Ionospheric Monitoring Techniques

O. K. OBROU

October 5, 2023

Université FHB Cocody
Laboratoire des Sciences de la Matière et l'Energie Solaire (LASMES)

Table of contents

Introduction

Introduction

The ionosphere is a region of an atmosphere where significant numbers of free thermal electrons and ions are present. All bodies in our solar system that are surrounded by neutral-gas envelope, due either to gravitational attraction (e.g., planets) or some other process such as sublimation (e.g., comets), have an ionosphere. Currently, ionospheres have been observed around all but two of the planets, some moons, and comets.

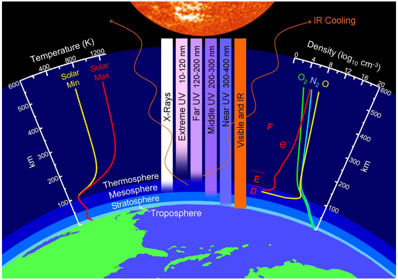


Figure 1: Process of the creation of the ionosphere

In 1901, Marconi succeeded in crossing the Atlantic with a radio transmission at a frequency of 300 kHz.

Introduction

The ionosphere is a region of an atmosphere where significant numbers of free thermal electrons and ions are present. All bodies in our solar system that are surrounded by neutral-gas envelope, due either to gravitational attraction (e.g., planets) or some other process such as sublimation (e.g., comets), have an ionosphere. Currently, ionospheres have been observed around all but two of the planets, some moons, and comets.

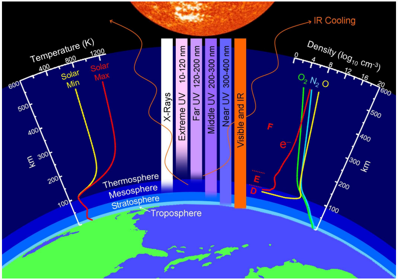


Figure 1: Process of the creation of the ionosphere

In 1901, Marconi succeeded in crossing the Atlantic with a radio transmission at a frequency of 300 kHz.

In 1902, Kennelly and Heaviside both independently suggested that Marconi's signal was propagated by reflection of signals from an ionised layer in the upper atmosphere.

Formation of the Ionosphere

Temperature profile of the Earth's atmosphere

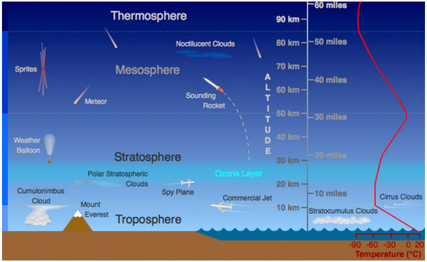
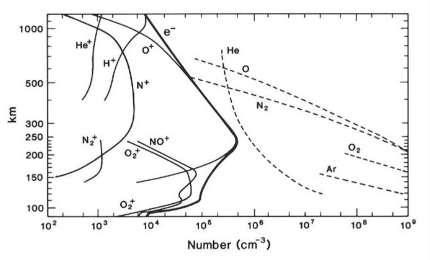


Figure 2: Temperature profile

The atmosphere can be described as a number of layers (-spheres) separated by transition fine layers (-pauses) defined as the inflection points of the temperature profile. This layers are as follow

- The *troposphere* is heated mainly by the ground, which absorbs solar radiation and re-emits it in the infra-red.
- The stratosphere above the troposphere has a positive temperature gradient due to heating from the ozone which absorbs the solar ultra-violet radiation that penetrates down to these altitudes.
- The mesosphere, above 50 km, where the density of ozone drops off faster than the increase of the incoming radiation. The temperature therefore decreases with the

Neutral Composition of the Atmosphere



The Earth's atmosphere is made up of a large number of chemical constituents

- Photochemical processes play a fundamental role in the middle and upper atmosphere including the ionosphere
- The density of all constituants decreases with increasing altitude
- N_2, O and He are the most important chemical elements in terms of density.

Chemical processes in the upper atmosphere

The ionosphere is formed when extreme ultraviolet light from the sun strips electrons from neutral atoms of the Earth's atmosphere.

Photoionization

When a bundle of EUV light also called photon hits a neutral atom such as oxygen atom, its energy is transferred to an electron in the neutral atom which can then escape from the atom and move freely around. The neutral atom becomes positively charged and is known as a positive ion. The process in which the photon strips an electron from a neutral atom to creat a positive ion is known as Photoionization.

Chemical processes in the upper atmosphere

The ionosphere is formed when extreme ultraviolet light from the sun strips electrons from neutral atoms of the Earth's atmosphere.

Photoionization

When a bundle of EUV light also called photon hits a neutral atom such as oxygen atom, its energy is transferred to an electron in the neutral atom which can then escape from the atom and move freely around. The neutral atom becomes positively charged and is known as a positive ion. The process in which the photon strips an electron from a neutral atom to creat a positive ion is known as Photoionization.

Recombination

The production of free electrons in the ionosphere is balanced by a reverse process. A negatively charged electrons and positively charged ions combined together to produce neutral atoms. This is the main process by which electrons are lost in the ionosphere. Recombination

Chemical equations of the photoionization

Photodissociation ($\lambda > 130nm$)

$$AB + h\nu \longrightarrow A^{+} + B^{-}$$

Photoexcitation ($\lambda < 130nm$)

$$AB + h\nu \longrightarrow AB^{*}$$

Photoionization ($\lambda < 100nm$)

$$A + h\nu \longrightarrow A^{+} + e^{-}$$

Chemical equations of the recombination processes

Radiative recombination

$$X^+ + e^- \xrightarrow{\alpha_R} X + h\nu$$

Dissociative recombination

$$AX^+ + e^- \xrightarrow{\alpha_D} A + X$$

Ion-Ion recombination

$$X^+ + A_2 \xrightarrow{\alpha_i} XA^+ + A$$

Basic principles of magneto-ionic

Basic principes of magnetoionic

The techniques used for monitoring the ionized layers of the Earth's upper atmosphere are based on propagation effects that influence radio waves travelling through the ionosphere.

The Maxwell Equations

In a free space and an isotropous undisturbed homogeneous medium, the Maxwell equation are as follow:

$$div\,\overrightarrow{E} = 0 \tag{1}$$

$$div\,\overrightarrow{B} = 0 \tag{2}$$

$$curl\,\overrightarrow{E} = -\frac{\partial \overrightarrow{B}}{\partial t} \tag{3}$$

$$curl\,\overrightarrow{B} = \mu_o \varepsilon_o \frac{\partial \overrightarrow{E}}{\partial t} \tag{4}$$

In these equations $\overrightarrow{E}$ is the vector of the electric field expressed in V/m, $\overrightarrow{B}$ the vector of magnetic field in Tesla, ε_o the electric permittivity, and μ_o the magnetic permittivity.

1. Equation (1) is from the Gauss theorem, concerns the fact that the flux of the electric field $\overrightarrow{E}$ within a closed surface depends only on the electric charge inside this closed surface. In the case of a vacuum, this is equal to 0.
2. Equation (2) expressed the non divergence of magnetic field. The Magnetic field lines do not come from an isolated source but connect one pole to another.
3. Equation (3) regards the law of Faraday-Neumann-Lenz concerning the induction of an electric field by time variation of the vector of the magnetic field $\overrightarrow{B}$.
4. Equation (4) is the Ampere theorem, a variation in time of the vector $\overrightarrow{E}$ produces a mag- netic field of intensity B/μ_o

Wave propagation equations

Let apply the operator curl to equation (3) and (4).

$$curl\, curl\, \overrightarrow{E} = -\frac{\partial\, curl\, \overrightarrow{B}}{\partial t} = -\mu_o \varepsilon_o \frac{\partial^2 \overrightarrow{E}}{\partial t^2}$$
$$curl\, curl\, \overrightarrow{E} = \overrightarrow{grad}\, div\, \overrightarrow{E} - div\, \overrightarrow{grad}\, \overrightarrow{E} = -\nabla^2 \overrightarrow{E}$$

Finally

$$\nabla^2 \overrightarrow{E} = \mu_o \varepsilon_o \frac{\partial^2 \overrightarrow{E}}{\partial t^2} \tag{5}$$

$$\nabla^2 \overrightarrow{B} = \mu_o \varepsilon_o \frac{\partial^2 \overrightarrow{B}}{\partial t^2} \tag{6}$$

(5) and (6) are the propagation equations of the magnetic waves. For a wave propagating along the x axis with phase velocity $c = (1/\mu_o \varepsilon_o)$ corresponding, for a vacuum, to the velocity of light with $B_y = E_z = 0$. The general solution of these equations is for Ey :

$$E_y(x,t) = F(x - vt) - G(x + vt)$$

where $F(x - vt)$ and $G(x + vt)$ represent respectively the progressive and backward waves fonctions. As a specific case of progressive wave, $E_y(x,t)$ can be written as follow

$$E_y(x,t) = A \sin(\omega t - \psi)$$

A is the amplitude, and $(\omega t - \psi)$ is the phase at the instant t and at distance x from the origin, $\omega = 2\pi f$, the pulsation, f, the frequency and $k = 2\pi/\lambda$ (λ the wave length) is the wave number, which is the change of phase proportional to the distance x.

Group and phase velocity

According to the Fourier theorem, a given non harmonic wave may be considered as a result of n monochromatic waves, each with frequency and phase as follows:

$$E_y = a + \sum_{n=1}^{\infty} A_n \sin(n\omega t - \varphi_n)$$

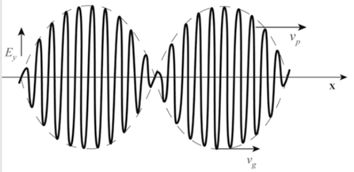
where a is the average value of E_y, $A_1 \sin(\omega t - \varphi_1)$ the first or fundamental harmonic, and the others for $n = 2, 3..$ are the second, third, etc.

A wave propagating in a media is then a composition of single monochromatic waves. It pulsation and initial phase are the average of the pulsations and the initial phases of the wave components.

For the case of two monochromatic waves, the phase and group velocity are respectively

$$v_p = (\omega_1 + \omega_2)/(k_1 + k_2)$$
$$v_g = (\omega_1 - \omega_2)/(k_1 - k_2)$$

Physical implications



The wave obtained from two monochromatic waves is a wave of amplitude oscillating at a velocity expressed by v_g. This is the velocity at which a group of waves, propagating at velocity v_p, are enveloped together.

v_p, v_g

In a medium like a dielectric the group velocity is the velocity at which the maximum of the wave is propagating and so represents the velocity of propagation of energy. The phase velocity is the velocity of the wave front, this being the plane along which the phase has, at a given instant, the same value.

The Appleton-Hartree Formula

Hypothesis

We consider a plasma (composed by ions, electrons, molecules, and is totally neutral) subject to an external magnetic field that is constant. The is supposed to be cold so that thermal movements can be ignored.

The interaction of a harmonic plane wave with positive or negative charged particles can be described with the following dynamics equation

$$md\overrightarrow{v}/dt = q\overrightarrow{E} + (q\overrightarrow{v} \wedge \overrightarrow{B}) - m\nu\overrightarrow{v} \tag{7}$$

where $\overrightarrow{v}$ is the velocity and m the mass of the free electrons and $m\nu\overrightarrow{v}$ the viscosity force. The mouvement of the electrons can be describe as a current, with a vector density $\overrightarrow{J} = Nq\overrightarrow{v}$; $d\overrightarrow{v}/dt = i\omega\overrightarrow{v} = i\omega\overrightarrow{J}/Nq, i^2 = -1$, $\overrightarrow{v} = v_o i \exp(\omega t - \varphi)$
The current is

$$-\overrightarrow{J} = iNq^2\overrightarrow{E}/m\omega + iq\overrightarrow{J}/m\omega \wedge \overrightarrow{B} - i\nu\overrightarrow{J}/Nq \tag{8}$$

$$X = \frac{Ne^2}{\varepsilon_o m\omega^2} = f_N^2/f^2 \tag{9}$$

$$Y = f_H/f \tag{10}$$

$$Z = \frac{\nu}{\omega} \tag{11}$$

Physical meaning of f_N and f_H

1. $f_N = \sqrt{\frac{Nq^2}{4\pi^2\varepsilon_o m}}$ the plasma frequency, which represents the frequency of free oscillation of the electrons
2. $f_H = \frac{q|B|}{2\pi m}$ the gyrofrequency, which is the frequency of the circular motion of the free electrons subject to a magnetic field $\overrightarrow{B}$ according to Lorentz's law.

The Appleton-Hartree Formula is expressed as follow

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{Y_T^2}{2(1-X-iZ)} \mp \left[\frac{Y_T^4}{4(1-X-iZ)^2} + Y_L^2\right]^{1/2}} = (\mu - i\chi)^2 \qquad (12)$$

where

$$Y_L = \frac{eB_L}{m\omega}$$

$$Y_T = \frac{eB_T}{m\omega}$$

B_L is longitudinal component of $\overrightarrow{B}$ while B_T is transversal component.

Meanin of double index

The double index of refraction n means that when an electromagnetic wave propagates in a dispersive and anisotropic medium, the propagation of two waves of the same frequency and with different phase velocities are observed. What is not the case in free space.

In the ionosphere, the collision frequency is negligeable ($Z = 0$). Furthermore, in the absence of an external magnetic field $Y_T = Y_L = 0$ Appleton-Hartree equation for the phase refractive index can be written in its simplest form

The simplest form of the Appleton-Hartree formula

$$n^2 = 1 - X \tag{13}$$

For a total reflexion of an electromagnetic wave in the ionosphere, $n = 0$. Resolving the above equation yield

$$f = f_N \tag{14}$$

$$f_z = \sqrt{(f_N^2 + f_H^2/4)} - f/2 \tag{15}$$

$$f_x = \sqrt{(f_N^2 + f_H^2/4)} + f/2 \tag{16}$$

Radio soundings of the ionosphere

Radio soundings of the ionosphere

The observation of the ionosphere is mainly based on the use of radio wave. Our knowledge of the ionosphere comes from remote sensing by radio waves.

Time of flight
The time of flight is the time delay of a radio wave. There are two methods of measurement

- measurement of the time delay of a pulse
- determination of the stationary phase

Frequency variations
The frequency difference Δf between an echo signal and that of a reference signal is given by

$$\Delta f = -\frac{1}{2\pi}\frac{d\phi}{dt}$$

When the phase ϕ is recorded digitaly Δf can be obtained by numerical differentiation.

Ionosondes

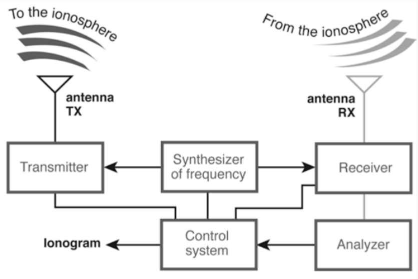
The ionosonde is a sweep-frequency pulsed radar device used to monitor the ionosphere. It frequency can range from below 0.1 MHz to 30 MHz or more with a sweep duration from a few seconds to a few minutes. As the frequency is increased the pulse penetrates to higher levels in the ionosphere. The virtual height increases until the signal penetrates at the critical frequency f_c, which is related to the maximum electron density N_{max} by

$$N_{max} = 1.24 \times 10^{10} f_c^2$$

where N_{max} is in electrons per cubic meter and f_c is in megahertz. The time delay is obtained by the following equation

$$\Delta t = \frac{2}{c} \int_0^{z(f_p)} \frac{dz}{n}$$

where n is the refractive index.



An ionosonde is composed of

1. a synthesizer that generates the radio frequency to be transmitted and a transmitter that amplifies the electromagnetic pulse to be emitted from an antenna system;
2. a receiver apparatus with an antenna system that amplifies the received signal;
3. finally, a control system able to pilot the emission time in accordance with the expected arrival of the signal at the receiver, and analyze and elaborate the signal received as a graphic trace.

Interpretation of Ionogram

According to the URSI Handbook of ionogram interpretation and reduction edited by W. R. Piggot and K. Rawer, the following tasks are required at any sounding station

- Monitor the ionosphere above the station.
- Obtain significant median data to evaluate long-term changes.
- Study phenomena peculiar to the region.
- Study the global morphology of the ionosphere.

For a simple description of the ionosphere by vertical sounding it is convenient to consider the ionosphere as schematically divided into the conventional regions D, E, F, and the sporadic Es

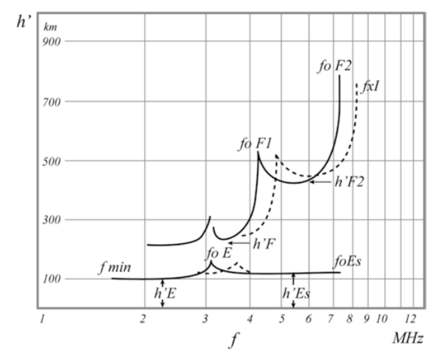
F Region

$foF2$: critical frequency of the ordinary trace of the highest layer of the F region,called the F2 layer when the F1 layer is present.
fxI : highest frequency recorded by a reflection from the F region.
$foF1$: critical frequency of the ordinary trace of the F1 layer when present.
$h'F2$: minimum virtual height of the ordinary trace of the F2 layer. $h'F$: lowest virtual height of the ordinary trace of the F region.

E Region

foE : critical frequency of the ordinary trace of the E region.

$h'E$:minimum virtual height of the ordinary trace of the E region.



Es Sporadic E layer

foE_s:highest frequency of the ordinary trace of the continuous sporadic E layer.

$h'E_s$:minimum virtual height of the ordinary trace of the Es layer.

f_bE_s :blanketing frequency of the Es layer.

f_{min}:lowest frequency recorded in the ionogram.

Ionospheric data base

The measurements of the principal ionospheric characteristics obtained from scaled ionograms are stored in data based.

1. SPIDR Space Physics Interactive Data Resource:
   `http://spidr.ngdc.noaa.gov/spidr/`
2. ESWUA Electronic Space Weather Upper Atmosphere:
   `http://www.eswua.ingv.it/`
3. DIAS Digital Ionospheric Upper Atmosphere Service:
   `http://www.iono.noa.gr/DIAS/`
4. UMass. Lowell Center for Atmospheric Research:
   `http://umlcar.uml.edu/`

Ionospheric Sounding with GNSS Signals

The refractive index of the ionosphere can be expressed as follows

$$\mu = (1 - X)^{1/2}$$

with

$$X = \frac{\omega_p^2}{\omega^2}$$

where ω_p and ω are respectively the plasma frequency and the frequency of the propagating wave. In fisrt order approximation [1] the phase refractive index is

$$\mu_p \approx 1 - \frac{1}{2}X = 1 - \frac{Ne^2}{2\varepsilon_o m\omega^2}$$

so that

$$\mu_p = 1 - \frac{40.3N}{f^2}$$

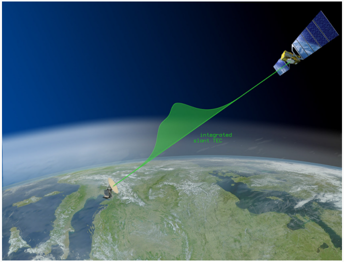
and the groupe refractive index is

$$\mu_g = 1 + \frac{40.3N}{f^2}$$

[1] $(1 + x)^a = 1 + ax + \frac{a(a-1)}{2}x^2$

Total Electron Content

The total electron content (TEC) is the number of electrons in a column of one metre-squared cross-section along a trans-ionospheric path. It can be obtained by different means, mainly from GNSS and satellite born altimeters signals



The time delay induced by the phase index is

$$\Delta\tau = \frac{1}{c}\int_{u}^{s} (\mu_p(l) - 1)\, dl$$

$$TEC = \int_{u}^{s} N(l) dl$$

where N is the electron density of the plasma.
The TEC is expressed in TECU. $1\, TECU = 10^{16} el/m^2$

Thanks for Your Attention !