Basics of radio astronomy IV

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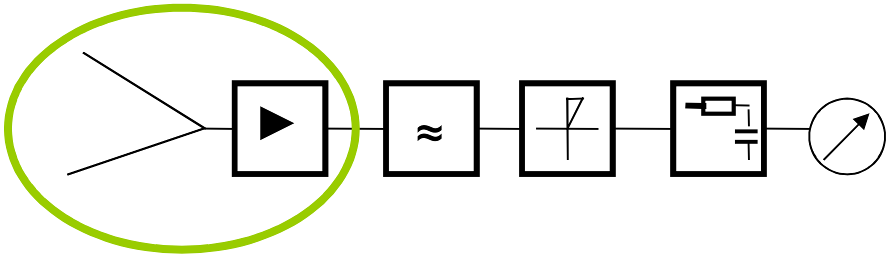
Radiometer: Feed and Amplifier



An electromagnetic wave is measured which has a well-defined relationship between amplitude and phase. The free wave is adapted by the feed onto the dipol. Which transforms the EM wave to a cable. The high-electron mobility transistor (HEMT) enhances the signal by 10^3 to 10^6.

The bandpass selects a part of the frequency spectrum. This selection limits the receivable variation variety of the signal!

The diode converts the voltage variations into currents.

These current variations are summed up in the integrator over a certain period of time and then read out at the measuring device.

We therefore analyze the variation variety of the signal in a certain band averaged over a time interval.

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Radiometer equation

$$\sigma_T \approx \frac{T_{sys}}{\sqrt{\Delta\nu \cdot \tau}}$$

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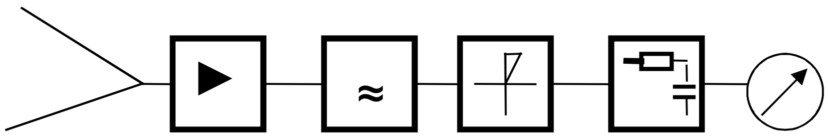
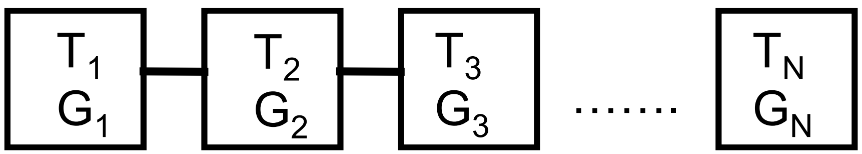
Temporal stability of receivers

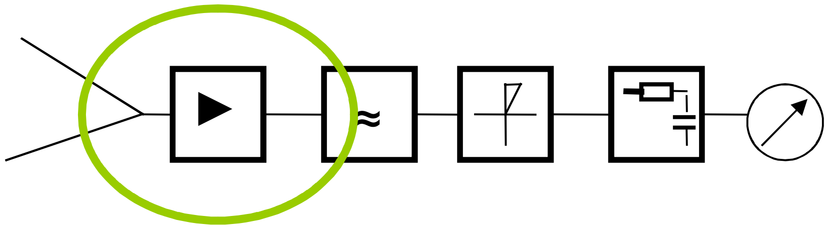
The thermal noise of the first amplifier





$$T = T_1 + \frac{T_2}{G_1} + \frac{T_2}{G_1 * G_2} + \ldots + \frac{T_N}{G_1 * G_2 * \ldots * G_{N-1}}$$

Amplifiers are not stable noise sources!



$$S_v = G * k * T_{Sys}$$

$$\Delta S_v = \Delta G * k * T_{Sys}$$

Radiometer equation: Amplifier variations

- Amplifier fluctuations occur, for example, due to thermal fluctuations. Therefore, they also follow a statistical distribution and cannot be distinguished from the statistical fluctuation of the signal.

- The variances add up:

$$\sigma^2_{\text{total}} = \sigma^2_{\text{noise}} + \sigma^2_{\text{amplifier}}$$

- Thus, the practical radiometer equation is :

$$\sigma_{\text{total}} \simeq T_{Sys} * \sqrt{\left[\frac{1}{\Delta\nu\ \tau} + \left(\frac{\Delta G}{G}\right)^2\right]}$$

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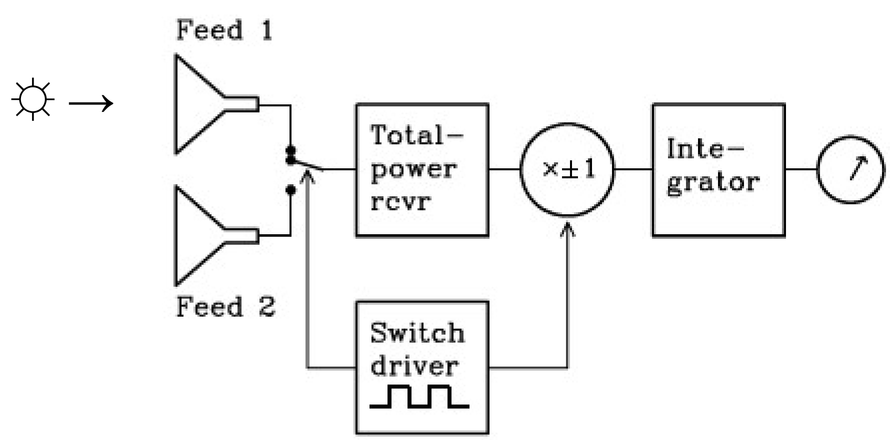
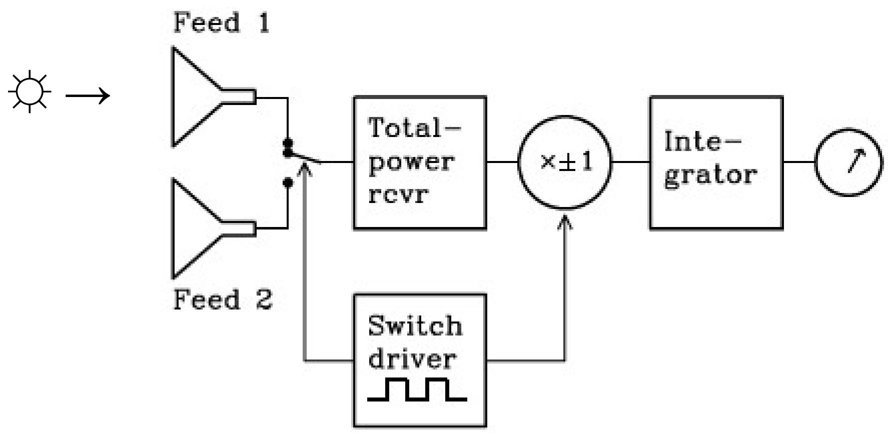
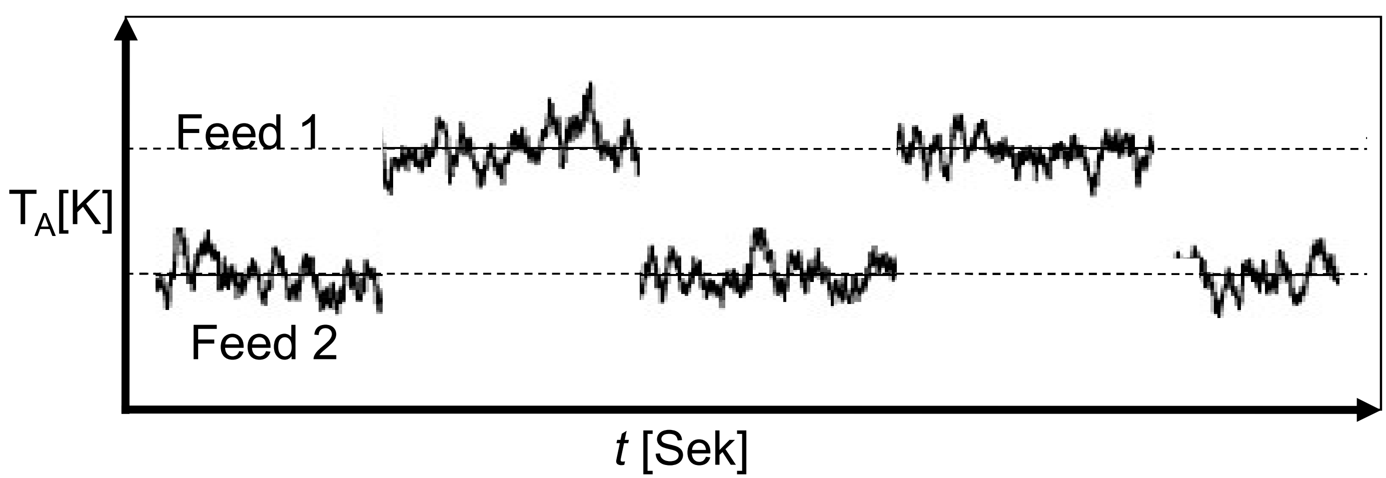
Dicke receiver

- In order to separate the statistical fluctuations, generated by the amplifier fluctuations, and also the noise of the Earth's atmosphere from each other, measurement methods have to be applied which allow a differential measurement. One such measurement method is the Dicke receiver.



Dicke receiver





Dicke receiver

Switching between the horns therefore causes a measurement of the:

statistical fluctuations of horn 1 (Feed 1),

statistical fluctuations of horn 2 (Feed 2),

statistical fluctuations of the atmospheric emission.

Switching is performed at 10 to 1000 Hz, so that even the smallest and shortest fluctuations in the amplifier chain can be detected.

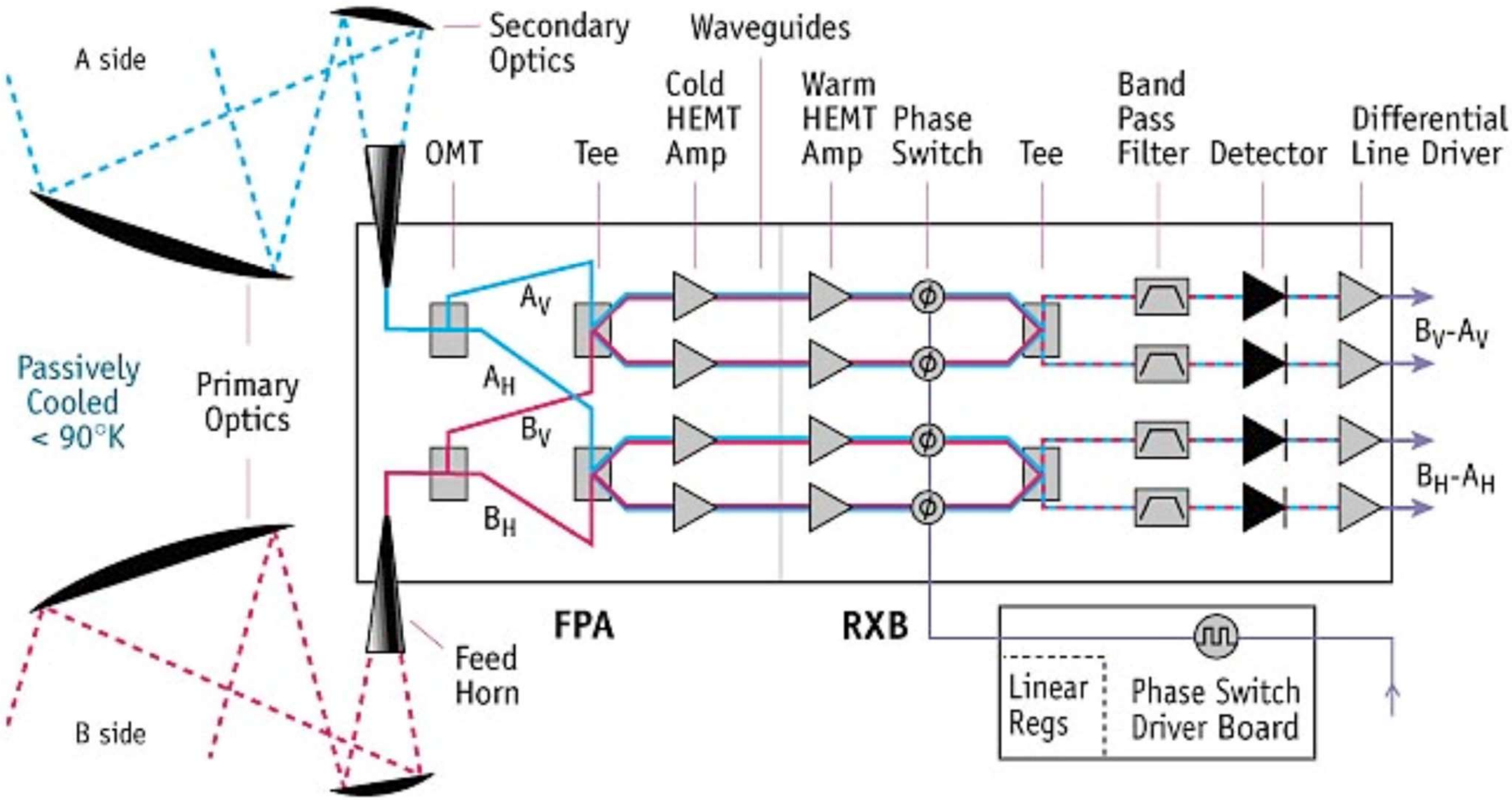
$$\Delta T_{\text{Ampl.}} \simeq \left(T_1 - T_2\right) * \frac{\Delta G}{G} << T_1 \frac{\Delta G}{G}$$

Disadvantage:

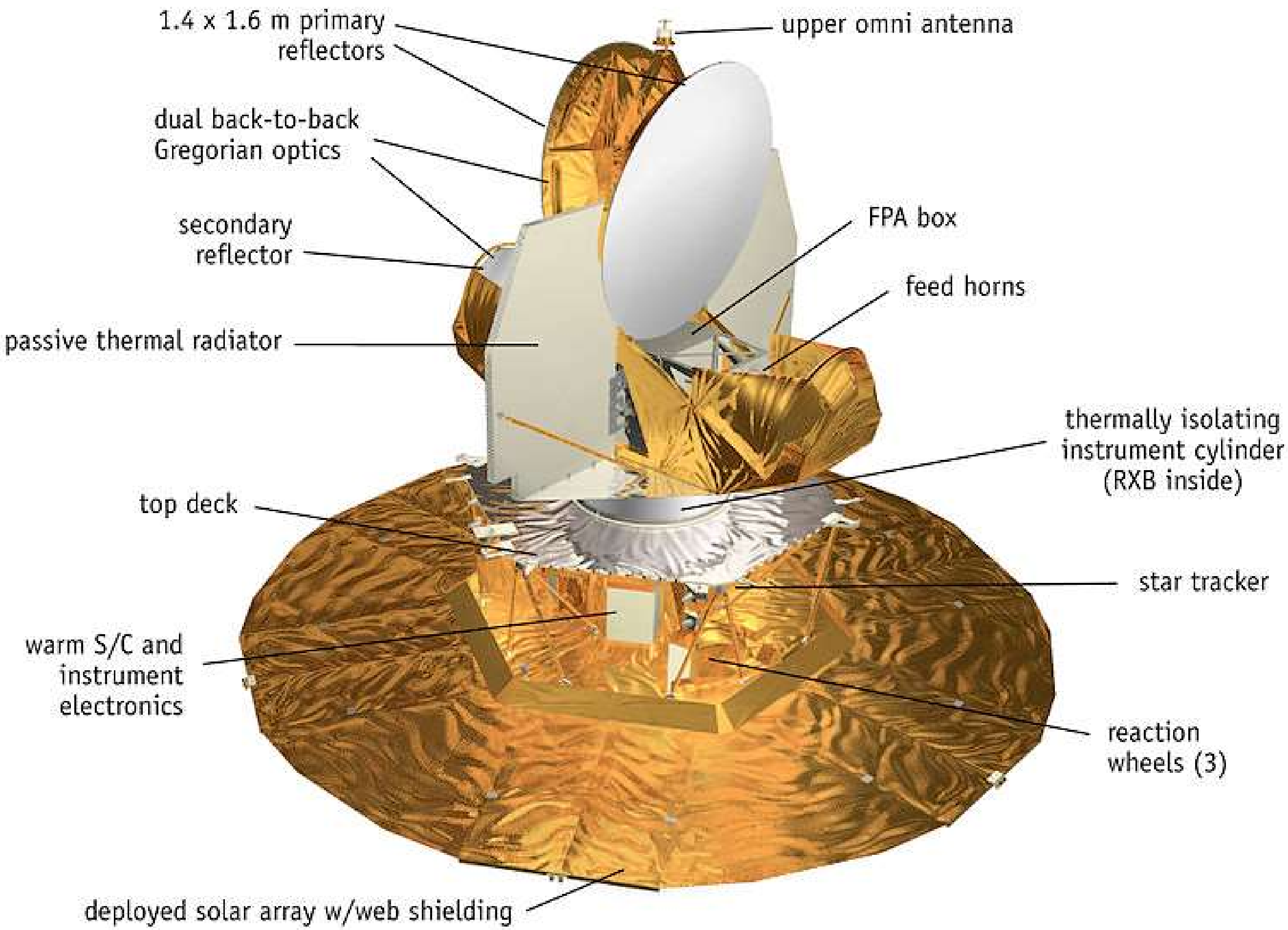
$$\Delta T = \frac{2 * T_{Sys}}{\sqrt{\Delta \nu \ \tau}}$$

WMAP: Dicke receiver

$$\Delta T = \frac{\sqrt{2} * T_{Sys}}{\sqrt{\Delta\nu\ \tau}}$$



WMAP: Wilkinson-Microwave Anisotropy Probe



Why was WMAP a sattelite observatory?

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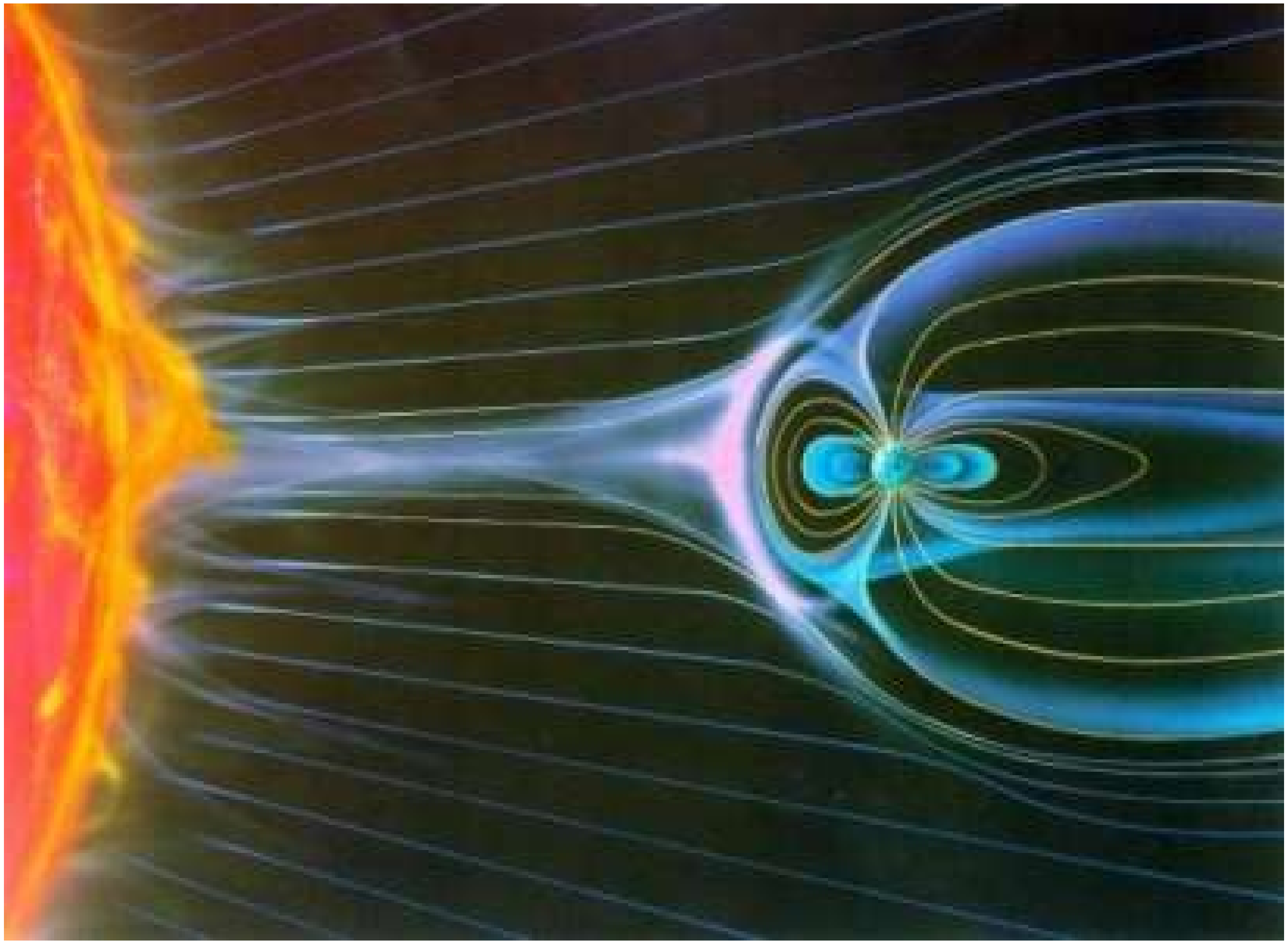
Electromagnetic waves: Earth‘s atmosphere

The sun sends about 1.3 kW s^{-1} (solar constant) of radiation to the Earth. This ionizing radiation leads to the formation of the ionosphere, where ions and electrons dominate. The troposphere (weather layer) hosts a mixture of molecules and ions/electrons.



http://www.esa.int

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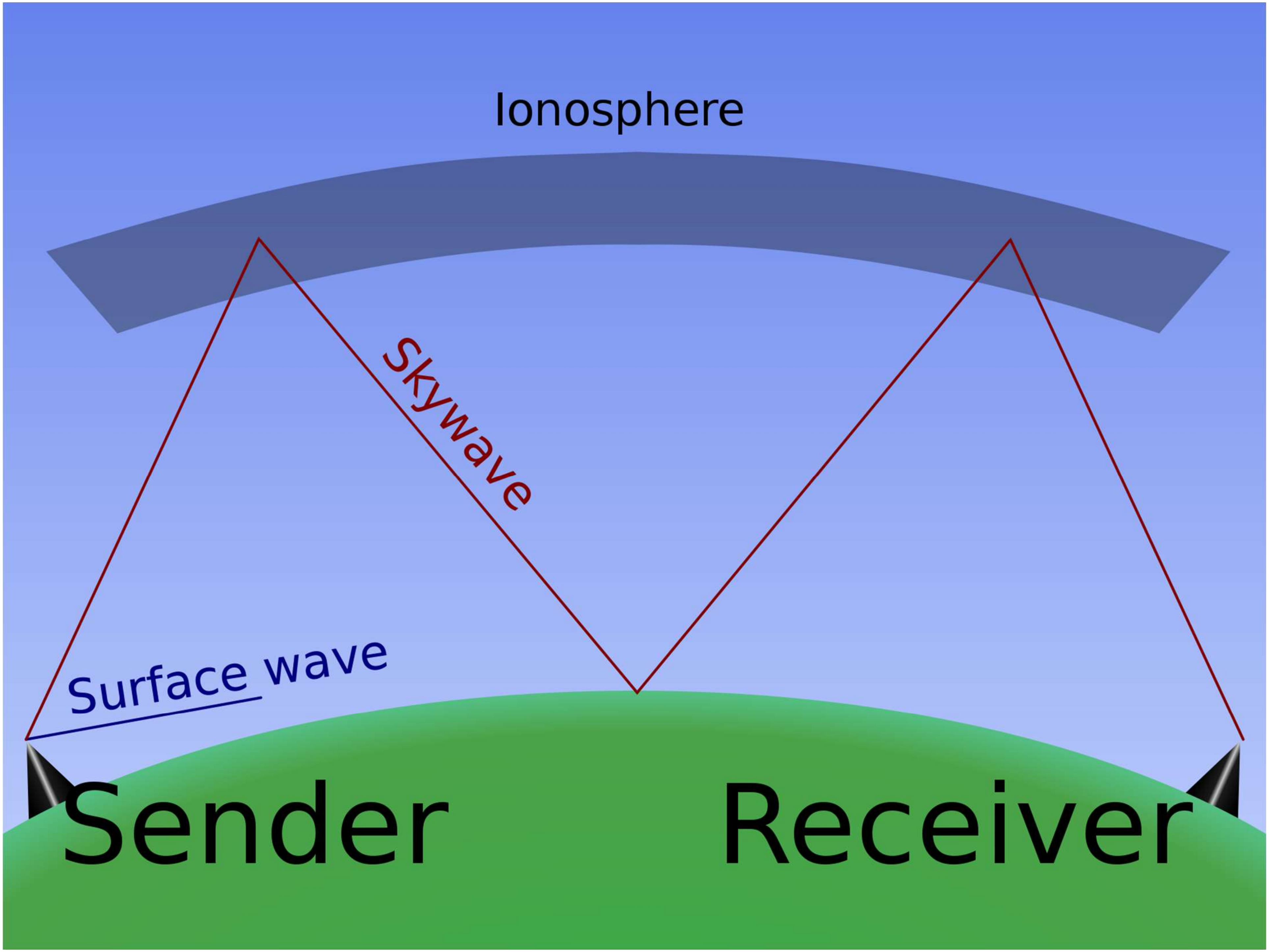
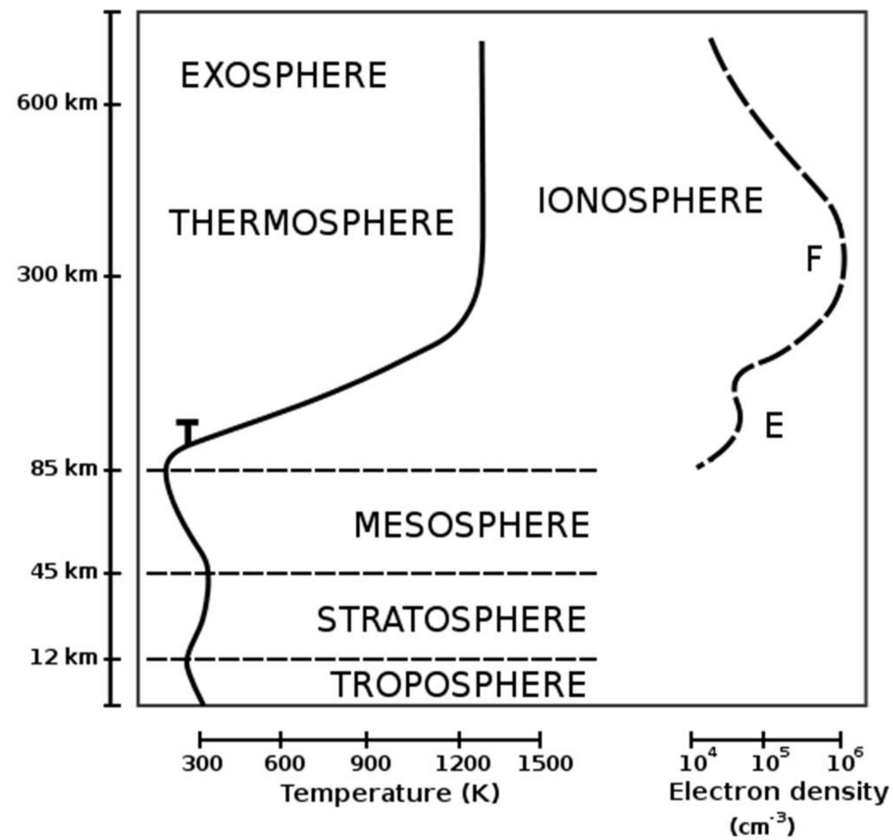

Ionosphere
Skywave
Surface wave
Sender
Receiver

Electromagnetic waves: Earth‘s atmosphere

- The main physical interactions between the electromagnetic wave and the Earth's atmosphere occur in the
- Ionosphere
- Troposphere
- The following effects are observed:
- Reflection (ionosphere)
- Rotation of polarization (ionosphere)
- Absorption (troposphere)
- Refraction (ionosphere and troposphere)
- Scintillation (ionosphere)



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Electromagnetic waves: Earth's atmosphere

The free electrons of the ionosphere do not allow the propagation of EM waves below a cut-off frequency ν_{min}.

ν_{min} = 3 MHz (solar minimum)

ν_{min} = 24 MHz (solar maximum).

Below this cutoff frequency, the signals are reflected back into space.

Depending on the solar irradiance, the cutoff frequency varies on different time scales.

n_e is the electron density and *m* the electron mass.

$$n = \sqrt{1 - \frac{4\pi n_e e^2}{m\omega^2}}$$

$$\nu_{\min} = \sqrt{\frac{e^2 n_e}{m\pi}}$$

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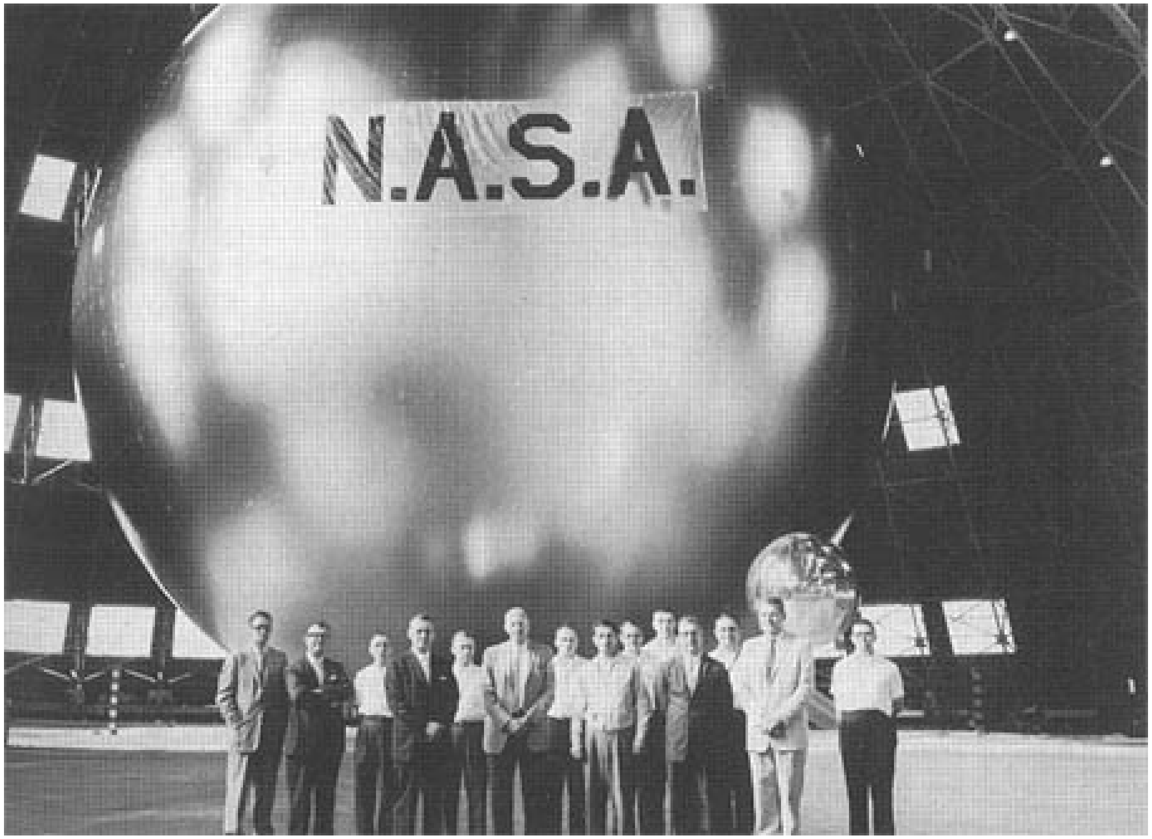
Echo Project: 1960 - 1964



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The Echo Project tried at higher frequencies that are not reflected from the ionosphere. High frequencies can transmit more information. The Echo satellites were about 30m (ECHO1) and 40m (Echo2) satellites consisting of a 0.2 micrometer thin Mylar foil. They were designed to reflect a signal sent from the earth and to receive this reflection at another location. Today satellite transponders are used.

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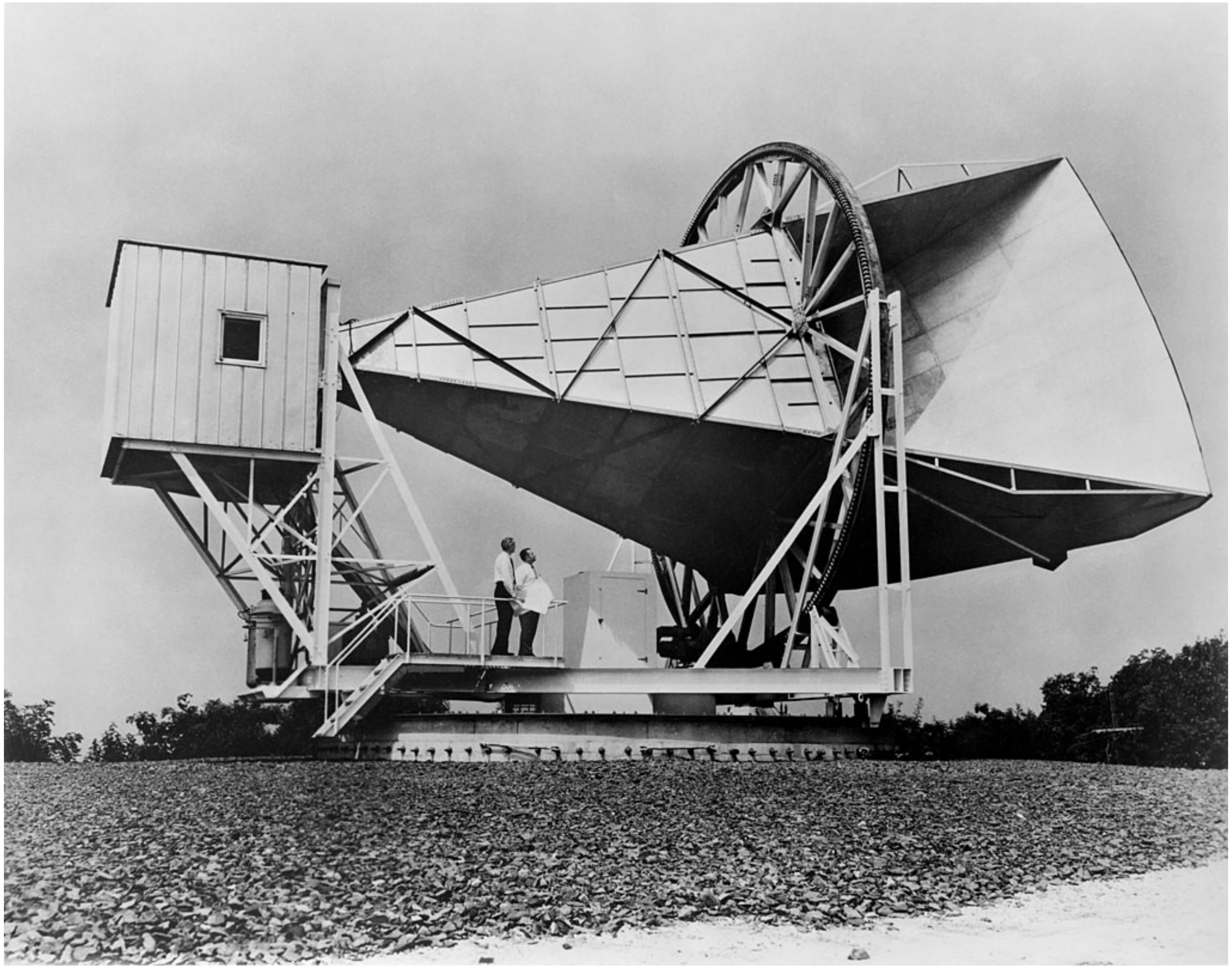
Echo Project: 1960 - 1964



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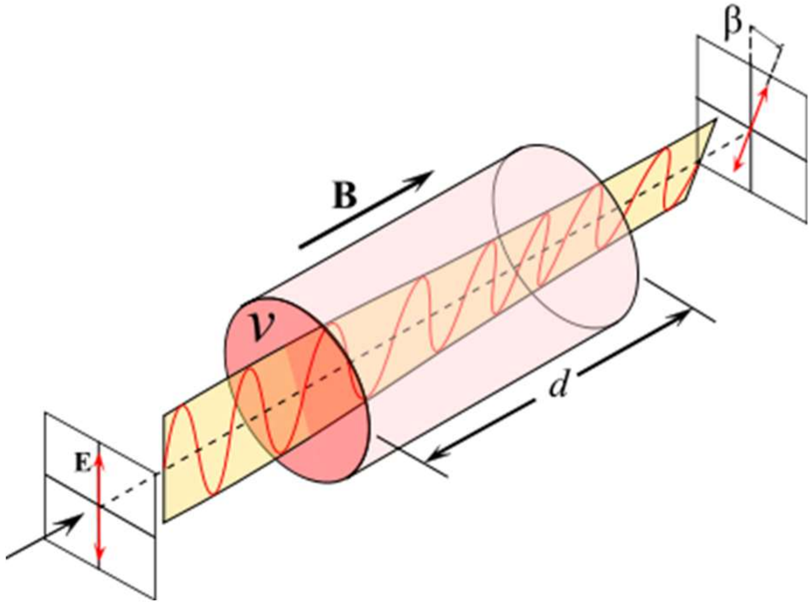
Part of the Echo Project was the Holmdel antenna in New Jersey which became world famous in 1965.
With it, Pensias and Wilson discovered the cosmic microwave background. The antenna is a single feed. It has no mirror! The feed is so huge that it focuses the radiation directly on the Hertzian dipole.

Earth's atmosphere: Faraday rotation

- The Earth's magnetic field causes a phase shift of the EM wave. If we imagine a circularly polarized wave, generated from two linearly polarized wave trains along with phase shift, then proportional to the thickness of the ionized layer and the magnetic field along the line of sight, the phase is shifted.
- This effect is called *Faraday rotation*.



$$RM = 0.81 \int_0^{r_0} \left(\frac{n_e}{\mathrm{cm}^{-3}} \right) \left(\frac{B_{\parallel}}{\mu\mathrm{G}} \right) \left(\frac{dr}{\mathrm{pc}} \right) \mathrm{rad\ m}^{-2}$$

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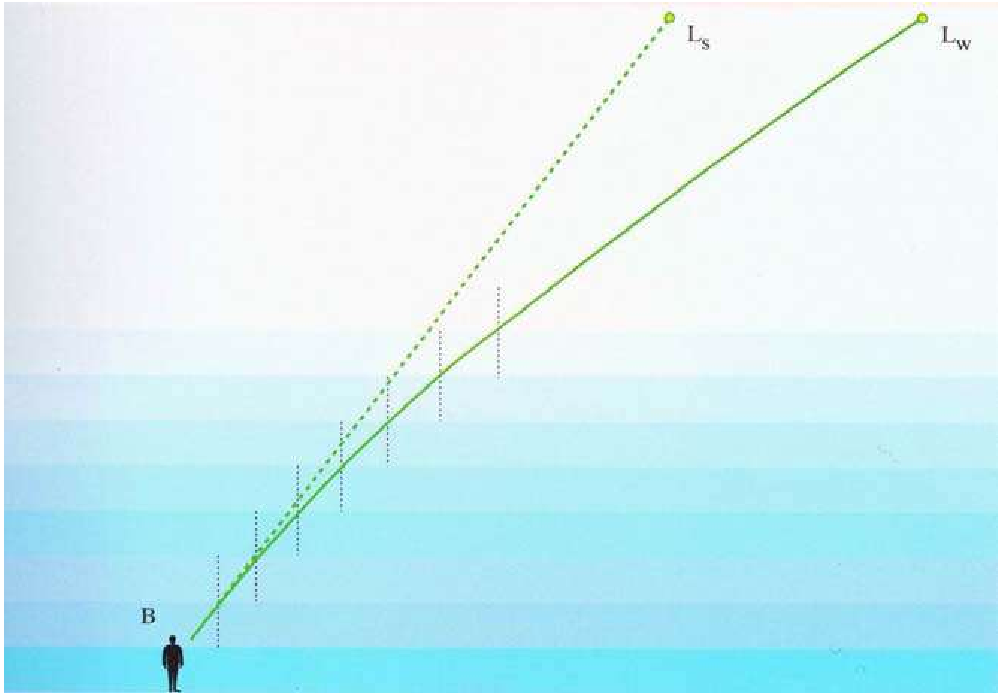
https://www.universetoday.com/tag/atmospheric-refraction/

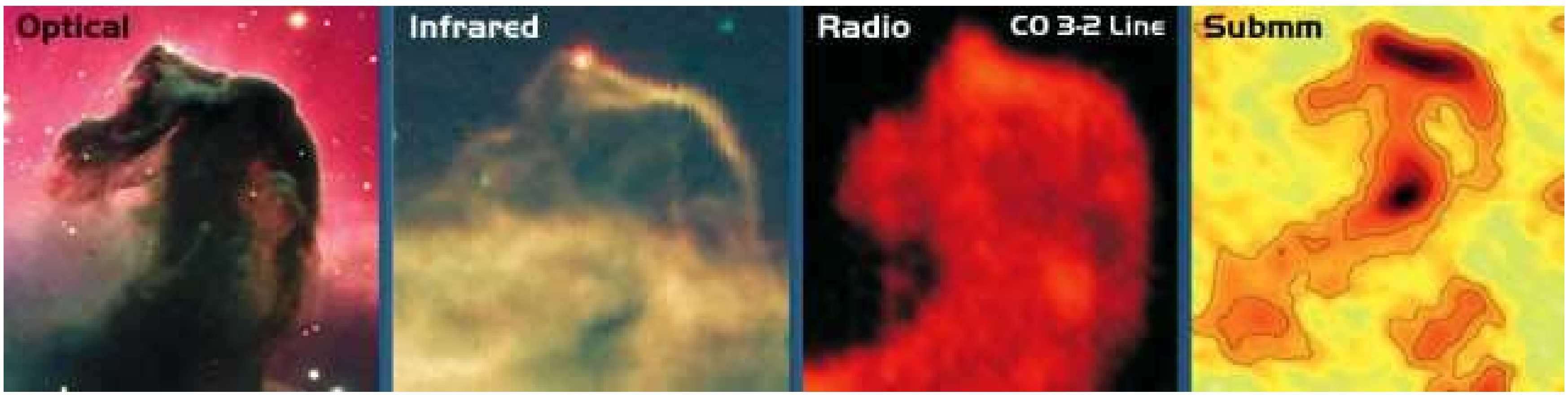
Earth‘s atmosphere: refraction

- Near the cutoff frequency, the refractive index of the ionosphere varies significantly. Such refractive index variations also exist in the troposphere. This causes the source to appear to be higher in the sky at the horizon.
- At the horizon, the refraction in the radio range is almost 1°.

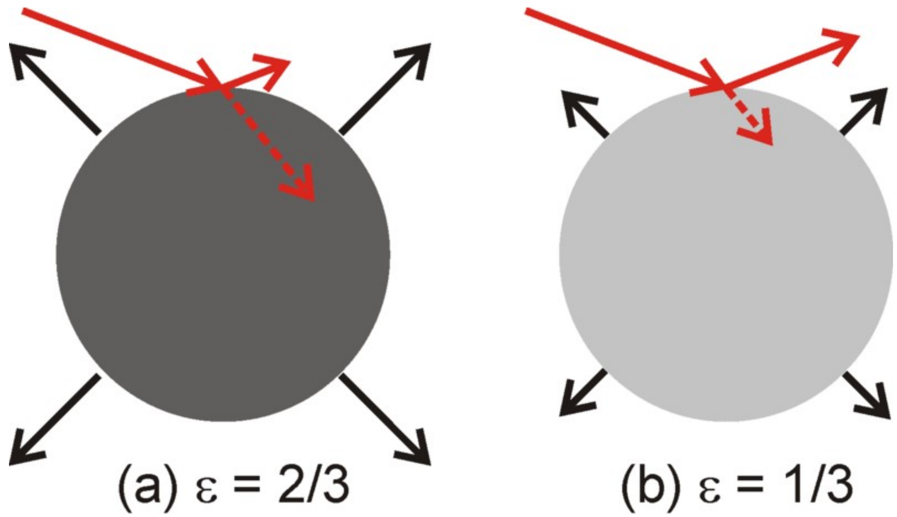


$$\Delta Elevation(\lambda) = (n_0(\lambda) - 1) \cdot \tan(z)$$

Kirchhoff's law of thermodynamics



Earth‘s atmosphere: Kirchhoff‘s law



$$\frac{dU}{dT} = C_{\nu}^{'} - C_{\nu}^{''}$$

- According to Kirchhoff’s law of thermodynamics, there is a direct relationship between emission and absorption of a body in thermodynamic equilibrium.

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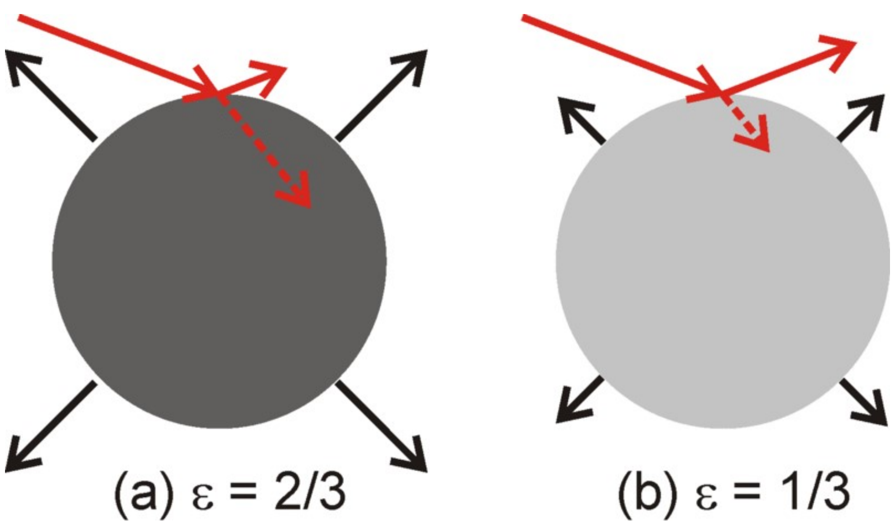
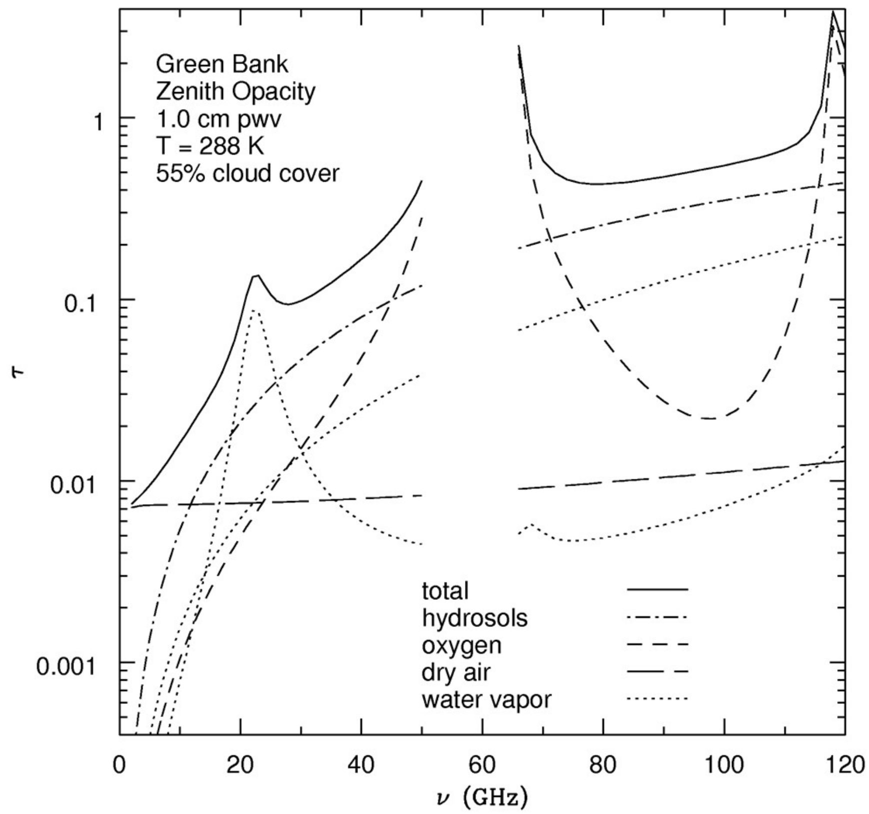
Earth‘s atmosphere: Kirchhoff‘s law



- If a body absorbs electromagnetic radiation well, it also re-emits this amount of energy.
- For the Earth's atmosphere, this means that the amount of energy absorbed by the molecules must be re-emitted.
- This radiation is thermal and its radiation characteristics can be described by a statistical noise.
- Changes in the atmosphere and the solar radiation therefore lead to different radiations.

Earth‘s atmosphere: absorption

- On the right is logarithmically plotted the attenuation of the radio astronomical signal in the GHz range for a "normal" astronomical site.
- Molecular oxygen has a permanent magnetic dipole moment. This absorbs almost completely the radio radiation between 52 and 68 GHz. The width of the lines is determined by the air pressure.
- At 22 GHz we see the attenuation of the water vapor. The air pressure widens the line to 4 GHz.
- Hydrosols are smallest water droplets (r ~ 0.1 mm), whose effect can be described by Rayleigh scattering.



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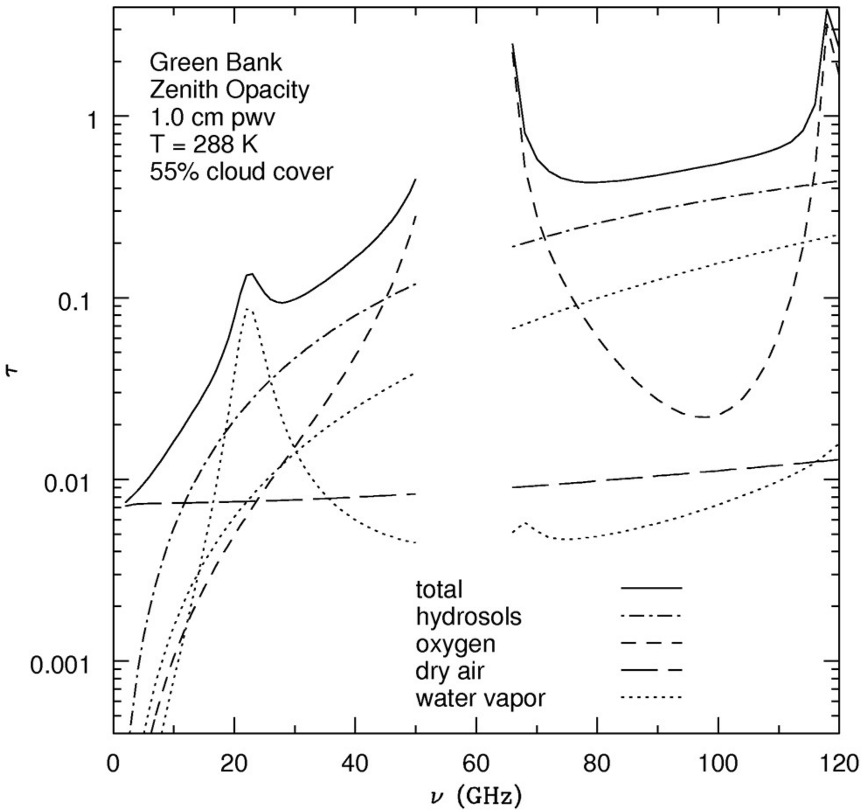
Earth‘s atmosphere: emission



- The Earth's atmosphere emits thermal radio radiation.
- This thermal radiation is strong in the frequency ranges where also much energy is received or absorbed. The energy levels and excitation and de-excitation mechanisms of the atmospheric molecules cause only small shifts.
- Thus, not only the astronomical signal is strongly attenuated, it is also overlaid by strong atmospheric noise.

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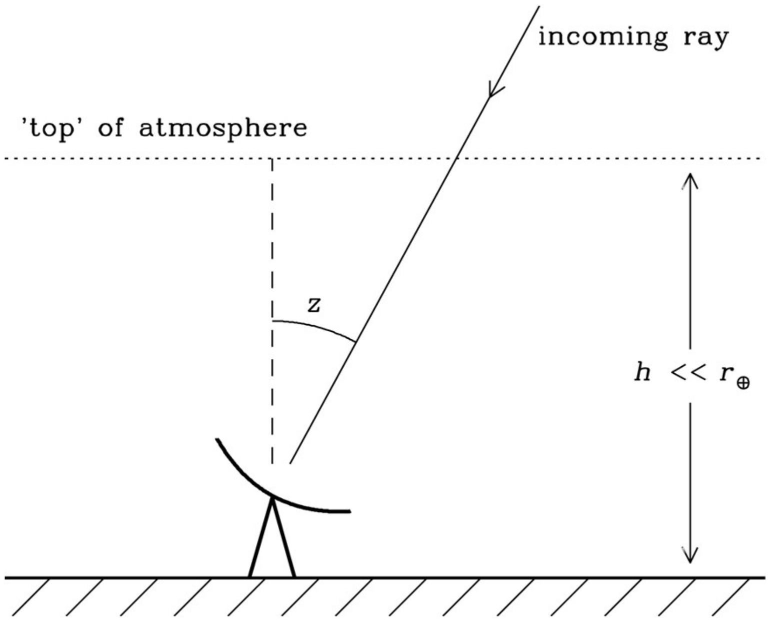
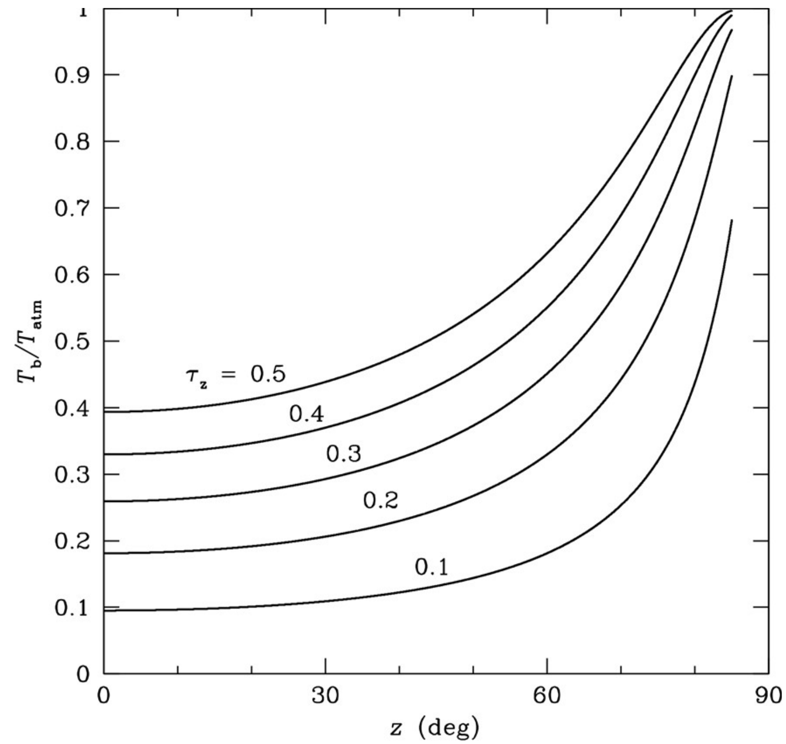




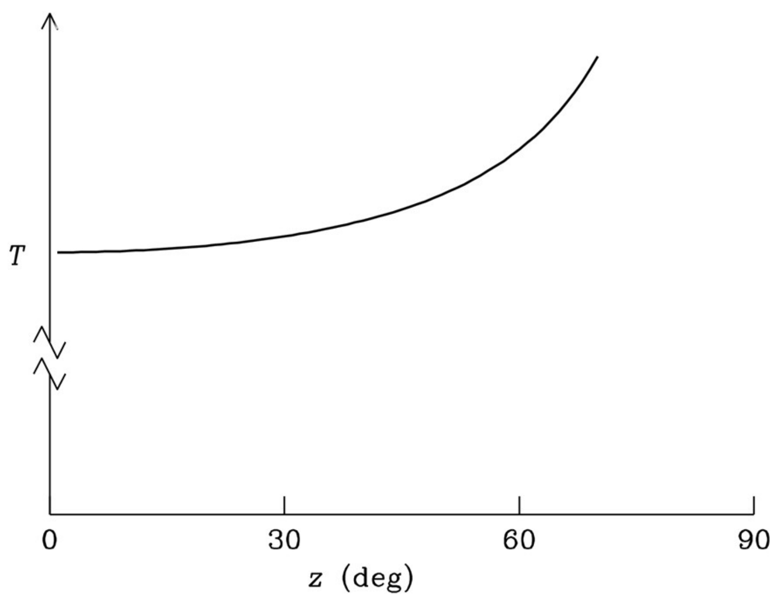
$$\frac{dI}{ds} = -\kappa_\nu \cdot I_\nu + j_\nu$$

$$j_\nu = B_\nu \cdot \kappa_\nu$$

Kirchhoff law of thermodynamics, thermal equilibrium

$$\frac{1}{\kappa_\nu} \cdot \frac{dI}{ds} = \frac{dI}{d\tau} = -I_\nu + B_\nu$$

$$I_\nu(\tau) = (1 - e^{-\tau}) \cdot B_\nu$$



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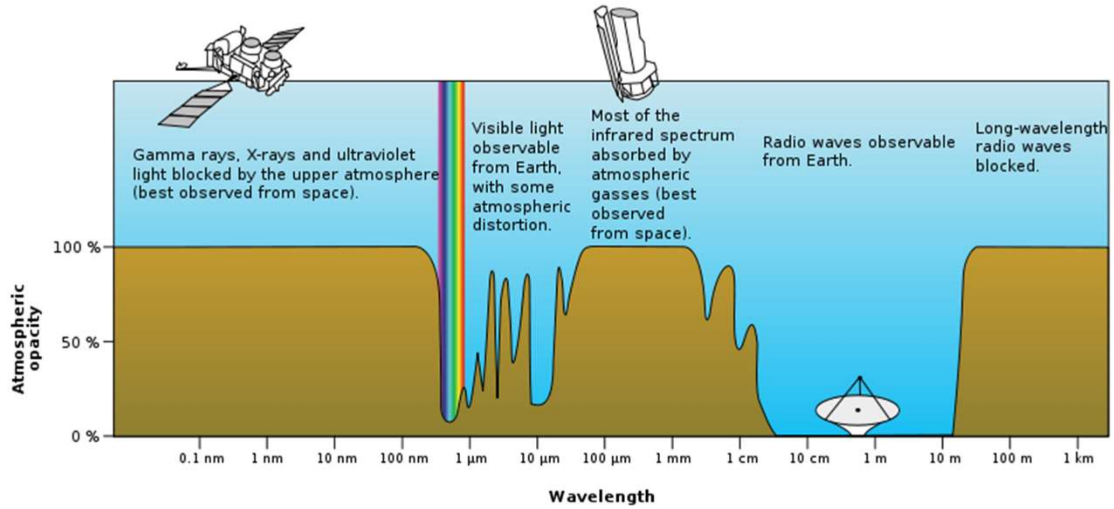
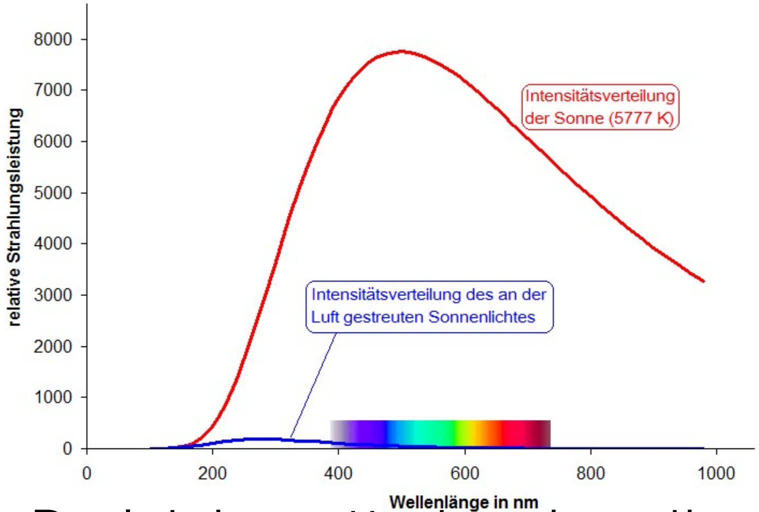
Windows to the Universe



- The Earth's atmosphere allows the observation of astronomical objects in certain wavelength ranges, which are called "astronomical windows".
- In the optical window, which is self-revealing, we see the radiation from astronomical sources with temperatures (keyword: blackbody or Planckian radiator) between 3,000 K and 30,000 K.

Windows to the Universe



$$\sigma(\nu) \approx \sigma_{Thomson} \left(\frac{\nu^4}{\nu_0^4} \right)$$

- Rayleigh scattering describes the interaction of electromagnetic waves with scattering bodies, which is small compared to the wavelength of the radiation.
- Rayleigh scattering of sunlight occurs only on the gas particles, but the water droplets and ice crystals are larger than the wavelength of visible light. These large bodies reflected the short wavelengths. The scattering causes the clear unclouded sky to show its sky blue.
- High frequency EM radiation is therefore strongly scattered, while low frequency light experiences little scattering.

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Windows to the Universe

- Radio waves are much longer wavelength than the largest scattering particles in the Earth's atmosphere. Therefore, Rayleigh scattering dominates.
- Due to the large difference between wavelength and the size of the scatterer, scattering at radio wavelength is not an issue.
- The Sun is a relatively weak radiator in the radio wave range, therefore the sky is always dark for radio astronomy!
- Therefore radio astronomical measurements are possible at day and at night in nearly the same quality.