Interaction of Radio Waves with Plasma

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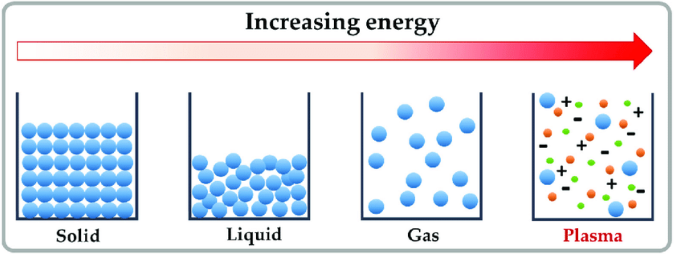
Outline

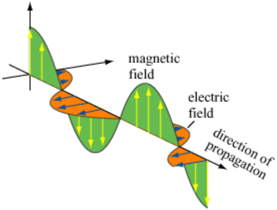
1. The Basics
   - Reflection
   - Absorption
2. Relevant Complications
   - Radio wave retardation
   - Oblique incidence reflections
   - Magnetised plasma
   - Inhomogeneous plasma & scintillation

The Basics

Preliminary: What is a plasma, and why do we care?

At sufficiently high energies, electrons can detach from atoms, resulting in a mixture of *free electrons* and positively charged *ions*.



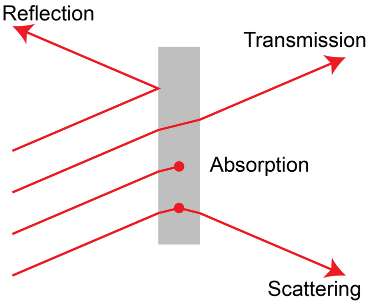


The electric field of the radio wave causes free electrons to oscillate with same frequency, reradiating the wave.

The basics

When a radio waves encounters a plasma, three things can happen:

1. Reflection of the waves,
2. Absorption (energy dissipated as heat),
3. Radio waves go through (but with distortion).



Important note: Reflection or not is a binary one-or-the-other, but absorption happens in degrees.

Reflection: the plasma frequency

Whether or not a signal is reflected depends on (1) the radio frequency, and (2) the electron (not ion) density in the plasma. The refractive index is:

$$n = \sqrt{1 - \frac{\omega_0^2}{\omega^2}}.$$

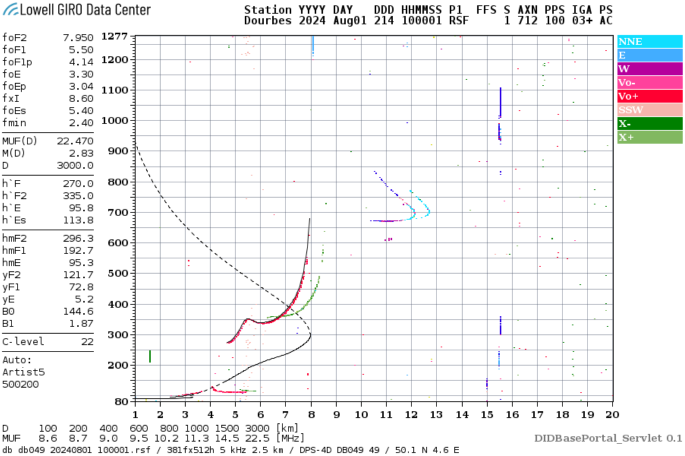
The plasma frequency depends on the density of free electrons:

$$\omega_0 = \sqrt{\frac{N_e e^2}{m_e \varepsilon_0}} \propto \sqrt{N_e}.$$

Reflection condition:

Radio waves are *reflected* by a (cold) plasma if their frequency is below the plasma frequency, higher frequencies pass through.

An example



The red line shows reflection of frequencies up to 7.95 MHz, but not above (ignore everything else, for now...).

Absorption

Reflection occurs by radio wave electric field causing free electron oscillation, resulting in reradiation. But what if electrons cannot oscillate?

If the electron mean free path is small compared to wavelength (or ω small compared to collision frequency ν), energy gets dissipated before reradiation can occur. This results in radio wave absorption.

Consequences:

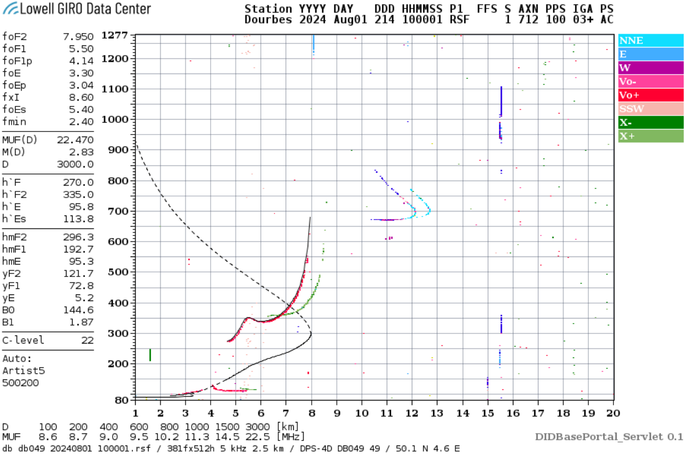
1. More absorption at longer wavelengths (*i.e.*, lower frequencies).
2. In a *partially ionised plasma*: densities of neutral component is very important.

Relevant Complications

Radio signal group velocity:

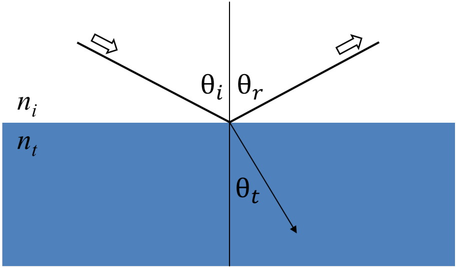
$$v_g = c\sqrt{1 - \frac{\omega_0^2}{\omega^2}}$$

Thus: signals go slower than c, and slower in denser plasma.



Frequencies both above and below ω_p are asymptotically retarded.

Oblique incidence reflection



Snell's law: $n_i \sin\theta_i = n_t \sin\theta_t$.
Assume $n_i = 1$ (vacuum);
maximum reflection for $\theta_t = \frac{\pi}{2}$.
Then:

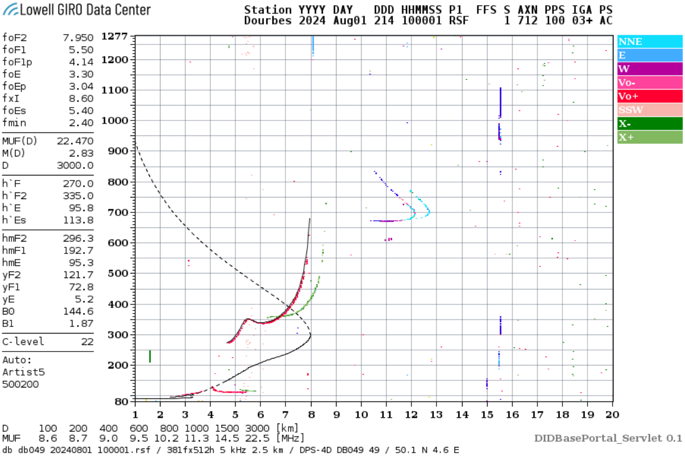
$$n_t = \sqrt{1 - \frac{\omega_0^2}{\omega_{\mathrm{max}}^2}} = \sin\theta_i.$$

Thus:

$$\omega_{\mathrm{max}} = \frac{\omega_0}{\cos\theta_i}.$$

This results in a Maximal Usable Frequency (*MUF*) for oblqiue HF communications, dependent on distance (longer distance $\longrightarrow$ larger θ_i $\longrightarrow$ larger ω_{max}).

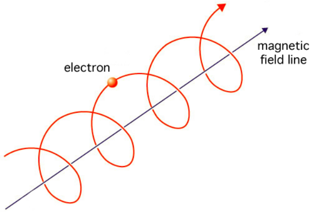
The example, again



Obliquely received signals appear at higher frequencies than vertical reflections, up to the *MUF* at the relevant distance (here 1080 km).

Magnetised plasma

What if the plasma is inside a magnetic field B_0? Electrons spiral around magnetic field lines with the *gyro frequency*:



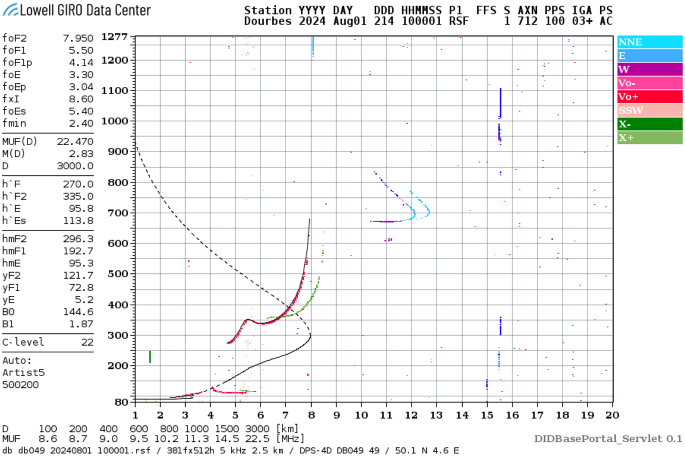
$$\omega_H = \frac{B_0 e}{m}.$$

Appleton-Hartree equation for refraction index (simplified, ignoring absorption):

$$n = \sqrt{1 - \frac{\omega_0^2\left(\omega^2 - \omega_0^2\right)}{\omega^2 - \omega_0^2 - \frac{\omega_H^2 \sin^2\theta}{2} \pm \sqrt{\left(\frac{\omega_H^2 \sin^2\theta}{2}\right)^2 + \left(\omega^2 - \omega_0^2\right)^2 \omega_H^2 \cos^2\theta}}}.$$

Faraday rotation: circular polarised signal will rotate its polarisation vector. The important point: two solutions, so O- and X-polarisations behave differently.

The example...

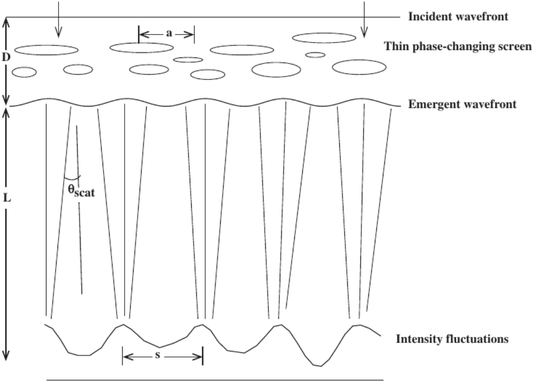


Red and green curves are reflections of O- and X-polarised waves. The difference here is 0.65 MHz, but depends on the local magnetic field strength. Similar for oblique traces at higher frequencies.

Radio scintillation

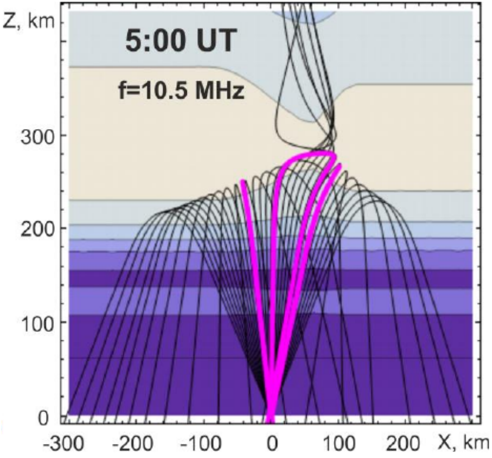
Irregularities in the plasma can cause rapid fluctuation (in phase & amplitude) of passing radio waves.

Mostly important for higher frequencies (VHF, UHF, L-band), not for HF.



An dose of reality

Reality is not so simple...



Talking about reflections etc. is an approximation.

Summary

Radio waves can *pass through* a plasma, be *reflected* by it, or get *absorbed*.

1. Plasma frequency $\omega_p \propto \sqrt{N_e}$.
2. Absorption in partially ionised plasma depends on neutral density.
3. Complications due to B: Faraday rotation, polarisation splitting.
4. Higher frequencies suffer scintillation from inhomogeneities.

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The end!

Questions?