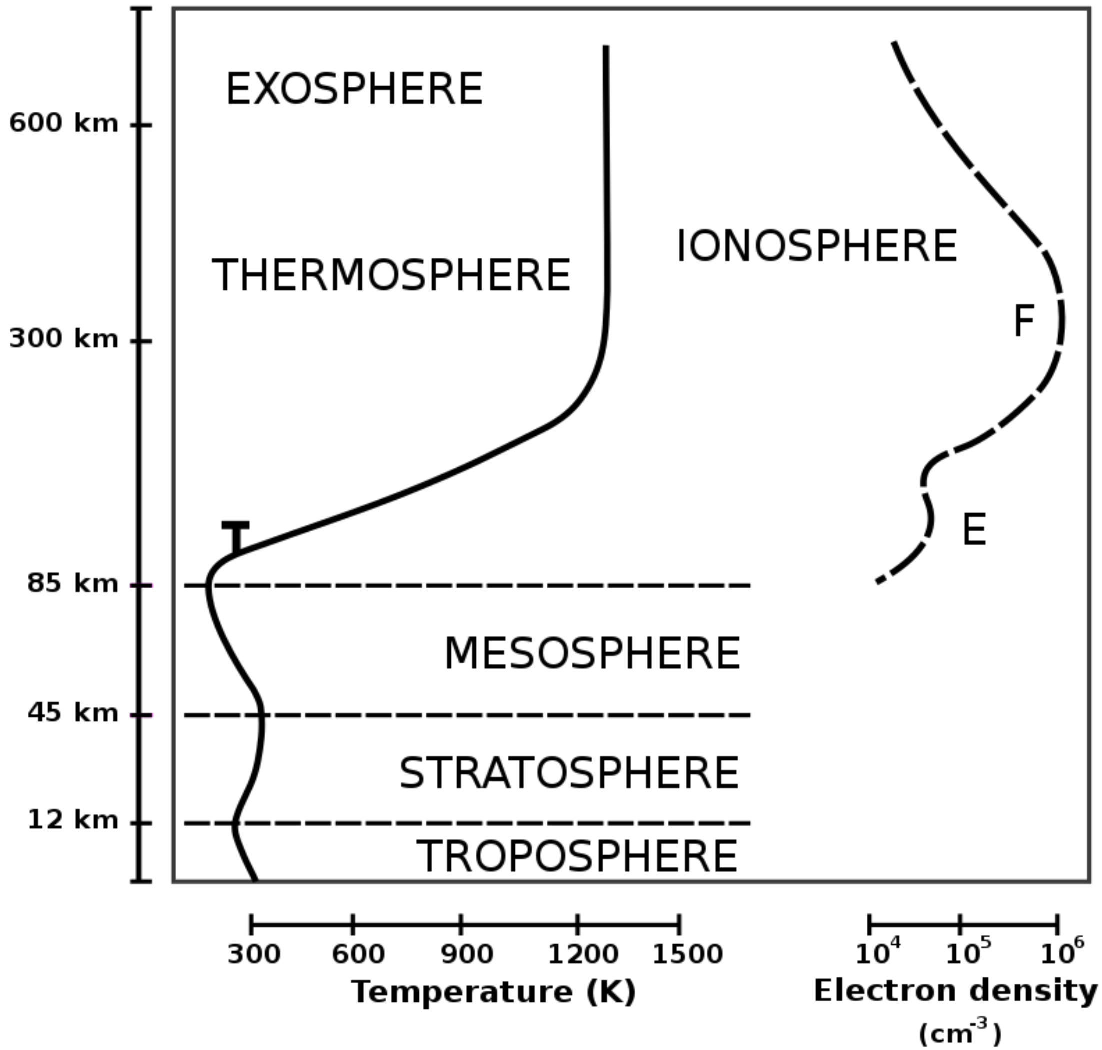
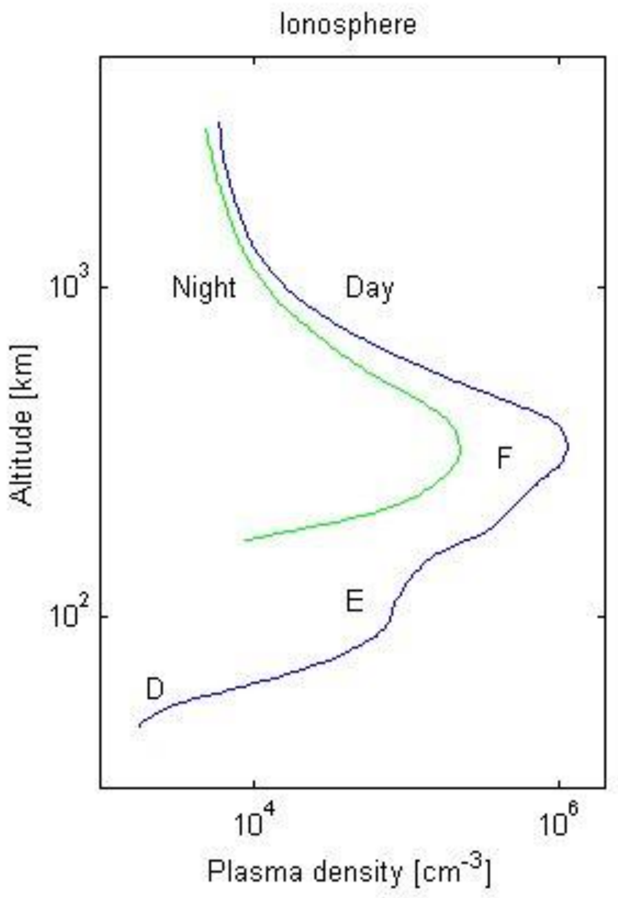
What ?

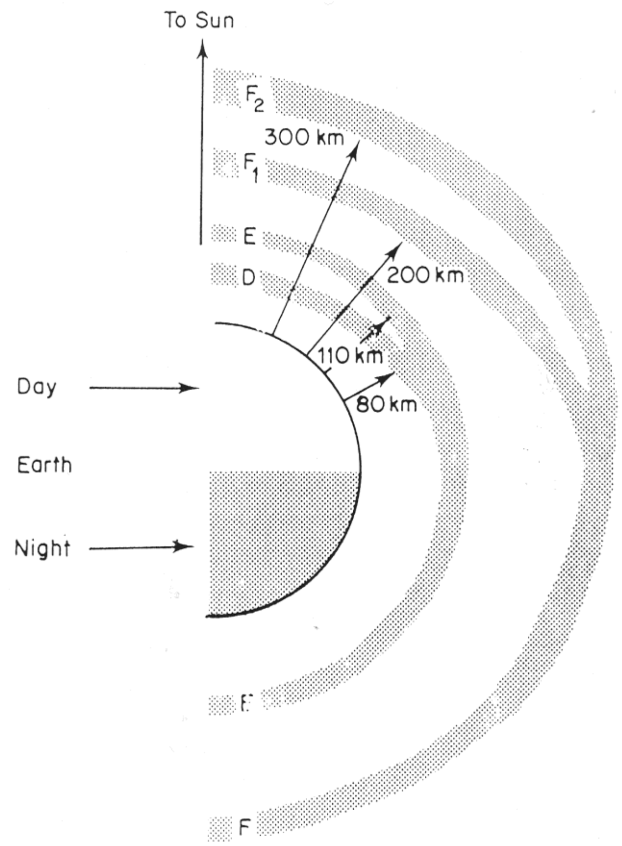
- The ionosphere is the ionized part of earth's upper atmosphere, from about 60 km to 1000 km altitude.
- The ionosphere is ionized by solar radiation.
- It influences radio propagation to distant places on the earth

Structure


EXOSPHERE
THERMOSPHERE
IONOSPHERE
F
E
MESOSPHERE
STRATOSPHERE
TROPOSPHERE
600 km
300 km
85 km
45 km
12 km
300
600
900
1200
1500
Temperature (K)
10^4
10^5
10^6
Electron density
(cm^{-3})

Structure



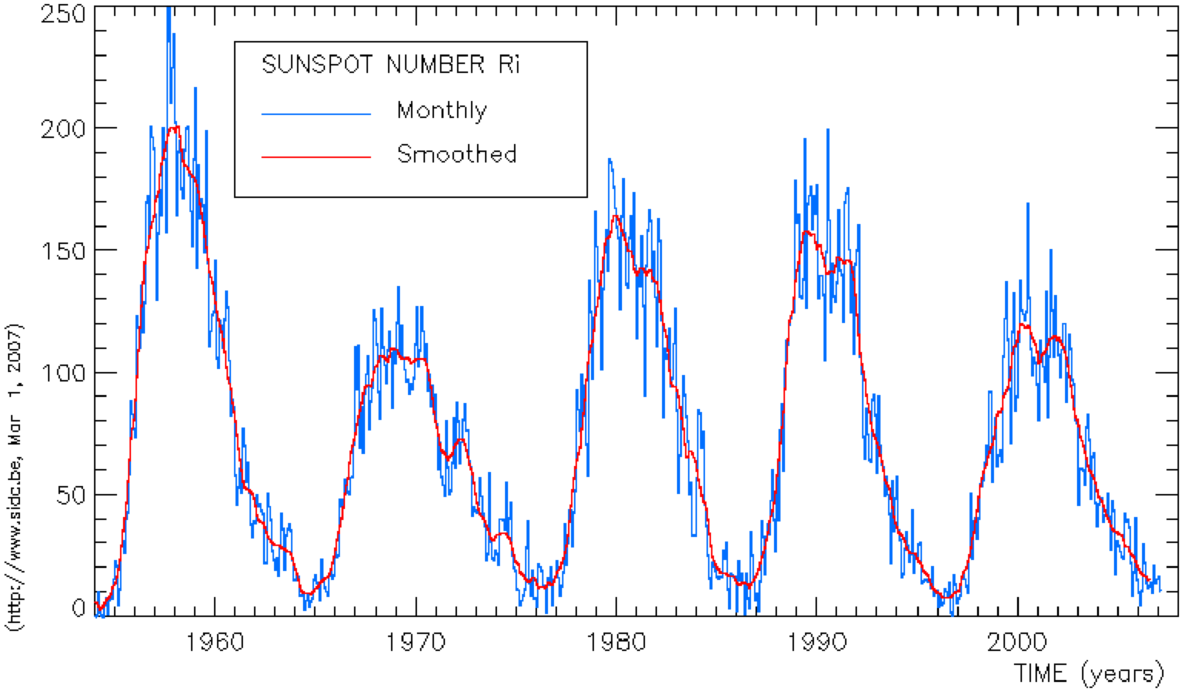


Regions of the ionosphere

Ionisation by solar radiation

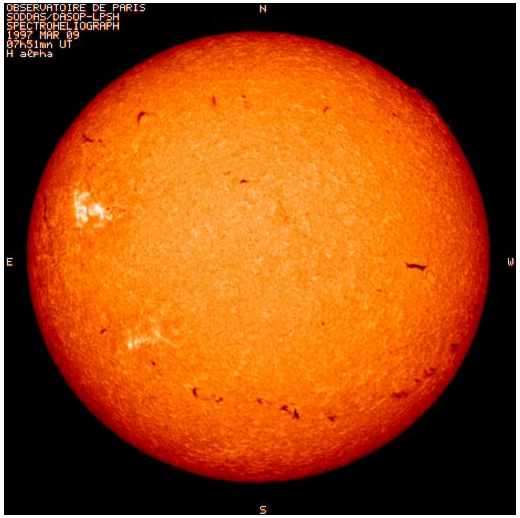
Ionisation by solar radiation

- Solar activity has a period of about 11 years

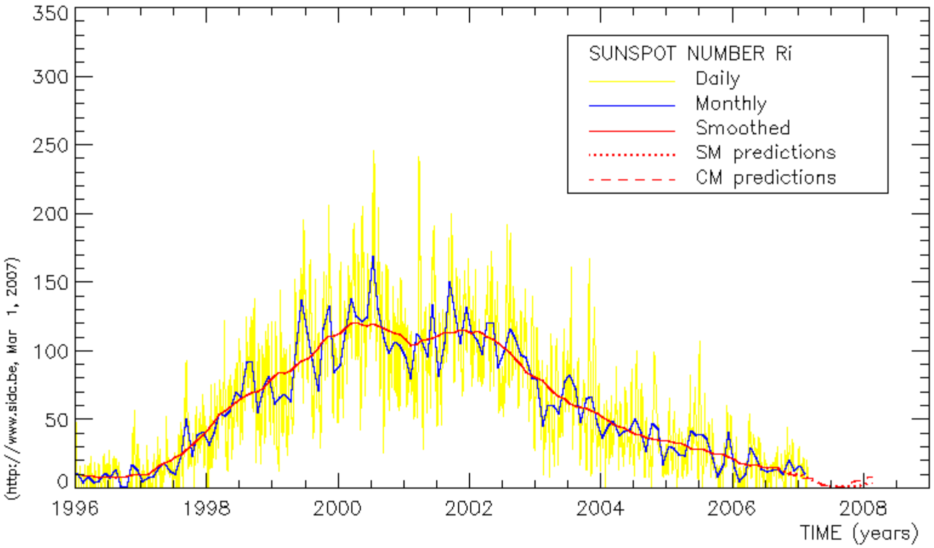


Ionisation by solar radiation

- It is strongly related to the number of “dark” spots on the sun
- Continuously monitored: world center is in Ukkel
  - http://sidc.oma.be/sunspot-index-graphics/sidc_graphics.php

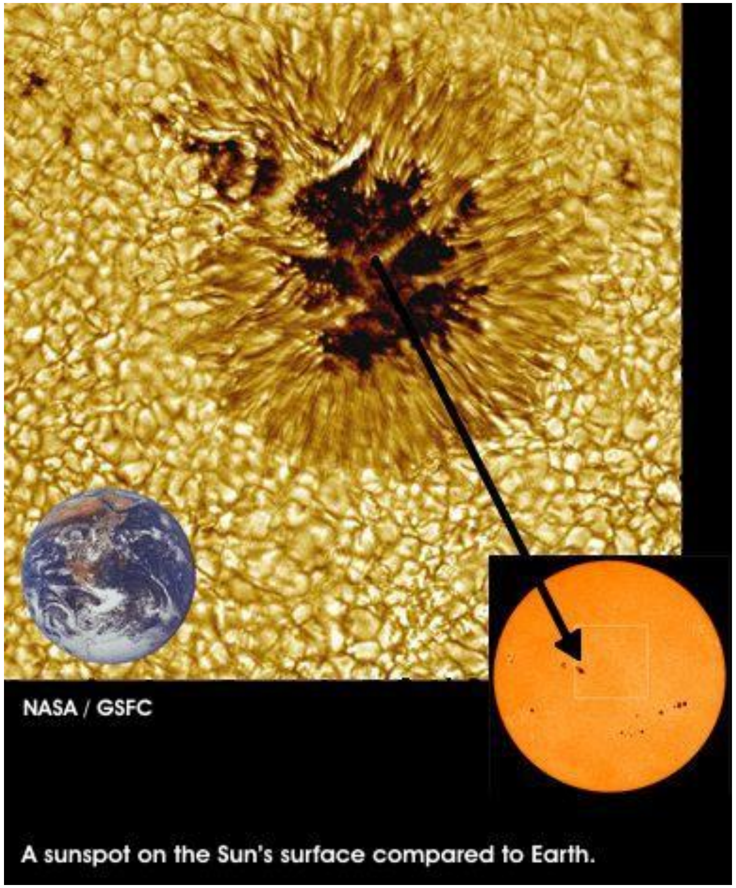


Picture from 9/3/1997



Ionisation by solar radiation

- Animation showing effect of sunspots (4000°K vs. 6000°K)



Calculation of propagation constant

Current at specific point: $\mathbf{j} = -eN\mathbf{v}$

$e =$ electron charge $= 1.602 \cdot 10^{-19}$ C, $N =$ electron density, $\mathbf{v} =$ electron velocity

Motion equation for oscillation: $\mathbf{F} = m\mathbf{a}$ (Newton) $\Rightarrow -e\mathbf{E} - m\nu\mathbf{v} = m(j\omega\mathbf{v})$

$m =$ electron mass $= 9.107 \cdot 10^{-31}$ kg, $\nu =$ number of collisions per second

Insert this in Maxwell's equations:

$$\nabla \times \mathbf{H} = j\omega\varepsilon_0\mathbf{E} + \frac{e^2 N}{j\omega m + m\nu}\mathbf{E} = j\omega\varepsilon_0(1 - \frac{Ne^2}{m\varepsilon_0\omega(\omega - j\nu)})\mathbf{E} = j\omega\varepsilon_0(1 - \frac{\omega_p^2}{\omega^2}\frac{1}{(1 - \frac{j\nu}{\omega})})\mathbf{E}$$

$\omega_p = e\sqrt{N / (m\varepsilon_0)} =$ plasma frequency

$1 - \frac{\omega_p^2}{\omega^2}\frac{1}{(1 - \frac{j\nu}{\omega})}$ can be interpreted as a complex relative permittivity

Propagation constant is thus: $\gamma_0^2 = (\alpha_0 + j\beta_0)^2 = -\omega^2\mu_0\varepsilon_0(1 - \frac{\omega_p^2}{\omega^2}\frac{1}{(1 - \frac{j\nu}{\omega})})$

Calculation of propagation constant

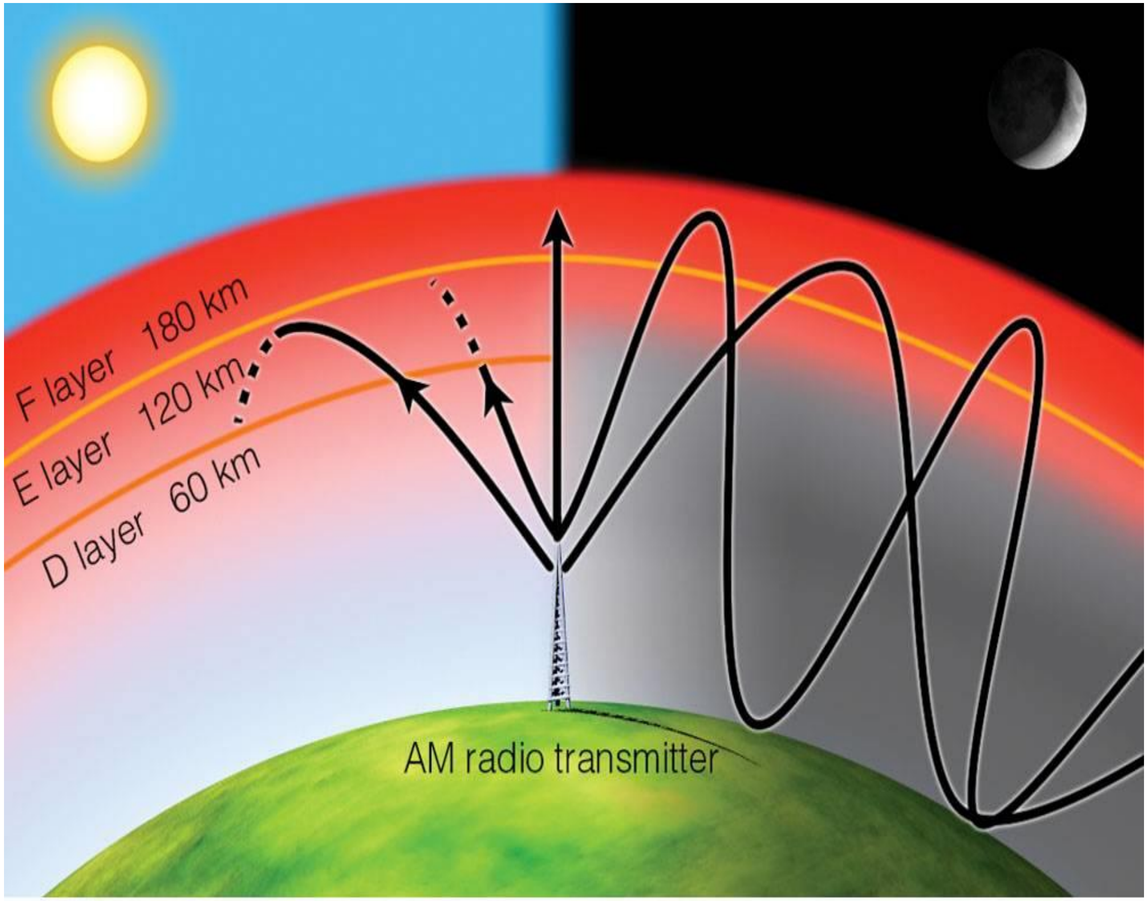
$$\gamma_0^2 = (\alpha_0 + j\beta_0)^2 = -\omega^2\mu_0\varepsilon_0\left(1 - \frac{\omega_p^2}{\omega^2}\frac{1}{(1-\frac{j\nu}{\omega})}\right)$$

$$\alpha_0 = \omega\sqrt{\mu_0\varepsilon_0}\,\mathrm{Re}\left(\sqrt{\frac{\omega_p^2}{\omega^2}\frac{1}{(1-\frac{j\nu}{\omega})}-1}\right) = \omega\sqrt{\mu_0\varepsilon_0}\,\mathrm{Re}\left(\sqrt{\frac{\omega_p^2}{\omega^2}\frac{(1+\frac{j\nu}{\omega})}{(1+(\frac{\nu}{\omega})^2)}-1}\right)$$

$$\beta_0 = \omega\sqrt{\mu_0\varepsilon_0}\,\mathrm{Re}\left(\sqrt{1-\frac{\omega_p^2}{\omega^2}\frac{1}{(1-\frac{j\nu}{\omega})}}\right) = \omega\sqrt{\mu_0\varepsilon_0}\,\mathrm{Re}\left(\sqrt{1-\frac{\omega_p^2}{\omega^2}\frac{(1+\frac{j\nu}{\omega})}{(1+(\frac{\nu}{\omega})^2)}}\right)$$

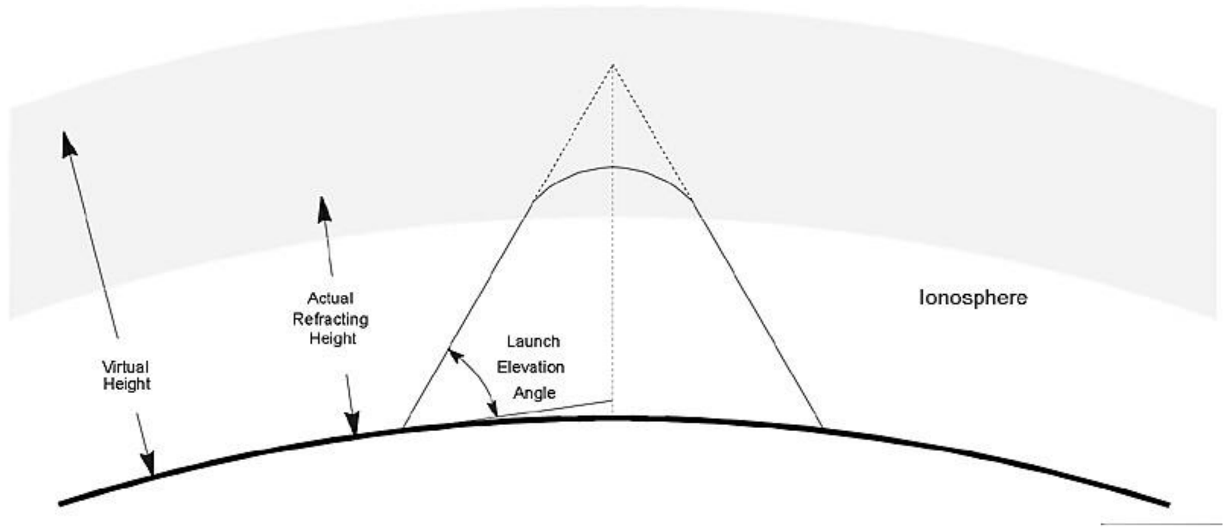
- At high frequencies only a small attenuation
- At low frequencies mostly attenuation
- At plasma frequency: $\beta_0 \approx 0$ thus no propagation

Effect on propagation



Effect on propagation

- Similar as in ducting session, but determined by electron profile.



Session Ducting: $n(h)(R_a + h)\cos(\psi(h)) = Cte$

Effect on propagation

$$n(h)(R_a + h)\cos(\psi(h)) = Cte$$

Since $n \approx \sqrt{\varepsilon},\ R_a + h \approx Cte$, and zenith angle $\varphi = \pi / 2 - \psi$

$$\sqrt{\varepsilon(z)}\sin\varphi(z) \approx Cte$$

Highest point z_h is reached when $\varphi(z) = \pi / 2$

$$\varepsilon(z_0)\sin^2\varphi(z_0) = \varepsilon(z_h)$$

or $\dfrac{\omega_p^2(z_h)}{\omega^2} \approx \cos^2\varphi_0$ with $\varphi_0 = \varphi(z_0)$

The electron density is then

$$N = \frac{\omega^2 m\varepsilon_0}{e^2}\cos^2\varphi_0$$

The maximal frequency that can be used for the communication is

$$f_{\max} = \frac{e}{2\pi\sqrt{m\varepsilon_0}}\sqrt{N_{\max}} / \cos\varphi_0 = f_c / \cos\varphi_0$$

f_c is the critical frequency

Approximation in previous slide

$$\varepsilon(z_0)\sin^2\varphi(z_0) = \varepsilon(z_h)$$

$$\left[1 - \frac{\omega_p^2(z_0)}{\omega^2}\right]\sin^2\varphi(z_0) = \left[1 - \frac{\omega_p^2(z_h)}{\omega^2}\right]$$

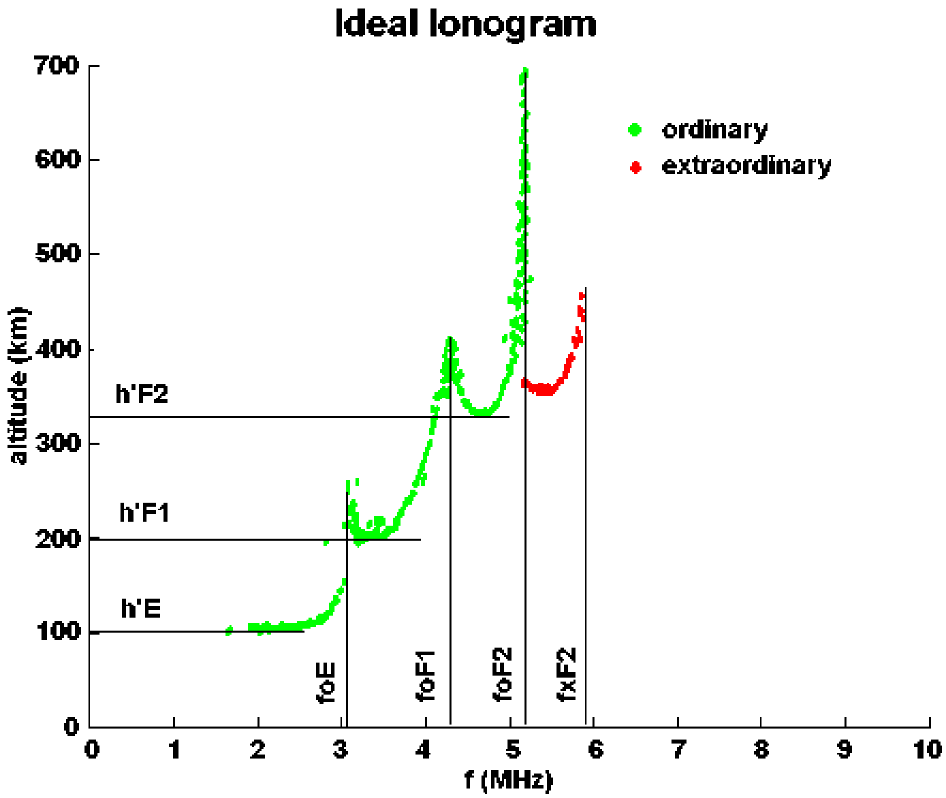
$$\left[-\frac{\omega_p^2(z_0)}{\omega^2}\right]\sin^2\varphi(z_0) + \frac{\omega_p^2(z_h)}{\omega^2} = \left[1 - \sin^2\varphi(z_0)\right]$$

$$\omega_p(z_0) << \omega_p(z_h)$$

$$\frac{\omega_p^2(z_h)}{\omega^2} \approx \cos^2\varphi(z_0)$$

Effect on propagation: ionogram

Vertical ionogram gives maximal frequencies reflecting vertically on the different layers in the ionosphere.



Effect on propagation: maximum distance in terms of height

$$d = \sqrt{(R_a + h)^2 - R_a^2} = \sqrt{2R_a h + h^2}$$

$$\tan\alpha = \frac{\sqrt{(2R_a + h)h}}{R_a}$$

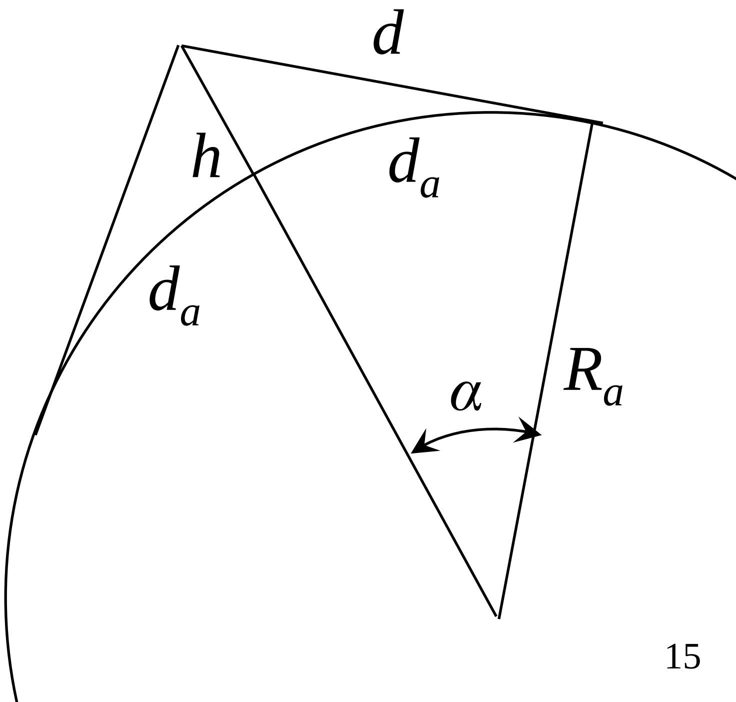
$$2d_a = 2R_a \arctan\left(\frac{\sqrt{(2R_a + h)h}}{R_a}\right)$$

$$= 2R_a \arctan\left(\sqrt{\left(2 + \frac{h}{R_a}\right)\frac{h}{R_a}}\right)$$

$$\approx 2\sqrt{2hR_a}$$

example:

$h = 300 \text{ km} \Rightarrow 2d_a = 3908 \text{ km}$



Effect on propagation: elevation angle in terms of distance

This is essentially the problem of determining all sides and angles of a triangle of which 2 sides and 1 angle are known.

Law of sines: $\frac{R_a + h}{\sin(\psi + \pi/2)} = \frac{R_a}{\sin\varphi} = \frac{d}{\sin\alpha}$ and also $d_a = R_a\alpha$ and $d\cos\varphi + R_a\cos\alpha = R_a + h$

$$\frac{R_a + h}{\cos\psi} = \frac{R_a}{\sin\varphi} = \frac{(R_a + h - R_a\cos(d_a/R_a))/\cos\varphi}{\sin(d_a/R_a)}$$

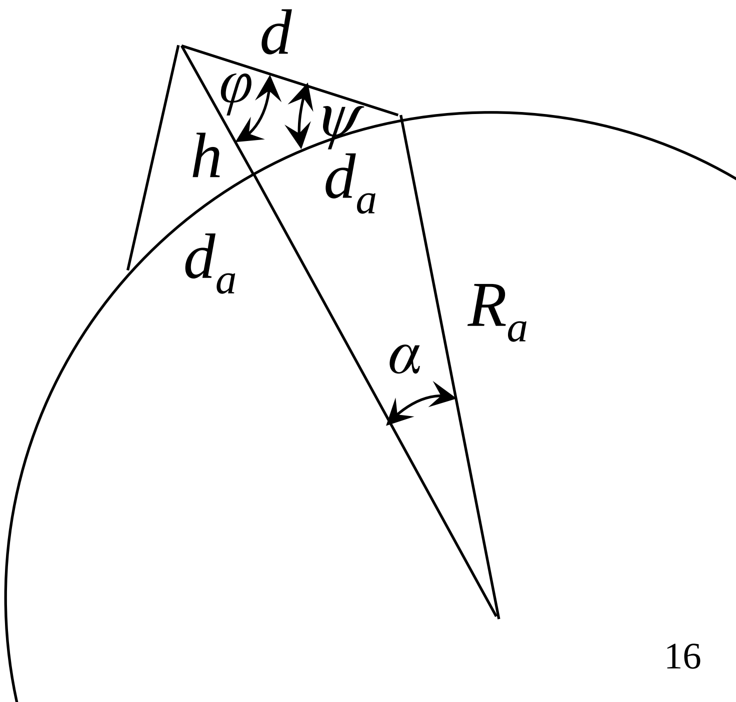
From last equation: $\tan\varphi = \frac{R_a\sin(d_a/R_a)}{(R_a + h - R_a\cos(d_a/R_a))}$

And from the first equation:

$$\psi = \arccos\left(\left(1+\frac{h}{R_a}\right)\sin\left(\arctan\left(\frac{\sin(d_a/R_a)}{(1+\frac{h}{R_a} - \cos(d_a/R_a))}\right)\right)\right)$$

which can be approximated for $\frac{h}{R_a} << 1$ by

$$\psi = \frac{\pi}{2} - \arctan\left(\frac{\sin(d_a/R_a)}{(1+\frac{h}{R_a} - \cos(d_a/R_a))}\right) - \frac{d_a}{R_a} = \frac{\pi}{2} - \varphi - \frac{d_a}{R_a}$$



Effect of earth magnetic field

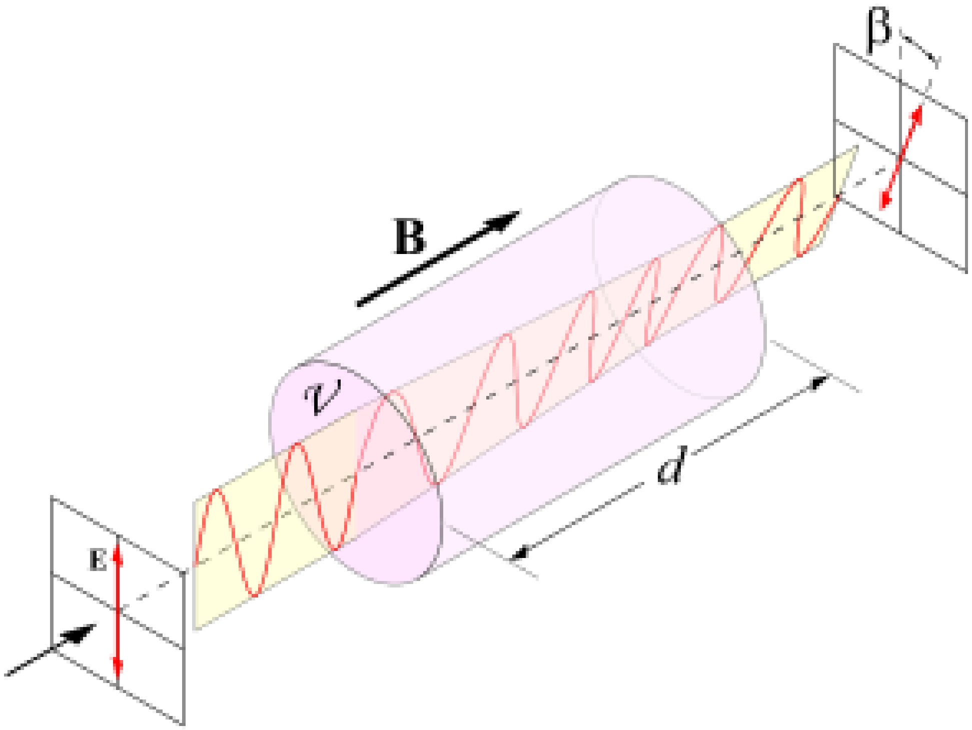
- Earth magnetic field ca. 5×10^{-5} Wb/m²
- Cannot be neglected if $f < 5$ MHz
- Has effect on behaviour electron density cloud

- **Result = FARADAY ROTATION**

  - Can be calculated but the math is beyond the scope of this course …
  - Linear polarisation = sum of two circular polarisations (CP)
  - These CP wave travel with a different speed

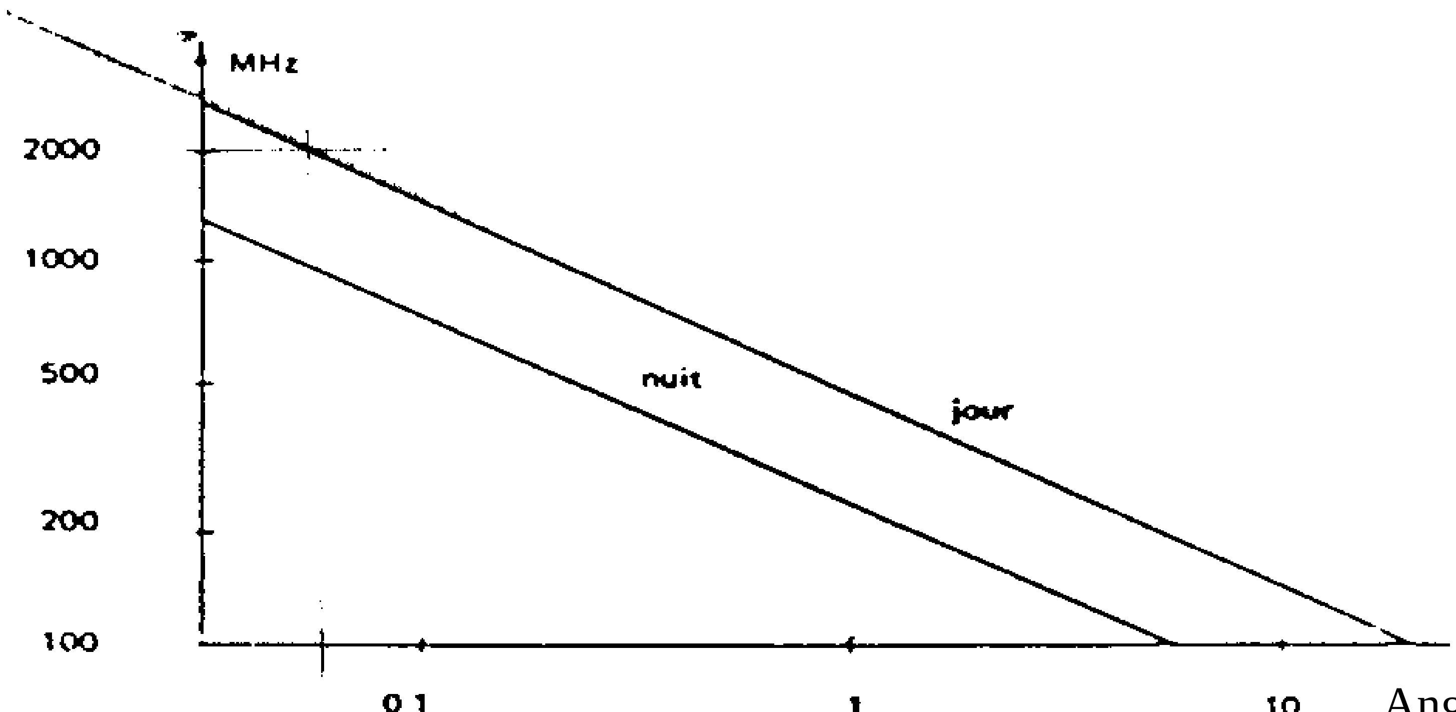
- This is the main reason why antennas used in satellite communications often have circular polarisation.

Faraday rotation



Effect of earth magnetic field

- Effect decreases with frequency
- Upper curve = day; lower curve = night



Angle in degrees

Conclusions

- The ionosphere can be effectively used to communicate over large distances, even taking into account the curvature of the earth.
- There is a set of maximum frequencies below one has to communicate to use this paradigm.