Astronomical Techniques II : Lecture 1

Ruta Kale

- Introduction to the course
- Overview of relevant concepts
- Antennas

www.ncra.tifr.res.in/~ruta/astrotech22.html

Google classroom

Course information

- 14 lectures (2 per week):

Tuesdays and Thursdays 11.30 – 12.30.

- *May 23 instead of May 31* (will be announced closer to the date)*

- June 9 : GMRT visit (tentative date)

Evaluation

- Weightage: Assignments (30%+30%); Final Exam (40%)
- Final exam tentative date: 28th June 2022
- You will need knowledge of python/ any other scripting language for plotting and data analysis in the assignments.
- Assignments: problem solving, hands-on analysis, reading summary.

Course contents

- Introduction to radio astronomy
- Single dish radio telescope
- Two element interferometer
- Aperture synthesis
- Correlators
- Calibration
- Imaging and deconvolution
- Introduction to the GMRT
- Sensitivity
- W-term
- Self-calibration
- Special topics in interferometry

References:

Not limited to these though !

Interferometry and synthesis in radio astronomy, Thompson, Moran, Swenson

Synthesis imaging in radio astronomy II, Taylor et al.

Fundamentals of radio astronomy, Marr, Snell and Kurtz

Antenna Theory, C. Balanis

Radio astronomy, Kraus; Antennas, Kraus

Low frequency radio astronomy, Chengalur, Gupta and Dwarakanath

https://science.nrao.edu/opportunities/courses/era

More references will be provided as and when needed.

Lecture 1

Radio astronomy – some history

Antennas

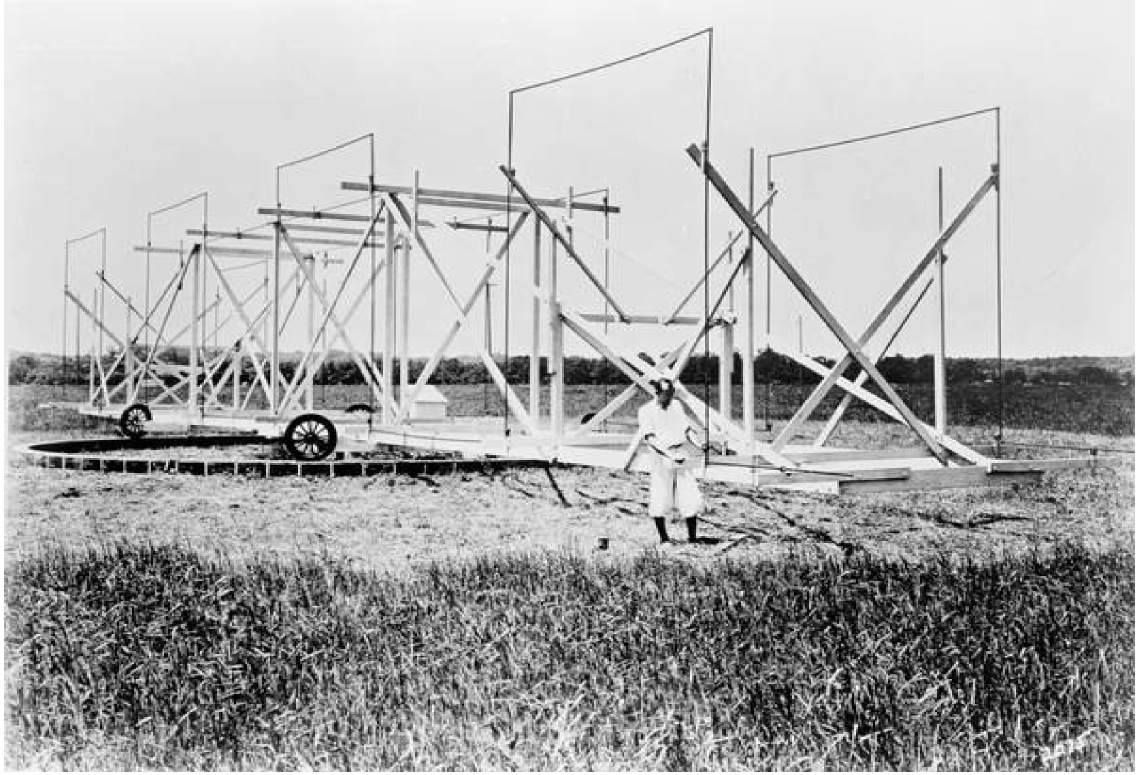
Quantities relevant for measurements

Origin of radio astronomy

- Maxwell’s equations: any wavelength of light is possible and the visible window is only a tiny fraction of it. (~1860s)
- 1887: Hertz produced radio waves in the lab
- Around 1900s : experiments to detect radio waves attempted but failed.
- *Amplification* crucial to detect radio signals from celestial bodies.
- 1932: Karl Jansky of Bell labs made the first successful detection.

Origin of radio astronomy

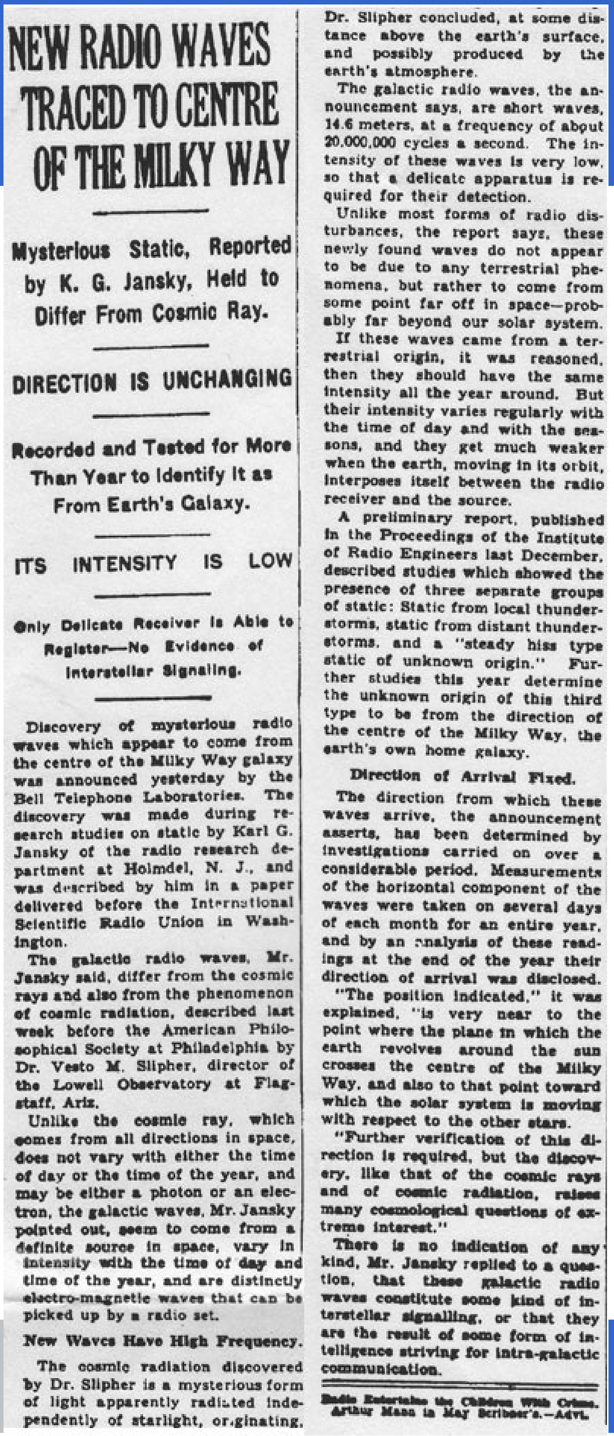
Karl Jansky and his antenna



Images from wikipedia

Origin of radio astronomy

- Jansky was studying the direction and level of static that interfered with long distance short-wave radio communications.
- Detected a hiss: found it had *directionality* and that direction was fixed relative to stars – narrowed it to the plane of our Galaxy and to its centre.
- The discovery did not get much attention and was not pursued much.



NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

DIRECTION IS UNCHANGING

Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

ITS INTENSITY IS LOW

Only Delicate Receiver Is Able to Register—No Evidence of Interstellar Signaling.

Discovery of mysterious radio waves which appear to come from the centre of the Milky Way galaxy was announced yesterday by the Bell Telephone Laboratories. The discovery was made during research studies on static by Karl G. Jansky of the radio research department at Holmdel, N. J., and was described by him in a paper delivered before the International Scientific Radio Union in Washington.

The galactic radio waves, Mr. Jansky said, differ from the cosmic rays and also from the phenomenon of cosmic radiation, described last week before the American Philosophical Society at Philadelphia by Dr. Vesto M. Slipher, director of the Lowell Observatory at Flagstaff, Ariz.

Unlike the cosmic ray, which comes from all directions in space, does not vary with either the time of day or the time of the year, and may be either a photon or an electron, the galactic waves, Mr. Jansky pointed out, seem to come from a definite source in space, vary in intensity with the time of day and time of the year, and are distinctly electro-magnetic waves that can be picked up by a radio set.

New Waves Have High Frequency.

The cosmic radiation discovered by Dr. Slipher is a mysterious form of light apparently radiated independently of starlight, originating, Dr. Slipher concluded, at some distance above the earth's surface, and possibly produced by the earth's atmosphere.

The galactic radio waves, the announcement says, are short waves, 14.6 meters, at a frequency of about 20,000,000 cycles a second. The intensity of these waves is very low, so that a delicate apparatus is required for their detection.

Unlike most forms of radio disturbances, the report says, these newly found waves do not appear to be due to any terrestrial phenomena, but rather to come from some point far off in space—probably far beyond our solar system.

If these waves came from a terrestrial origin, it was reasoned, then they should have the same intensity all the year around. But their intensity varies regularly with the time of day and with the seasons, and they get much weaker when the earth, moving in its orbit, interposes itself between the radio receiver and the source.

A preliminary report, published in the Proceedings of the Institute of Radio Engineers last December, described studies which showed the presence of three separate groups of static: Static from local thunderstorms, static from distant thunderstorms, and a "steady hiss type static of unknown origin." Further studies this year determine the unknown origin of this third type to be from the direction of the centre of the Milky Way, the earth's own home galaxy.

Direction of Arrival Fixed.

The direction from which these waves arrive, the announcement asserts, has been determined by investigations carried on over a considerable period. Measurements of the horizontal component of the waves were taken on several days of each month for an entire year, and by an analysis of these readings at the end of the year their direction of arrival was disclosed.

"The position indicated," it was explained, "is very near to the point where the plane in which the earth revolves around the sun crosses the centre of the Milky Way, and also to that point toward which the solar system is moving with respect to the other stars.

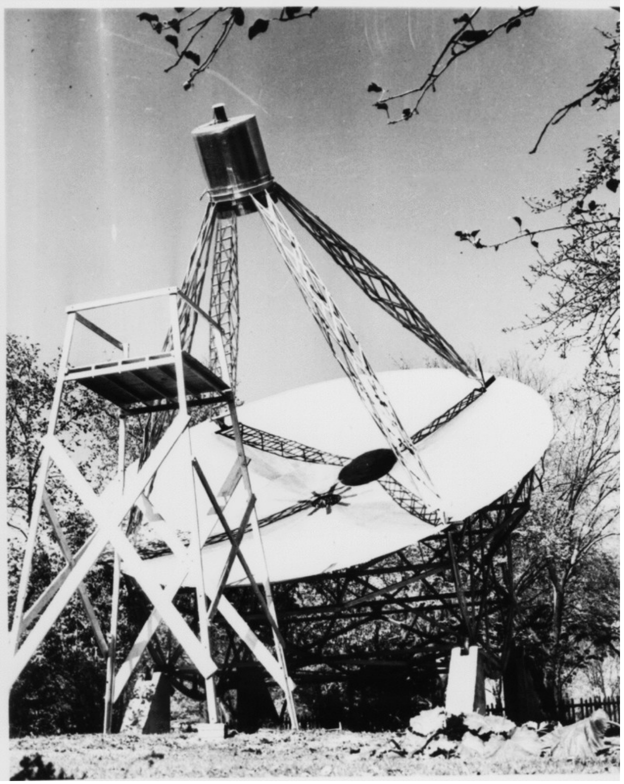
"Further verification of this direction is required, but the discovery, like that of the cosmic rays and of cosmic radiation, raises many cosmological questions of extreme interest."

There is no indication of any kind, Mr. Jansky replied to a question, that these galactic radio waves constitute some kind of interstellar signalling, or that they are the result of some form of intelligence striving for intra-galactic communication.

New York Times on May 5, 1933

Origin of radio astronomy

- Except by Grote Reber, a professional engineer, built his own antenna in his backyard and mapped the sky in radio !
- **Grote Reber and his telescope**



Images from wikipedia

Origin of radio astronomy

- For military reasons during World War II there was a significant technological development in radio wave communication technology.
- Radio emission from the Sun; variability in Cyg A etc discovered.
- Jan Oort and Hendrik van de Hulst: 21 cm line due to spin flip transition of Hydrogen predicted and in 1951 was observed by Harold Ewen and Edward Purcell. 1950s saw HI maps of the Milky Way by groups in Netherlands and Australia.

Origin of radio astronomy

- 1946: breakthrough in making high resolution radio observations by Martin Ryle and D. D. Vonberg using a pair of antennas – interferometer. Precise positions of radio sources found.
- In 1959 a map of 471 sources at 159 MHz: Third Cambridge Catalogue (3C).
- Detections brought new challenges for explanation: theory of synchrotron radiation.
- ...

Radio astronomy

Antenna theory

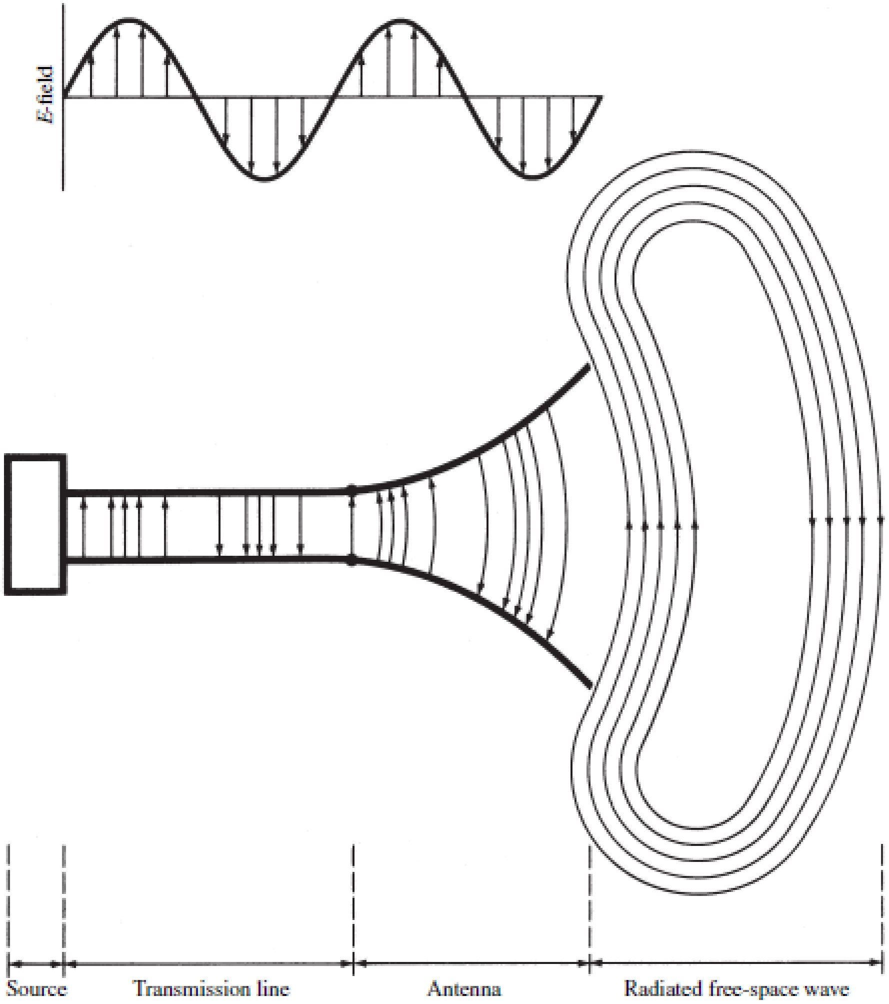
Antenna: “That part of a transmitting or receiving system that is designed to radiate or to receive electro-magnetic waves.”

IEEE* Std definitions 145-1993
*Institute of Electrical and Electronic Engineers

Also serves as a directional device – accentuate the radiation in certain directions and suppress in others.

Antenna : transmission device

Ideal
generator



Ref: Balanis

Radiated power: Poynting flux

$$\vec{S} = \frac{c}{4\pi} \vec{E} \times \vec{B} .$$

erg s^{-1}cm^{-2}

- Radiation from an accelerated charge

Total power emitted by an accelerated charged particle is

$$\boxed{P = \frac{2}{3} \frac{q^2 \dot{v}^2}{c^3} .}$$

Larmor's equation

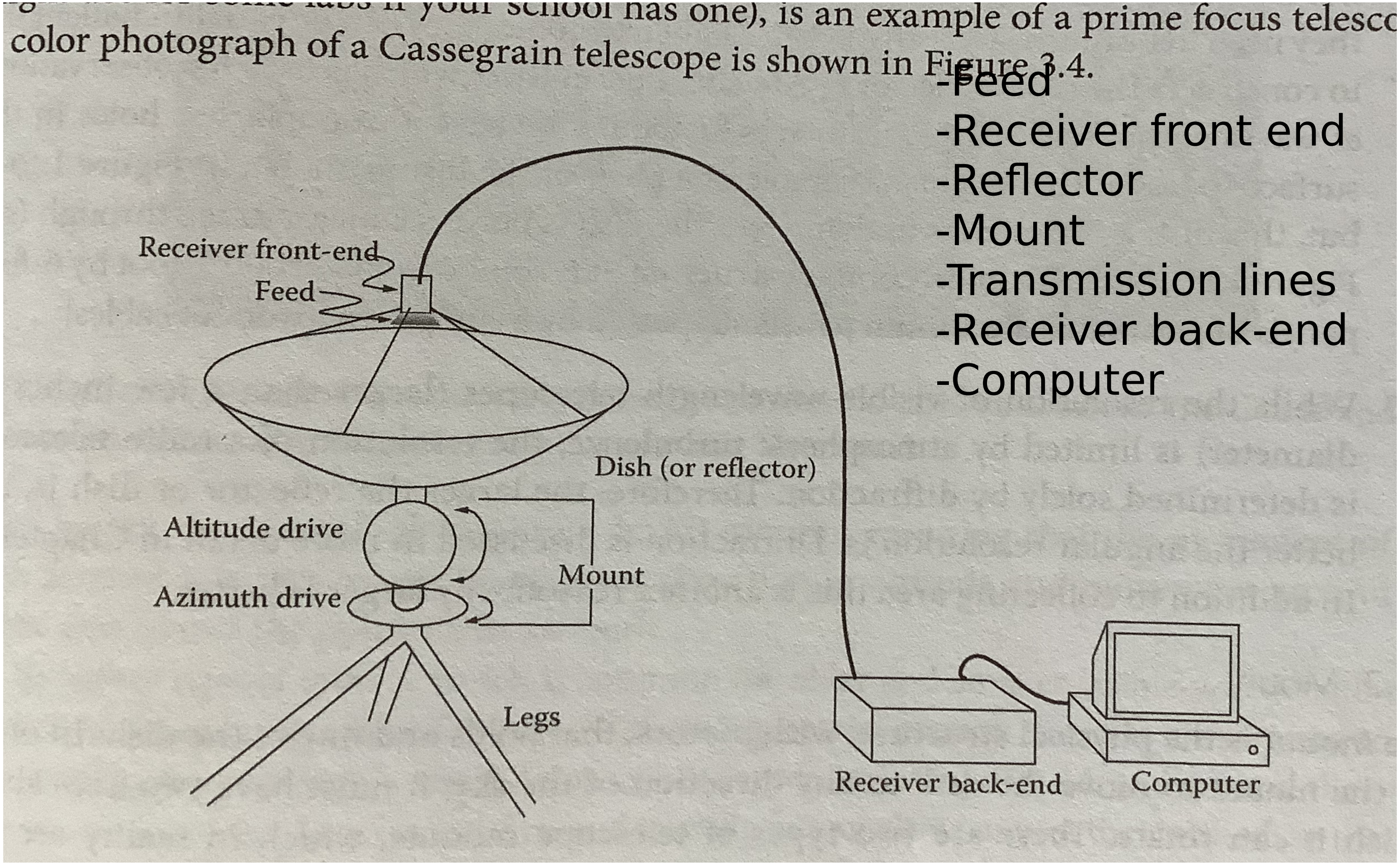
Radiated power is proportional to the square of the acceleration.

Reciprocity

- Many antenna properties are the same for both transmitting and receiving.

- The power pattern of an antenna is the same for transmitting and receiving.

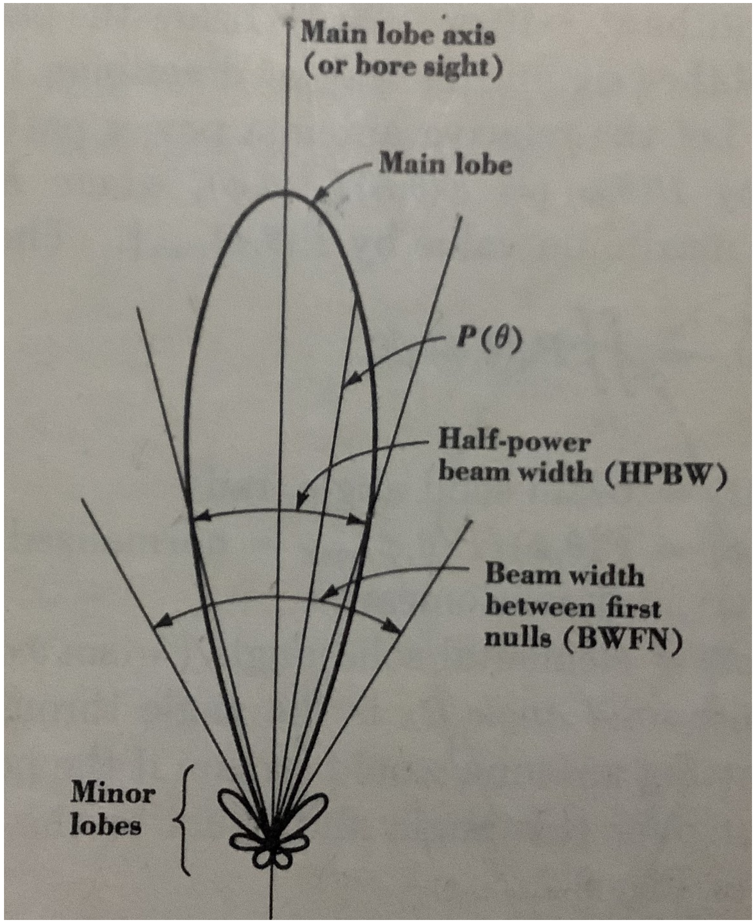
A basic radio telescope

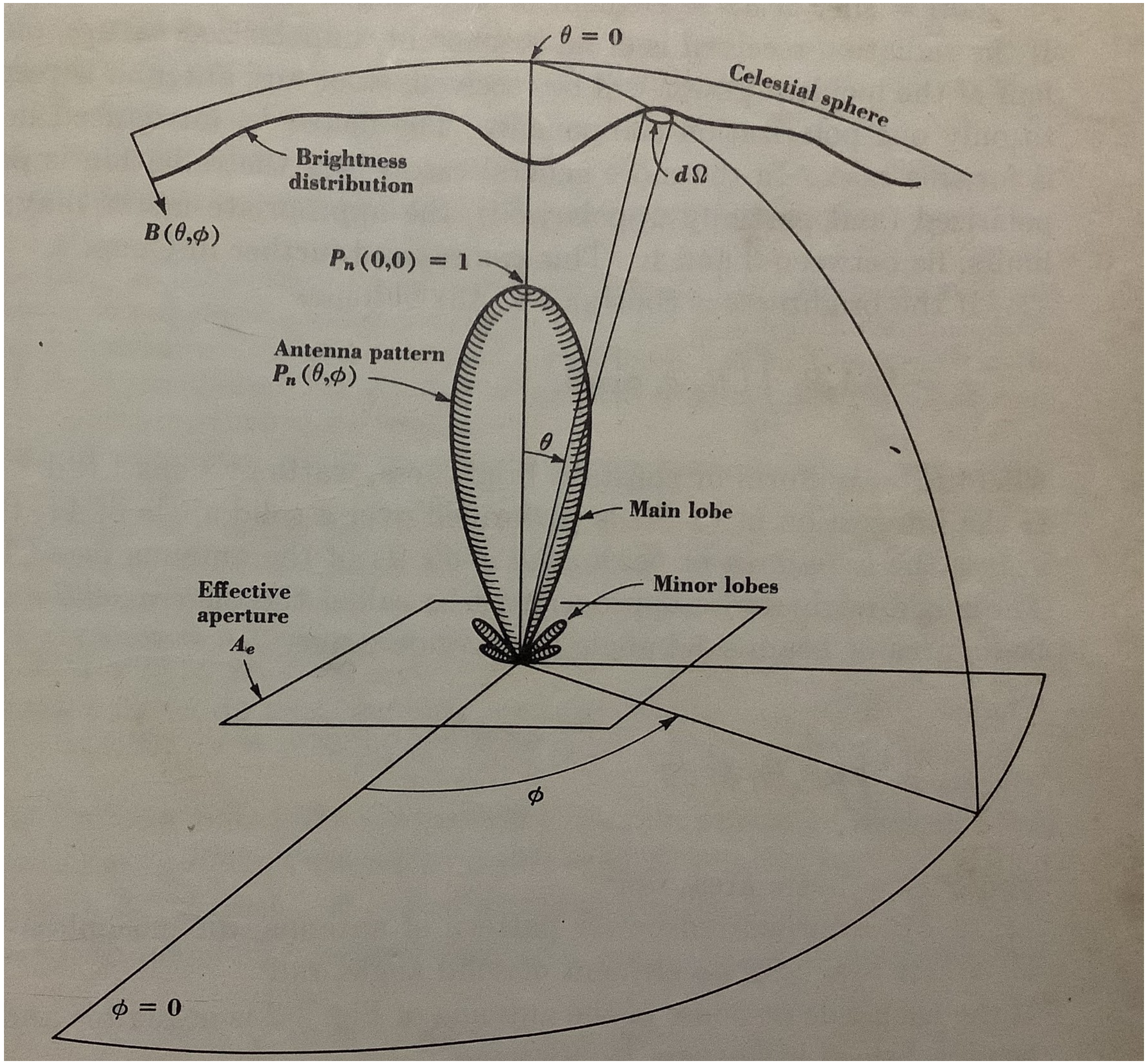


your school has one), is an example of a prime focus telesco
color photograph of a Cassegrain telescope is shown in Figure 3.4.

- -Feed
- -Receiver front end
- -Reflector
- -Mount
- -Transmission lines
- -Receiver back-end
- -Computer

Antenna beam and celestial sphere





What do we measure ?

- Voltages induced in antennas by radiation from cosmic sources are generally referred to as signals.
- Have the form of Gaussian random noise (~).
- The strength of the radio signal received from a discrete source is expressed as *spectral flux density* or *spectral power flux density* and is measured in units of Watts per square metre per Hertz
- 1 Jansky = 1 Jy = 10^{-26} W m^{-2} Hz^{-1}
- Referred to as flux density as well.

What do we measure ?

- The measure of radiation integrated over a spectral band is referred to as power flux density – it has units of W m^{-2} (*time average of the Poynting vector of the wave*).
- Spectral power flux density emitted per unit solid angle subtended by the radiating surface is called intensity, specific intensity or brightness:

  W m^{-2} Hz^{-1} sr^{-1}

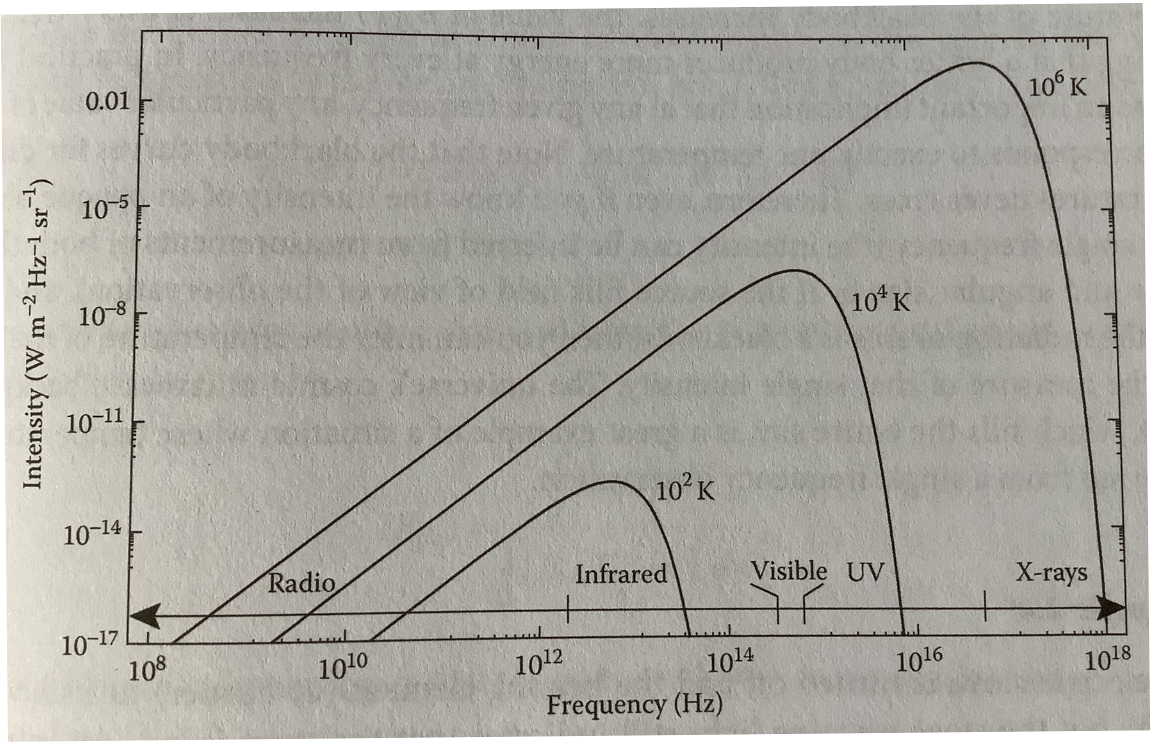
- Denoted by I or B_ν or I_ν

Planck's formula

$$I_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{exp(\frac{h\nu}{kT}) - 1}$$

$$Wm^{-2}Hz^{-1}sr^{-1}$$

T = temperature, K
k = Boltzmann's constant = 1.38 x 10^{-23} J K^{-1}
c = speed of light = 3 x 10^8 m s^{-1}
h = Planck's constant = 6.63 x 10^{-34} J s



Brightness temperature

$$I_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{exp(\frac{h\nu}{kT}) - 1}$$

Rayleigh-Jeans approximation

$$\frac{h\nu}{kT} << 1$$

$$I_\nu(T) = \frac{2kT\nu^2}{c^2}$$

Brightness temperature

$$T_B = \left(\frac{\lambda^2}{2k}\right) I_\nu$$

“**Equivalent**”
Not physical temperature
of the source in general

Brightness temperature

One can express the measured intensity in terms of a temperature – could be from a source or even be noise from the receiver. Thus in radio astronomy often one talks in terms of temperature (receiver temperature, sky temperature, antenna temperature etc.).

Brightness temperature

$$T_B = \left(\frac{\lambda^2}{2k}\right) I_\nu$$

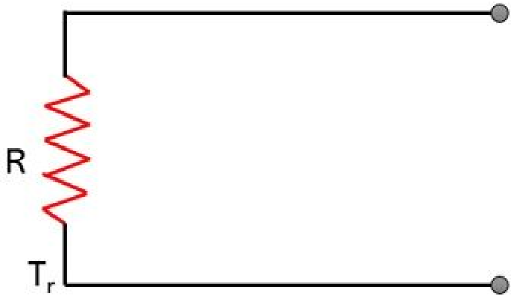
“**Equivalent**”

Not the physical temperature of the source in general

Temperature and noise

The noise power per unit bandwidth available at the terminals of a resistor of resistance, R and temperature T is given by (Nyquist, 1928):

$$w = kT$$



Resistor (R) at temperature (T)

w = spectral power $\mathrm{W\,Hz^{-1}}$
T = absolute temperature of resistor, K

Image credit: https://electronicsdesk.com/antenna-temperature.html

Temperature and noise

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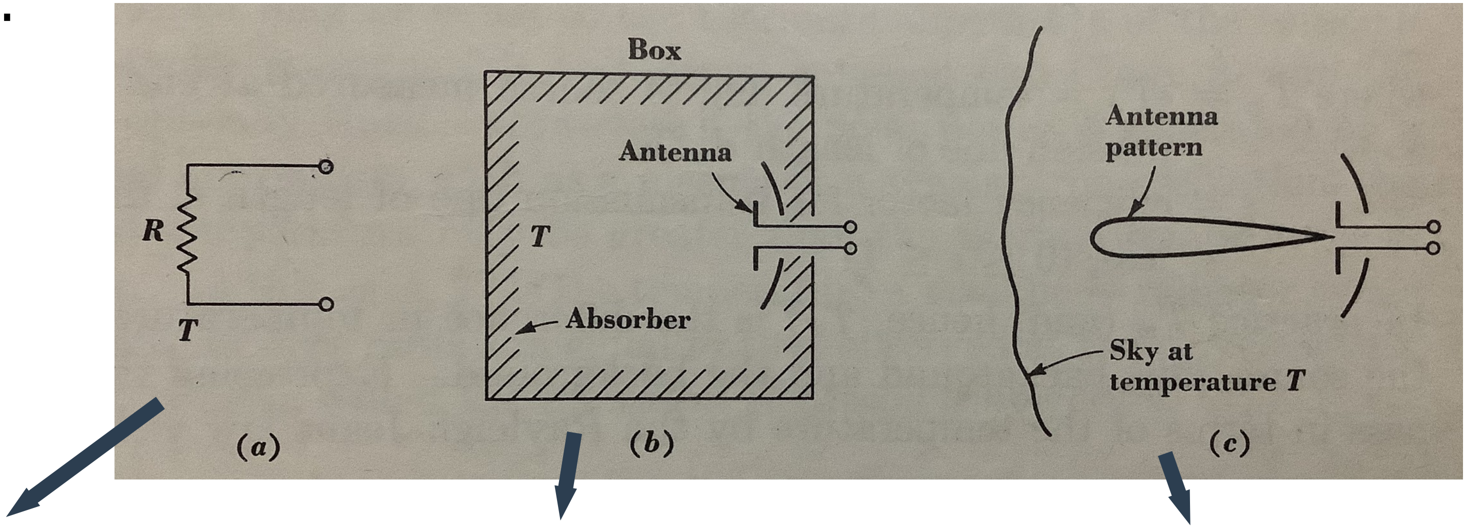

a) Resistor at temperature T

b) antenna in an absorbing box at temperature T

c) antenna observing sky of temperature T

The noise generated by a resistor is indistinguishable from the noise coming from a receiving antenna surrounded by blackbody radiation of the same temperature.

Reception of signal by an antenna

For a randomly polarized source of flux density S (size smaller than that of the antenna beam) observed with antenna with effective collecting area A, the received power delivered by the antenna to a matched load in a bandwidth $\Delta\nu$ from this source is given by:

$$P_A = \frac{1}{2} A S \Delta\nu$$

The factor ½ takes into account that the antenna responds to only one-half of the power in the randomly polarized wave.

$$P_A = k T_A \Delta\nu$$

Antenna temperature* is used for the component of the antenna output power that results from the source under study.

Expressing antenna temperature in terms of the flux density and putting in the constants gives:

$$T_A(K) = S(Jy) A(m^2)/2800$$

*also used in another context to refer to the unwanted components coming from the antenna

Antenna performance measure

$$T_A(K) = S(Jy)A(m^2)/2800$$

Performance of an antenna often expressed in terms of Jansky per Kelvin, that is *the flux density of a point source that increases the antenna temperature by one kelvin*:

$$S(Jy)/T_A(K) = 2800/A(m^2)$$

Antenna performance measure

System equivalent flux density (SEFD): is an indicator of the combined sensitivity of both an antenna and receiving system.
It is equal to the flux density of a point source in the main beam of the antenna that would cause the noise power in the receiver to be twice that of the system noise in the absence of a source.

$$SEFD = \frac{2kT_S}{A}$$

T_s denotes the system temperature: associated with a matched resistive load that would produce an equal power level in an equivalent noise-free receiver when connected to the input terminals: composed of receiver and antenna temperature.

Minimum detectable temperature and flux density

The minimum temperature that a radio telescope can detect is limited by fluctuations in the receiver output caused by the statistical nature of the wave form. This noise is proportional to the system temperature of the radio telescope. This system noise can be reduced by increasing the integration time, increasing the bandwidth or by taking more than one observation.
The minimum detectable temperature of a radio telescope is:

$$\Delta T_{min} = \frac{K_s T_{sys}}{\sqrt{\Delta\nu t n}}$$

K_s = sensitivity constant, dimensionless
$\Delta\nu$ = *bandwidth*
t = integration time
n = number of records averaged

Other concepts to revise before rest of the course

- Fourier transform and its properties
- Auto-correlation
- Cross-correlation

Reference: Fourier Transforms and its Applications by Bracewell