Ionospheric Propagation of Radio Waves

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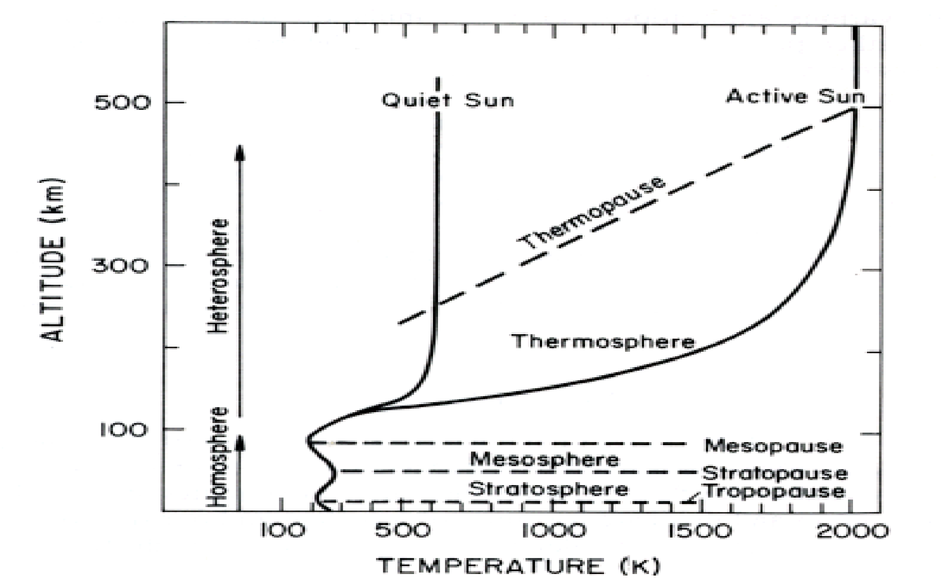
Outline

- Introduction
- Ionospheric Structure
- Formation of the Ionosphere
- Model of the ionosphere
- Ionospheric propagation
- Conclusion

Introduction: Definitions

Ionosphere is the region within the upper atmosphere where there are *sufficient ions* to influence radio propagation

The height range is 60 - ~500 Km



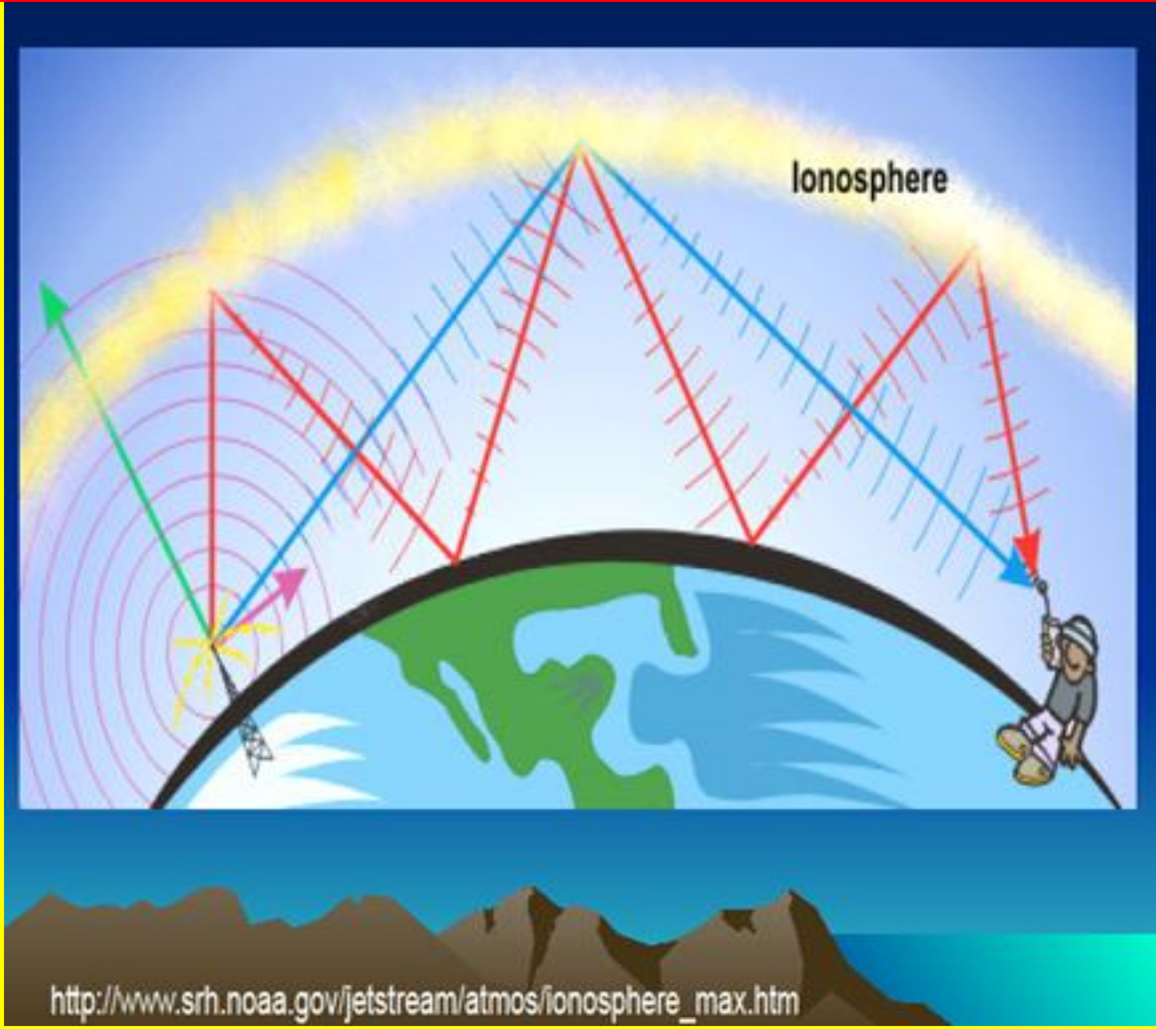
Ionospheric or space wave

- radio wave propagated over large ranges, capable of single or multiple reflections from ionosphere
- longer than 10 meters in wavelength,
- is scattered from inhomogeneities in the ionosphere and reflected from the ionized trails of meteors.

Introduction: Discovery of the ionosphere

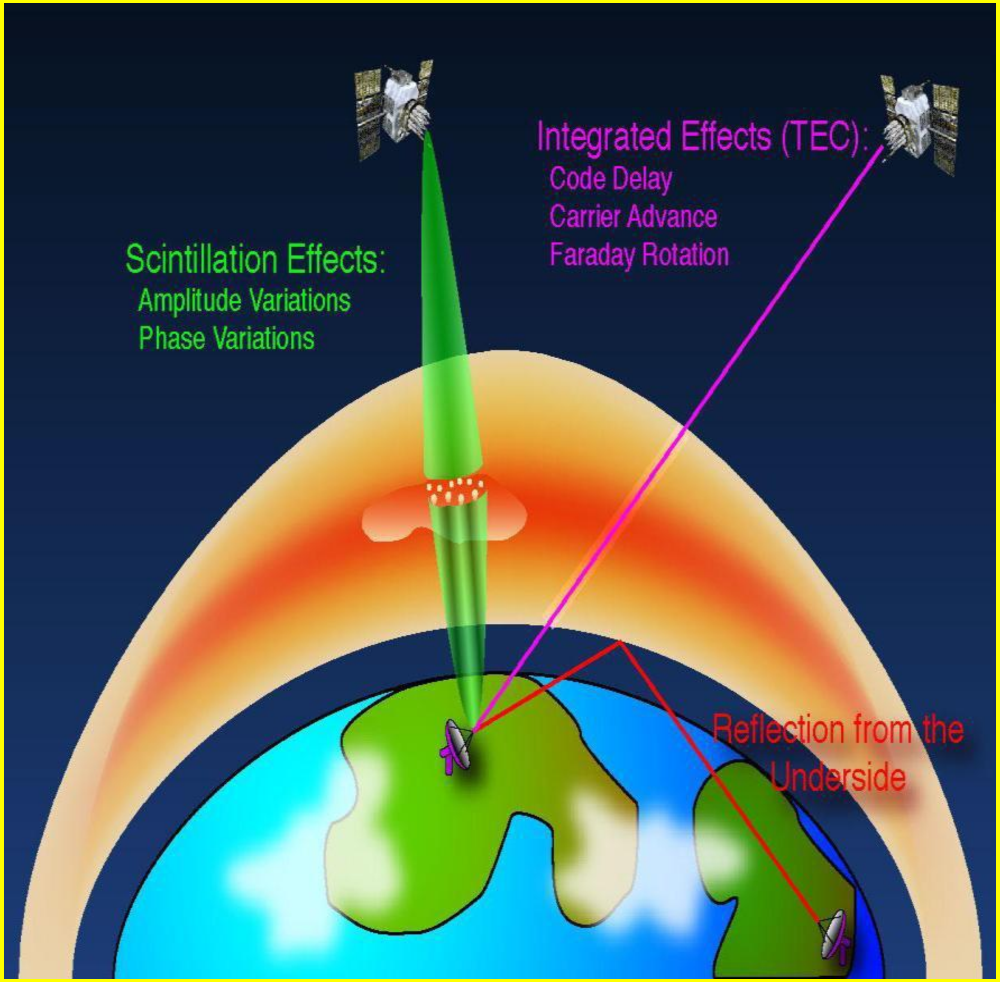
History of discovery:

- James Clark Maxwell (1864), discover radio wave
- Henry Hartz (1880) carried out the first radio transmission
- **Marconi (1901) transmitted radio signal across the Atlantic ocean (from England to Canada)**
- The discovery of ionosphere was rather accidental

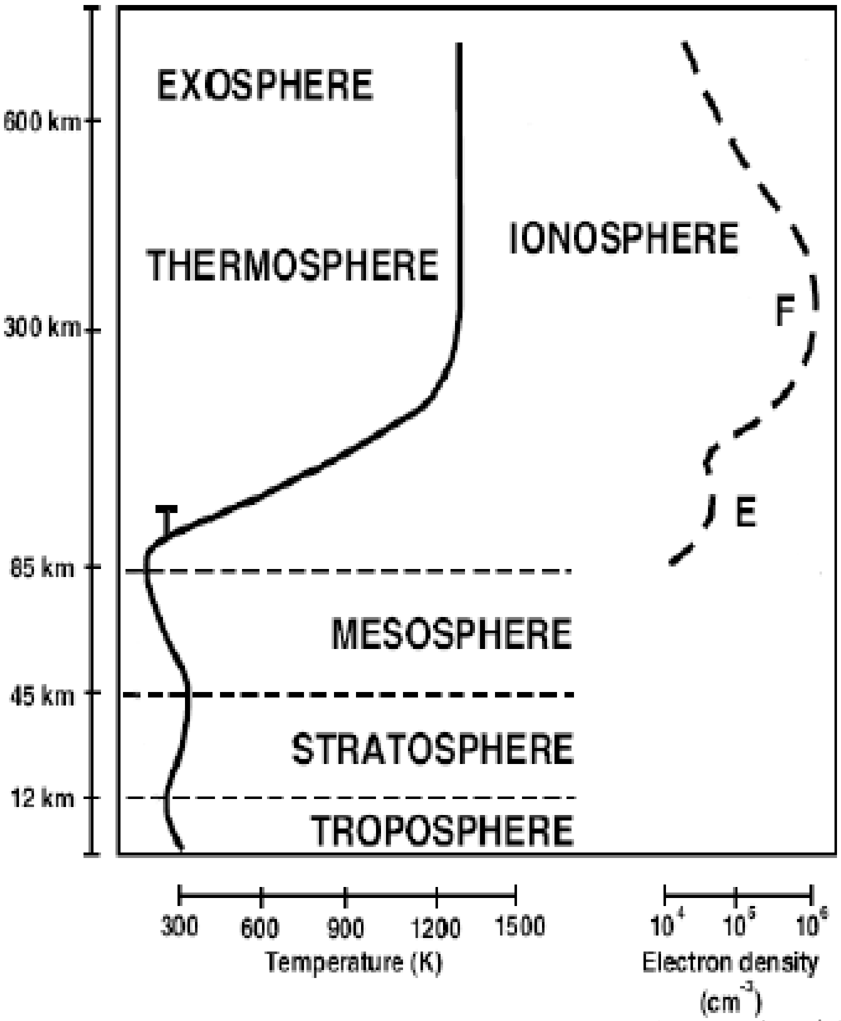


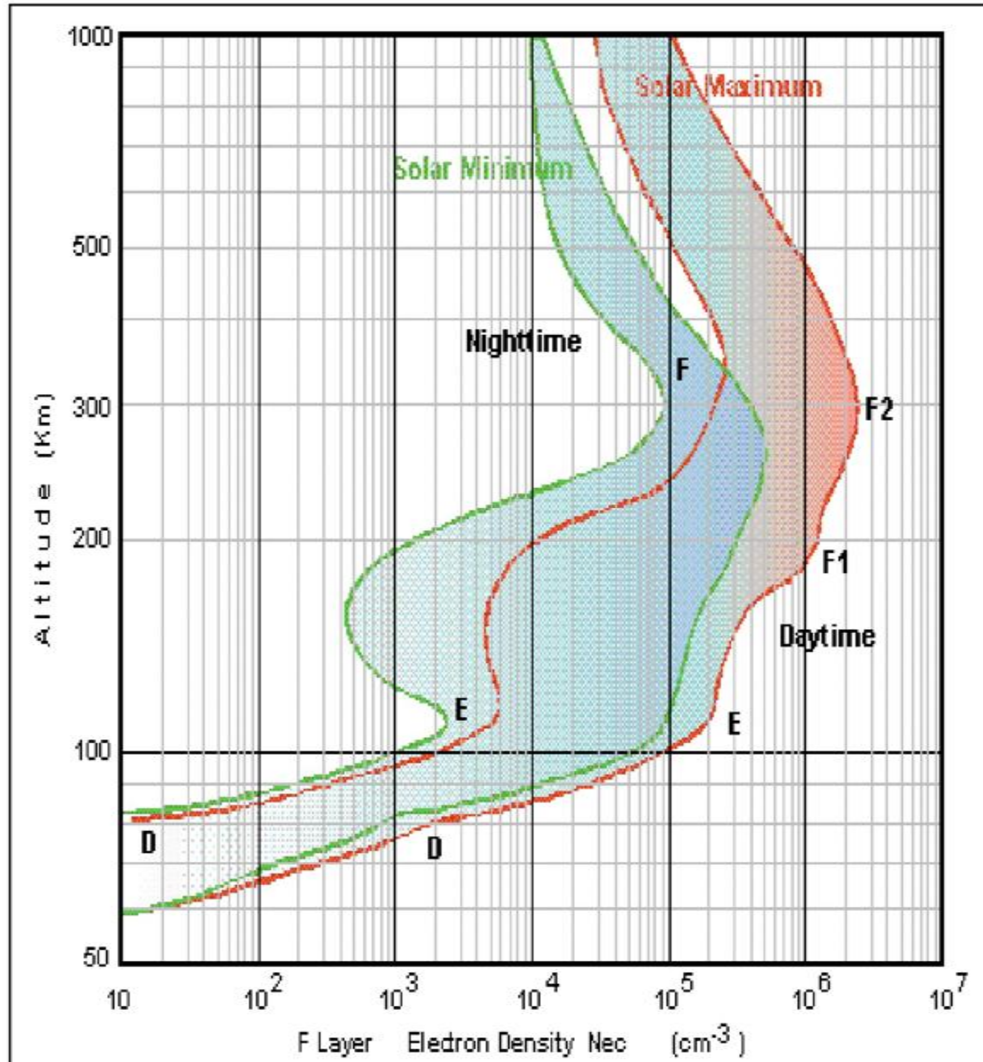
Introduction: Applications

1. **Space wave propagation**
2. **Line of sight communication- GNSS**
3. **Domain of Research**



The Ionosphere: Structure

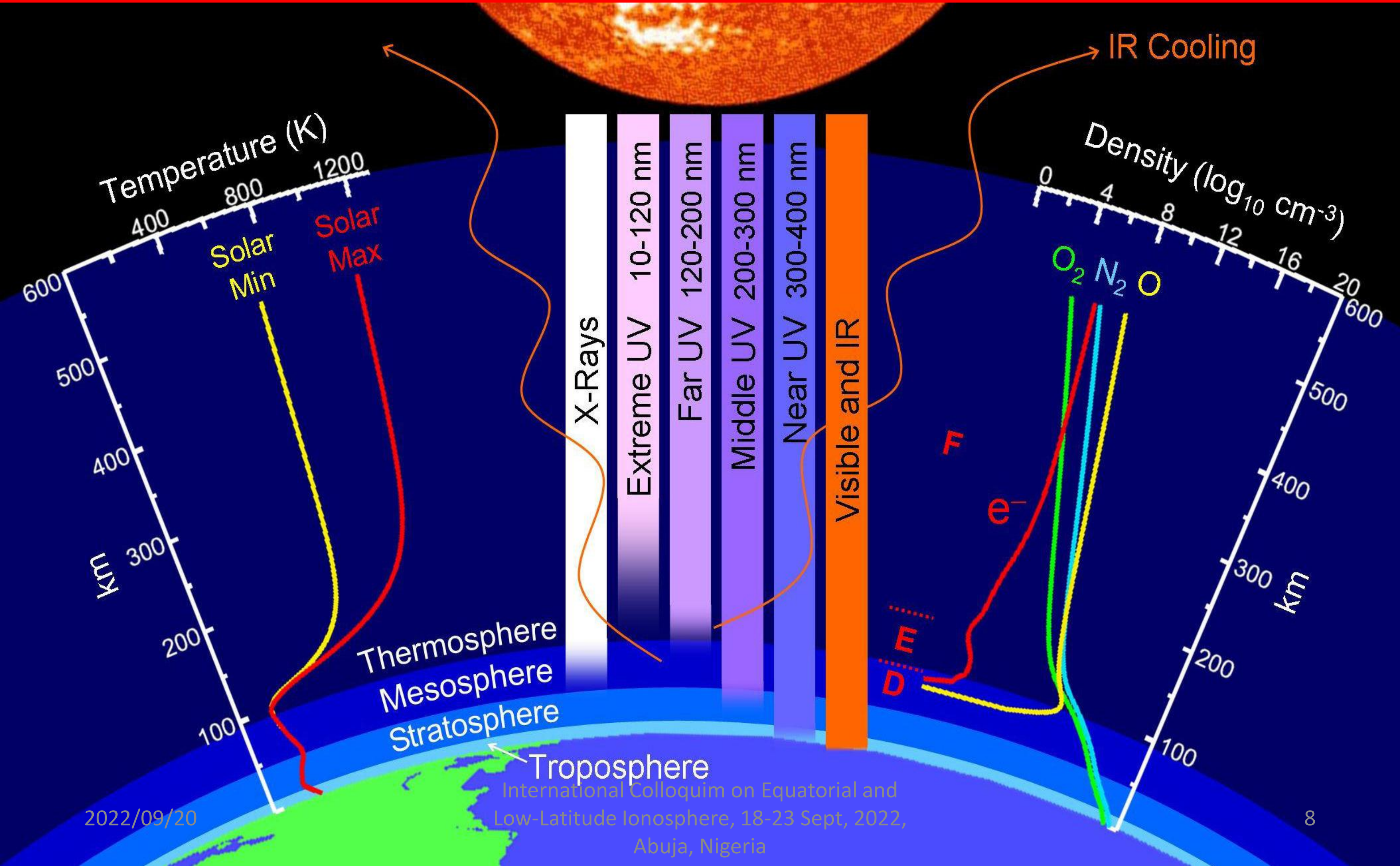




Ionospheric layers

Layer	Approximate Elevation	Major Component	Importance	When Present
Topside F Plasmasphere	> 450 km > 1200 km	O+ H+	Domain of line of sight propagation	Always
F	F1:140 km - 200 km F2:200 km – 450 km	F1:O+, NO+ F2: O+, N+	Main "reflection" region	Always - stronger during daytime
E	90 km - 140 km	O2+, NO+	Lower frequency "reflection" region	Always - but very weak at night
D	60 km – 90 km	NO+, O2+	Main absorption region	Daytime only

Formation of the Ionosphere - 1



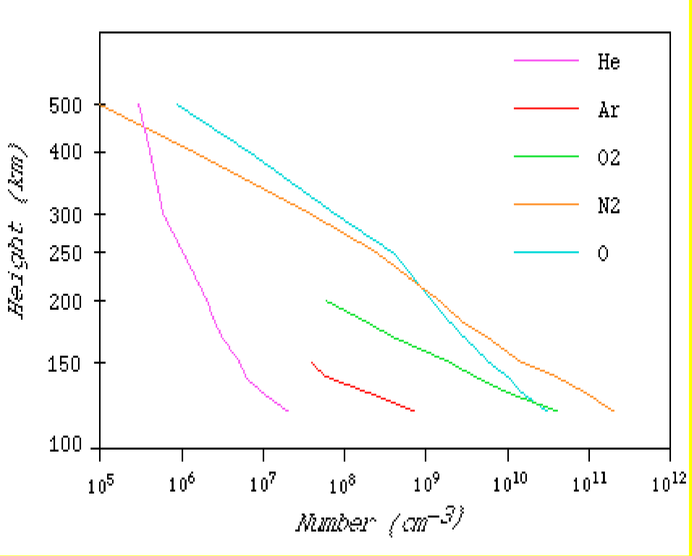
Formation of the ionosphere-2

Bear's law of radiation absorption::

$$dI_\gamma = -KI_0\eta dl$$

$$I = I_\infty e^{[-H_0 K\eta_0 sec\chi e^{-z}]}$$

$$\eta = \eta_0 e^{-z(\beta+1)}$$

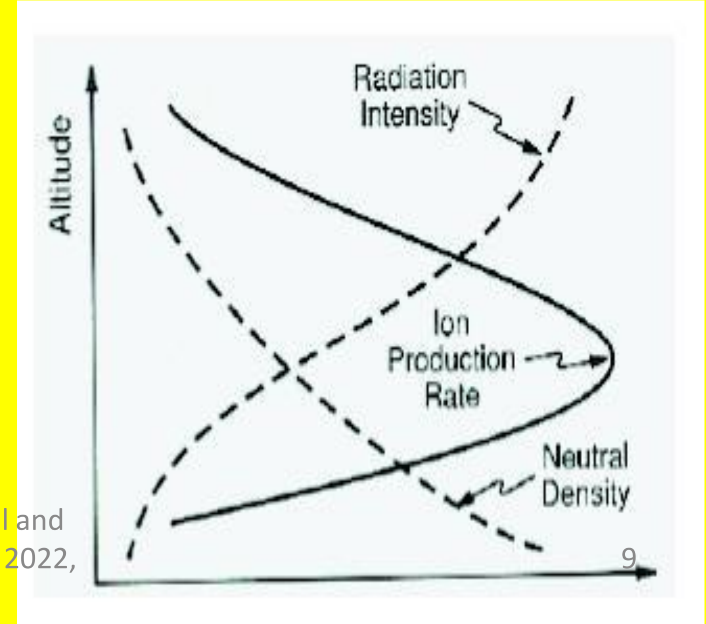


Ionization production term:

$$q \alpha \eta I$$

$$q = \delta\eta I$$

$$q_m = q_0(cos\chi)^{\beta+1}$$



Processes of ionization

Ionization process can be grouped into three stages:

1. Photo dissociation (λ > 130 nm):

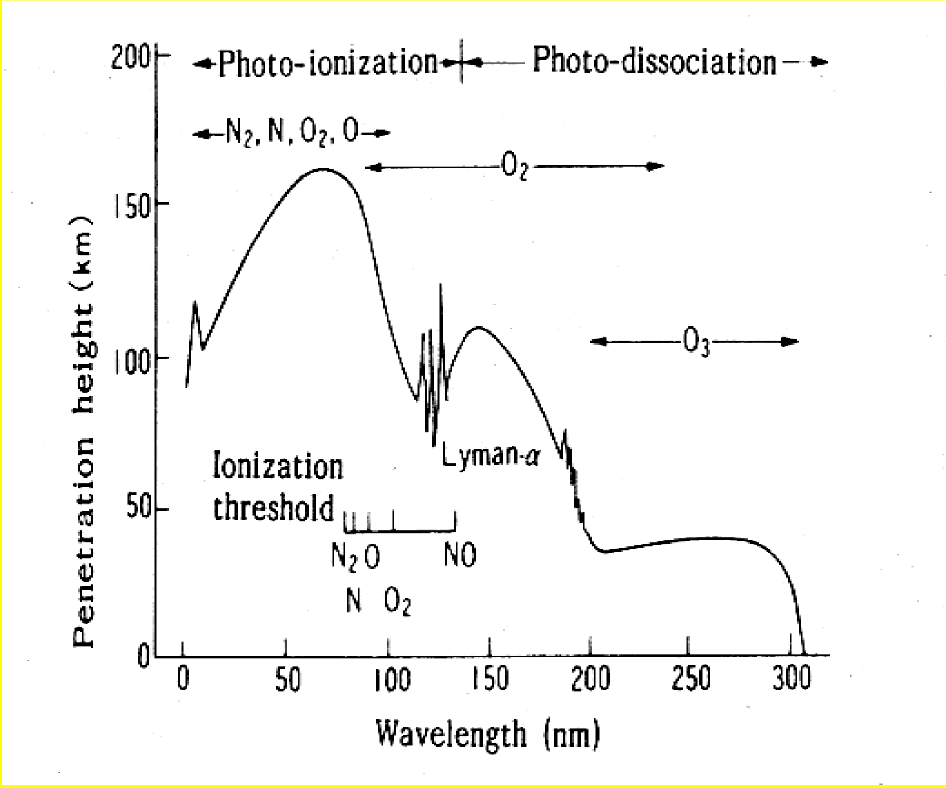
$$AB + h\nu \rightarrow A + B$$

2. Photo excitation (λ < 130 nm)

$$AB + h\nu \rightarrow AB^*$$

3. Photo ionization (λ < 100 nm)

$$A + h\nu \rightarrow A^+ + e^-$$



Development of Ionospheric model: Sydney Chapman

Solving the Continuity equation and imposing some assumptions

$$\frac{dN}{dt} = q(z,\chi) - L(N) - div(N.\bar{v})$$

Chapman assumptions:

-Flat earth

-Monochromatic radiation

Single ionizing constituents

-Electrically neutral ionosphere

-Dynamic equilibrium

Two models:

1. **Chapman Beta model – the lower ionosphere:**

$$q(\chi) = \beta N$$

$$N = \left(\frac{q_0}{\beta}\right) cos\chi^{(\beta+1)}$$

2. Chapman Alpha model – upper ionosphere:

$$q(\chi) = \alpha N^2$$

$$N = \left(\frac{q_0}{\alpha}\right)^{\frac{1}{2}} cos\chi^{\frac{1}{2}(\beta+1)}$$

Properties of the Ionosphere

1. **Ionized**
2. **Optical medium**
3. **In-homogenous, as result of the presence of permanent magnetic field due to the earth**

- The presence of **Earth's magnetic** field renders the ionosphere anisotropic and birefringent.

Propagation of radio waves through the ionosphere

Radio signals, being e/m waves propagate through the ionosphere by causing (through the electric field component) displacement of electrons

Basic Definitions:

1. **Current density**
2. **Polarisation**
3. **Equation of motion**

$$\bar{J} = Ne\frac{\delta r}{\delta t}$$

$$\bar{P} = Ne\bar{r}$$

$$F = ma$$

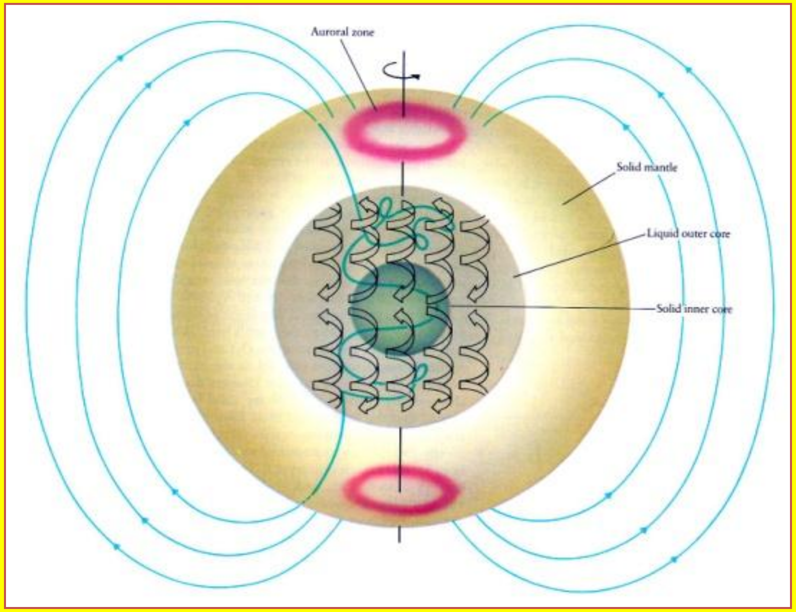
$$F = \bar{E}e \qquad E = E_0 e^{j\omega t}$$

Propagation of radio waves through the ionosphere

Three possible conditions in the ionosphere that influence motion of e/m wave through the ionosphere:

1. **Ionization**
2. **Collision among species**
3. **Presence of permanent magnetic field.**

The problem is to obtain the wave polarization term P from the three possible equations of motion emanating from the conditions above



Propagation of radio wave through the ionosphere

$$\bar{E}e = m\frac{\delta^2\bar{r}}{\delta t^2} \quad \ldots\ldots\ldots\ldots\ldots(1)$$

$$Ee = \frac{m}{Ne}\frac{\delta^2 P}{\delta t^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Equation of motion for the first condition (undamped ionized medium):

The alternating electric field of the wave polarized along the X – axis will acts on the electrons thereby causing electrons to oscillate in the z-axis

with:

$$E = E_0 e^{j\omega t}, P = P_0 e^{j\omega t}$$

Soln: $P = -\varepsilon_0 XE \quad \ldots\ldots\ldots\ldots\ldots\ldots(3)$

where:

$$X = \frac{Ne^2}{\varepsilon_0 m\omega^2} = \frac{\omega_N^2}{\omega^2} = \frac{f_N^2}{f^2}$$

Plasma frequency:

$$f_N^2 = \frac{e^2}{\varepsilon_0 m(2\pi)^2}N \Longrightarrow f^2 \alpha N$$

Propagation of radio wave through the ionosphere

The second condition is the inclusion of collision among particles. Equation of motion:

$$\bar{E}e = m\frac{\delta^2 \bar{r}}{\delta t^2} + F_c$$ .... (1)

$$\bar{E}e = \frac{m}{Ne}\frac{\delta^2 \bar{P}}{\delta t^2} + \frac{mv}{Ne}\frac{\delta P}{\delta t}$$ .... (2)

$$\bar{P} = \frac{Ne^2}{m}\left(\frac{1}{j\omega v - \omega^2}\right)\bar{E}e$$ .... (3)

$$P = \frac{-\varepsilon_0 X E}{1 - jZ}$$

$$X = \frac{Ne^2}{\varepsilon_0 m \omega^2} \qquad j = \frac{\nu}{\omega}$$

Collision has the effect of reducing the extent of polarization of the electric field.

Propagation of radio waves through the ionosphere

The third case is the inclusion of the permanent magnetic field in the equation of motion:

The magnetic field exerts the Lorentz force on the electron which causes it to follow a curved trajectory

$$F_m = qv \wedge B$$

$$F_m = e\frac{\delta \bar{r}}{\delta t} \wedge B$$

Propagation of radio waves through the ionosphere

Equation of motion incorporating collision and the permanent magnetic field

$$\bar{E}e + e\frac{\delta\bar{r}}{\delta t} \wedge B = m\frac{\delta^2\bar{r}}{\delta t^2} + mv\frac{\delta\bar{r}}{\delta t} \qquad \text{.........} \quad (1)$$

Soln: $$-\varepsilon_0 XE = \bar{P}(1 - jz) + j\bar{P} \wedge \bar{Y} \qquad \text{.........} \quad (2)$$

Where $\bar{E} = E_x + E_{y'} + E_z$ and $E = E_0 e^{j\omega t}$

$\bar{Y} = Y_x + Y_{y'} + Y_z$ and $Y = EY_0 e^{j\omega t}$

$$\bar{Y} = \frac{e\bar{B}}{m\omega}, \qquad X = \frac{Ne^2}{\varepsilon_0 m\omega^2}, \qquad z = \frac{v}{\omega}$$

Equation (2) is the solution to equation (1). It is a three dimension matrix of vector product.

Propagation of radio wave through the ionosphere

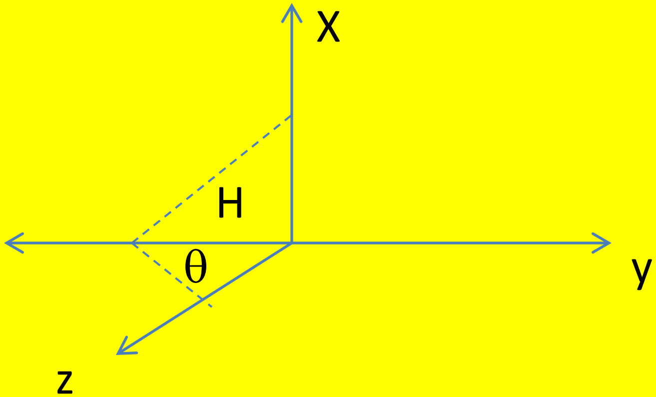
The matrix equations to be solved are :

$$-\varepsilon_0 X E_x = U P_x + j P_y Y_z - P_z Y_y \qquad \text{.................. (a)}$$

$$-\varepsilon_0 X E_y = -j P_x Y_z + U P_y - j P_z Y_x \qquad \text{............... (b)}$$

$$-\varepsilon_0 X E_z = j P_x Y_y - j P_y Y_x - U P_z \qquad \text{........... (c)}$$

If we assume that propagation is in the z-axis while the magnetic field is in the x-y-z plane, then the equations becomes;



$$-\varepsilon_0 X E_x = U P_x + j P_y Y_z - 0 \qquad \text{.......... (a)}$$

$$-\varepsilon_0 X E_y = -j P_x Y_z + U P_y - j P_z Y_x \qquad \text{........ (b)}$$

$$-\varepsilon_0 X E_z = 0 - j P_y Y_x - U P_z \qquad \text{................ (c)}$$

Propagation of radio waves through the ionosphere

The total polarization D= Eε+P is now a resultant of the electric field due to the e/m and the electrons. By the condition imposed on the direction of propagation, Dz =0., hence Pz is obtained and can be used in conjunction with equations (a) and (b) to obtain the wave polarization equation

The wave polarization relation is obtained by solving the third and fourth Maxwell's equation for Ex and Ey. Thus :

$$\rho = \frac{E_y}{E_x} = \frac{P_y}{P_x} \quad \text{............. (4)}$$

Implementing equation (4) above leads to the desired wave polarization equation

$$\rho^2 + \frac{Y_x^2}{jY_z(U - X)}\rho + 1 = 0 \quad \text{............... (5)}$$

$$\rho = \frac{jY_x^2}{2Y_z(1 - X - jz)} \pm j\left[\frac{Y_x^4}{4Y_z^2(1 - X - jz)} + 1\right]^{1/2} \quad \text{.......... (6)}$$

Propagation of radio waves through the ionosphere

Equation (6) is referred to as the wave polarization equation of the **magneto-ionic theory. This equation arises as a direct result of the permanent magnetic field which makes the ionized gas behaves like an *anisotrpoic* medium for radio waves. As a consequence, the polarization is a double polarization.**

The two polarized waves are referred to as *ordinary ρ0* and *extra-ordinary wave ρx polarization*

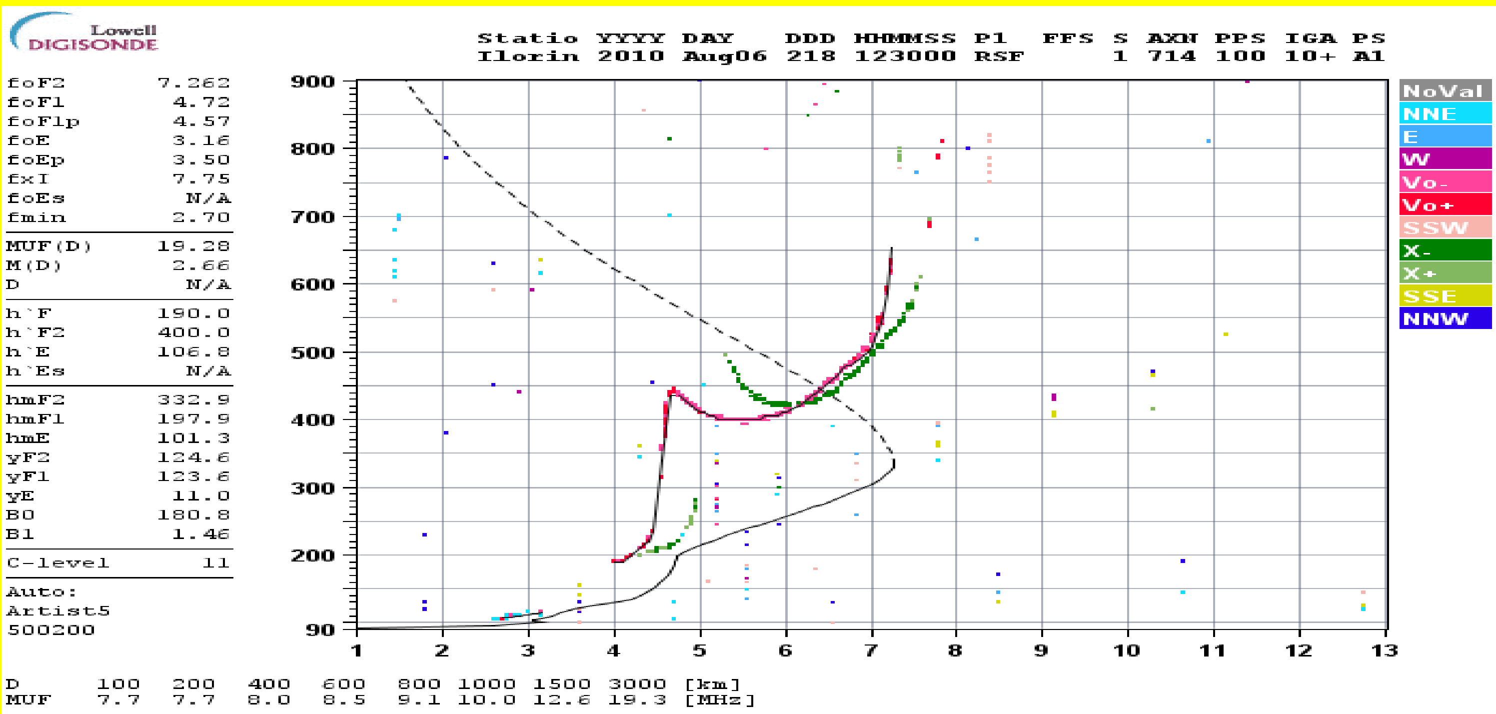
These two waves are refracted differently as shown in the equation (7) below:

Possible conditions and resultant effect on radio wave:

1. **Absence of magnetic field = no polarization of wave**
2. **When the angle between the electric and magnetic fields θ=0, we have longitudinal polarization, a situation whereby the wave is circularly polarized. This is what entails in the polar regions.**
3. **When θ =90, we have N-S polarization of ordinary wave and E-W polarization of the extra-ordinary waves.**

Propagation of radio wave though the ionosphere

The splitting of the transmitted wave into the o- and x-waves, clearly displayed in ionogram traces.



Reflection of radio wave in the ionosphere

Appleton – Hartree formula for the refractive index of radio wave

$$n^2 = 1 - \frac{X}{(1-jz) + \left\{\frac{-Y_x^2}{2(1-X-jz)} \mp \left[\left(\frac{Y_x^4}{4(1-X-jz)^2}\right) + Y_z^2\right]^{1/2}\right\}} \quad \text{............ (7)}$$

Recall:

$$\bar{Y} = \frac{e\bar{B}}{m\omega}, \qquad X = \frac{Ne^2}{\varepsilon_0 m\omega^2}, \qquad z = \frac{\nu}{\omega}$$

High electron density implies low refractive index leading to refraction of the e/m wave. i.e. Refractive index varies with height.
At normal incidence, the ionosphere will reflect only the waves whose frequency does not exceed the critical value i.e. f=fp

In the short-wave band, fx > fo at any given electron density . Thus for any fixed frequency, x-wave will be reflected from a higher level than the o-wave.

Reflection occurs when:
f = fo (o-wave)
X = 1-Y
X = 1+Y (x-wave)

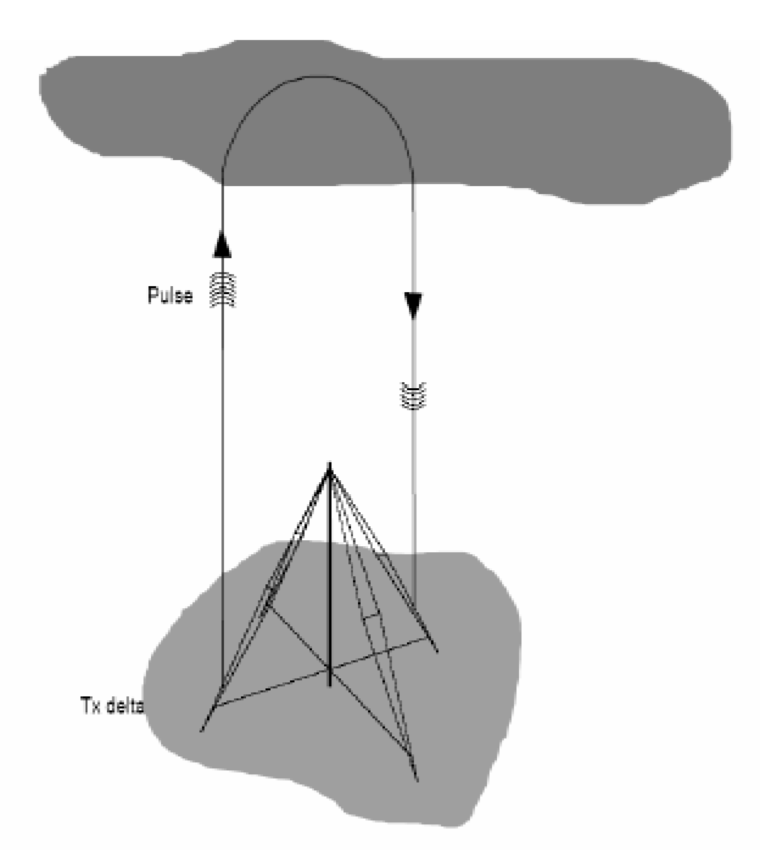
Reflection of radio wave in the ionosphere

At vertical incidence, when the ray is nearly horizontal to the layer, the condition for reflection is :

For o-wave: $$sin^2\varphi_0 = n_2^2$$

For x-wave $$sin^2\varphi_0 = n_1^2$$

n1 and n2 are the refractive indices for o- and x- waves as given by equation (7) above.



Conclusion

- Propagation of HF radio waves is made possible by the presence of the ionosphere
- Electron in the ionosphere is the most important player in propagation (courtesy the Sun)
- The presence of permanent magnetic field in the upper atmosphere is a critical factor in HF radio wave propagation.

Thank you for listening