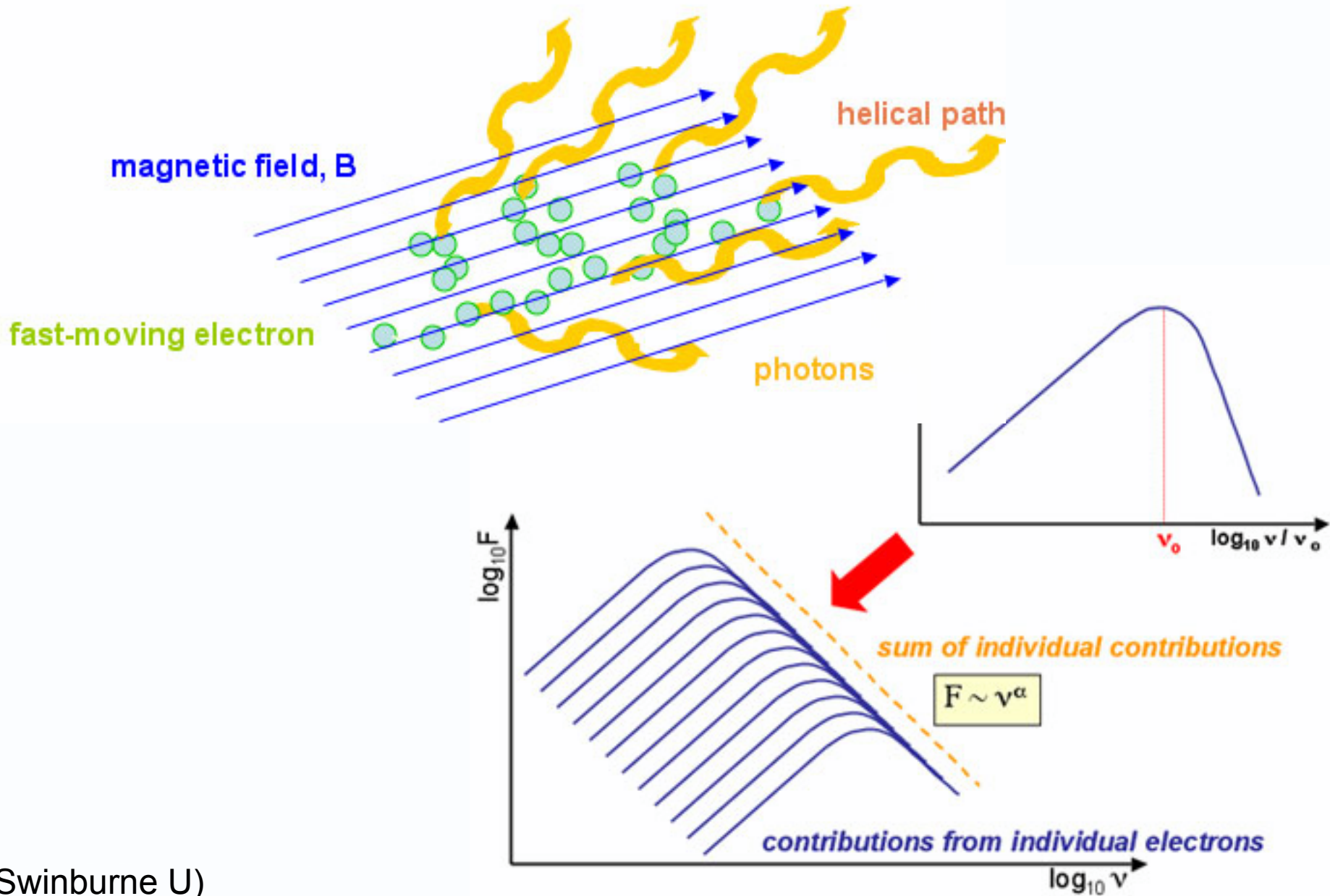


3 The shock also provides energy to free some molecules from the grains and ejects these molecules into the surrounding gas.

1 MICRON



Synchrotron emission

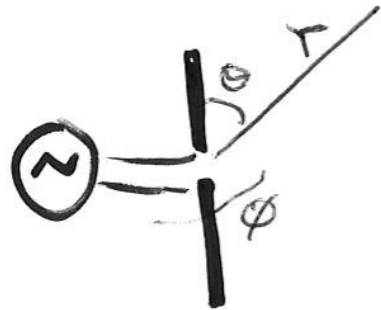


(Swinburne U)

The Radio Universe

<http://www.cv.nrao.edu/course/astr534/Tour.html>





short dipole
($l \ll \lambda$)

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

$$\langle P \rangle = \frac{\pi^2}{3c} \left(\frac{I_0 l}{\lambda} \right)^2$$

(Practical dipoles are usually $\lambda/2$ (or $\lambda/4$ over a ground plane))

Feeds

Crossed-dipole
or simple Yagi

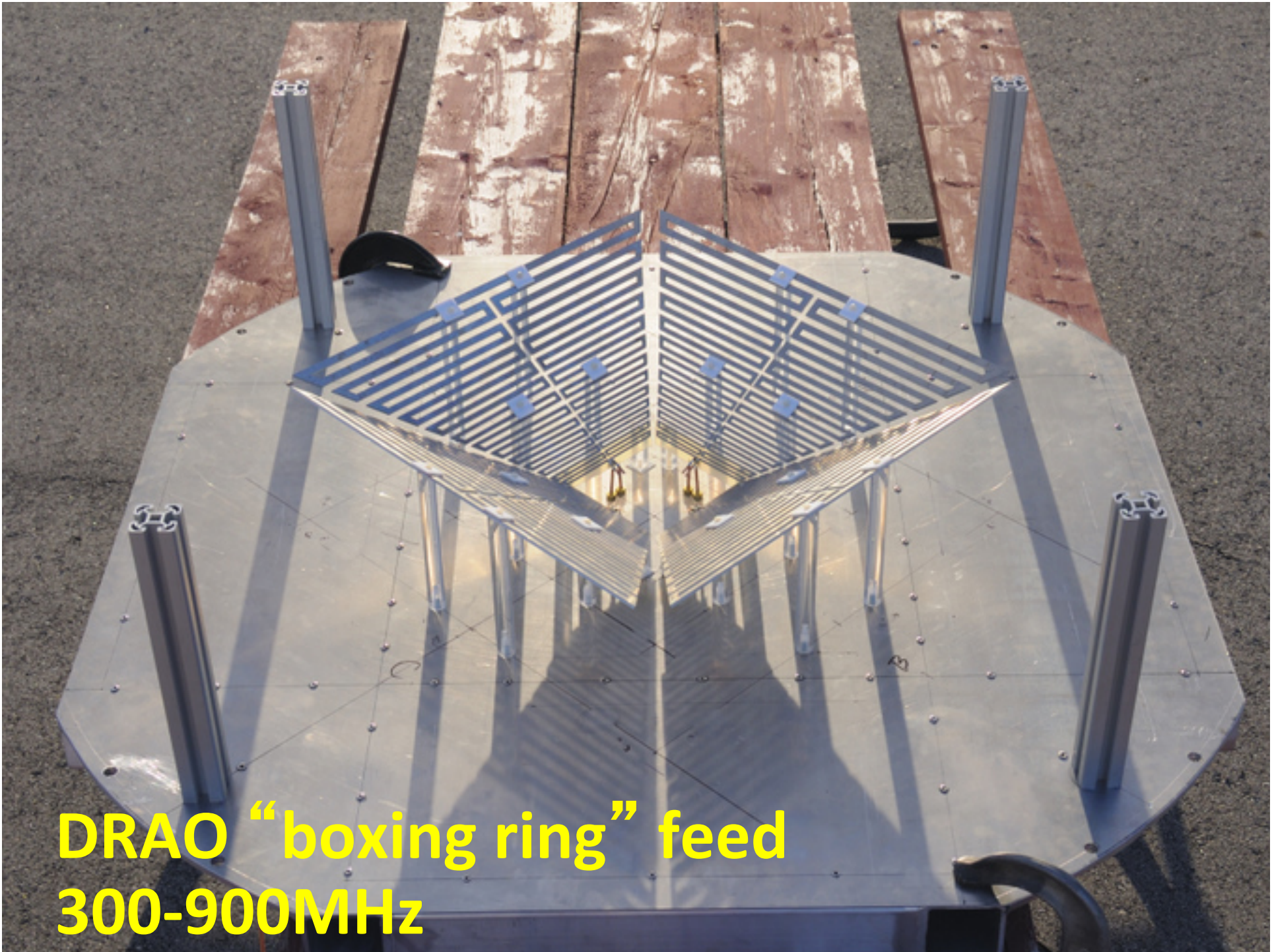


More feeds

Cavity-backed
disk feed

(70cm 420MHz)





DRAO "boxing ring" feed
300-900MHz

Multibeam Feeds

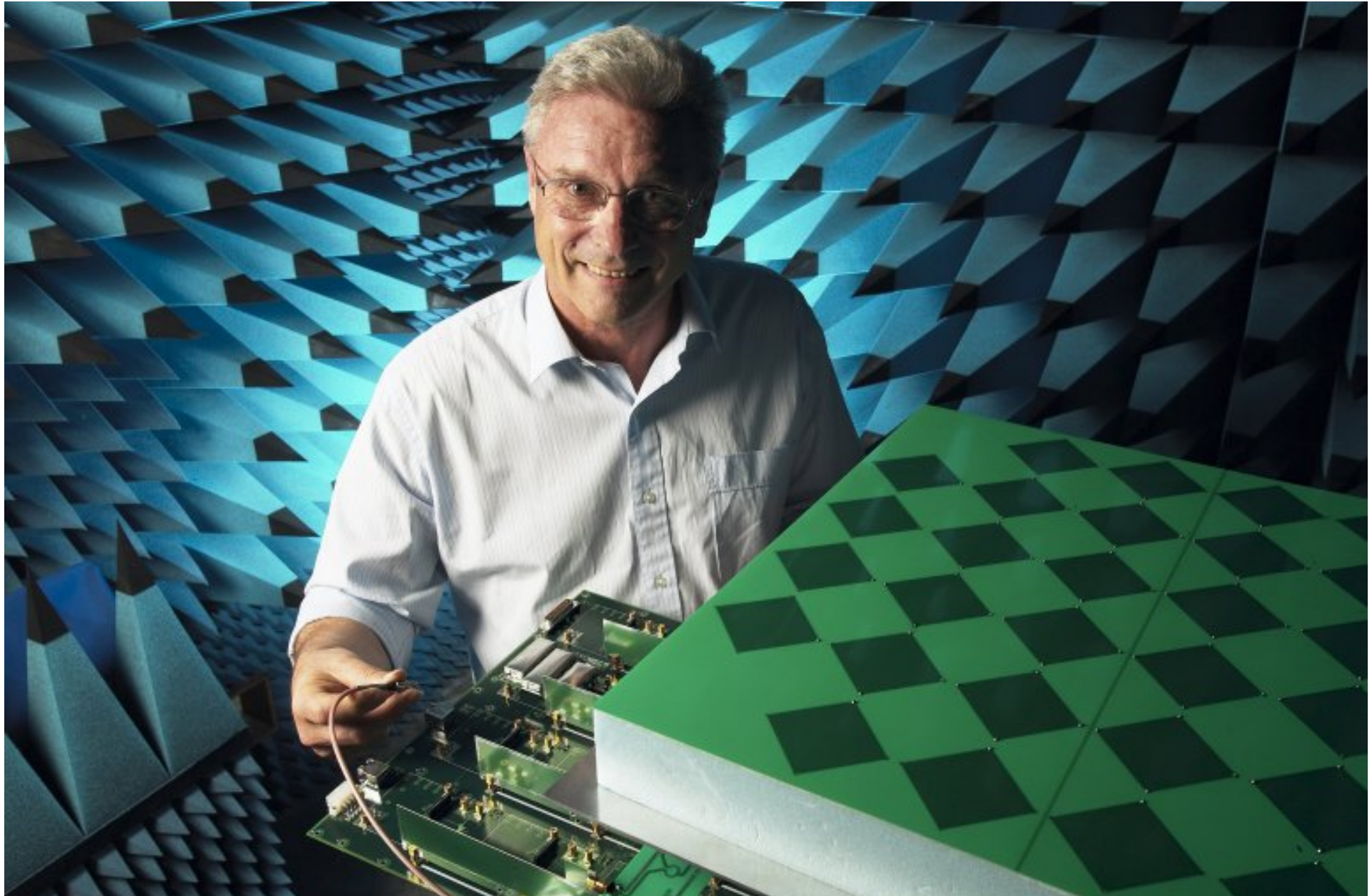
Why stop at one?

The simple parabolic reflector is best.

Shaped reflectors and Cassegrains can't compete



The new frontier: PAF=FPA



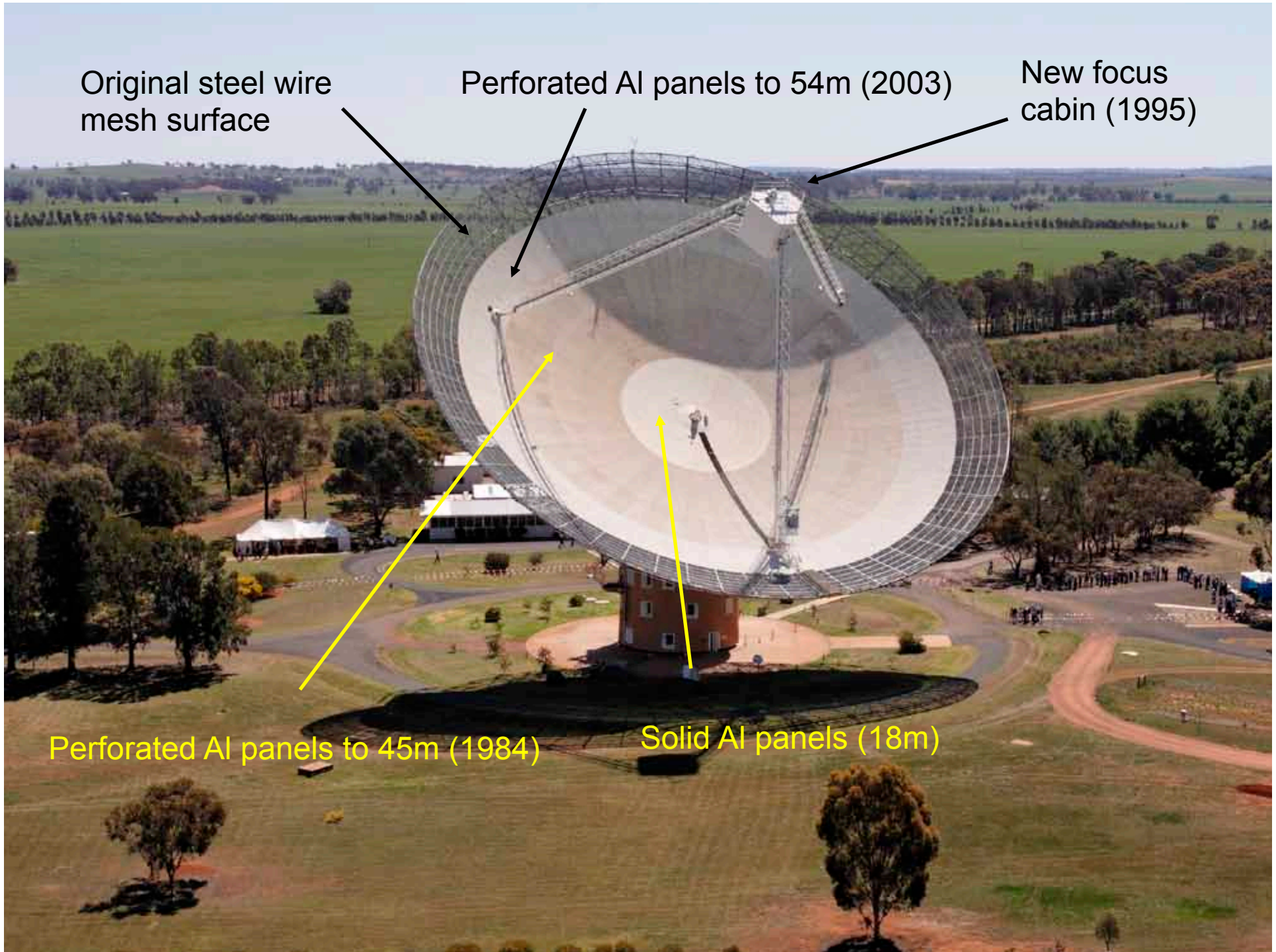
Original steel wire mesh surface

Perforated Al panels to 54m (2003)

New focus cabin (1995)

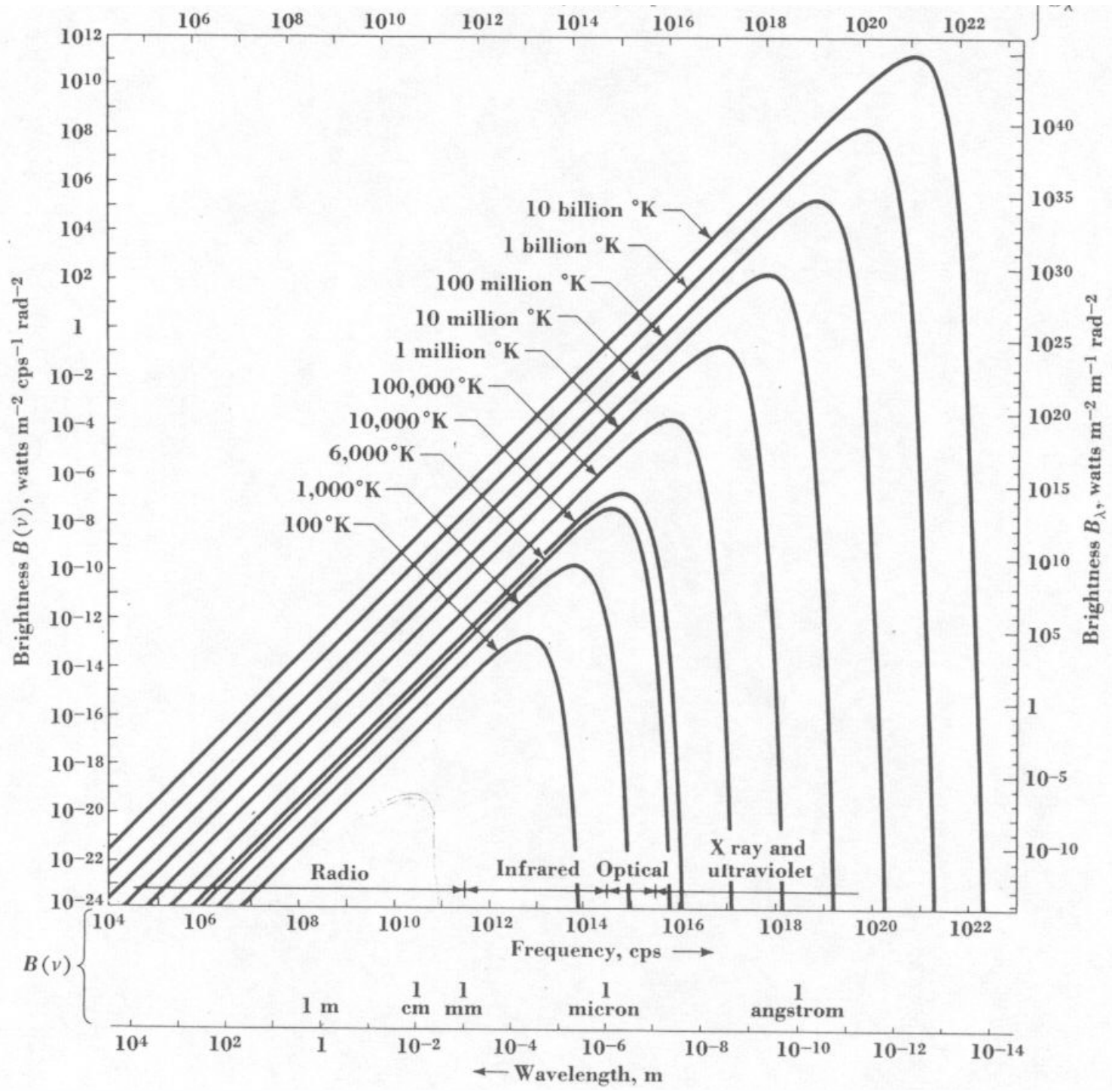
Perforated Al panels to 45m (1984)

Solid Al panels (18m)





The drawback:
cost $\sim D^{2.8}$



- Intensity units: $I(\mathbf{s}, \nu, \text{polarization}, \text{time})$ Watts $\text{m}^{-2}\text{str}^{-1}\text{Hz}^{-1}$
- Brightness Temperature
for black body radiation

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

T is the **brightness temperature** of an equivalent black body radiator.

$$h/k = 4.8 \text{ [GHz/100] K}$$

- Rayleigh Jeans brightness temperature
For $h\nu/kT \ll 1$,

$$I = 2kT/\lambda^2 [1 - h\nu/2kT + \dots]$$

Rayleigh Jeans brightness temperature, $I = 2kT_b/\lambda^2$

- Flux density

$$S = \int I \delta\Omega$$

1 Jansky = 10^{-26} Watts $\text{m}^{-2}\text{Hz}^{-1}$

e.g. Planet with uniform brightness temperature T ,

$$S = 2kT/\lambda^2 \Delta\Omega$$

where $\Delta\Omega$ is the solid angle subtended by the planet.

- Brightness units: Kelvin, Jy/pixel, Jy/beam

Main Beam and Sidelobes

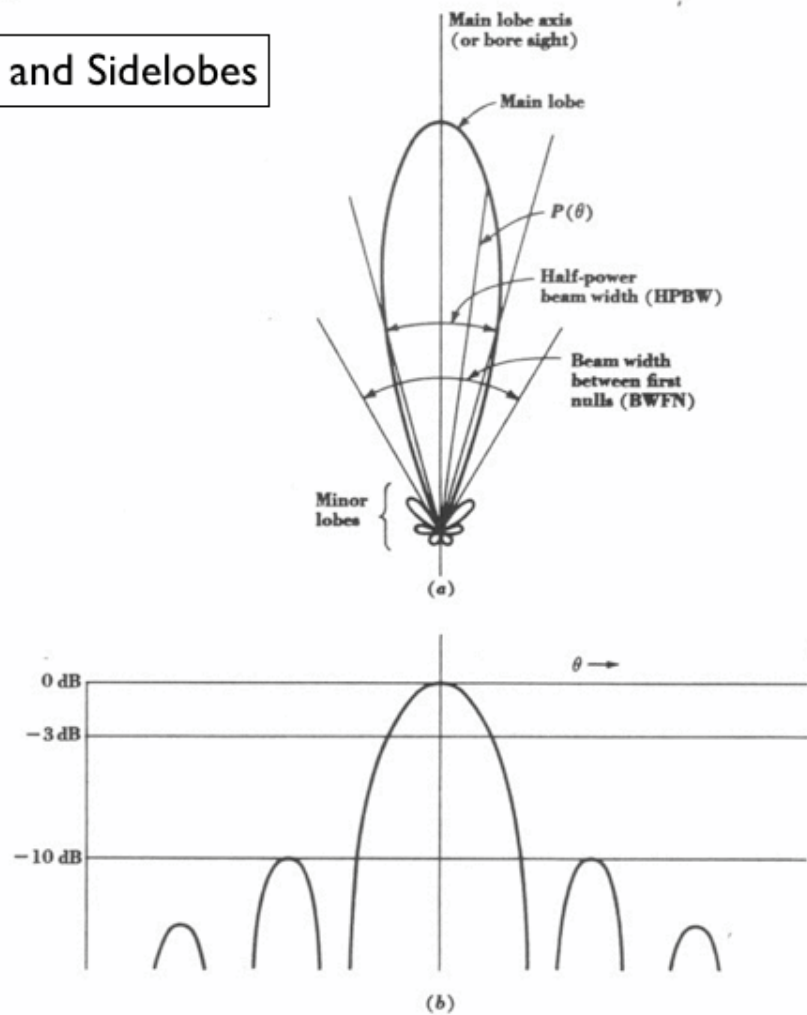


Fig. 6-1. (a) Antenna pattern in polar coordinates and linear power scale; (b) antenna pattern in rectangular coordinates and decibel power scale.

(from Kraus 1966)

$$\eta_{mb} = \frac{\Omega_{mb}}{\Omega_a}$$

Main Beam Efficiency

$$\Omega_{MB} \equiv \int_{MB} P_n(\theta, \phi) d\Omega$$

Geometric Area

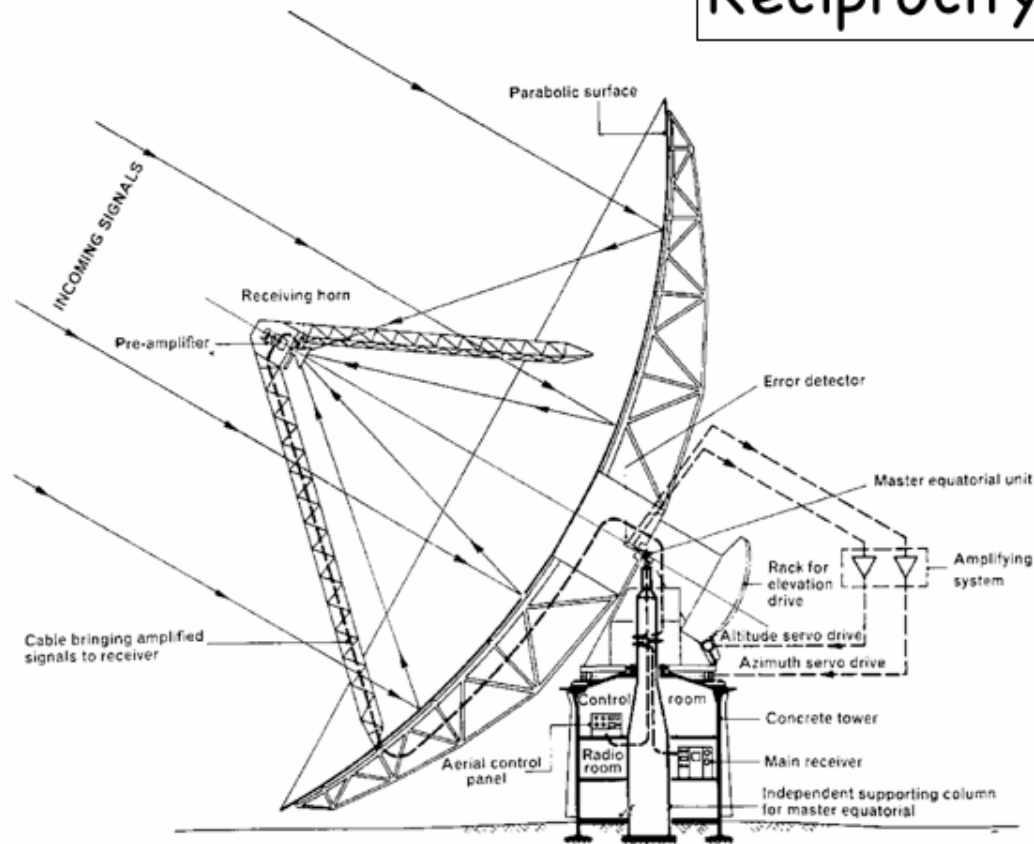
$$A_g = \pi r^2 \text{ (m}^2\text{)}$$

Effective Area

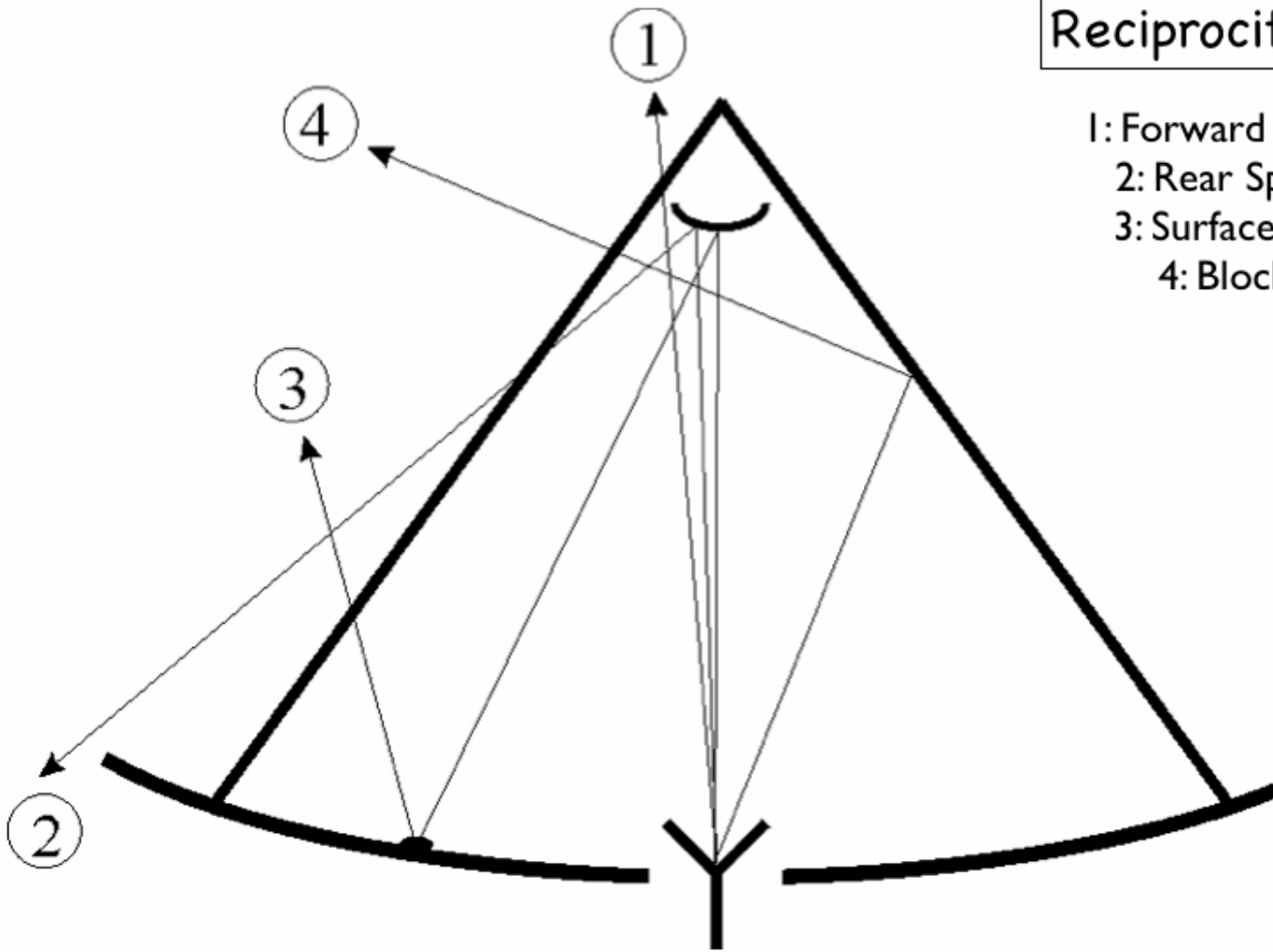
$$A_e = \eta_a A_g \text{ (m}^2\text{)}$$

$$\eta_a < 1.0$$

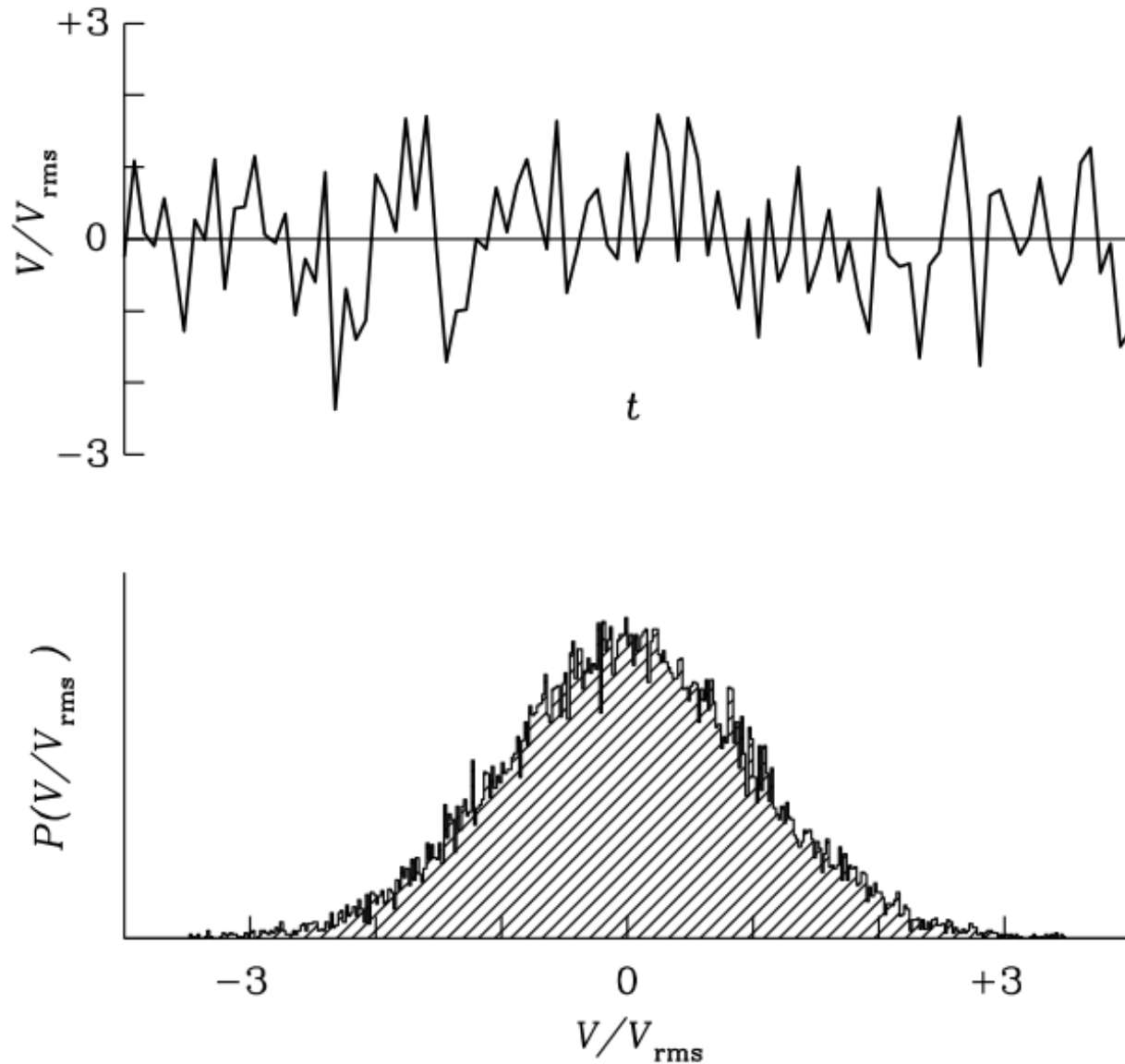
Reciprocity: $f(t) = f(-t)$



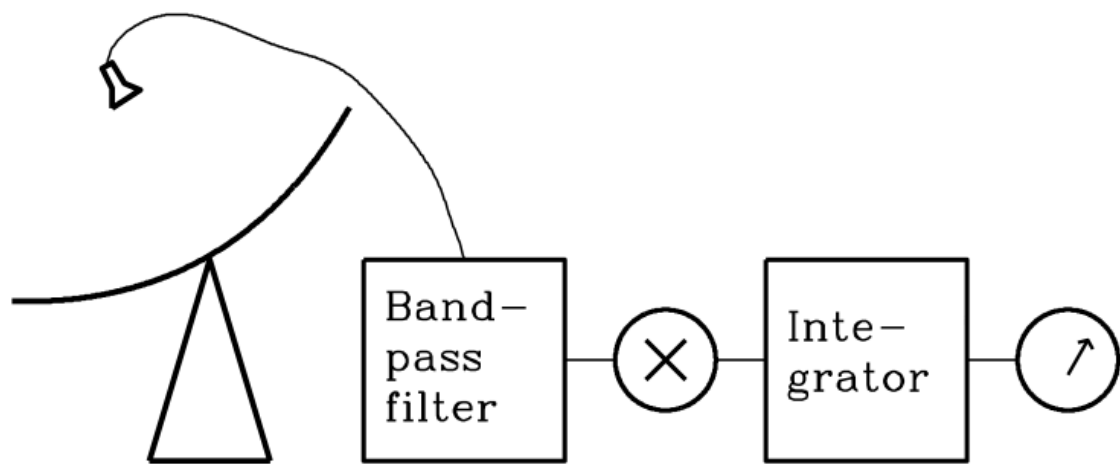
Reciprocity in action

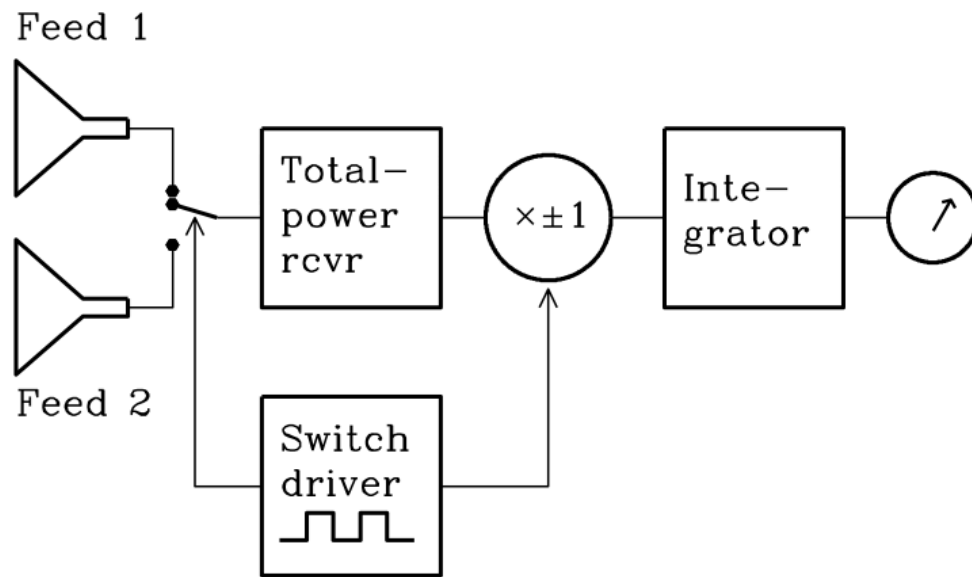


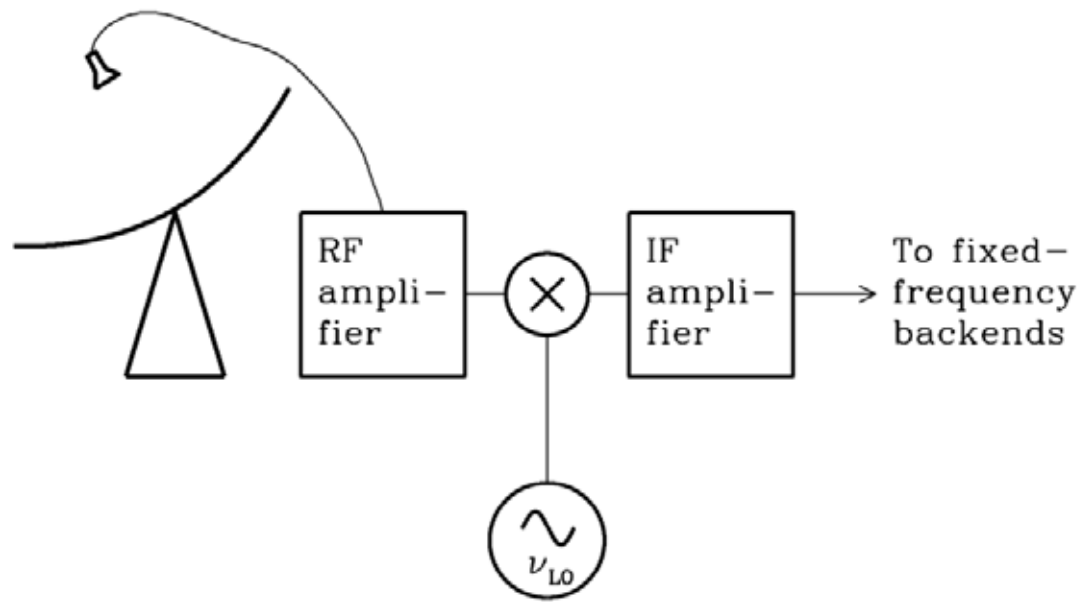
Diffractive Optics:
4m at $5000\text{\AA} = 8 \times 10^6 \lambda$
100m at 21cm = 475λ



Antenna temp; $T_{\text{ant}} = P_v / k$







$$T_{\text{sys}} = T_{\text{ant.}} + T_{\text{spill}} + T_{\text{rx}} + T_{2.7} + T_{\text{sky}}$$

$$T_{\text{sky}} = T_{\text{source}} e^{-\tau} + 290 \text{ K} (1 - e^{-\tau})$$

Radiometer equation:

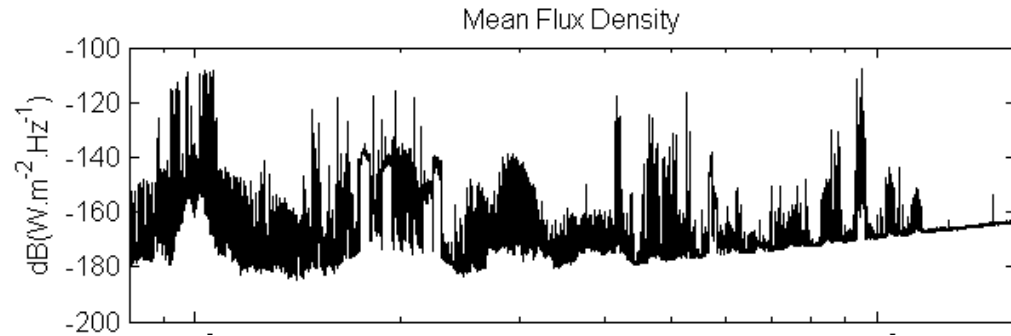
$$\sigma = \frac{T_{\text{sys}}}{\sqrt{\Delta\nu \tau}}$$

SEFD (system equivalent flux density)

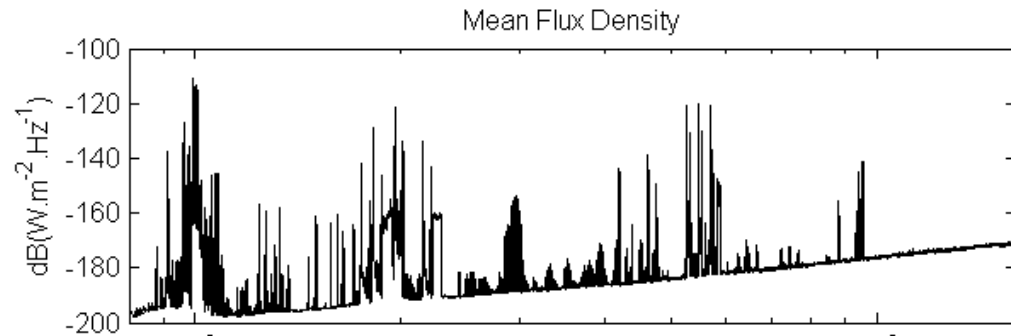
= The flux density of the source that would double the system temperature of the telescope (J/K)

Why is ASKAP in remote Western Australia ? - the RF environment !

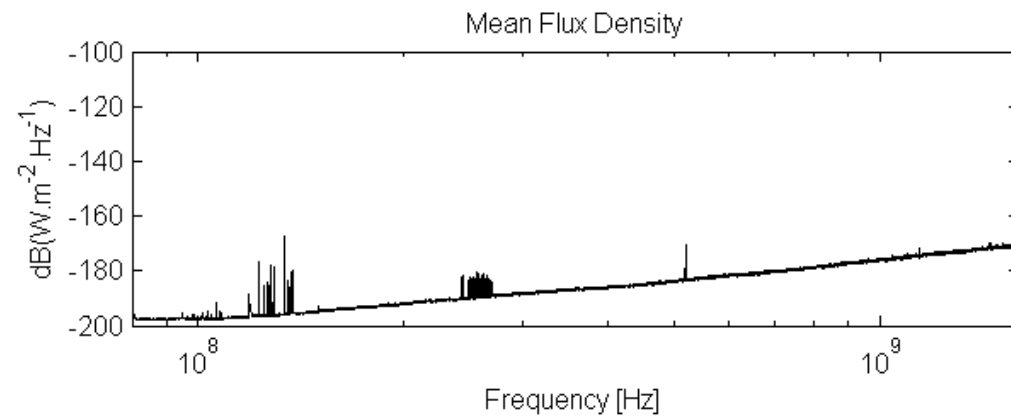
Sydney
Pop. 4 million



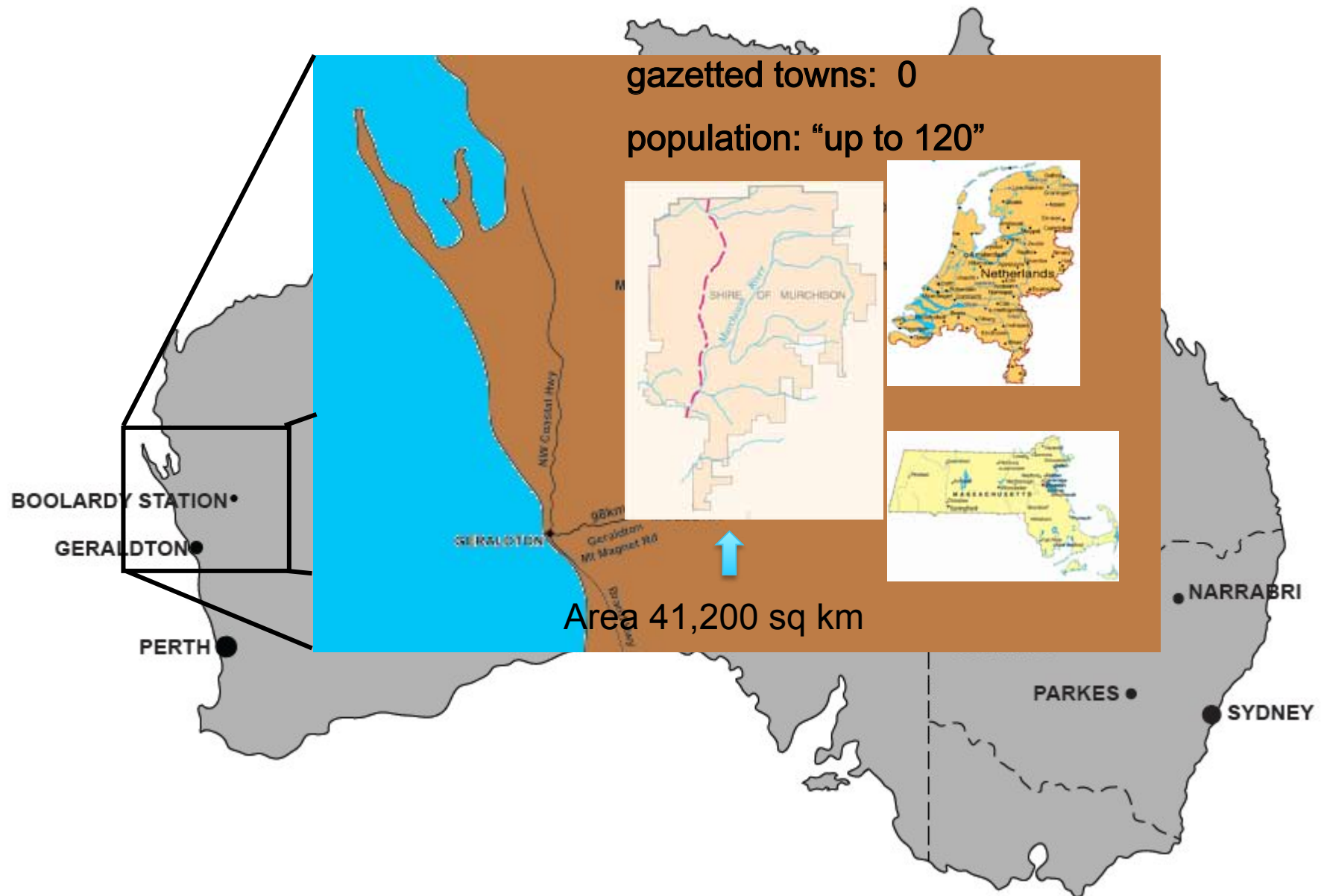
Narrabri (ATCA)
Pop. 6,000



Murchison Shire
(Equal area MA)
Pop. 100



Murchison Radio-astronomy Observatory



References / further reading

1. Condon and Ransom lecture notes:
<http://www.cv.nrao.edu/course/ast534/ERA.shtml>
2. Synthesis Imaging in RA II (ASP Conf Ser. 180, 1999)
 - Chapter 2. Fundamentals of Radio Astronomy (Thompson)
 - Chapter 3. Primary Antenna Elements (Napier)
 - Chapter 9. Sensitivity (Wrobel & Walker)
3. Thompson, Moran & Swenson (2001)
4. Christiansen & Hogbom (1985)
5. Kraus (1966)

Acknowledgements

With thanks to those who previously prepared some of the slides and figures:

John Reynolds (feeds & Parkes)

Jay Lockman (reciprocity)

Mel Wright (intensity and f.d.)

Dave McConnell (the black ones)

Condon and Ransom (figs in slides 27-30): <http://www.cv.nrao.edu/course/astr534/ERA.shtml>

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