A review of the ionospheric measurement techniques

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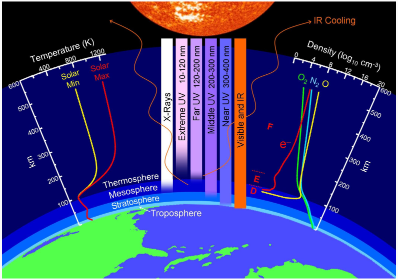
Introduction

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. We will talk about only the Earth's ionosphere in this presentation



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1925 : Appleton & Barnett proved the existence of the ionized layer and found its height by doing a phase comparison of two signals from a transmitter, one the ground wave, and the other reflected from the ionosphere

1926 : Breit & Tuve used a pulse technique to measure the heights and critical frequencies of a number of ionospheric layers. Theirs was the first true ionosonde, and may have been the first radar

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1931 : Chapman presented a theory for the formation of an ionized layer due to the action of solar ultraviolet radiation

1932 : Appleton developed an extensive set of equations used to describe the propagation of radio waves in the ionosphere. These included absorption effects and modification due to the Earth's magnetic field

Formation of the Ionosphere

Temperature profile of the Earth's atmosphere

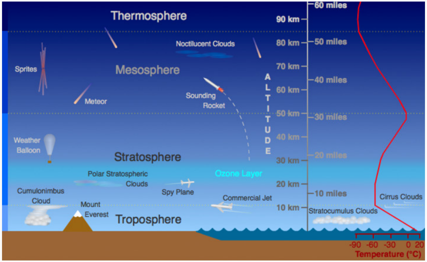
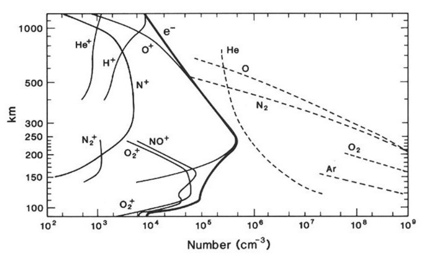


Figure 1: Temperature profile

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 altitude.
- The thermosphere is heated mainly by absorption of EUV and XUV radiation through dissociation of molecular oxygen.

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

Hydrostatic equilibrium of the Atmosphere

Pressure gradient : $\overrightarrow{\nabla}(p) = \rho \overrightarrow{g}$

In the vertical direction, the Hydrostatic relation expressed the balance between the gravitational force and the pressure grandient

$$\frac{dp}{dz} + \rho g = 0$$

Perfect gaz law : $p = nkT = \frac{\rho}{M} kT$

$\rho = p \frac{M}{kT}$

If g and T are not function of z, then

$$\frac{dp}{dz} = -p \frac{Mg}{kT} = -\frac{p}{H}$$

where $H = \frac{kT}{Mg}$, the scale factor defined has a distance over which a quantity decreases by a factor of e.
As an example, the neutral scale height is $H = 9 \times 10^3 m = 9km$

$$p(z) = p(z_0) \exp\left(\frac{z - z_0}{H}\right)$$

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.

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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.

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 :	$X^{+} + e^{-} \xrightarrow{\alpha_R} X + h\nu$
$h\nu$, the radiated energy	α_R :radiative recombination rate

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

Ion-Ion recombination :	$X^{+} + A_2 \xrightarrow{\alpha_i} XA^{+} + A$

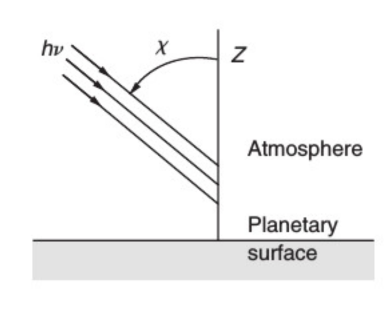
Absorption of solar radiation

EUV radiation and particle are the two major sources of energy input into the thermosphere and the Ionospheres in the solar system. Relatively long wavelength photons ($\gtrsim 900\AA$) generally cause dissociation, while shorter wavelength cause ionization. The resulted distribution depends on the relevant cross sections and the atmospheric species.

Chapman layer theory

The basic physical principles of the Chapman theory are as follow

- (a) the radiation is monochromatic (single wavelength)
- (b) the atmosphere consists of a single absorbing species, which decreases exponentially with altitude with a constant scale H
- (c) the atmosphere is plane and horizontally stratified



Basic equations of solar radiation

Let σ be the absorption cross section, I the photon flux, $n(z)$ the neutral density, at the altitude z and χ the solar zenith angle. As the photon flux penetrates the atmosphere, it is attenuated by absorption. The decrease in intensity of the flux after it travels an incremental distance is given by

$$\frac{dI}{dz}\cos\chi = n(z)I\sigma$$

The intensity of the photon flux at an arbitrary altitude can be written as

$$I(z,\chi) = I_\infty \exp\left[-\frac{Hn(z)\sigma}{\cos\chi}\right]$$

where I_∞ is the unattenuated flux at the top of the atmosphere.

The Chapman function

If the probability of a photon absorption, resulting in the production of an ion-electron pair, is denoted by η, then this rate of production, called the `Chapman production function`, P_c , is written as

$$P_c(z,\chi) = I(z,\chi)\eta n(z) = I_\infty \exp\left[-Hn(z)\sigma \sec\chi\right]\sigma n(z)$$

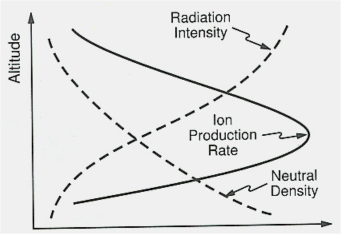
This equation clearly indicates that the production rate is proportional to the intensity of solar ionizing radiation, which increases with altitude, and the neutral gas density, which decreases with altitude.

Solving the equation

$$\frac{d}{dz}\left(P_c(z,\chi)\right) = 0$$

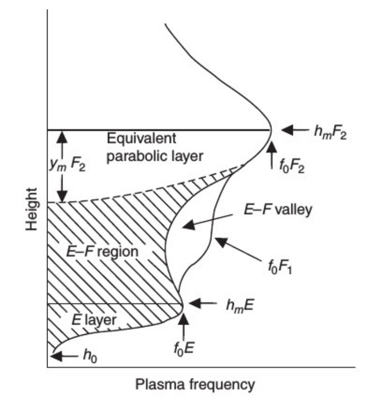
give the altitude of the maximum production.

$$z_{max} = z_0 + Hln\left[n(z_0)H\sigma \sec\chi\right],$$



Characteristics of the Ionosphere

Ionospheric layers



Due to different ionization production and loss processes the electron density profile with altitude shows a layered structure that changes with time, location and solar activity as it is seen in the figure.

- The D region is situated around 90 km with a maximum density of about $1.5 \times 10^4 e/cm^3 (noon)$. Enhanced ionization following solar flares. $\alpha = 3 \times 10^{-8} cm^3/s$
- The E region height is about 110 km with a maximum density of $1.5 \times 10^5 e/cm^3 (noon)$. The production of electron is essentially due to the absorption of EUV ($h\nu > 12eV$) by O_2. The main recombination process is dissociative ($O_2^+ + e^- \rightarrow O + O$) and ($NO^+ + e^- \rightarrow N + O$). $\alpha_D = 1 \times 10^{-8} cm^3/s$

Ionospheric layers cont.

- The F1 region is due to the ionization of O by Lyman "continium" or by emission lines of He. F1 disappers rapidly after sunset. It is located around 200 km with a maximum density of about $2.5 \times 10^5 e/cm^3 (noon)$. $\alpha_i = 7 \times 10^{-9} cm^3/s$. O^+ transfer charge to NO
- The F2 region height is above 300 km with a maximum density of $10^6 e/cm^3 (noon)$ and $10^5 e/cm^3 (night)$. The production of electron is essentially due to ionization of O_2. The main recombination process is radiative with a rate α_R oscillating between 10^{-10} and $10^{-9} cm^3/s$. The height and electron density in the F2 region are highly variable and depends on the day, season and solar sunspot cylce.

The equatorial ionosphere

The equatorial ionosphere

By definition
The equatorial and low latitude ionosphere is the region where the Earth's magnetic field lines are nealy horizontal. At this latitudes the electric field $\overrightarrow{E}_y$ (eastward) is mutually perpendicular to the magnetic field $\overrightarrow{B}$ (northward) and the electron gradient $\overrightarrow{V}_d$ (upward).

The sheet current

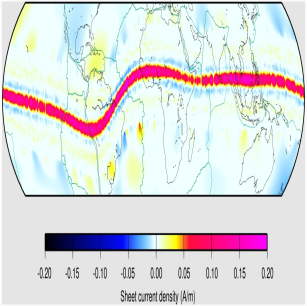


Figure 2: The Current sheet along the magnetic equator

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iv) Equatorial Spread F (ESF)

Equatorial Electrojet

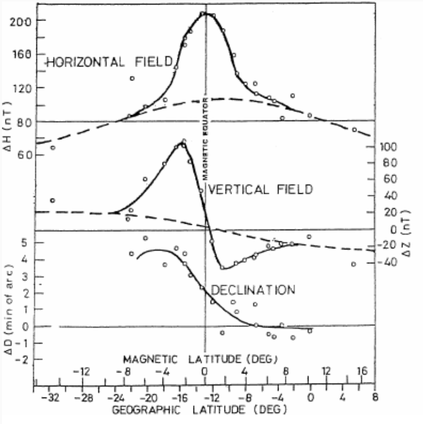

Figure 3: Latitudinal variations of the daily range of H, D and Z along the 75°W meridian during the IGY (Forbush & Casaverde 1961)

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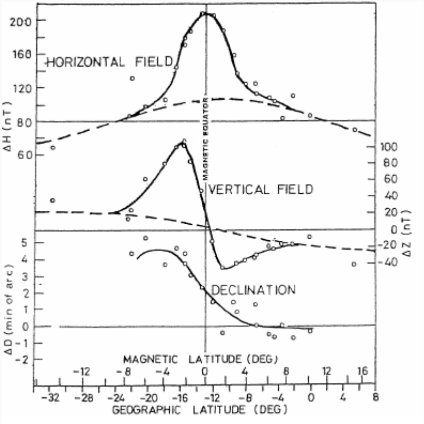
Equatorial Electrojet



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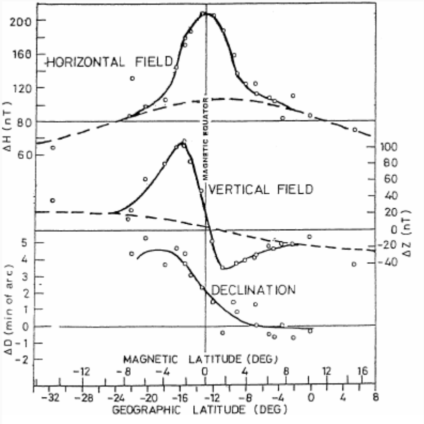

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2. Egedal (1947) found an abnormal intensification of the daily range of *H* over the dip equator.
3. This phenomenon was ascribed by Chapman (1951) as due to an eastward band of electric current in the ionosphere, which he named the *'equatorial electrojet'*

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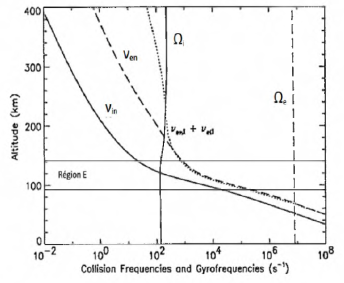
- Below the E region the collision frequency (ν_{in}, ν_{en}) are greater than the gyrofrequency (Ω_i , Ω_e). The electron and the ions are carried by the neutral wind at the same speed. No current is established



The Basic Equations in 3 steps

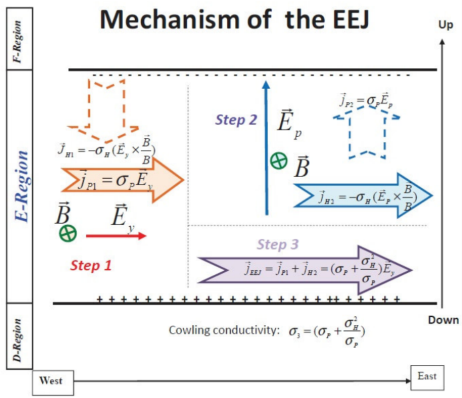


Figure 4: Mecanism of the EEJ(Grodji et al., 2016

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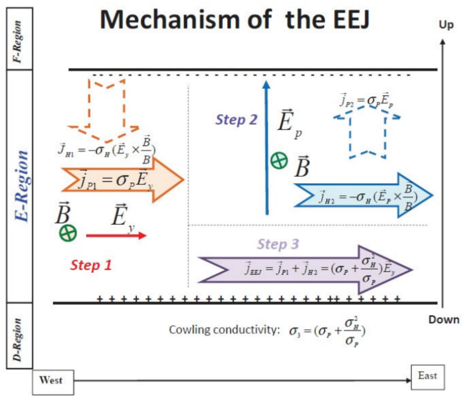

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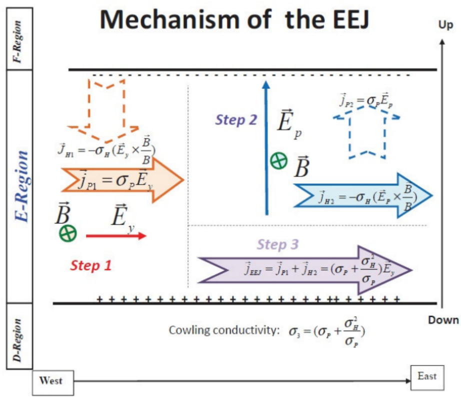

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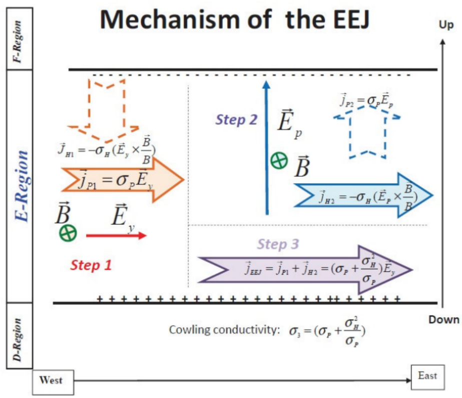

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- Step 3 : When the polirization process is complet $\overrightarrow{J}_{H1} + \overrightarrow{J}_{p2} = \overrightarrow{0}$ The total eastward current is

$$\overrightarrow{J}_{EEJ} = \left(\sigma_p + \frac{\sigma_H^2}{\sigma_p}\right)\overrightarrow{E}_y \qquad (1)$$

The caracteristics of the EEJ

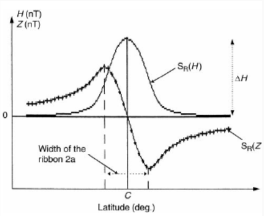
The equatorial electrojet is considered as a current ribbon, flowing eastward along the geomagnetic equator, at an altitude $h = 105$ km.(Fambitakoye and Mayaud (1976a)

Estimation of the current
The maximum amplitude I_0 of the ionospheric electric current can be estimated from

$$\Delta H = 0.4 I_0 \arctan\left(\frac{a}{h}\right) \qquad (2)$$

a, the half width of the ribbon
h, the altitude of the ribbon

Magnetic effect of a parabolic current



Doumouya et al.,(1998)

Magnetic observations

Latitudinal variation of H, Z and D

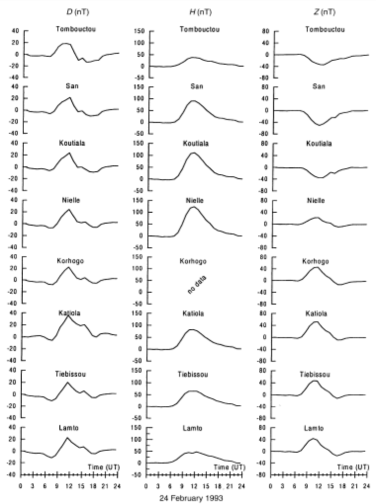
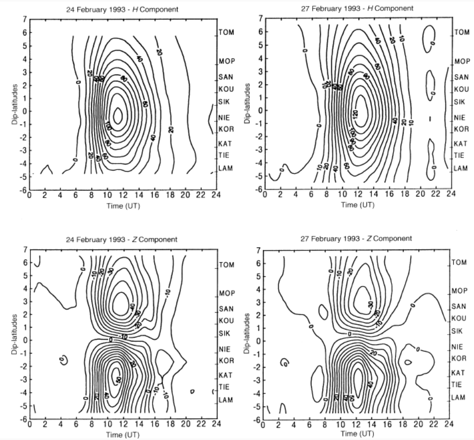
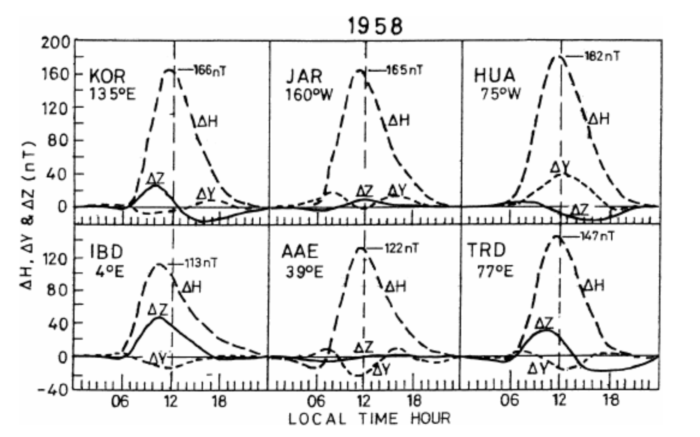


Figure 5: Doumouya et al.,(1998)

Contour maps of H and Z, on 24 and 27 February 1993 (Doumouya et al.,1998)



The S_q variations of H, Y and Z fields averaged over the International Quiet Days of the year 1958, at Ibadan (IBD) at 4^o E longitude, Addis Ababa (AAE) 39^o E longitude, Trivandrum (TRD) 77^o E longitude, Koror (KOR) 135^o E longitude, Jarvis (JAR) 160^o W longitude and Huancayo (HUA) 75^o W longitude sector.(Rastogi (2004)



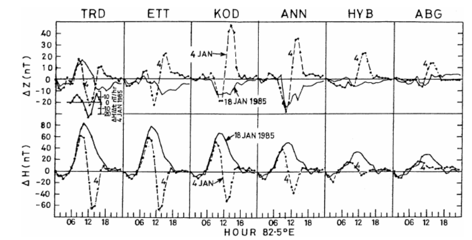
Counter Electrojet

At time on quiet days, ΔH decrease Abnormally to negative value and then recovers to its normal positive value (Gouin and Mayaud, 1967). The phenomenon is called the Counter Equatorial Electrojet.

Possible explanations

- Possible reversal of the vertical polirization electric field $\overrightarrow{E}_p$ due to local interaction of height varying winds (Richmond, 1973, Fambitakoye et al., 1976)
- Possible reversal of the eastward electric field $\overrightarrow{E}_y$ due to abnormal combination of global scale tidal wind mode (Forbes and Lindzen, 1976, Schieldge et al., 1973)

Daily variations of H and Z at each of the stations TRD, ETT, KOD, ANN, HYB and ABG in India (Rastogi, 2004)



Observation techniques 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

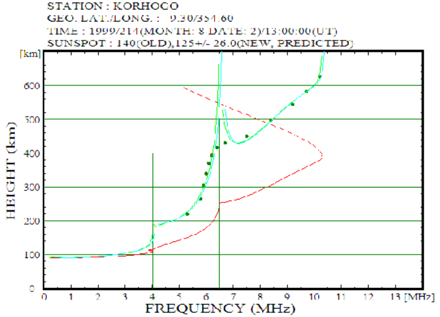
$$N_{max} = 1.24 \times 10^{10} f_c^2$$

where N_{max} is in electrons per cubic meter and f_c is in megahertz.

The time delay is obtained by the following equation

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

where μ is the



1. On the left we have a scaled ionogram. With the electron density profile in red.
2. On the right an overview of a Kel Aerospace type of ionosonde.

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.

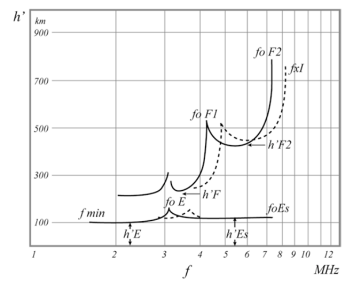
For a simple description of the ionosphere by vertical sounding it is convenient to consider the ionosphere as schematically divided into the conventional regions D, E, F, and the sporadic Es

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/`

Lamgmuir Probe

A Langmuir probe is a device used to determine the electron temperature, electron density, and electric potential of a plasma. It works by inserting one or more electrodes into a plasma, with a constant or time-varying electric potential between the various electrodes or between them and the surrounding vessel. The measured currents and potentials in this system allow the determination of the physical properties of the plasma.
This technique is an in situ measurements of ionospheric densities and temperatures based on the laboratory technique developed and discussed by Irving Langmuir and co-workers.

Radio Ocultation

Radio occultation (RO) measurements have been used to study planetary atmospheres (Kliore et al., 1965). It is an active technique. The paths of radio signals are bent by refractive index gradients in the atmosphere/ionosphere.
According to the Snel's Law of refraction

$$n_1 \sin i_1 = n_2 \sin i_2 \tag{3}$$

– bending occurs when refractive index changes. The radio ocultation method is based on the fact that radio waves transmitted from a satellite, as it flies behind a solar system body (e.g., planet or moon), pass through an atmosphere and ionosphere and undergo refractive bending, which introduces a Doppler shift in addition to its free space value. This difference, commonly called Doppler residual, Δf_d , is proportional to the refractive index of the media through which the wave travels.

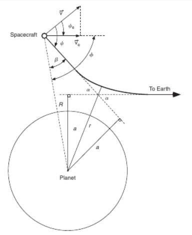


Figure 6: Schematic diagram

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

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

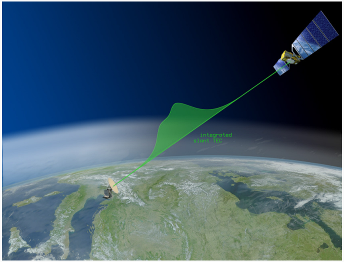
and the groupe refractive index is

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

[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

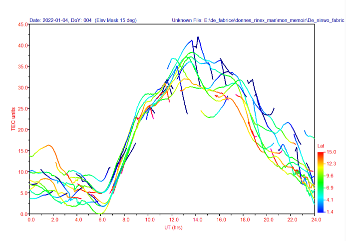
$$\Delta\tau = \frac{1}{c}\int_{u}^{s} \left(\mu_p(l) - 1\right) dl$$

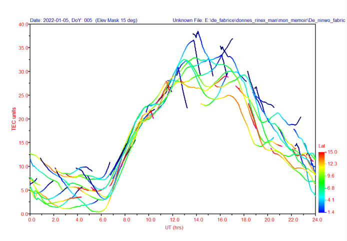
$$TEC = \int_{u}^{s} N(l) dl$$

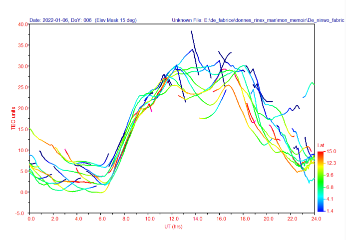
where N is the electron density of the plasma.
The TEC is expressed in TECU. $1\,TECU = 10^{16} el/m^2$

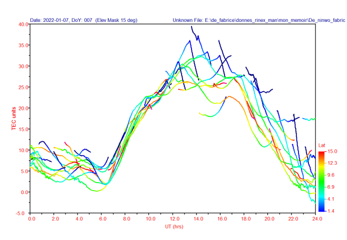
Some Results

TEC variation at U-Man (courtesy of J. N. Yao)









S4 variation over Korhogo (courtesy of M. N. Mene)

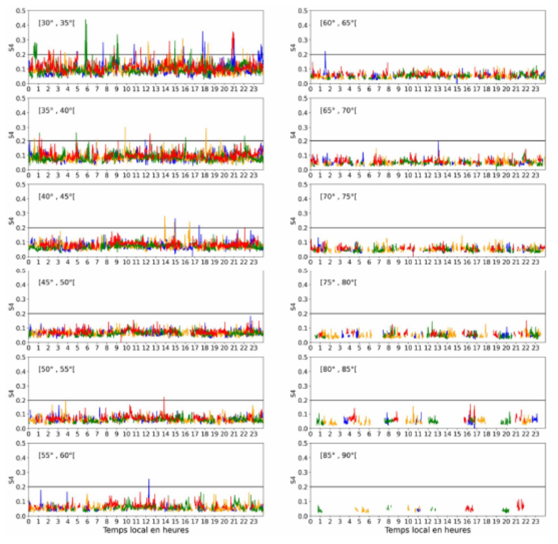


Figure 7: Variation of the S4 index with respect to the elevation angle over Korhogo

Solar flare effects on GNSS derived TEC (courtesy of S. Mahie)

- The sun is a star, an almost entirely ionized ball of plasma, consisting of electrons and ions
- One ofthe primary manifestations of solar magnetic activity is the appearance of sunspots, which are dark regions on an active Sun.
- Sometimes there are powerful explosions in the atmosphere above sunspots, which are called solar flares.

The solar flare is associated with significant enhancements in EUV and X-ray radiations, with larger enhancements in X-rays and short wavelength EUV and relatively smaller enhancements in long wavelength EUV.

Data used for the study

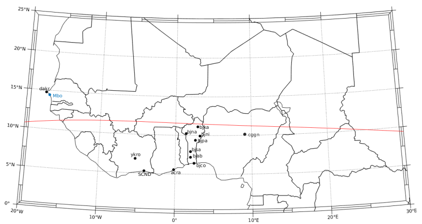


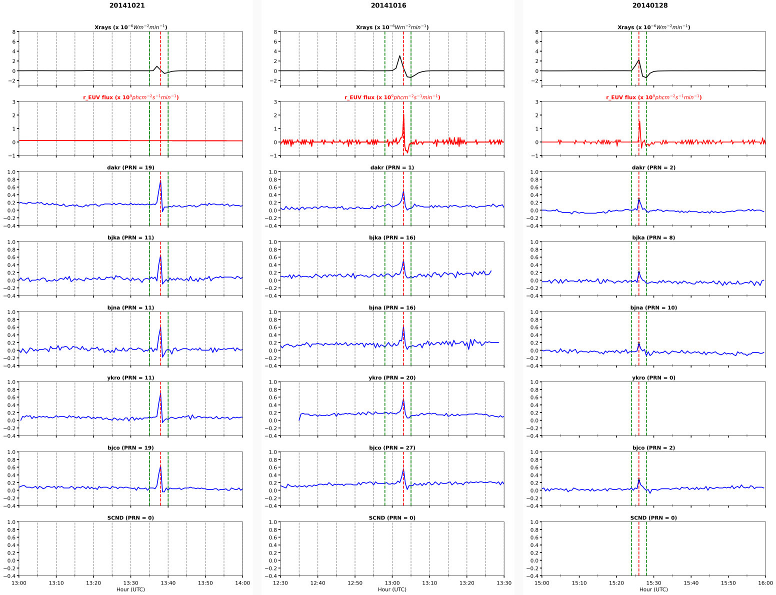
Figure 8: Map of the GPS stations

N°	Station Id	Location	Country	Geographic coordinates	
				Lat(°)	Long(°)
1	acra	Accra	Ghana	5.56N	0.203W
2	bjab	Abomey	Benin	7.18N	2.001E
3	bjco	Cotonou	Benin	6.39N	2.450E
4	bjka	Kandi	Benin	11.13N	2.928E
5	bjna	Natitingou	Benin	10.25N	1.381 E
6	bjni	Nikki	Benin	9.95N	3.204E
7	bjpa	Parakou	Benin	9.36N	2.626E
8	bjsa	Savalou	Benin	7.93N	1.993E
9	cggn	Toro	Nigéria	10.12N	9.118E
10	dakr	Dakar	Sénégal	14.72N	17.44W
11	Abja	Abidjan	Côte d'Ivoire	5.32N	4W
12	ykro	Yamoussou	Côte d'Ivoire	6.87N	5.24W

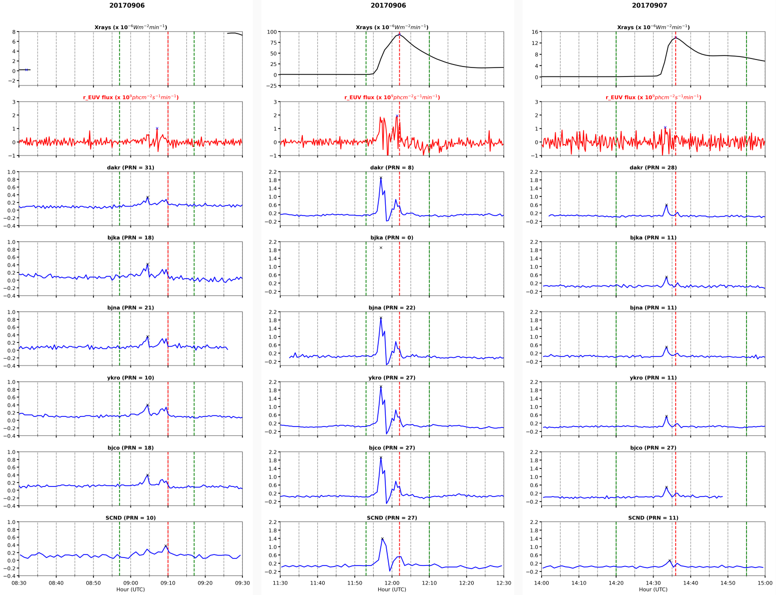
Figure 9: Coordinates of the stations

The TEC used in this current study are derived from GPS receivers data collected from the above station mainly localized in West Africa.

Variation of the time rate of change of TEC, X-ray and EUV



Variation of the time rate of change of TEC, X-ray and EUV



Thanks for your attention !