

Interaction of Radio Waves with Plasma

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Role of the ionosphere and space weather in military communications



Solar-Terrestrial
Centre of
Excellence

1 The Basics

- Reflection
- Absorption

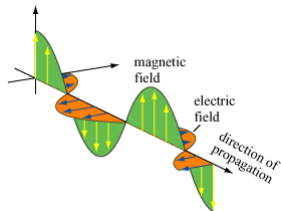
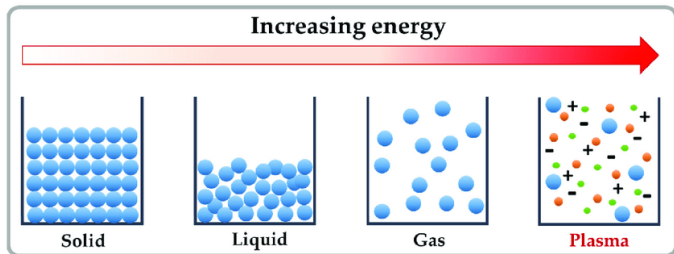
2 Relevant Complications

- Radio wave retardation
- Oblique incidence reflections
- Magnetised plasma
- Inhomogeneous plasma & scintillation

The Basics

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

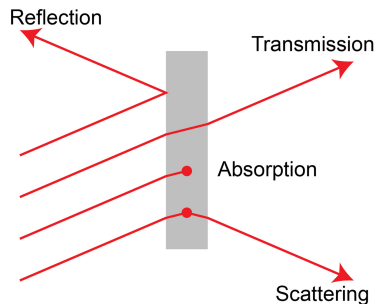
At sufficiently high energies, electrons can detach from atoms, resulting in a mixture of *free electrons* and positively charged *ions*.



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

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:

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

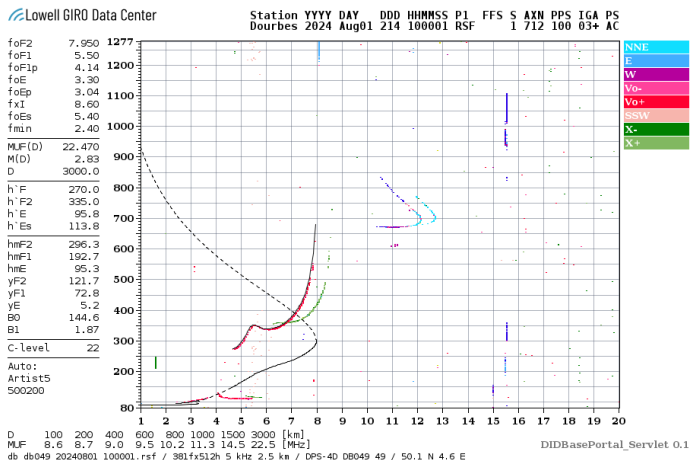
The plasma frequency depends on the density of free electrons:

$$\omega_0 = \sqrt{\frac{N_e e^2}{m_e \epsilon_0}} \propto \sqrt{N_e}.$$

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...).

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 retardation

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.

Lowell GIRO Data Center

Station YYYY DAY DDD HHMMSS P1 FFS S AXN PPS IGA PS
Dourbes 2024 Aug01 214 100001 RSF 1 712 100 03+ AC

foF2 7.950 1277
foF1 5.50
foF1p 4.14
foE 3.30
foEp 3.04
fxI 8.60
foEs 5.40
fmin 2.40

MUF(D) 22.470
M(D) 2.83
D 3000.0

h'F 270.0
h'F2 335.0
h'E 95.8
h'Es 113.8

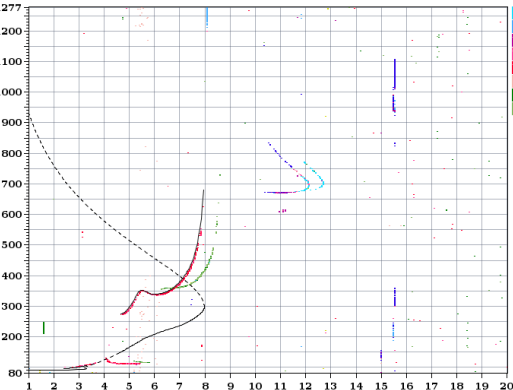
hmF2 296.3
hmF1 192.7
hmE 95.3
yF2 121.7
yF1 72.8

YE 5.2
BO 144.6
B1 1.87

C-level 22

Auto:
Artist5
500200

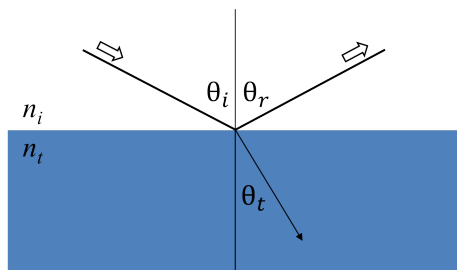
D 100 200 400 600 800 1000 1500 3000 [km]
MUF 8.6 8.7 9.0 9.5 10.2 11.3 14.5 22.5 [MHz]
db db049 20240801 100001.rsf / 381fx512h 5 kHz 2.5 km / DPS-40 DB049 49 / 50.1 N 4.6 E



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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:

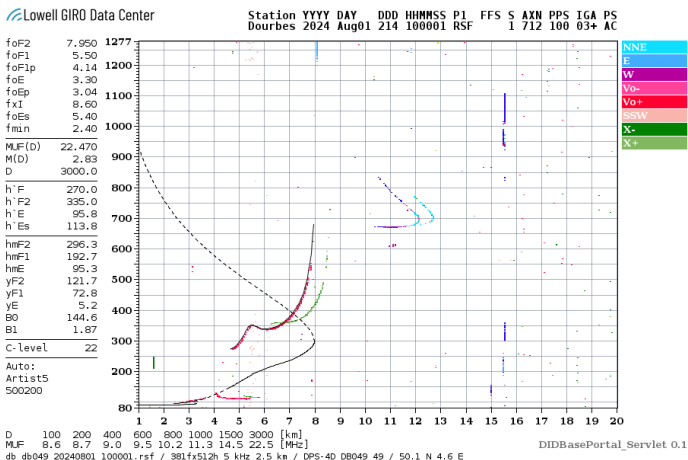
$$n_t = \sqrt{1 - \frac{\omega_0}{\omega_{\max}}} = \sin \theta_i.$$

Thus:

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

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

The example, again

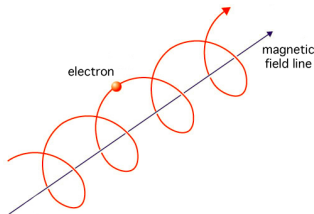


Obliquely received signals appear at higher frequencies than vertical reflections, up to the MUF at the relevant distance (here 1080 km).

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):

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

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

The example...

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Station YYYY DAY DDD HMMSS P1 FFS S AXN PPS IGA PS
Dourbes 2024 Aug01 214 100001 RSF 1 712 100 03+ AC

foF2 7.950 1277
foF1 5.50
foF1p 4.14 1200
foE 3.30
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MUF(D) 22.470
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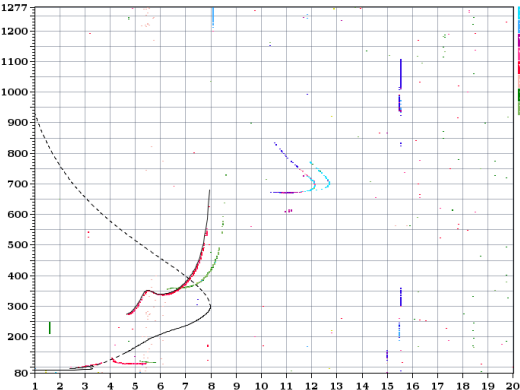
h'F 270.0
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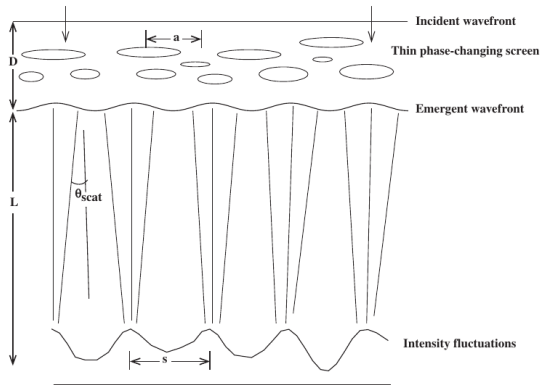
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Red and green curves are reflections of O- and X-polarised waves. The difference here is 0.65 MHz, but depends on the local magnetic field strength. Similar for oblique traces at higher frequencies.

Radio scintillation

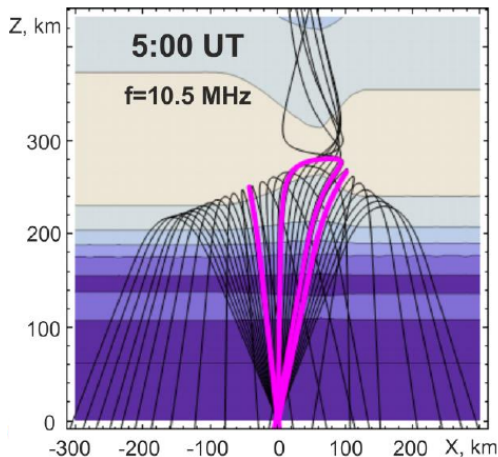
Irregularities in the plasma can cause rapid fluctuation (in phase & amplitude) of passing radio waves.

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.

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?