

The Radio Sky

Lecture 2

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PHY-236.3



The Giant Metrewave Radio Telescope (GMRT)



Credit: GMRT 45 m antennas at Khodad, with the SMART rope-truss reflector structure. NCRA-TIFR GMRT

GMRT: a low-frequency array built in India

- Conceived 1984, built 1985 to the mid-1990s under Swarup; operated by NCRA-TIFR near Narayangaon, north of Pune.
- **30 antennas, 45 m each**: 14 in a compact central square (about 1 km across) and 16 along three arms of a Y-shaped array with baselines up to ≈ 25 km.
- Lightweight design (SMART): wire-mesh reflector on a rope truss.
- Resolution $\sim \lambda/B$: $\approx 16''$ at 150 MHz and $\approx 1.7''$ at 1.4 GHz.

uGMRT (upgrade completed in the 2010s)

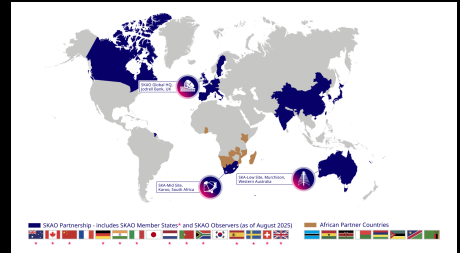
Near-seamless coverage ~ 120 – 1450 MHz with up to 400 MHz instantaneous bandwidth (Gupta et al. 2017, [doi:10.18520/cs/v113/i04/707-714](https://doi.org/10.18520/cs/v113/i04/707-714)).

Science used in this course

pulsars and transients, HI and the early Universe, AGN and cluster haloes, cosmic magnetism, solar radio, star formation.

India and the Square Kilometre Array (SKA)

- SKA Observatory (SKAO): two arrays, **SKA-Low** (50–350 MHz, Western Australia) and **SKA-Mid** (~ 0.35 –15 GHz, South Africa).
- India joined the design effort around 2012: NCRA led the seven-member consortium designing the **Telescope Manager**.
- India became an SKAO member state in 2024. The SKA-India Consortium (nodal institute NCRA-TIFR) has > 20 institutions; India plans software, SKA-Low station hardware, and a Regional Centre for SKA data.
- The uGMRT's low-frequency capability makes it a training ground for SKA-Low science.



SKAO partnership, August 2025.

Source: SKAO, <https://www.skao.int/en/partners/skao-members/393/india>.

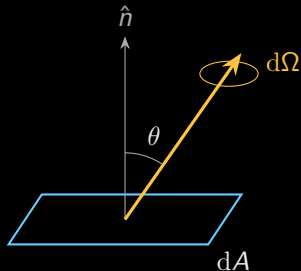
Specific intensity: the fundamental quantity

Energy dE crossing area dA , in solid angle $d\Omega$, bandwidth $d\nu$, time dt , at angle θ to the normal:

$$dE = I_\nu \cos \theta dA d\Omega d\nu dt$$

I_ν Units: $\text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1}$.

- I_ν is **conserved along a ray** in free space.
- Hence surface brightness is independent of distance (for $z \ll 1$).



At cosmological distances, surface brightness dims as $(1+z)^{-4}$

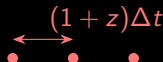
A source at redshift z , compared with the same source in a static universe at the same (comoving) distance. Four factors of $(1+z)$:

1. Energy



$$h\nu \rightarrow h\nu/(1+z)$$

2. Arrival rate



time dilation

3, 4. Solid angle

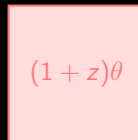


image larger in both directions

$$\frac{\text{flux}}{\text{solid angle}} : \underbrace{(1+z)^{-1}}_{\text{energy}} \underbrace{(1+z)^{-1}}_{\text{rate}} \underbrace{(1+z)^{-2}}_{\text{solid angle}} \Rightarrow I_{\text{obs}} = \frac{l_{\text{em}}}{(1+z)^4}$$

Bolometric intensity $I = \int I_\nu d\nu$. Blue: static universe; red: expanding universe. Tolman 1930, *PNAS* **16**, 511.

Where the four factors come from

D_M : comoving (transverse) distance; A : proper area of the source; L : its luminosity.

Flux: photons spread over a sphere of area $4\pi D_M^2$ today, each with energy $\div(1+z)$, arriving at rate $\div(1+z)$:

$$F = \frac{L}{4\pi D_M^2(1+z)^2} \equiv \frac{L}{4\pi D_L^2}$$

Angle: the light left when the Universe was $(1+z)$ times smaller, so the source looks larger:

$$\theta = \frac{\ell(1+z)}{D_M} \equiv \frac{\ell}{D_A}, \quad \Omega = \frac{A(1+z)^2}{D_M^2}$$

$$\boxed{\frac{F}{\Omega} = \frac{L}{4\pi A} (1+z)^{-4}}$$

- The distance cancels: only z remains. For $z \ll 1$ this is “surface brightness is independent of distance”.
- Same result in one line: I_ν/ν^3 is invariant (photon phase-space density), so $I = \int I_\nu d\nu \propto \nu^4$.

What $(1+z)^{-4}$ means for radio observations

At fixed observed ν , since l_ν/ν^3 is invariant:

$$l_\nu^{\text{obs}}(\nu) = \frac{l_\nu^{\text{em}}((1+z)\nu)}{(1+z)^3}$$

For $l_\nu \propto \nu^\alpha$: $l_\nu^{\text{obs}}(\nu) = l_\nu^{\text{em}}(\nu)(1+z)^{\alpha-3}$.

Brightness temperature: $T_b^{\text{obs}} = T_b^{\text{em}}/(1+z)$
(as for the CMB, $T \propto 1+z$).

z	$(1+z)^4$ bolometric	$(1+z)^{3.7}$ $\alpha = -0.7$
0.1	1.5	1.4
1	16	13
3	256	170
6	2400	1300

- Beyond $z \approx 1.6$ sources stop getting smaller on the sky (Planck 2018 cosmology), but keep getting fainter per beam.
- **Consequence:** diffuse sources (lobes, haloes, relics) at high z are **surface-brightness limited**, not flux limited. They drop out of surveys first (Lectures 19–20).

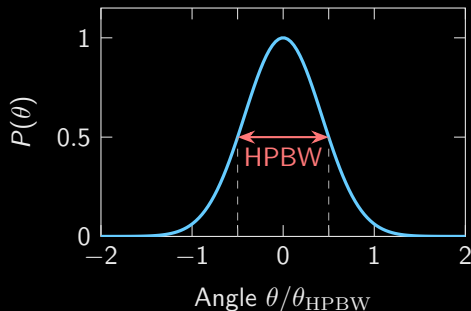
The beam: a telescope sees the sky through a blur

- A telescope does not respond to one direction only. Its **power pattern** $P(\theta)$ (the **beam**) has a main lobe of half-power width

$$\theta_{\text{HPBW}} \sim \lambda/D$$

(D : dish diameter, or longest baseline for an interferometer).

- 1.4 GHz ($\lambda = 21$ cm): one 45 m GMRT dish gives $\approx 16'$; the 25 km GMRT array gives $\approx 2''$.
- A radio image is the true sky **convolved with the beam**: structure finer than θ_{HPBW} is smoothed out.



Gaussian main lobe; real beams also have sidelobes.

Jy beam⁻¹: the unit of a radio image

- Each image pixel holds the flux density collected by a beam centred there: units Jy beam⁻¹.
- **Point source** (smaller than the beam): peak value in Jy beam⁻¹ = its flux density in Jy.
- **Extended source**: the image samples the intensity, averaged over one beam. To convert, divide by the beam solid angle. For a Gaussian beam with half-power widths $\theta_{\text{maj}}, \theta_{\text{min}}$:

$$\Omega_b = \frac{\pi \theta_{\text{maj}} \theta_{\text{min}}}{4 \ln 2} \approx 1.133 \theta_{\text{maj}} \theta_{\text{min}}, \quad I_\nu [\text{Jy sr}^{-1}] = \frac{\text{map value} [\text{Jy beam}^{-1}]}{\Omega_b}$$

- Example: 2'' beam, $\Omega_b = 1.07 \times 10^{-10} \text{ sr}$; 1 mJy beam⁻¹ = $9.4 \times 10^6 \text{ Jy sr}^{-1}$.
- Total flux of an extended source: sum the pixels and multiply by $\Omega_{\text{pix}}/\Omega_b$ (pixels per beam).

Flux density: what a radio telescope actually reports

Integrate intensity over the source solid angle:

$$S_\nu = \int_{\text{source}} I_\nu \cos \theta \, d\Omega \approx \int_{\text{source}} I_\nu \, d\Omega \quad (\theta \ll 1)$$

- The **jansky**: $1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1} = 10^{-23} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$.
- Strongest discrete sources: 10^3 – 10^4 Jy at low frequency. Deep surveys: μJy .
- An **unresolved** source gives S_ν but *not* I_ν : the solid angle is unknown.
- A **resolved** source gives I_ν ($\text{Jy beam}^{-1} \rightarrow \text{Jy sr}^{-1}$).

Convention in this course: SI with janskys, cgs where the literature is cgs; each derivation states which.

Luminosity density

For an isotropic emitter at distance D with $z \ll 1$:

$$L_\nu = 4\pi D^2 S_\nu \quad [\text{W Hz}^{-1}]$$

- S_ν is **observed**; L_ν is **inferred** and requires a distance and an isotropy assumption.
- Beamed sources (pulsars, blazar jets) violate isotropy: $4\pi D^2 S_\nu$ is then an *isotropic-equivalent* luminosity.
- At cosmological distances: $D \rightarrow D_L$, and the observed band samples a different rest-frame frequency (K-correction, Lecture 19).

Pitfall

Bolometric luminosity $L = \int L_\nu d\nu$ is rarely measured in radio. Quote L_ν at a stated frequency.

Worked example: flux to luminosity

A radio galaxy has $S_{1.4\text{ GHz}} = 1\text{ Jy}$ at $D = 100\text{ Mpc}$ (illustrative values).

$$D = 100 \times 3.086 \times 10^{22}\text{ m} = 3.09 \times 10^{24}\text{ m}$$

$$\begin{aligned} L_\nu &= 4\pi(3.09 \times 10^{24})^2 \times 10^{-26}\text{ W Hz}^{-1} \\ &= 1.2 \times 10^{24}\text{ W Hz}^{-1} \end{aligned}$$

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- The Milky Way at 1.4 GHz: $L_\nu \sim 10^{21}\text{ W Hz}^{-1}$ (order of magnitude).
- So this source is $\sim 10^3$ times more radio-luminous than a normal spiral: a radio-loud AGN is the natural first hypothesis.
- **Still an inference:** a compact starburst can reach 10^{23} W Hz^{-1} .

Concept test

Question

A source is moved to twice its distance with unchanged luminosity. By what factor does its flux density change?

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Answer: one quarter

1. $S_\nu = L_\nu / (4\pi D^2) \propto D^{-2}$.
2. Doubling D multiplies S_ν by $2^{-2} = 1/4$.

Brightness temperature: definition

The Planck function in the **Rayleigh–Jeans limit** $h\nu \ll k_B T$:

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/k_B T} - 1} \longrightarrow \frac{2k_B T \nu^2}{c^2}.$$

Define T_b as the temperature a blackbody would need to produce the observed intensity in this limit:

$$T_b \equiv \frac{c^2}{2k_B \nu^2} I_\nu = \frac{\lambda^2}{2k_B} I_\nu$$

- T_b is a *unit of intensity*, linear in I_ν .
- It equals a physical temperature *only* for an optically thick thermal emitter (Lecture 3).
- Rayleigh–Jeans holds when $\nu/\text{GHz} \ll 21 (T/\text{K})$. It fails for the 2.7 K CMB above ~ 50 GHz.

Brightness temperature from flux and size

For a source of solid angle Ω_s and uniform brightness, $I_\nu = S_\nu/\Omega_s$:

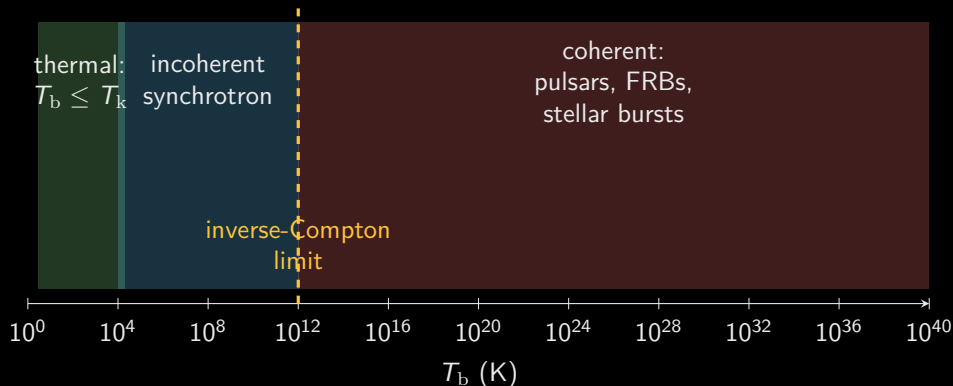
$$T_b = \frac{c^2 S_\nu}{2k_B \nu^2 \Omega_s}.$$

For an elliptical Gaussian with FWHM θ_1, θ_2 : $\Omega_s = \frac{\pi \theta_1 \theta_2}{4 \ln 2}$.

$$T_b \approx 1.22 \times 10^3 \text{ K} \left(\frac{S_\nu}{\text{mJy}} \right) \left(\frac{\nu}{\text{GHz}} \right)^{-2} \left(\frac{\theta_1 \theta_2}{\text{arcsec}^2} \right)^{-1}$$

- An **unresolved** source gives only an upper limit on size, so a **lower limit** on T_b .
- Same formula with λ : $T_b \approx 1.36 \text{ K} (\lambda/\text{cm})^2 (S_\nu/\text{mJy}) (\theta_1 \theta_2/\text{arcsec}^2)^{-1}$ [ERA Ch. 2].

Brightness temperature is a classification tool



- Thermal emitters cannot exceed the kinetic temperature of the gas.
- Incoherent synchrotron: $T_b \gtrsim 10^{12}$ K causes catastrophic inverse-Compton losses (Kellermann & Pauliny-Toth 1969; [doi:10.1086/180305](https://doi.org/10.1086/180305)). Lecture 6.
- Above that, *coherent* emission or relativistic beaming is required.