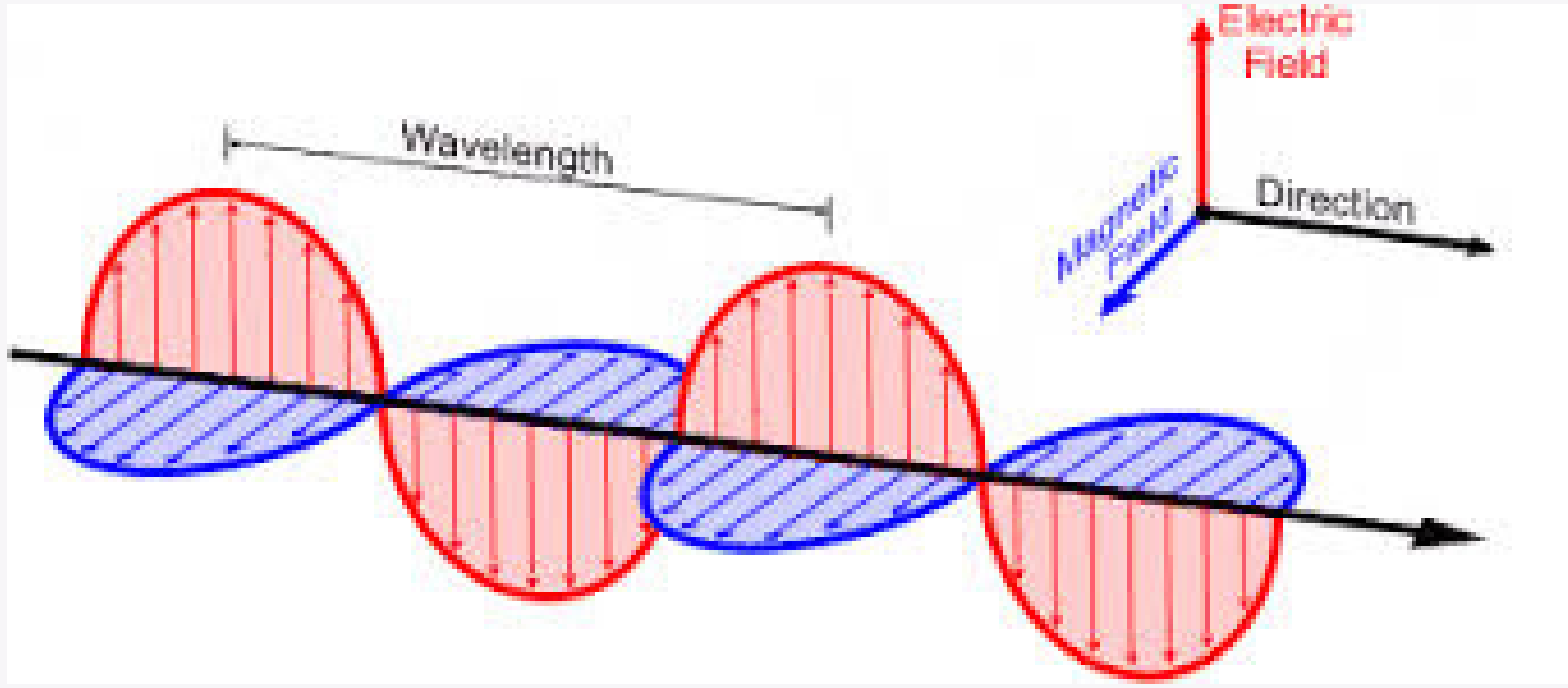
AN INTRODUCTION TO

Radio Astronomy

What Are Radio Waves?



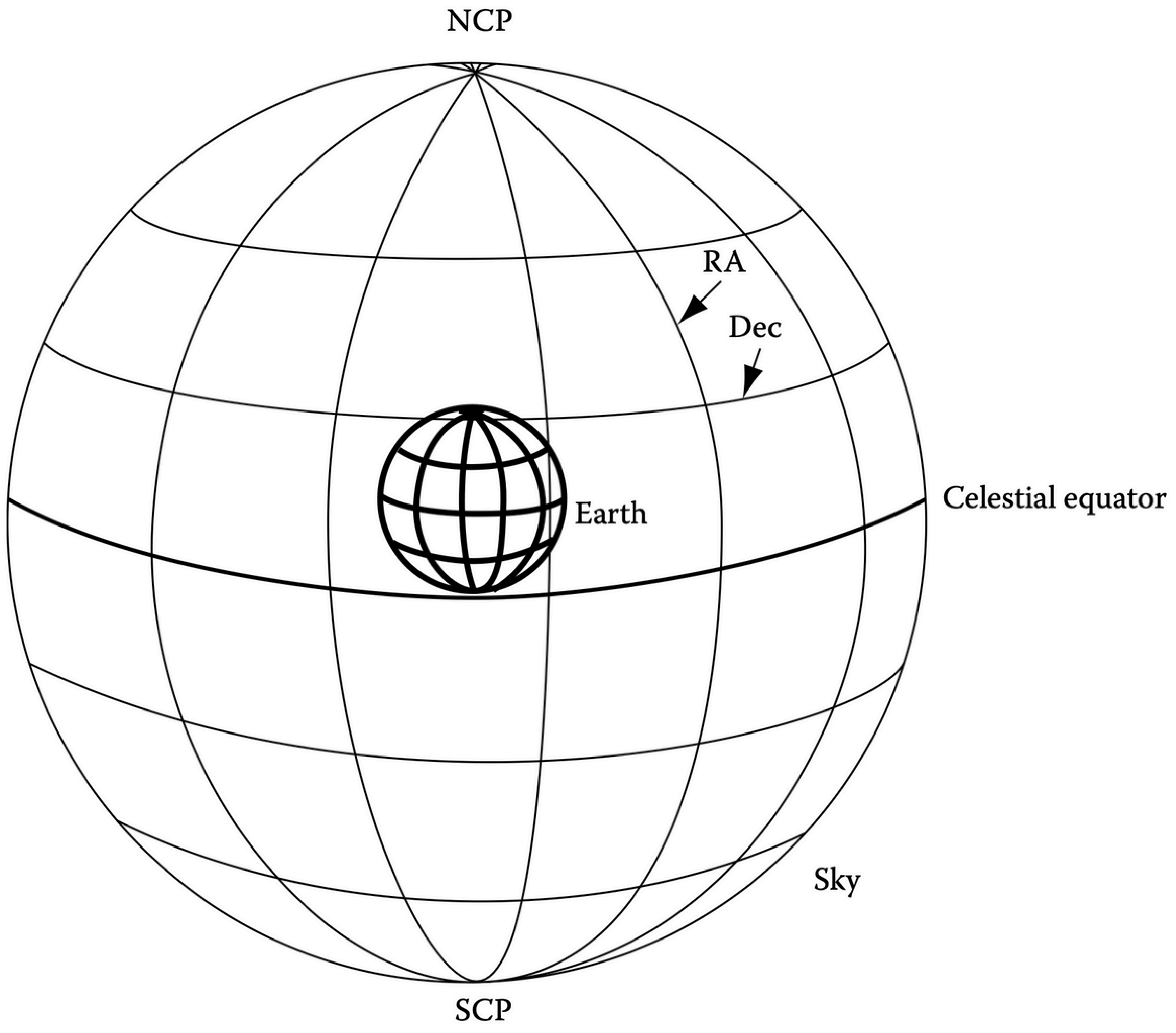
Radio waves are a form of electromagnetic (EM) radiation, just like visible light but at frequencies that are far too low for our eyes to detect

- The radio window, as it can be called, ranges in frequency from 10 MHz (1 × 107 Hz) up to 300 GHz (3 × 1011 Hz), or in wavelengths from 30 m down to 1 mm.
- The boundaries of the radio window are due to atmospheric and ionospheric processes. At low frequencies (below about 10 MHz), free electrons present in the ionosphere easily absorb and/or reflect radiation.

Sky Coordinate System

Extensions of the lines of longitude on Earth produce similar lines on the sky, which we call lines of right ascension (RA), often represented by the Greek letter a. Extensions of the lines of latitude make lines on the sky called declination (Dec), represented by the Greek letter δ

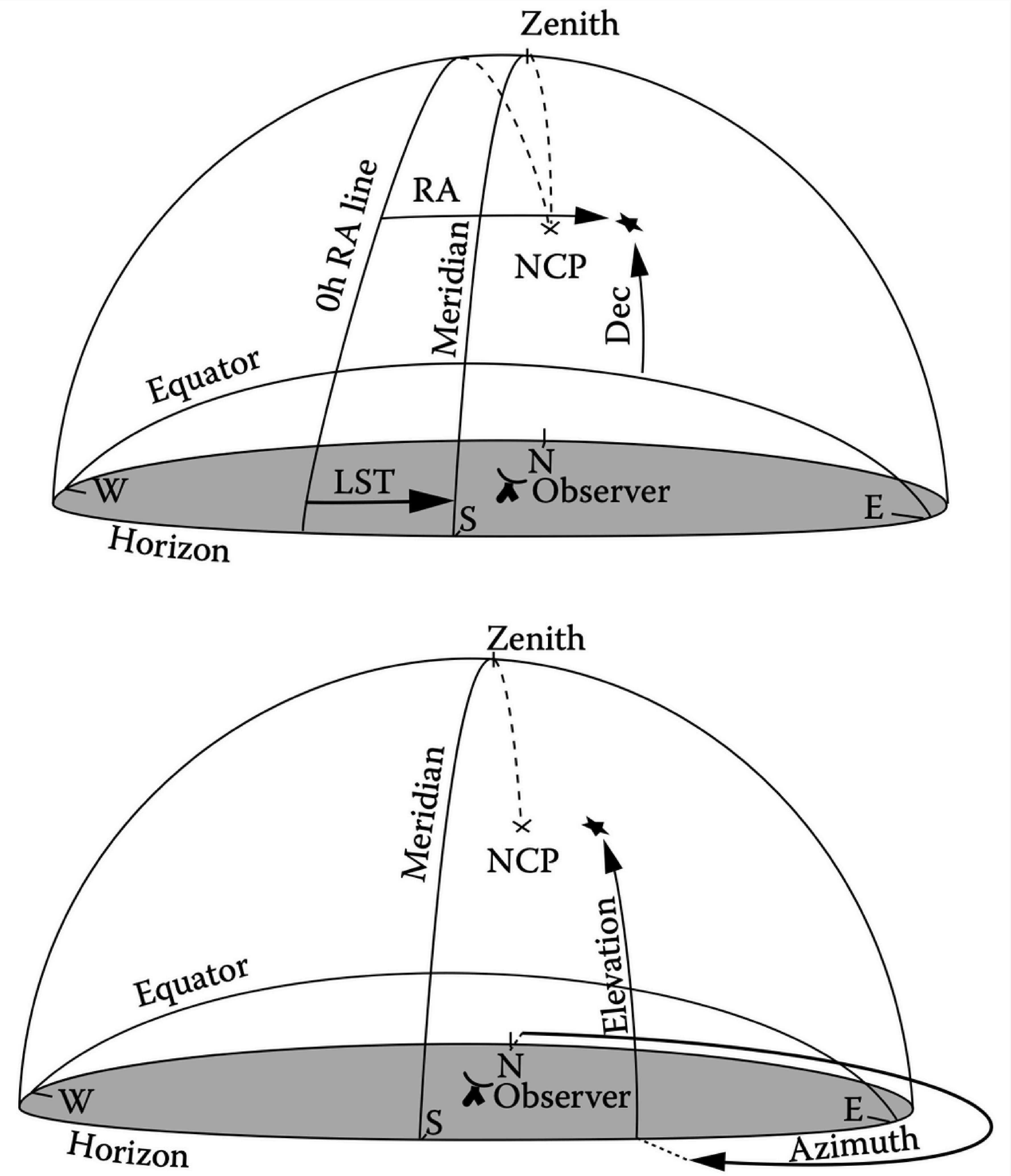
Seconds of arc = 15 cos (δ)× seconds of RA



Observer-Centered Definitions

Terms include:

- Horizon
- Zenith
- Altitude
- Azimuth
- Meridian
- Hour Angle(HA)

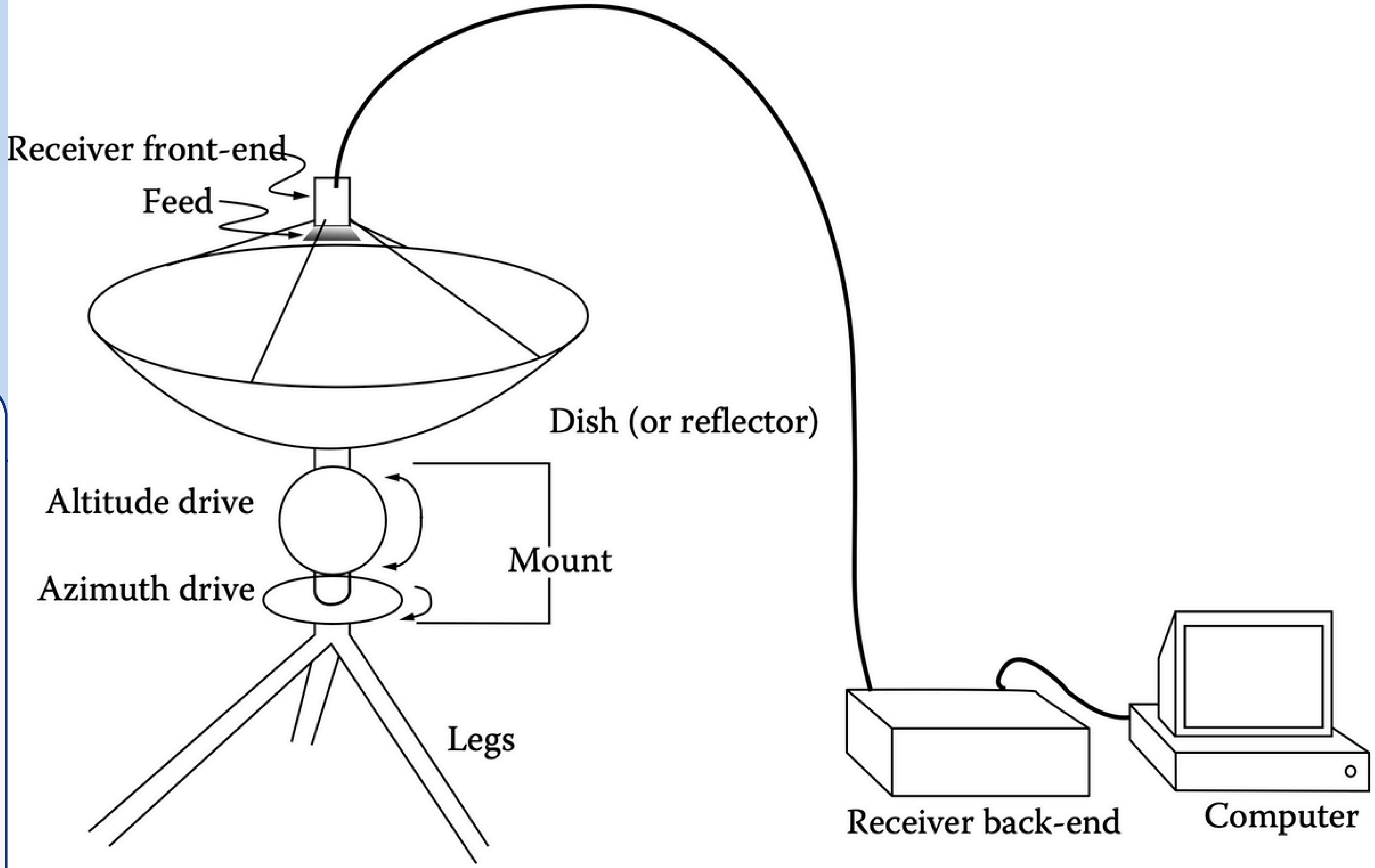


BASIC STRUCTURE OF A TRADITIONAL RADIO TELESCOPE

All modern radio telescopes have altitude-azimuth or *Alt-Az mounts*

With an equatorial mount, the axes correspond to the sky coordinates

Each feed–receiver assembly comprises a single detector



there must be a minimum size for the opening of the feeds, to ensure that the radiation is not reflected, but rather passes through the opening

Radiation Physics

At radio wavelengths (as well as with almost all bands of the EM spectrum except perhaps for X-rays and γ-rays), we generally measure the amount of radiation by its energy, rather than by the number of photons.

Luminosity

One calculates a source's luminosity or power by dividing the amount of energy emitted by the length of time over which the energy was emitted. This yields the rate of emission.

Flux

the amount of light energy per unit time per unit area

The fraction that we detect is given by the ratio of the effective area of our telescope
to the area of the entire spherical shell.

$$F = \frac{p}{A_{eff}} = \frac{L}{4\pi d^2}$$

Radiation Physics (cont.)

Flux Density

Flux density (Fν or Fλ) is the flux per unit frequency (or wavelength) in the observed spectral range

$$F_v = \frac{F}{\Delta v}(or F_\lambda = \frac{F}{\Delta\lambda})$$

Power is given as:

$$P = F_v A_{eff} \Delta v (or P = F_\lambda A_{eff} \Delta\lambda)$$

Intensity

Intensity or *surface brightness* and sometimes just *brightness*, is the flux density per unit solid angle.

Flux density is independent of distance and is a direct measure of the object's surface brightness

$$I_v \approx \frac{F_v}{\Omega} \approx \frac{L}{4\pi \Delta v A}$$

Energy Flux

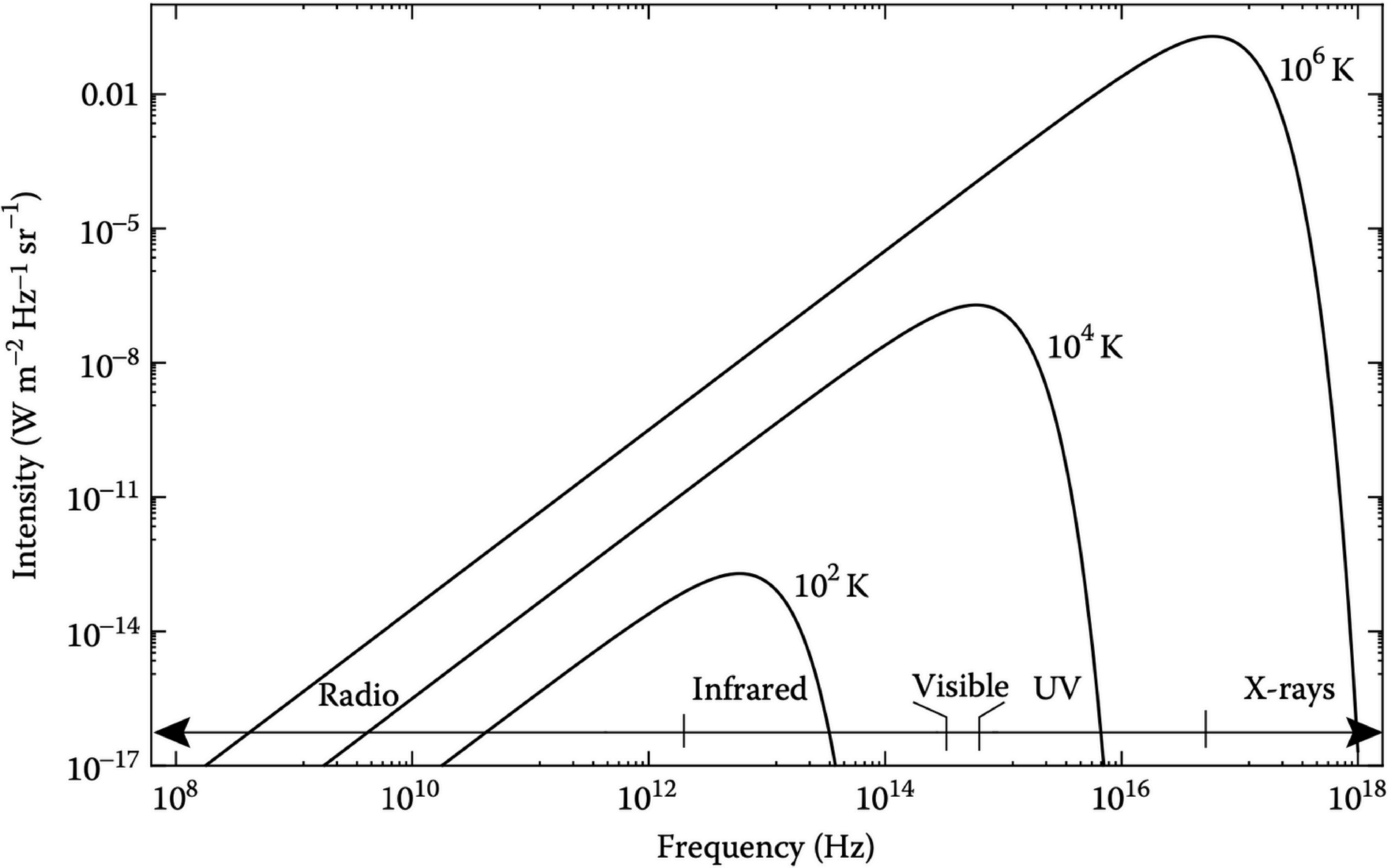
The energy flux of the radiation in terms of those fields is described by a quantity known as the Poynting vector.

$$S = \frac{1}{2} c \epsilon_0 E_o^2$$

Planck Function

In terms of the emitted flux per unit frequency interval per unit steradian, the Planck function is given by:

$$B_V(T) = \frac{2hv^3}{c^2}\frac{1}{e^{\frac{hv}{kT}}-1}$$



$$F = \sigma T^4$$

$$\sigma = 5.67 \times 10^{-8} W m^{-2} K^{-4}$$

This is known as the Stefan–Boltzmann law and the constant is known as the Stefan– Boltzmann constant.

Wien displacement law

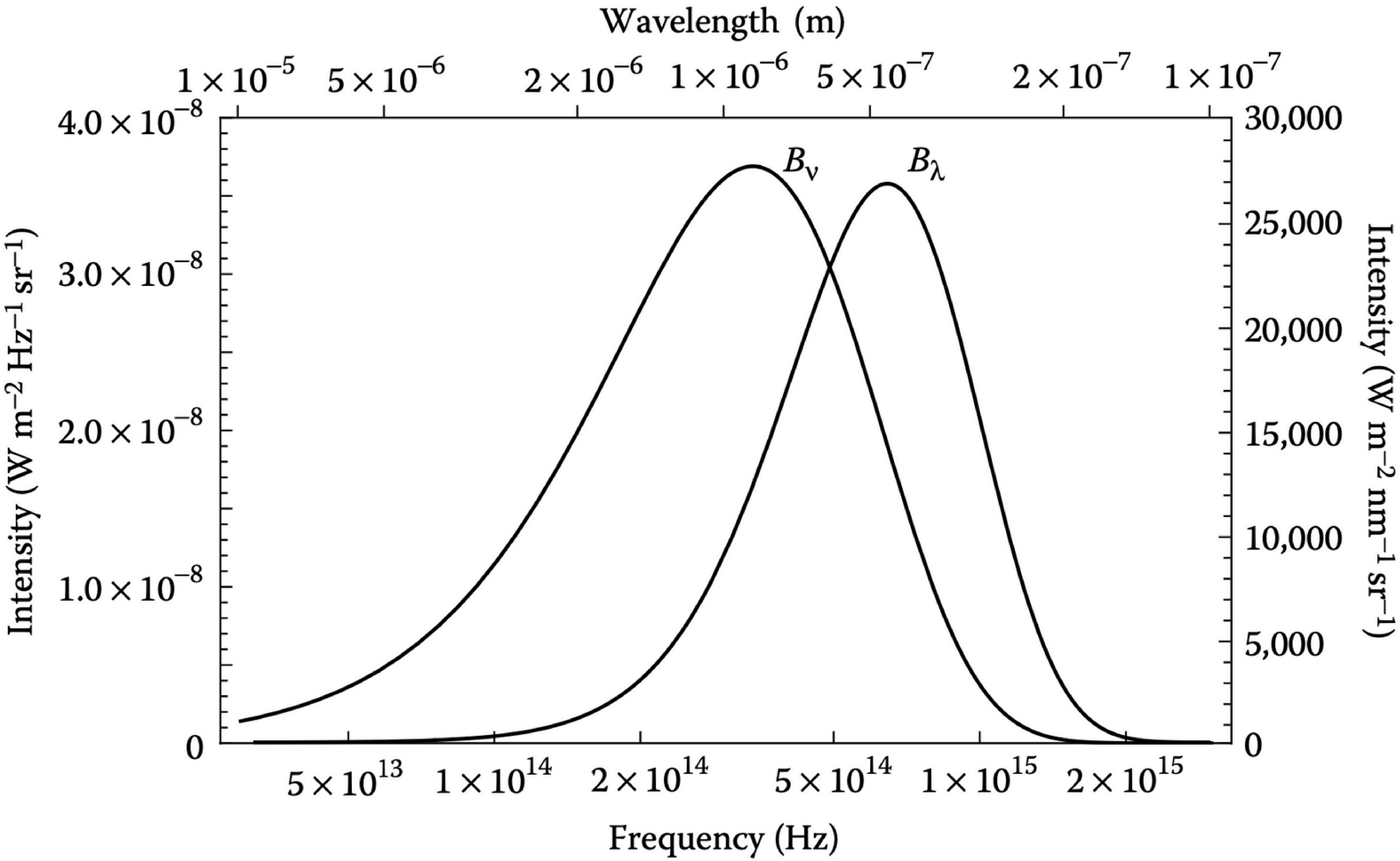
The equation relating to the location of the peak to the body's temperature is called the *Wien displace- ment law*.

$$v_{peak} = (5.879 \times 10^{10} HzK^{-1})T$$

$$\lambda_{peak} = \frac{(2.898 \times 10^{-3} mK)}{T}$$

The functions *Bν(T)* and *Bλ(T)* cannot be the same quantity, for they even have different units.

$$I_\lambda = \frac{c}{\lambda^2} I_v$$



RAYLEIGH–JEANS APPROXIMATION

At most radio wave-lengths, the frequency, ν, is so small that hν/kT << 1 for any reasonable temperature. The exponential in the denominator of the Planck function then can be approxi- mated by a Taylor series expansion.

$$B_v(T) \approx \frac{2kT}{\lambda^2}$$

This expression is known as the *Rayleigh–Jeans approximation*, often referred to as the *Rayleigh–Jeans law*.
only at the highest radio frequencies and with observations of cold objects does the approximation start to differ from the full expression

Brightness Temprature

- the radiation intensity from a thermal source is related to, and is a rough measure of, the source temperature
- In the Rayleigh–Jeans approximation, we define the brightness temperature, TB, as

$$T_B = (\frac{\lambda^2}{2k})I_v$$

TB is a property of the *radiation*, not the emitting object

Coherent Radiation

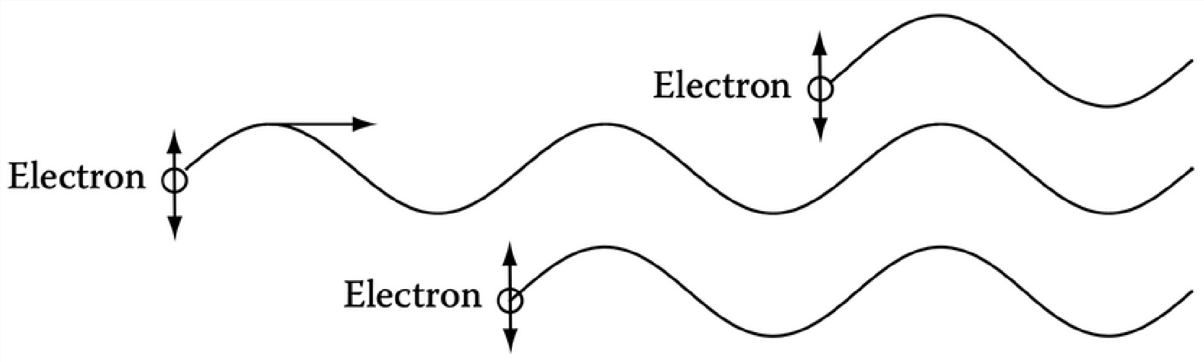
Coherence of radiation is often defined as when radiation at any location in space and time has a specific phase

intensity of the light is proportional to the square of the electric field, averaged over time

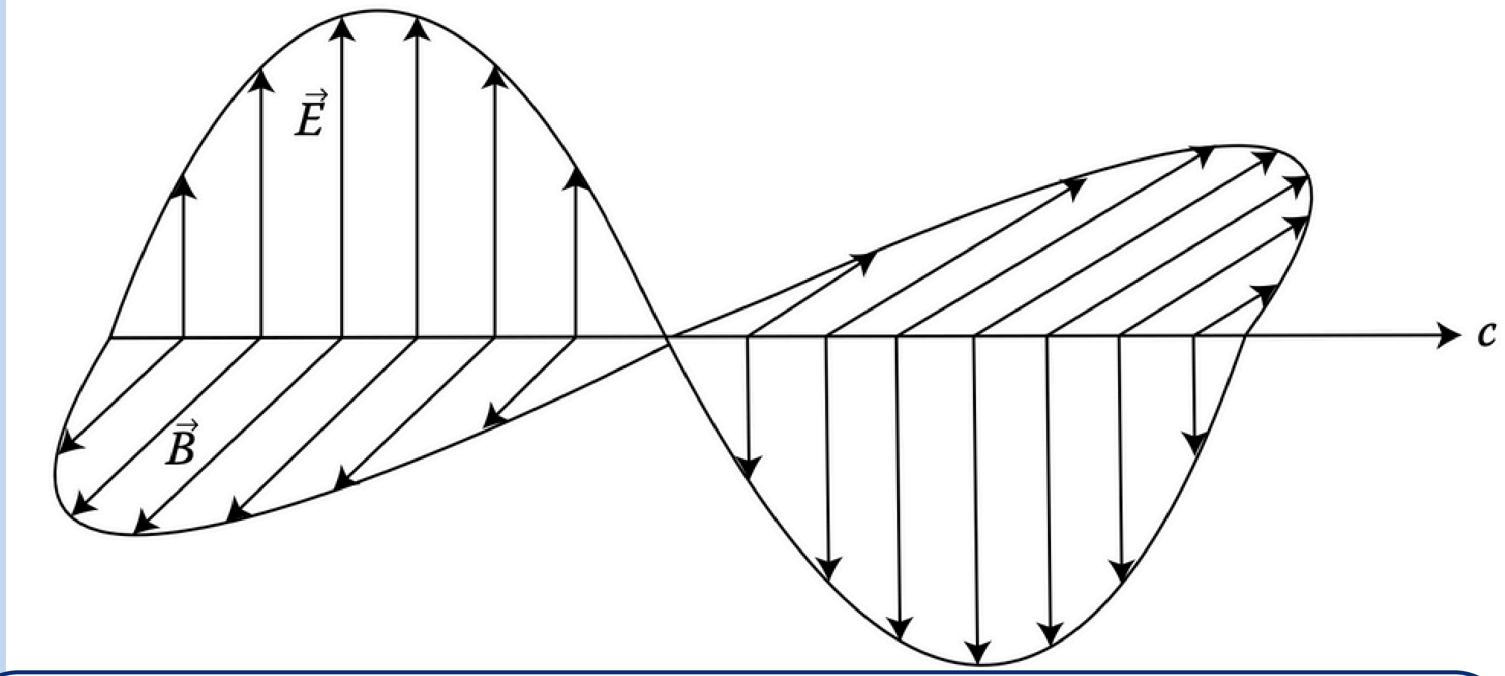
with incoherent light, the total intensity equals the sum of the component intensities, whereas with coherent light, the total intensity grows as the square of the sum of the component intensities.

$$I \propto E^2$$

$$F_v = \int I_v d\Omega dv$$



Polarisation of Radiation



The consequence of differing phases for the x- and y-components is that the total electric field vector rotates as it travels.

Types of Polarisation:

- *circular polarization*
- *elliptical polarization*
- *linear polarization*

STOKES PARAMETERS

$$I = I_x + I_y$$
$$Q = I_x - I_y$$
$$U = I_a - I_b$$
$$V = I_R - I_L$$
$$L = \sqrt{Q^2 + U^2}$$

if the detected radiation has no net polarization, linear *or* circular, then

$$Q = V = U = 0$$

The total fractional polarization can in general be expressed as

$$\frac{\sqrt{Q^2+U^2+V^2}}{I}$$

The polarization angle is related to *Q* and *U* by

$$\theta = \frac{1}{2}tan^{-1}(\frac{U}{Q})$$

The degree of ellipticity is determined from Stokes parameters by

$$\beta = \frac{1}{2}tan^{-1}(\frac{V}{Q})$$

Radio Telescopes

- At shorter wavelengths, one detects the particle nature of light, meaning the individual photons.
- Radio photons, which have energies of order 10−5 eV, are usually insufficient to produce a measurable effect in a semiconductor device.

At radio wavelengths we must understand the detection of the radiation in terms of large ensembles of photons and make use of the wave nature of light.

RADIO TELESCOPE REFLECTORS, ANTENNAS, AND FEEDS

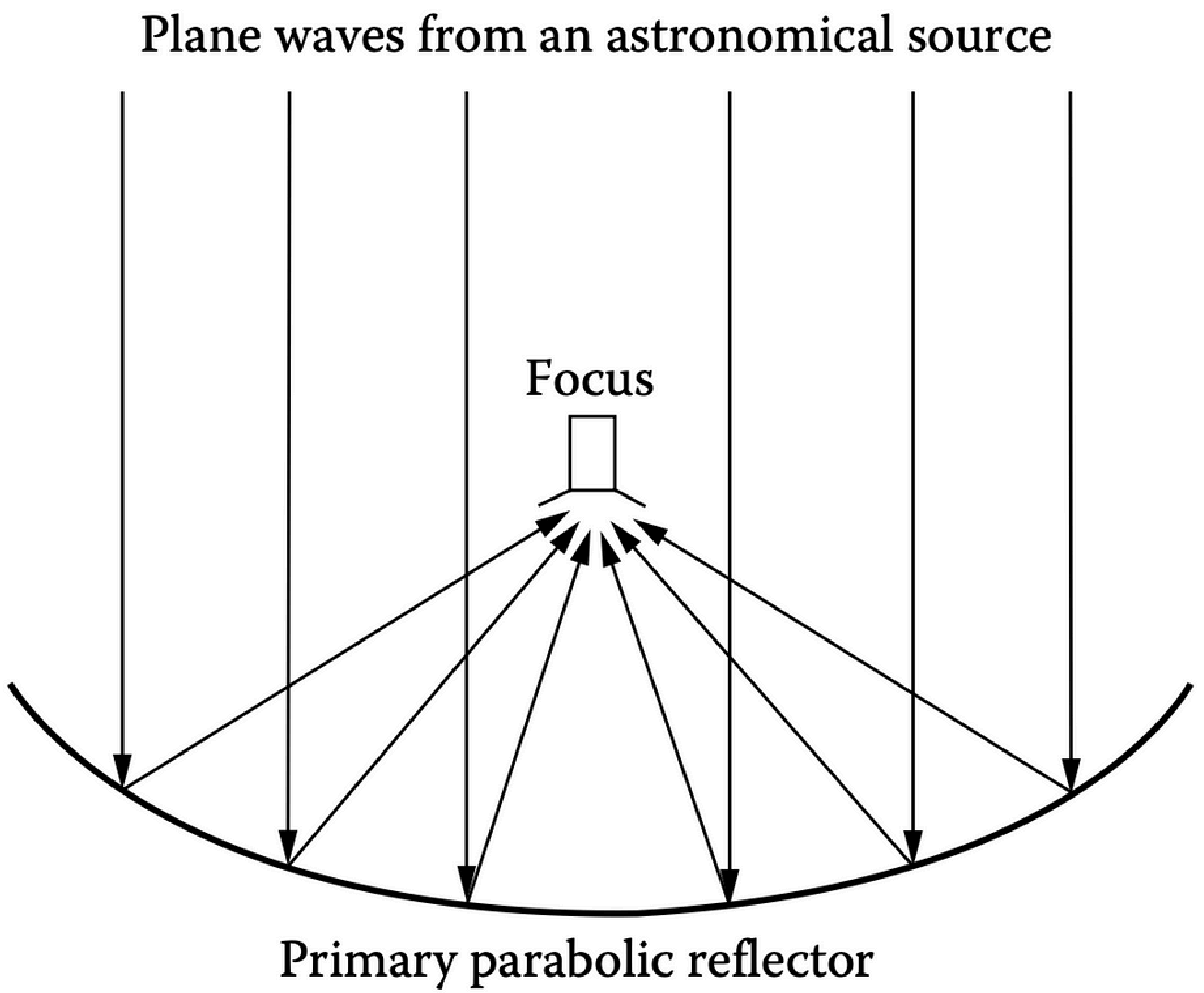
- An **antenna** is a device that couples electromagnetic (EM) waves in free space to confined waves in a transmission line, while **reflectors**, which are usually parabolic in shape, collect and concentrate the radiation.
- Most large radio telescopes employ a **reflector** as the first element, but they still need an antenna to couple the EM waves into a transmission line, which then carries these waves to the **receiver**.
- the **dish**, which is often used to refer to the reflector, and the **feed**, which is the device that couples the radiation concentrated by the reflector into a trans- mission line.

Primary Reflector

- The parabolic shape causes all waves approaching the dish from the direction perpendicular to the entrance plane to come to a single point, known as the focus of the telescope
- It collects and focuses the radiation from astronomical sources, making faint sources more detectable. The amount of radiation collected depends on the telescope's *effective area* (Aeff), which is closely related to the physical area of the primary reflector.

$$P = F_v A_{eff} \Delta v$$

- primary reflector provides directivity, which is a telescope's ability to differentiate the emission from objects at different angular positions on the sky.



This is a prime focus telescope because the feeds (and receivers) are placed at the focus of the primary reflector.

Beam Pattern

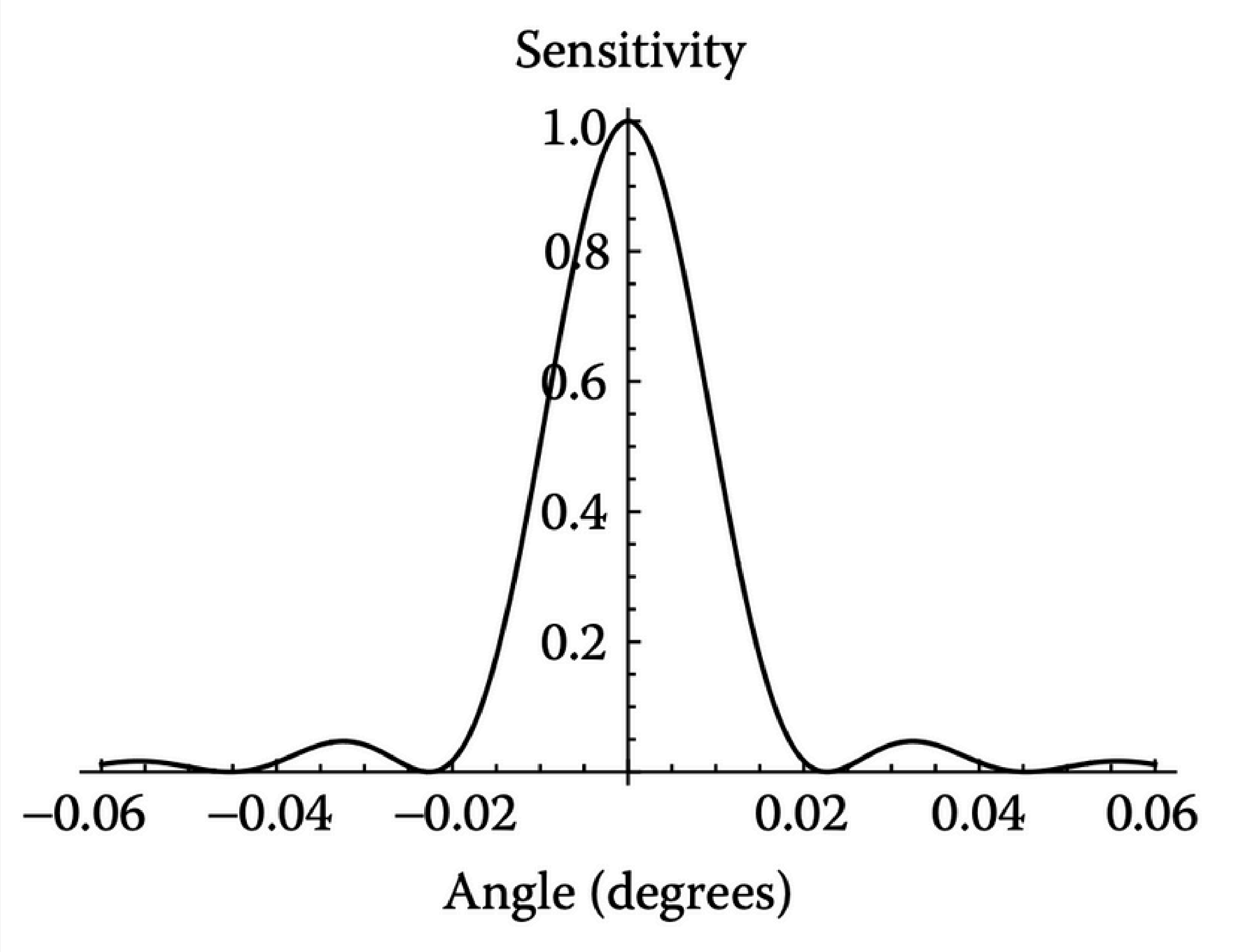
The beam pattern is a measure of the sensitivity of the telescope to incoming radio signals as a function of angle on the sky. A more precise calculation of the beam pattern of a radio telescope can be made using the Fourier transform.

For a source located at a small angle, θ, expressing the phase difference in radians gives:

$$\Delta\phi = 2\pi\frac{\Delta s}{\lambda} = 2\pi\frac{L\theta}{\lambda}$$

The canonical resolution angle of a visible-wavelength telescope is

$$\theta_{res} = 1.22\lambda/D$$



The width of the central peak of the Airy pattern is used to define the angular resolution of a single-dish telescope. By custom, we measure the angular width of this peak between the two points where the received power falls to one-half of the on-axis value. We call this angle the full width at half maximum (FWHM) of the main beam of the telescope.

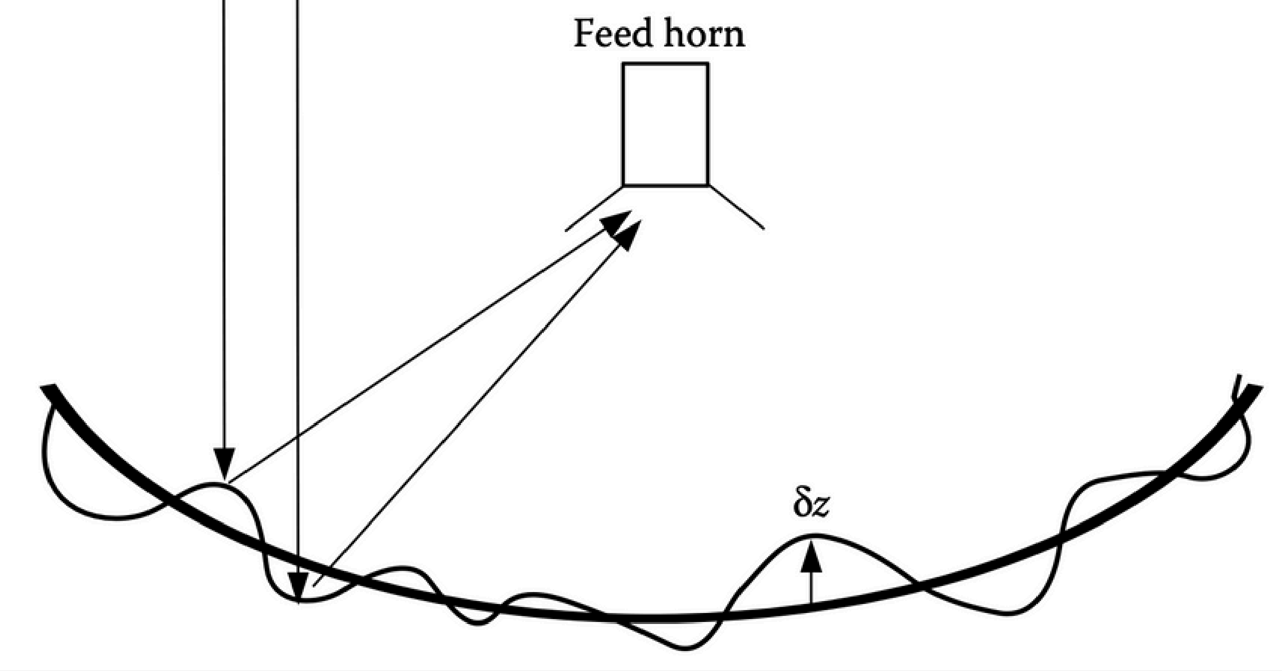
These off-axis responses are called sidelobes and are undesirable as they can add confusion to observations

Feeds and Primary Reflector Illumination

The flared end of the horn has a size at least as large as the wavelength of the light

At the focus of a radio telescope, we need antennas to couple the EM waves in free space into waves confined to transmission lines, so that we can send the waves to the receivers. Each feed is connected to one receiver, each of which produces a single measure of detected power.

Edge taper, which is defined as the ratio of the sensitivity at the center of the reflector to that at the edge, is proportional to λ/D, where D, now, is the size of the large flared end of the horn.
A large edge taper optimises the spillover efficiency, while a small edge taper optimizes the illumination efficiency.



Surface Errors

- The primary reflector of a radio telescope is never a perfect parabola
- path differences cause phase differences that produce less than full constructive interference; therefore, these deviations reduce the power collected by the telescope

The Ruze Equation is given by

$$A_\delta = A_0 e^{-(4\pi\delta z/\lambda)^2}$$

- a reflector should have rms surface errors less than 1/20th of the wavelength of the light being detected to have a reasonable performance.
- reasons as to why the effective collecting area of a telescope is smaller than the physical area of the reflector the loss due to limited surface accuracy, the loss due to the illumination pattern, and the loss due to physi- cal blockage by the feed horn and receiver or by the secondary reflector. One should not be surprised that large radio telescopes have effective collecting areas that are only about one-half of the physical area of their primary reflector.

Noise, Noise Temperature, And Antenna Temprature

All the components in the receiver, especially the amplifiers, generate their own electrical signals that propagate through the receiver and are unrelated to the signal from the astronomical source. The power measured coming out of the detector, then, includes these extra signals. These extra signals are undesirable, but cannot be avoided. We call this unwanted signal noise

A resistor in the circuit will add electrical noise with a power per Hz that depends solely on the resistor's temperature. For this reason, the electronic power in a circuit, in general, can be described in terms of an equivalent temperature, Tequiv, which is equal to the temperature of a resistor that would produce the same amount of power as the resistor

$$T_{equiv} = \frac{P}{k\Delta v}$$

We call the equivalent temperature of the power that the antenna delivers to the transmission line, the antenna temperature, T_A.

We describe the total noise power by the noise temperature, TN, and each component in the receiver is characterized by its own noise temperature

The equivalent temperature of the final power output is not simply the sum of the equivalent temperatures of all the sources in the path.

$$P = Gk\Delta v T_A$$

At each stage, the source signal is either amplified (when passing through an amplifier) or reduced by a loss, when passing through an amplifier, G > 1, and when there is a loss, G < 1.

The total noise produced by all the components in the receiver is called the receiver noise temperature,

$$T_N = T_{N1} + \frac{T_{N2}}{G_1} + \frac{T_{N3}}{G_1 G_2} + \ldots$$

Accounting for the noise power coming out of all the amplifiers, the power becomes:

$$P = Gk\Delta v(T_A + T_N)$$

The switched observations remove the *offset* in the measured power caused by the noise, but the *fluctuations* in the noise power still affect our measurement and dominate our uncertainty in the antenna temperature.
the variance in power must relate to fluctuations in the arrival rate of the photons. The power in the radiation is also proportional to *E^2* in the waves, and so the variance also depends on the fluctuations in the waves.

$$\sigma^2 \propto n + n^2$$

where, $n = \frac{1}{e^{hv/kT} - 1}$