

# 54<sup>th</sup> Inaugural Lecture

## VARIABILITY IN THE IONOSPHERE AS FOUND IN LIFE

By

**Professor Emmanuel Olufemi Somoye**

The Vice Chancellor,

The Deputy vice chancellor,

The Registrar,

The Librarian,

The Bursar,

Provost and Deans,

Directors and HODs,

Professors,

Distinguished Academic Colleagues,

Distinguished Non Academic Colleagues,

Distinguished Guest and Friends,

My students (past and present).

### 1.0 PREAMBLE

Mr Vice-Chancellor Sir, I give all the glory and honour to the almighty God, the King of Kings and the Lord of Lords, the source of wisdom for this privilege He has given me to deliver the 53<sup>rd</sup> Inaugural lecture of this great University. It is necessary for me to give praise to the Lord, for the scripture says, “Oh that men will praise the Lord for His goodness and for His wonderful works to the children of men for He has broken the gate of brass and cut iron bars assunder (Psalm 107 verse 15). I also like to thank the Vice Chancellor, Professor Olanrewaju Adigun Fagbohun, the Cyrus of God for this University (check Isaiah chapter 45 for the promises of God concerning Cyrus) with whose permission I stand here today before this distinguished audience. I should say that I was really delighted when Dr. Kayode Oyende told me a few weeks ago that our Vice – Chancellor also delivered his inaugural lecture a few months after being declared a professor. I now understand your delight, Sir, when I made my intention known.

Mr Vice- Chancellor Sir, the Inaugural Lecture of today is the ---- in the Faculty of Science and the first in the Department of Physics.

Science was made fascinating to me by my Principal in the secondary school, Offa Grammar School, Offa. In a class of 144 students, my Principal, a Geographer, Mr. A. Adelowo, placed the best 36 students in science class where we were to offer subjects that included Physics, Chemistry and Add (Hard) Mathematics. The next 36 students were not to offer Add Maths (Further Math) while those

following them were to drop both Add Math and Physics. The last 36 students in the class, called Art Class, were to content themselves with Biology as their only science subject. My interest in Physics was further heightened when by form three, I could explain the operation of a refridgerator. As time went on, I realised that with the knowledge of Physics, one could explain the operations of many gadgets. This is further elucidated in the article I contributed to General Studies Book of Readings titled “The Impact of Physics on Humanity” (Somoye, 2006).

## 2.0 INTRODUCTION

Mr Vice-Chancellor Sir, my field is Ionospheric Physics while my research focus is in the twin areas of ionospheric “climatology” and “space weather”. While ionospheric climatology deals with mean behaviour of the ionosphere, a substantial aspect of space weather (Rishbeth and Mendillo, 2001), variability, is concerned with deviations from the mean behaviour.

Life is not always smooth. It is full of variations or changes. The common saying that CHANGE is the only permanent thing in life is seen not only in all affairs of human lives but also in other creations of God. It is only God, the creator that is constant. In James 1 verse 17, we are told that there is no shadow of turning or variability with God. Nature is hardly a straight line graph. For example, in Figure 1, which illustrates the variation of heights of some children with their ages, it is obvious that the points do not all fall in line.

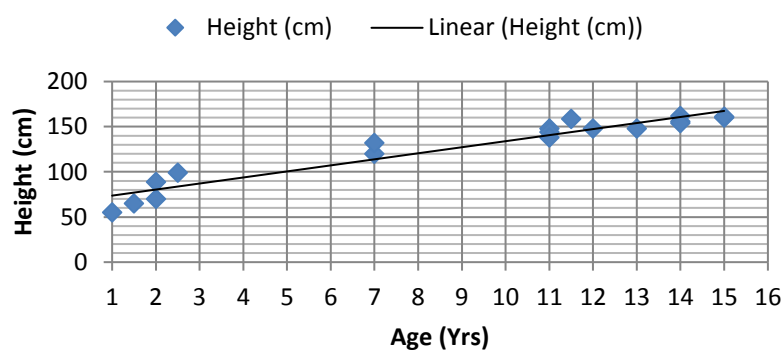


Figure 1: Variation of height with age of children

The line of fit drawn just gives an average expectation to guide our judgement, it is not exact. Other examples of deviations or variability in human life are those of

- (a) Weight and height which are not always commensurate
- (b) Weight and age which varies from one person to another
- (c) When one drives on the road, the speed of the vehicle varies depending on the following factors: (i) nature of the road (ii) the number of vehicles on the road (iii) if there is a toll mounted on the road. This is not a contradiction of Newton’s first law of motion which states that every object continues in a state of uniform (constant motion), in a specified direction, or rest unless compelled by an external force. Each of the factors mentioned above actually represents an external force necessitating the change (i.e. variation in speed).
  - (i) Income of civil servants like us, change (vary) yearly, if not from a level to a higher level (in the case of promotion, it is from a step to a higher one (yearly increment or yearly variation)
  - (ii) The income of businessmen also changes (varies) randomly depending on factors such as (i) how connected he/ she is to those in charge of contract. (ii) his/ her competence. (iii) market forces, for traders.
  - (iii) The intensity of rainfall varies from day to day, from month to month and from year to year. For example, the intensity of rainfall in June last year differs from that of this year.

(iv) Also, the intensity of sunshine differs daily, monthly and yearly. This is even more obvious now because of global warming.

### 3.0 THE IONOSPHERE

#### 3.1.1 DEFINITION AND EXISTENCE

Mr Vice-Chancellor, Sir, the ionosphere is the part of the earth's atmosphere that contains ions and free electrons in sufficient quantities to affect the propagation of radio waves (Craig, 1965). The possibility of the existence of this conducting layer of the earth's atmosphere – the ionosphere – was first mentioned by Stewart (1882) in his theory on diurnal variations in the earth's magnetic field. Inside the core of the earth is an imaginary magnet having north and south poles with invisible lines of force (field lines) that link the poles (Ahrens, 2000) from which a constant main field is produced. Superimposed on this main field are small transient variations which are explained in terms of the current systems in the upper atmosphere – the ionosphere. The dynamo theory of Stewart (1882) and developed quantitatively by Schuster (1908) explains this. Tidal forces in the atmosphere produced by the sun and moon set up standing waves which result in the air motions. The movement of air across the earth's magnetic field causes electromotive force, emf, to be induced. This emf drives current at heights where electrical conductivity (i.e. in the E-layer – 100km). Currents driven by this emf at heights where conductivity is appreciable are responsible for the transient variations in geomagnetic field referred to as solar quiet day,  $S_q$ , variations).

The electrical conductivity,  $\sigma$ , varies horizontally and vertically, thus hindering free flow of current in all directions. As such, polarization charges that are set up modify the flow of current. The electrostatic fields due to these charges are transmitted to F2-layer along the geomagnetic lines where they cause drift (Rishbeth and Garriot, 1969). Marconi's (1901) success in transmitting radio wave signal across the Atlantic lent credence to the existence of a conducting layer from which the radio waves were refracted around the earth's curvature.

#### 3.1.1 REFLECTION MECHANISM OF RADIO WAVES FROM THE IONOSPHERE

Reflection involves an abrupt or sudden change of phase of the (radio) wave from  $0^\circ$  to  $180^\circ$ . Refraction on the other hand, is a gradual change of phase of the wave incident on an interface between one medium to another. If a wave is propagated from a denser to a less dense medium, the wave refracts successively until it suffers a phase change of  $180^\circ$  (i.e. reflected). The atmosphere is actually successively less dense as altitude increases. For instance, the composition of the lowest atmospheric layer, the troposphere, is nitrogen (78%), oxygen (21%), carbondioxide (0.03%). By about 3000km, the atmosphere is composed principally of ionised hydrogen or protons, the reason for which that part of the atmosphere is called protonosphere. The protons are, of course, lighter than the nitrogen and oxygen molecules.

For the ionosphere, we can write  $\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$  (i.e. snell's law) (1)

where  $\theta_1$ , is the angle of incident in medium 1 and  $\theta_2$  is the angle of refraction in medium 2 and  $n_1$  and  $n_2$  are the refractive indices of the first and second media respectively. For more than two layers, equation 1 becomes

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 = n_3 \sin\theta_3 \quad (2)$$

Note that  $\theta_2$  which was the refracted angle now becomes incident angle for the next layer. See Figure 2.

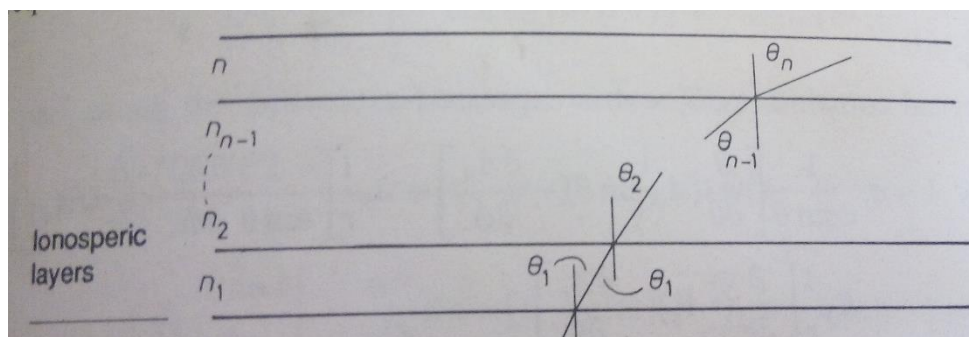


Figure 2: Reflection of radio waves

When the last incident angle exceeds the critical angle (i.e. the incident angle that makes refracted angle equals  $90^\circ$ ), total internal reflection occurs.

### 3.2 LOCATION

The earth's atmosphere is divided into various layers. Atmospheric layers include, in order of increasing altitude, troposphere (0-12km), stratosphere (12-50km), mesosphere (50-85km), thermosphere (85-500km), exosphere (500km and above). The ionosphere which begins from about 50km above the sea level extends to the top of the atmosphere. The ionosphere is thus located in the mesosphere and the layers above it (see Figure 3). It merges into the heliosphere and protonosphere and the magnetosphere.

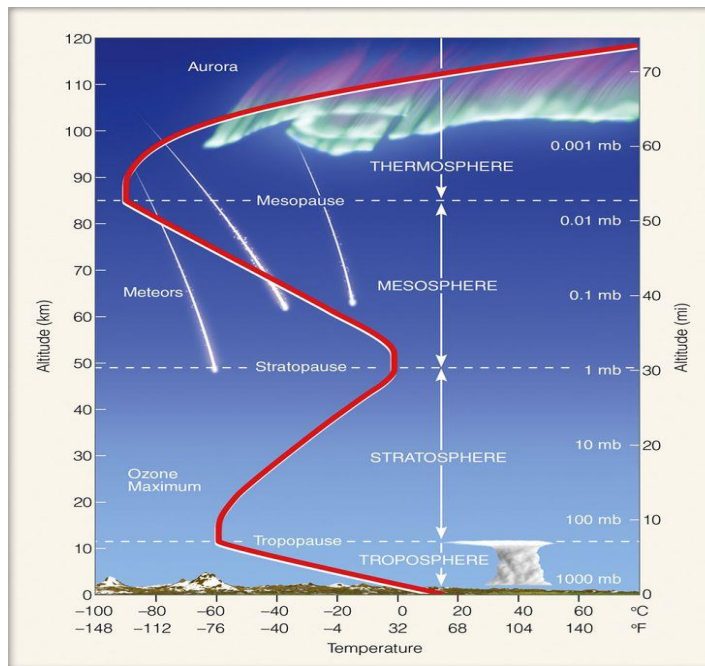


Figure 3: Altitude Vs temperature.

### 3.3 ORIGIN

Our universe contains billions of galaxies with each one made up of billions of stars. The earth's sun, an average size star is situated near the edge of the Milky Way galaxy (Ahrens, 2009). The earth is among other planets that revolve around the sun and together with materials such as comets, meteors, asteroids make up the solar system. The sun which is the major source of energy on earth through the electromagnetic radiations it produces ionizes the upper part of the earth from 50km upwards. The part of the electromagnetic spectrum responsible for this ionization are X-ray and Extreme Ultra Violet (EUV) radiation. The atmosphere surrounding the sun is in three layers. The first is the photosphere which is a few hundred kilometres in extent and it outlines the visible solar disc. The chromospheres

whose extent is more than ten thousand kilometres is next. The corona is the outermost atmosphere of the three layers. It is a thin hot atmosphere and extends to millions of kilometres beyond the disc. See Figure 4.

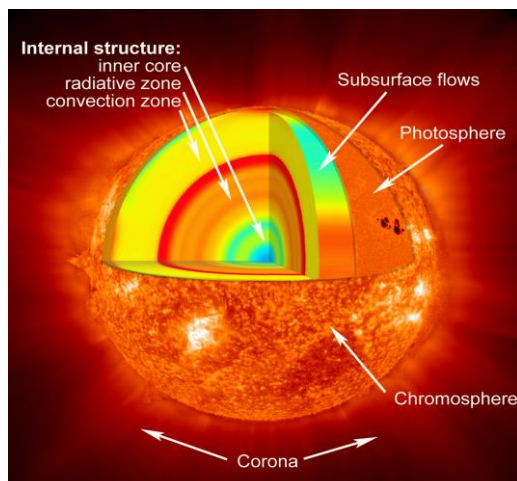


Figure 4: The sun and its layers

The earth is immersed in a stream of ionized particles mainly protons and electrons that flow from the sun in all directions. This solar wind distorts the sun's magnetic field and pulls it out along a radial direction making it still strong when it reaches the earth. It then interacts with earth's magnetic field or geomagnetic field in such a way to deform it (geomagnetic field). The region of the distorted magnetic field is called magnetosphere (Ratcliffe, 1970). The magnetosphere is the region in which the earth's magnetic field controls the dynamics of the ionosphere. The magnetosphere terminates at the magnetopause which is the boundary of the geomagnetic field that lies about ten earth radii (i.e. 64000km) during the day and much greater than this at night (Figure 5).



Figure 5: The Magnetosphere

The photoionization of the ionosphere is brought about, principally, by the X-ray and Ultra-Violet (UV) radiation from the sun. By absorbing these electromagnetic radiations, electrons are detached from the atoms or molecules of the upper atmosphere resulting in ionization. The electrons which are more important in the refraction of radio signals than the ionized atom or molecules are lost by recombination. The electrons are more important because they are easier to set in oscillation by the radio wave than the

massive ionized atoms and molecules which process leads to the reflection of the radio wave. The concentration of electrons is not the same as its production at any point in time and space because of the loss processes.

The equation of continuity can be rendered as:

rate of change of electron concentration = [gain by production of electron] – [loss of electron by recombination] – [change due to transport]

or, in symbols,

$\frac{\partial N}{\partial t} = q - l(N) - \Delta.(NV)$ , where  $N$  = electron density,  $q$  = production of electrons,  $l(N)$  = loss of electron and  $\Delta.(NV)$  = transport term ( $V$  being drift velocity).

helps to explain and determine the value of electron concentration at different times of the day and at different altitudes. When a photon (i.e. quantum of electromagnetic radiation) impinge on a neutral atom or molecule, an electron is removed leaving an ionized atom or molecule. This process of production of electrons is called photoionization and is illustrated in Figure 6 and by equation 3. Electrons are lost by two processes, viz, recombination and attachment. Recombination is the case when an electron attaches itself to a positively ionized atom/ molecule resulting in a neutral atom/ molecule. Figure 6 and equation 3 depict this. If on the other hand, an electron attaches itself to a neutral atom/ molecule to form a negative ion, the loss is referred to as attachment. See equation 3 and Figure 6.



(production by photoionization)



(loss due to recombination)



(loss due to attachment)

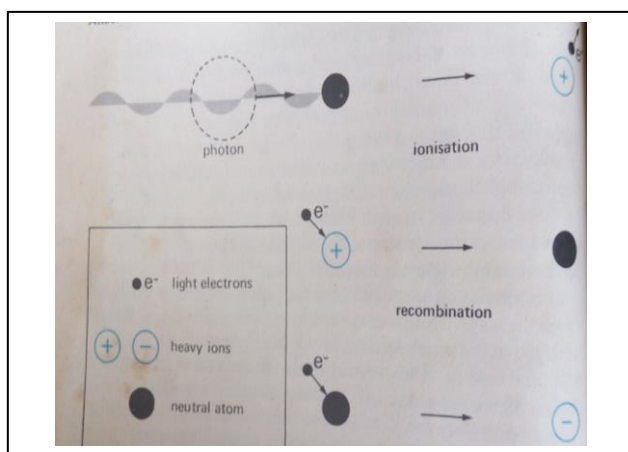


Figure 6: Photoionization [after Ratcliffe, 1970]

### 3.4 VARIATIONS IN THE IONOSPHERE

The ionosphere is known to exhibit regular and irregular variations.

#### 3.4.1 Regular Variations

The regular variations include

- i. Diurnal variations (i.e. hourly);
- ii. Day – to – day variations;
- iii. Seasonal variations;
- iv. Annual (yearly) variations;
- v. Solar cycle variations;
- vi. Latitudinal variations;
- vii. Longitudinal variations.

(i) Diurnal variations

The earth, whose vertical axis is tilted at an angle of  $66\frac{1}{2}^{\circ}$  to the horizontal rotates about this vertical axis once in a day. As a result, the ionizing radiations on any location on earth vary each hour. This results in the diurnal or hourly variations of ionospheric parameters. Ionospheric parameters are discussed later in Section 3.7. In Figure 7 is shown the tilted earth rotating about its axis as well as revolving round the sun simultaneously.

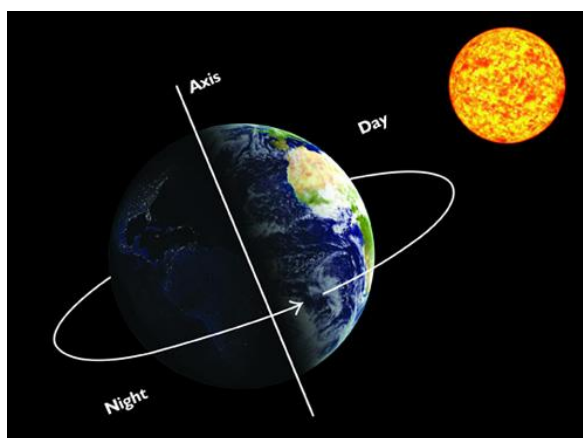


Figure 7: The tilted earth

(ii) Daily variations

The daily variation observed in ionospheric parameters is obviously due to the revolution of the earth and its atmosphere and therefore the ionosphere round the sun. This revolution shown in Figure 7 takes place once in  $365\frac{1}{4}$  (365 days, 6 hours). In four years the extra 6 hours make 1 whole day and added to the fourth year to give 366 days, referred to as a leap year. Thus, whenever you shout happy New Year at 12 midnight on December 31, on a year that is not a leap one, it is premature as the year has 6 hours to end. On the other hand, in a leap year the shout of happy New Year is belated.

Daily variations of ionospheric parameters are found to be more highly variable than diurnal variations. In Figures 8a and b are shown the scatter plots of daily variation and that of diurnal variation of F2 layer critical frequency (foF2) (Critical frequencies are discussed later in section 3.7). The randomness of the daily variation is much greater than that of diurnal variation such that the former can be said to suffer variability while the latter is said to show simple variation (Somoye, 2009). We can therefore say that the lack of readily observed trend in the scatter plot of a quantity or parameter implies variability while the observation of trend implies simple variation.

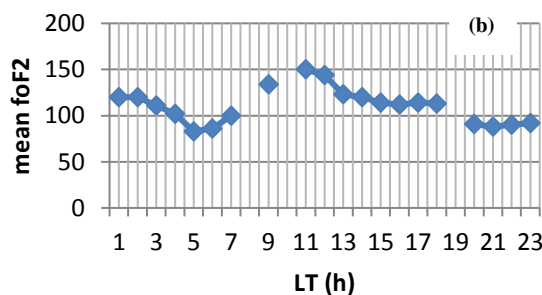
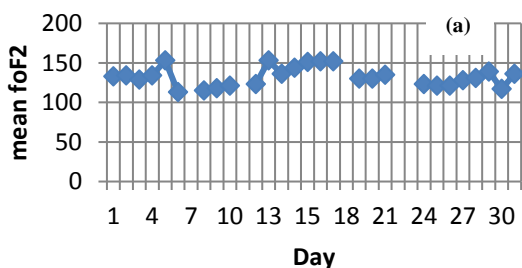


Figure 8: Scattergram of foF2 Daily and Diurnal values respectively.

(iii) Seasonal variation

The revolutions of the earth round the sun makes it (the earth) exposed to varying radiation from one month to another and therefore from season to season, the seasons being composed of months. One school of thought grouped the months into December Solstice comprising November, December, January, March Equinox (February, March, April), June Solstice (May, June, July) and September Equinox (August, September, October) ( Ogbuehi and Onwumechili, 1964). Another school of thought grouped the seasons into December Solstice (November, December, January and February), June Solstice (May, June, July and August) and the Equinoxes (March, April, September and October) (Bandyopadhyay and Montes, 1964).

In the Northern Hemisphere, December Solstice is also called Winter Solstice, March Equinox is referred to as Spring while June Solstice and September Equinox are called Summer Solstice and Autumn respectively. Note that in the Southern Hemisphere, the Winter Solstice becomes summer Solstice and vice-versa, while the Spring and Autumn are interchanged. It should be mentioned that December Solstice occurs on December 22 when the sun is overhead at the – of Capricorn while June Solstice is the day the sun is overhead at the – of Cancer, i.e. on June 21. March and September Equinoxes are two days the sun is overhead at the equator and occur on March 21 and September 22, respectively.

(iv) Solar Cycle variation

The activities of the sun on which the ionosphere depends for its ionization have a periodicity of 11 years, on the average. Two major indices of solar activity are the sunspot number and the solar decimetric flux density at 10.70cm wavelength ( $F_{10.7}$ ). The sunspots as illustrated in Figure 9 are dark spots on the solar disc.

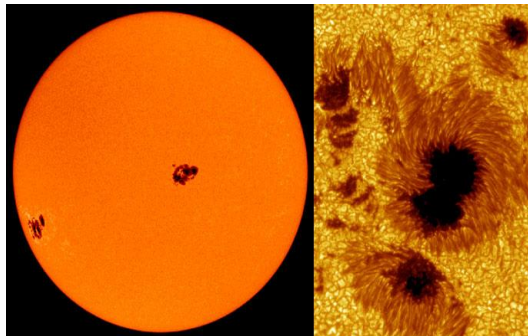


Figure 9: Sunspot

They appear dark relative to the brightness of the photosphere, their temperature being lower than that of the photosphere. The number of sunspots waxes and wanes with a characteristic 11 years periodicity. The electron density of the ionosphere varies directly with sunspot numbers. The  $F_{10.7}$  is the radio noise flux of wavelength 10.70cm (2800MHz). Its values range from 70 units at solar (sunspot) minimum to about 250 units at very high solar maximum where 1 unit equals  $10^{-22} \text{Wm}^{-2}\text{Hz}^{-1}$ .

(v) Latitudinal variation

The latitude of any place on earth is how far north or south, in degrees, it is from the equator (Ahrens, 2000). The equator which is the horizontal circle that divides the spherical earth into two hemispheres is given latitude  $0^\circ$  and the poles,  $90^\circ$  North and South as shown in Figure 10.

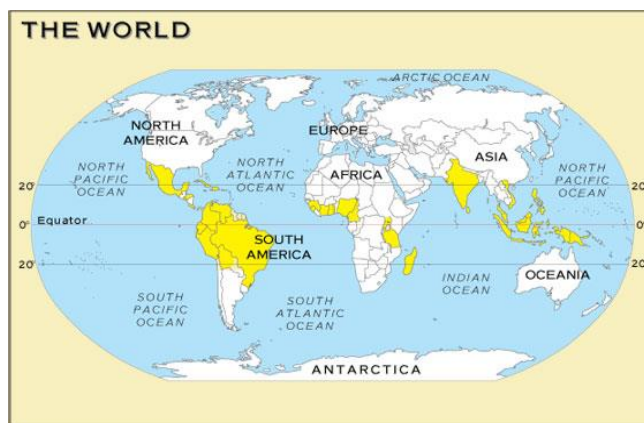


Figure 10: Map of the world

Observation of the sun's zenith angle ( $\chi$ ) at places of different latitudes at the same local time (LT) shows that  $\chi$  varies with latitude. The intensity or strength of solar radiation depends on  $\cos \chi$ . As a result, the ionosphere over different latitudes are ionized differently. This extends to the variation of ionospheric parameters with latitude. The sun being over head at the equator ( $\chi = 0$  but  $\cos 0 = 1$ ) leads to the ionosphere over the equator being the most ionized. The direction of zenith angle is shown in Figure 11.

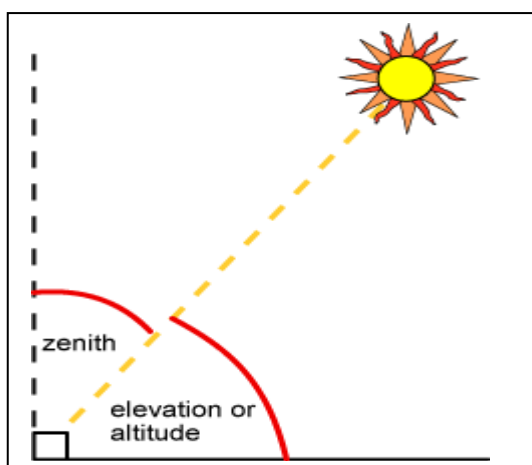


Figure 11: Zenith angle

- (vi) The longitude of any place on earth is how far east or west, in degrees, it is from the prime meridian. The prime meridian runs through Greenwich, England and is thus called Greenwich meridian. The prime meridian is the vertical circle that divides the earth vertically into two equal halves. It is given longitude  $0^\circ$ , for which reason it is also called zero meridian.

Researchers divide the earth into three major sectors. The sectors are the American sector, west of Greenwich meridian (GM). The Europe – African or simply Euro – African sector (in the neighbourhood of GM) and Asian sector (East GM). I should mention that declination which is defined as the angle between magnetic meridian and geomagnetic meridian is largest in the American sector (de Paula et al., 2007) and least in the Euro – African sector. The longitudinal variation of ionospheric parameters is important in understanding the dynamics of the global ionosphere.

### 3.4.2 Irregular Variations

Some variations in the ionosphere are irregular but they have serious effects on radio wave propagation as they are capable of affecting communication without warning. They are caused by sporadic E, sudden ionospheric disturbance (SID) and ionospheric storms.

- (i) Sporadic E  
Sporadic E phenomenon which is an irregular cloud-like patches of high ionization at the same height with normal E layer occur differently at the equator, the mid-latitude and the polar region. The critical frequency of sporadic E layer is very high and can be greater than double that of the normal E layer. It, thus, reflects radio wave to a distance of more than 2000km, though the layer disappears soon after.
- (ii) Sudden Ionospheric Disturbance (SID)  
Sudden Ionospheric Disturbance is the disturbance that accompanies solar flare, a sudden brightening of the sun. It results in a sudden increase of ionization in the ionosphere.
- (iii) Ionospheric storms  
This phenomenon is a disturbance in the in the earth’s magnetic field which is associated with solar eruptions. The effect is noticeable in the decrease (negative phase) and sometimes increase (positive phase) of critical frequency of the F2 layer.

### 3.5 IONOSPHERIC LAYERS

Due to variations in the physical properties of the atmosphere such as composition, density and temperature with increase in altitude, the ionosphere tends to be stratified rather than uniform. This stratification in the distribution of its ionization results in a range of four major layers. The layers are D, E, F1 and F2 in ascending order shown in **Figure 12**.

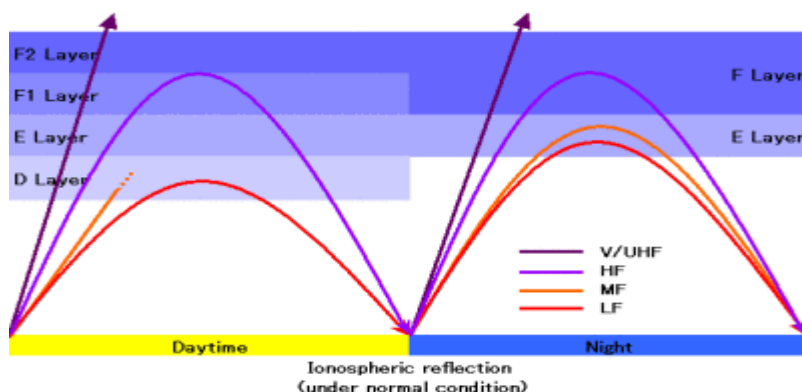


Figure 12: Layers of the Ionosphere

#### 3.5.1 The D layer

The D layer starts from about 50km above the earth surface. Its electron concentration is the least, being the layer contacted last by the ionizing radiation. Also the collision frequency (i.e. rate of collision of neutral molecules with electrons) is highest in this layer. Radio waves are thus attenuated because of absorption of their energy due to collision. As a result, reflection of radio wave from this layer is nearly impossible.

### 3.5.2 The E layer

The E layer which occupies the altitude of 90km to 150km has electron concentration (NmE) in the range  $1.6 \times 10^{11}$  to  $2.6 \times 10^{11}$  electron/ m<sup>3</sup> from minimum solar activity to maximum solar activity around the dip equator. Usually, radio signals of frequency 1.2 to 4.5MHz is reflected from the E layer, at vertical incidence, in the neighbourhood of the dip equator. Collisions between neutral molecules and electrons are less than what obtain in the D region. As such, absorption and attenuation of radio waves are also less than those of D region. The E region is largely a Chapman layer. That is, its rate of production of electron at the peak is proportional to  $\cos \chi$ .  $\chi$  is the angle between the direction of the suns radiation and the vertical. This angle is called zenith distance by astronomers (Ratcliffe, 1970). In the E layer heights, is observed another layer that is regular, random and transient with ionization much greater than that of the normal E layer. It is referred to as sporadic E (Es). I should mention that the ionization of the E layer is very small in the night since the source of ionization, the sun is no longer available. Kolawole (1974) mentioned that its nighttime electron concentration decreased to one – twentieth of its daytime value.

### 3.5.3 The F1 layer

The F1 layer which merges with the F2 layer at night to become simply F layer occupies the altitude range 150 – 180km. Its electron density varies with the sun's zenith angle and is in the range of  $10^{12}$  to  $10^{13}$  electrons/ m<sup>3</sup>. The F1 layer is thus a Chapman layer. It is more pronounced in summer and during solar cycle minimum.

### 3.5.4 The F2 layer

The F2 layer is the topmost layer of the bottomside ionosphere. This makes it to be the most ionized with electron density in the range  $2.5 \times 10^{13}$  to  $2.3 \times 10^{14}$  electrons/ m<sup>3</sup> being the first layer contacted by the ionizing radiation. As such it is the most reflecting medium and most applicable for high frequency (HF) radio propagation. The F2 layer is not a typical Chapman layer as it is still capable of reflecting radio signals much after sunset. Its midnight electron density is sometimes greater than that of noon (Awe, 1971). The layer is thus said to behave abnormally.

## 3.6 IONOSONDE AND IRREGULARITY CHARACTERISTICS FADING EQUIPMENT

Two equipments used in obtaining data for my research work are the ionosonde and the irregularity characteristics fading equipment. The ionosphere is probed by a sounder called ionosonde in which a transmitter and receiver are incorporated. It sends up vertically a series of short waves or variable high frequency (HF) radio signals or pulses. The time delay between transmission of signals and reception of echoes is recorded. The time delay,  $t$  is given by  $t = \frac{2h'}{c}$  (4)

$2h'$  being the distance of travel to and fro the height of reflection and  $c$  the speed of the radio wave transmitted. It has the same speed as that of visible light, another component of electromagnetic spectrum. It should be mentioned that the group velocity of the radio wave is less in the ionosphere than radio wave velocity in the neutral atmosphere. As a result, the true height,  $h$ , of reflection of echoes is less than the virtual height. As such  $h'$  is referred to as virtual height. The details of the ionosonde employed in obtaining the  $h'(f)$  (i.e. virtual height as a function of frequency curve called ionogram has been mentioned by Somoye (2009). The block diagram of ionosonde is shown in [Figure 13](#). Figure 14

shows a typical ionogram. Digital ionosonde, presently employed include KEL sounder, Advanced ionospheric sounder or Dynasonde.

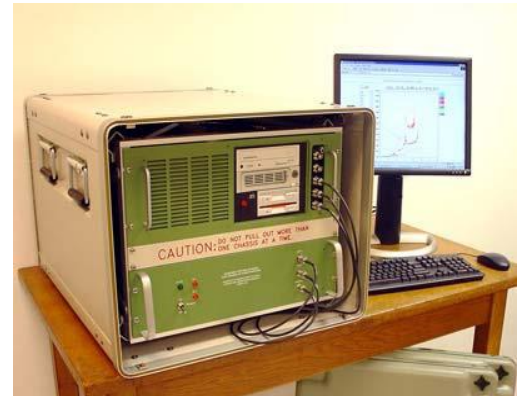
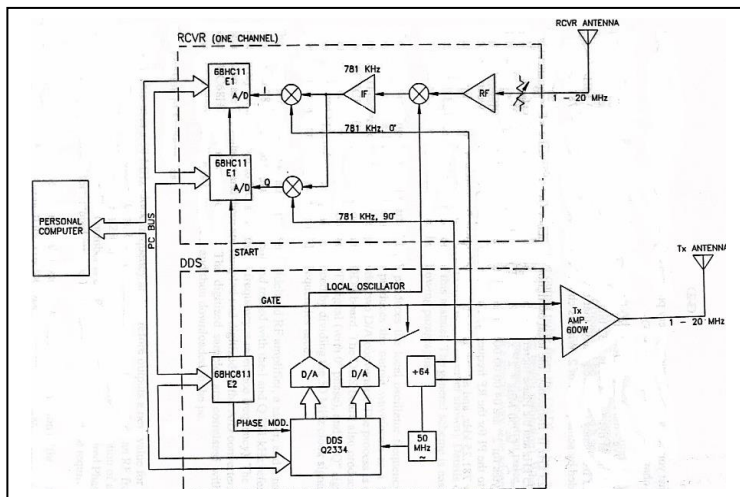


Figure 13: Block diagram of a digital ionosonde and a portable digisonde [CADI].

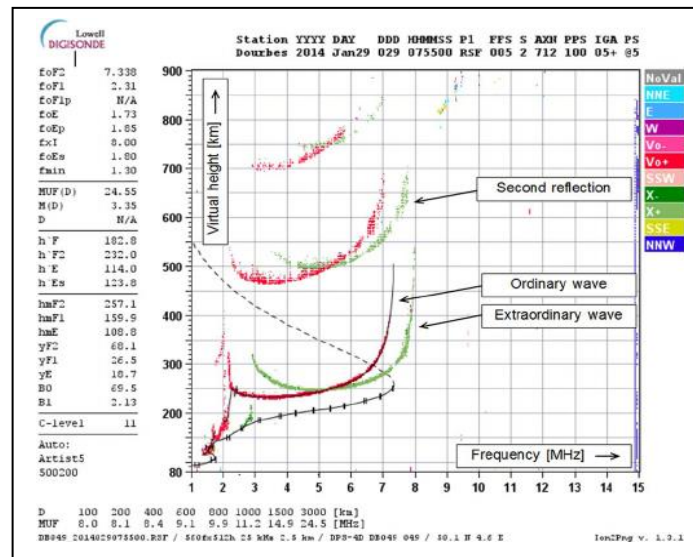


Figure 14: Ionogram

The block diagram of irregularity fading characteristics equipments used in obtaining amplitude fading records at three closely spaced aeriels is shown in Figure 15. Figure 16 shows the triangular aerial array arrangement.

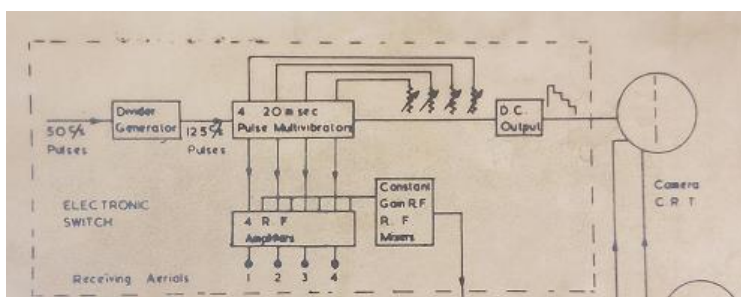


Figure 15: Block diagram of irregularity fading characteristics equipment.

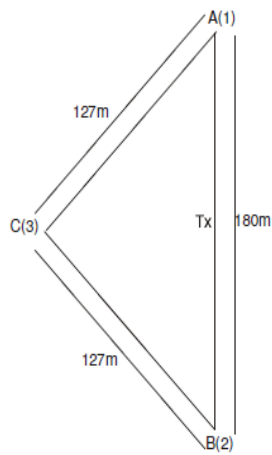


Figure 16: Triangular Aerial arrays

A sample of the amplitude fading records obtained is shown in [Figure 17](#).

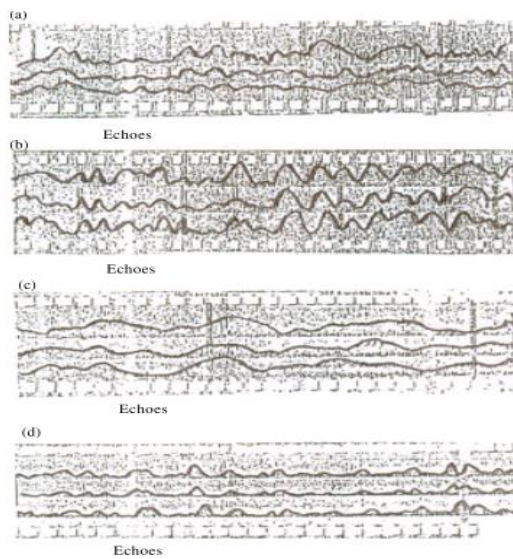


Figure 17: Amplitude fading records [after Somoye, 2010]

Auto correlation function between the fading observed at two points and cross-correlation function between the fading observed at two points given by

$$\rho = \frac{N\Sigma XY - \Sigma X\Sigma Y}{\sqrt{[(N\Sigma X^2 - (\Sigma X)^2)\{N\Sigma Y^2 - (\Sigma Y)^2\}]} \quad (5)$$

are used to find (i) the time interval for the cross-correlation to become maximum i.e.  $\tau'$  (ii) the time interval for the auto-correlation function to reduce to cross-correlation function maximum i.e.  $\tau_m$ . (iii) -  
---

These time intervals which are illustrated in Figure 18 in combination with the distance between pairs of aerials give apparent velocity and fading velocity from which the drift velocity, characteristic random velocity, axial ratio of characteristic ellipse of irregularity and North – South extent of irregularity are obtained.

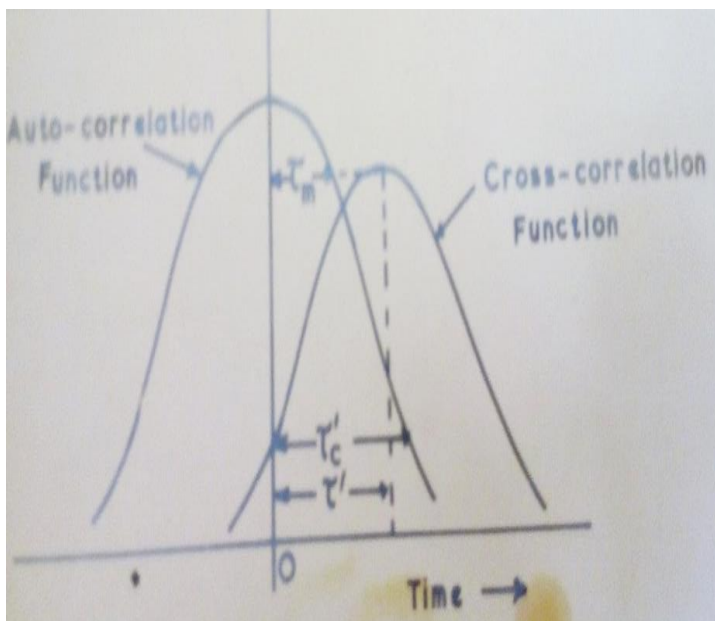


Figure 18: Auto-correlation and cross-correlation function

### 3.7 IONOSPHERIC PARAMETERS

Qualitative interpretation of the behaviour of the ionosphere requires the observation of parameters which include, but not limited to (i) maximum electron density of the different layers ( $N_m$ ). (ii) critical frequency of the different layers ( $f_o$ ). (iii) maximum useable frequency (MUF). (iv) propagation factor ( $M(3000)F2$ ). (v) maximum height of reflection of radio signals ( $h_m$ ).

- i. **Maximum electron density**  
This is the highest value of electron density of a layer. Electron density is the number of electrons in a unit volume, i.e.  $1m^3$ . Thus, it is also called electron concentration. The maximum electron density of D, E, F1 and F2 layers are denoted by  $N_mD$ ,  $N_mE$ ,  $N_mF1$  and  $N_mF2$  respectively.
- ii. **Critical frequency**  
The critical frequency or penetration frequency of a layer is defined as the frequency beyond which radio wave cannot be reflected at vertical incidence. It is the highest frequency of a layer. Any frequency greater than it penetrates to a higher altitude, hence the name penetration frequency. The critical frequency of D, E, F1 and F2 layers are denoted by  $f_oD$ ,

- foE, foF1 and foF2. The critical frequency of a layer is proportional to the electron concentration of the layer (*i. e.*  $f_o \propto (N_m)^{\frac{1}{2}}$ ).
- iii. The maximum useable frequency (MUF)  
The MUF is the highest radio frequency that is reflected at oblique incidence by any layer or that can be used for skywave communication between any two given points on earth. It is related to the critical frequency,  $f_o$ , by the secant law *i.e.*

$$MUF = f_o \sec i \quad (6)$$

$i$ , being the angle of incidence.

We can write equation (6) as

$$MUF = f_o * M(3000)F2 \quad (7)$$

where M(3000)F2 is referred to as propagation factor.

- iv. Propagation ( Transmission) factor (M(3000)F2)  
M(3000)F2 is the propagation factor for a radio signal transmitted and received on terrestrial earth 3000 km away, having been reflected from the F2 layer of the ionosphere. The propagation factor has an important role in High Frequency (HF) communication in frequency planning. It has also found usefulness in being used to determine ionospheric F2 peak (maximum) height ( $h_mF2$ ) based on the anti-correlation between the two parameters.
- v. Maximum height/ virtual height of reflection of signals  
The ionosonde as mentioned earlier measures the virtual height of reflection of signals ( $h'$ ) from the different layers. A signal of higher frequency is reflected from a higher level whose electron density is greater than at the lower level. Though an important parameter for research and practical application, the true maximum height is not measured directly. It is determined from the virtual height using some complex mathematics for the F2 layer. The true maximum height ( $h_mF2$ ) is found to show strong anti-correlation with the propagation factor (M(3000)F2). The former is thus derived from the relation

$$h_mF2 = \frac{1490}{[M(3000)F2 + \Delta m]} - 17 \quad (8)$$

where  $\Delta m$  is a correction factor that accounts for the delay effect caused by the ionization in the E layer that is related foF2/ foE ratio. This relation which was derived by Shimazaki (1955) has been modified by Bradley and Dudeney (1973), Eyfrig (1973), Bilitza et al. (1979), Adeniyi et al. (2003).

#### 4.0 CONTRIBUTION TO KNOWLEDGE

My research work is focus on (i) studies on mean (climatological) behaviour (ii) studies on ionospheric irregularities (iii) studies on space weather of the ionosphere

##### 4.1 Mean (climatological) behaviour of the ionosphere

The following are some of the results obtained in ionospheric climatological research.

- 4.1.1 The E layer of the ionosphere is said to be a chapman layer. That is, its ionization is dependent on the zenith distance ( $\chi$ ) of the sun as mentioned in Section 3.5. This can be rendered as

$$foE(\chi) = foE(0)(\cos\chi)^n \quad (9)$$

Where  $foE(\chi)$  is the critical frequency of the E layer for any  $\chi$  other than  $\chi = 0$  *i.e.* at noon when  $\chi$  is 0 (sun is overhead) at the equator. For a chapman layer, the index  $n$  is said to be 0.25. Ogabi and Somoye (2001) investigated the validity of equation 7 for different seasons of the International

Geophysical Year (IGY) which is a high solar activity year. We got results that shows that equation (6) is valid only during the Solstices, when  $n = 0.28$ . For the Equinoxes, index  $n$  is greater than 1.0 which is very much greater than the theoretically predicted value of 0.25.

4.1.2 Sode and Somoye (2010) found that the inclusion of the month of May in the seasonal grouping of June Solstice by many workers may be erroneous. In the plot of the ratio of F2 layer maximum electron concentration of high solar activity (HSA) to that of low solar activity (LSA) with local time (LT), shown in Figure 19, the ratio for the month of May behaved more like an equinoctial month than a solstitial month.

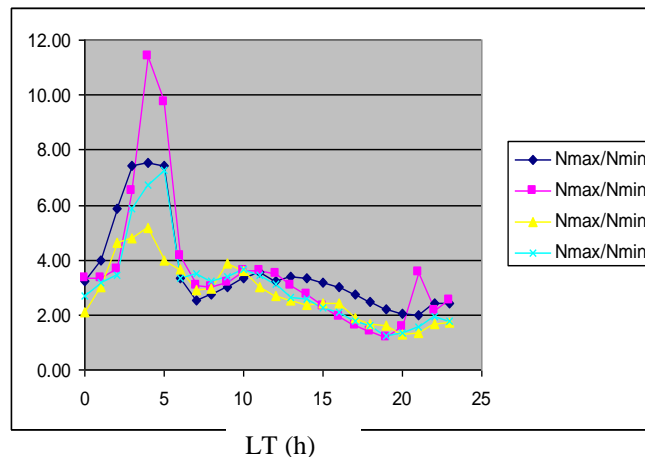


Figure 19:  $N_{MAX(1958/1965)}$  against hours for November, February, May, August [after Sode, 2013]

4.1.3 While the critical frequency of E layer (foE) is found to respond more rapidly to changes in sunspot numbers than that of F2 layer (foF2) (Friedman, 1960; Onori and Somoye, 2010), the electron concentration of F2 layer,  $NmF2$ , is found to respond more rapidly to changes in sunspots than that of E layer (Chikelezie et al. 2010). This seems contradictory since both parameters are related (e.g.  $Nm \propto fo$ ). The explanation for this seeming contradiction is that while foE varies directly with production of electrons in the E layer and therefore the sunspot number,  $R_z$ , foF2 is proportional to the square root of production of electron in the F2 layer. For the F2 layer, therefore, it is the square of its critical frequency that is directly proportional to production of electron and therefore to  $R_z$  while for the E layer it is a direct proportionality.

4.1.4 Somoye et al., (2012) reported that, at nighttime when the ionosphere is no longer exposed to sun's radiation, ionization of the F2 layer at the equatorial station of Ibadan compares with its daytime ionization during all the epochs of solar cycle. This is attributed to the storage of charges which have been uplifted by  $E \times B$  force at a region of great decay (i.e. at great heights) (Rajaram and Rastogi, 1977; Somoye, 2008). While the electric field,  $E$  is due to equatorial electrojet, an eastward current flowing--  
- +5,  $B$  is the earth's magnetic field.

4.1.5 The statement that the higher you go the cooler it becomes has been found to be limited to the top of the troposphere where temperature reduces from about 310K to 223K (see Figure 3). In actual fact, there are many inversions of temperature gradients in the atmosphere. The relationship between electron density, solar activity and ionospheric temperature represented in these equations:

$$T_e - T_i = A - BN_e \quad (10)$$

$$\frac{\partial N}{\partial t} = \text{production of electron} - \text{loss of electron} - \text{transport of ionization} \quad (11)$$

$$\frac{\partial T}{\partial t} = \text{Heating} - \text{cooling} - \text{conduction} \quad (12)$$

have been used by Iheonu and Somoye (2013) to determine the temperature of the ionosphere at height 300km to be 3000K. In equation (8),  $T_e$  is the temperature of the electrons while  $T_i$  is the temperature of the ions. In equation (10),  $T$  is temperature.

## 4.2 Studies on ionospheric irregularities

Most likely, we have all experienced reduction in the intensity of radio signal from our radio sets. The intensity increases again for a while and then another reduction is observed. This phenomenon is called fading of radio waves. Fading of radio waves is occasioned by three causes. The three causes are mentioned in section 4.2.2. One of the causes and which is one of the focus of this lecture is ionospheric irregularity. Simply put, ionospheric irregularity is inhomogeneity or fluctuation in the electron density of an ionospheric layer. It acts as a diffracting screen thereby modifying the phase and amplitude of the echoes.

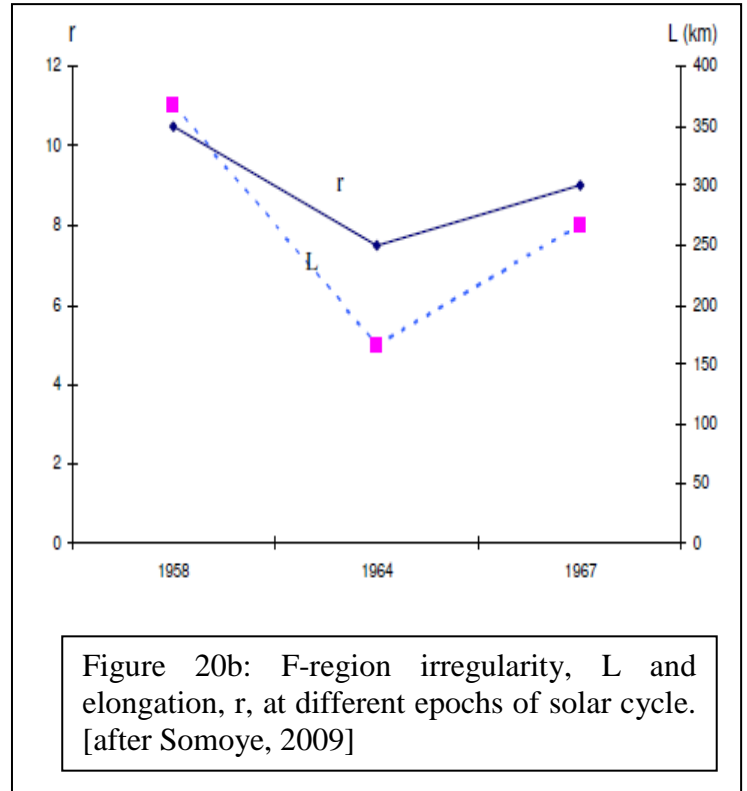
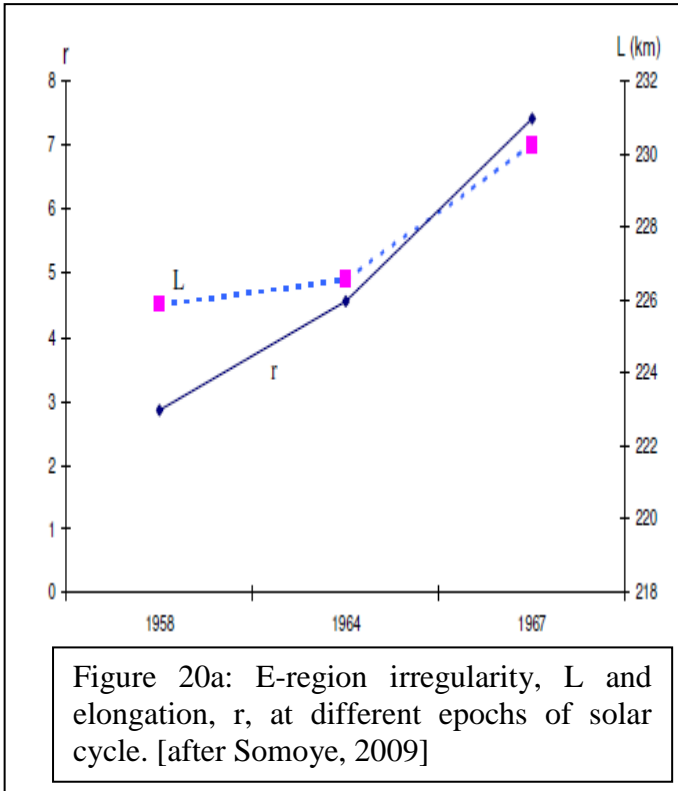
### 4.2.1 Drift velocity, size and shape of ionospheric irregularities

The irregularity causing fading of radio waves is found to drift and deform with time. The motion of ionospheric irregularities is observed by the Irregularity Fading Characteristic Equipment. Figure above 15 above shows the block diagram of the equipment. The major difference between the Irregularity Fading Characteristic Equipment and the ionosonde described in section 3.6 is that while echoes (i.e. the reflected signal) is received at one location in the ionosonde, it is received at three or more points arranged in a triangular array illustrated in Figure 16 and mentioned above. Auto-correlation and cross-correlation functions are determined by the full correlation method (Briggs et al., 1950; Phillips and Spencer, 1965) performed on the scaled amplitude fading records obtained from receivers fed by the aerials. The expressions for the auto-correlation and cross-correlation functions are shown in equations 4a and 4b (Section 3.6). Somoye (1996, 2009), using the full correlation method, obtained the drift velocity, size (North- South extent) and shape (axial ratio) of irregularities of E and F2 layers. Comparison of the parameters of the irregularities of both layers yielded the following results:

- i. The drift velocity, the size and the shape of F2 layer irregularity are greater than those of E layer irregularity during HSA but are of the same magnitude during LSA.
- ii. There is no solar cycle dependence on E layer irregularity parameters.
- iii. F2 layer irregularity parameters increase with increase in solar activity. See Table 1 and Figure 20. The implication of these results is that the intensity of HF echoes from F2 layer show greater fluctuation (fading) than HF echoes from E layer.

**Table 1.** Values of drift and pattern parameters of irregularities during HSA, MSA and LSA.

Parameters	Region	Solar	Cycle years	
		1958	1964	1967
Drift velocity V(m/s)	E	69±9	63±10	65±10
	F	122±20	62±9	100±12
Ratio of characteristics random v,vc/v	E	0.85±.16	0.81±.12	0.8±.15
	F	0.90±.14	0.89±.15	0.75±.15
Elongation (axial ratio) of irregularity r	E	4.5±0.9	4.5±.8	6.5±1.5
	F	11.0±1.6	5.2±0.9	8.3±1.5
Size of irregularity L(m)	E	225.3±50.8	226.1±25.8	230.6±46.5
	F	350.0±50.0	180.0±30.0	260.6±46.5



#### 4.2.2 Fading rate of E- and F2- layer echoes

E- and F2- layer echoes observed from ionospheric stations in the neighbourhood of the equator are found to show heavy fading. This is due to the enhancement of irregularity of ionization when the ionosphere is raised by the  $E \times B$  force (E being electric field of the electrojet and B the earth's magnetic field), a phenomenon that is pronounced at the equator. Somoye (2010) investigated the diurnal and seasonal variation of fading rates of E- and F-layer echoes during HSA and LSA. This investigation revealed that (a) while the fading rate of the E layer echoes is of the same order of magnitude during both low and high epochs of solar activity, those of F2 layer are found dissimilar. (b) the fading rate of E- and F-layer echoes are of the same order of magnitude during LSA but this is not the case during HSA. (c) the fading rate is maximum about noon and minimum at about sunrise and sunset – about the times reversal of both East – West and  $E \times B$  vertical drift – during both epochs for E-layer echoes and for F2-layer echoes during LSA. During HSA, fading rate is maximum at noon and minimum at sunrise and at 2000hrs. The maximum fading at noon appears to be due to (i) continuous daytime rise in peak height F2 layer echoes,  $h_m F_2$ , which enhances irregularities and (ii) spread F irregularities generated by sudden increase in  $E \times B$  plasma uplift not observed by the close-spaced antenna technique used in this investigation. (d) F2 layer fading rate is maximum during the Solstices while E-layer fading rates show no seasonal differences.

4.2.3 In the Irregularity Fading Characteristics Equipments mentioned in Section 4.2.1, the film speed of the camera can be varied by means of a calibrated motor attached to the camera. The film speed of 0.05inch per second and 0.10inch per second were normally used for LSA and HSA respectively. The

latter speed during HSA is higher due to more rapid fading during this epoch of solar cycle. This variation of the film speed with the intensity of solar activity, however did not take the peculiarity of the layers into consideration. Having found out that fading rate of E region echoes does not depend on the solar cycle epoch, I decided to investigate the validity of the speed of the film on which the amplitude fading records were photographed. The fading records were given a good magnification by a Dagma Super A (JH Mullens, N.V Denlaag, Holland) projector, scaled and subjected to full correlation analysis. Figure 10 shows the auto-correlation function with time. The auto-correlation function is a good approximation to a Gaussian function up till it falls to 0.61. For such a function,

$$\rho(\tau) = \exp\left(\frac{-\tau^2}{2\tau_o^2}\right) \quad (13)$$

$$\text{And time } \tau = \tau_o \text{ gives } \rho(\tau_o) = \exp\left(-\frac{1}{2}\right) = 0.61 \quad (14)$$

which may be taken as the fading period. Bowhill (1956) pointed out that in the case of a Gaussian time auto-correlation function, the fading period,  $\tau_o$  is related to the average time interval between successive maxima of the fading records, T. T, then, is the inverse of the fading speed. The relationship between T and  $\tau_o$  is

$$T = 3.62\tau_o.$$

Values of T and  $\tau_o$  determined from the amplitude fading records of echoes from E and F2 layers during low and high solar activity i.e. LSA and HSA are tabulated in Table 2.

**TABLE 2:** Fading Period and Time Interval between Successive Maxima of E- and F2 Layer Echoes

SOLAR CYCLE EPOCHS	E layer		F2 layer	
	$\tau$	T	$\tau$	T
LSA	1.13	3.33	1.24	3.33
HSA	0.92	3.33	0.64	1.67

From Table 2, calculation showed the following:  $T = 2.58\tau_o$  for E layer during LSA,  $T = 3.62\tau_o$  for E layer during HSA,  $T = 2.69\tau_o$  for F2 layer during LSA and  $T = 2.62\tau_o$  for F2 layer during HSA.

Comparison of these relations with the prediction of Bowhill (1956) indicated that it is only the amplitude fading records of E layer echoes during HSA that satisfies the theoretically predicted value. The amplitude fading records of E layer echoes during LSA and those of F2 layer echoes of both LSA and HSA were affected by the overestimate of the number of maxima due to the counting of maxima that have no significant effect on the auto-correlation function (Awe, 1960). This over estimate of maxima caused the underestimate of T. Thus, the film speed of 0.10inch per minute and 0.05inch per minute used for the F2 layer during HSA and LSA, respectively, are inadequate. Also inadequate was the film speed of 0.05inch per second used for E layer echoes during LSA.

Twice the film speed of what was used i.e. 10inch per second instead of 0.05inch per second for E layer echoes during both epochs is found to yield the factor that agree with the theoretically predicted value. For F2 layer echoes, the film speed of 0.10inch per second instead of 0.05inch per second during LSA and 0.20inch per second during HSA are appropriate.

Mr Vice Chancellor sir, let me say that appropriate film speed is important to the determination of the correct magnitude of drift pattern parameters of ionospheric irregularities responsible for the fading of radio signals.

#### 4.3.1 Diurnal effect of ionospheric day-to-day variability

The relative variability (VR) of ionospheric parameters differs much throughout the day. VR was found greater at night, especially just before sunrise and just after sunset for ionospheric parameters like peak (maximum) electron density of F2 layer, NmF2, critical frequency of F2 layer, foF2, critical frequency of E layer, foE and maximum useable frequency, MUF. Other parameters investigated are virtual height of F2 layer, h'F, propagation factor, M(3000)F2, critical frequency of F1 layer, foF1, and critical frequency of equatorial sporadic E layer, foEsq. The characteristic peaks of VR about sunrise and sunset are possibly due to the on-set and turn-off solar ionization radiation that occurs during these times of the day. Figures 21, 22 and 23, respectively, show the characteristic pre-sunrise and post-sunset peaks of NmF2 VR, MUF VR, foF2 VR.

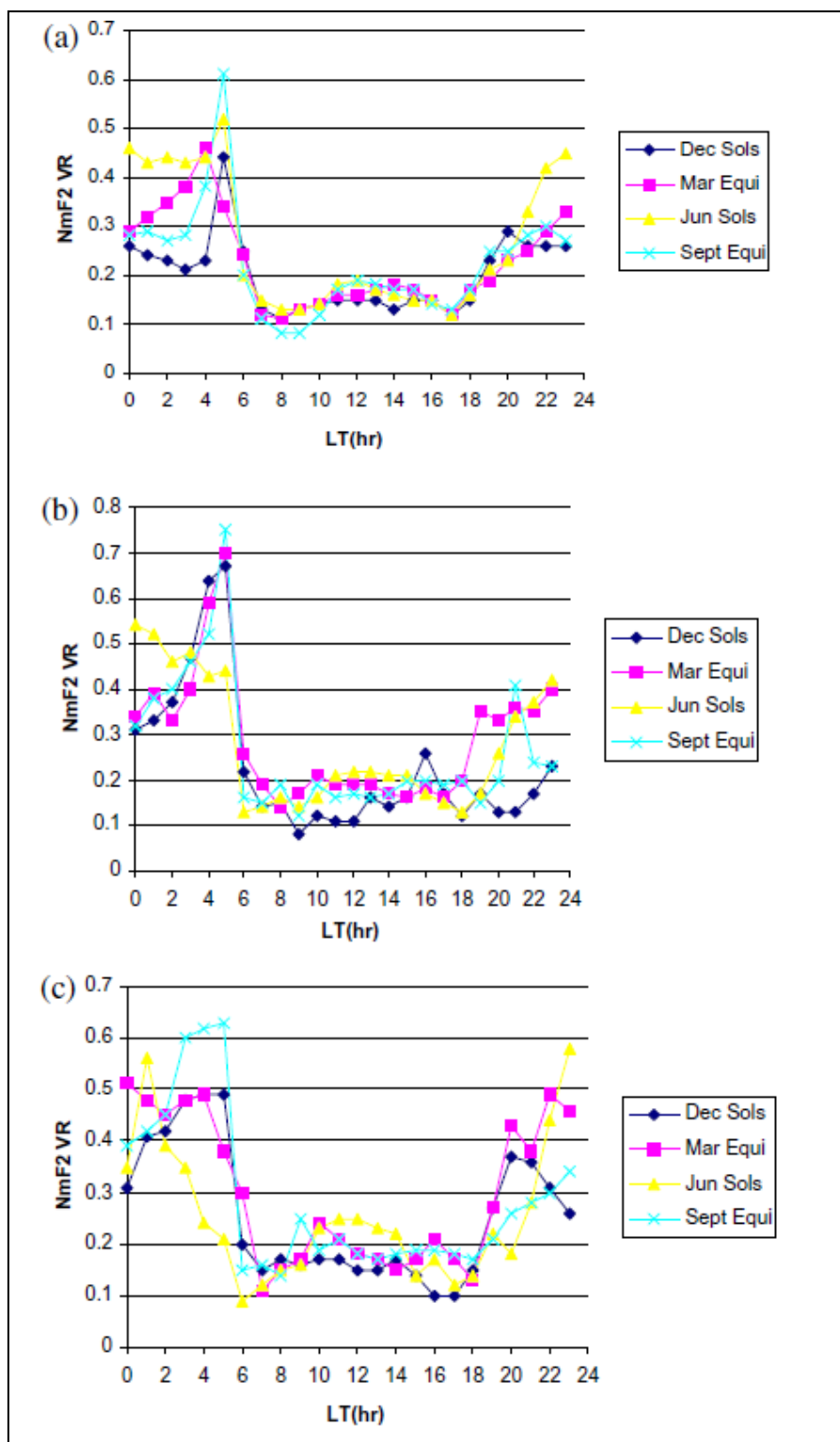


Figure 21: Diurnal variation of NmF2 Coefficient of Variability during (HSA), (MSA) and (LSA) year. (After Somoye and Akala, 2011)

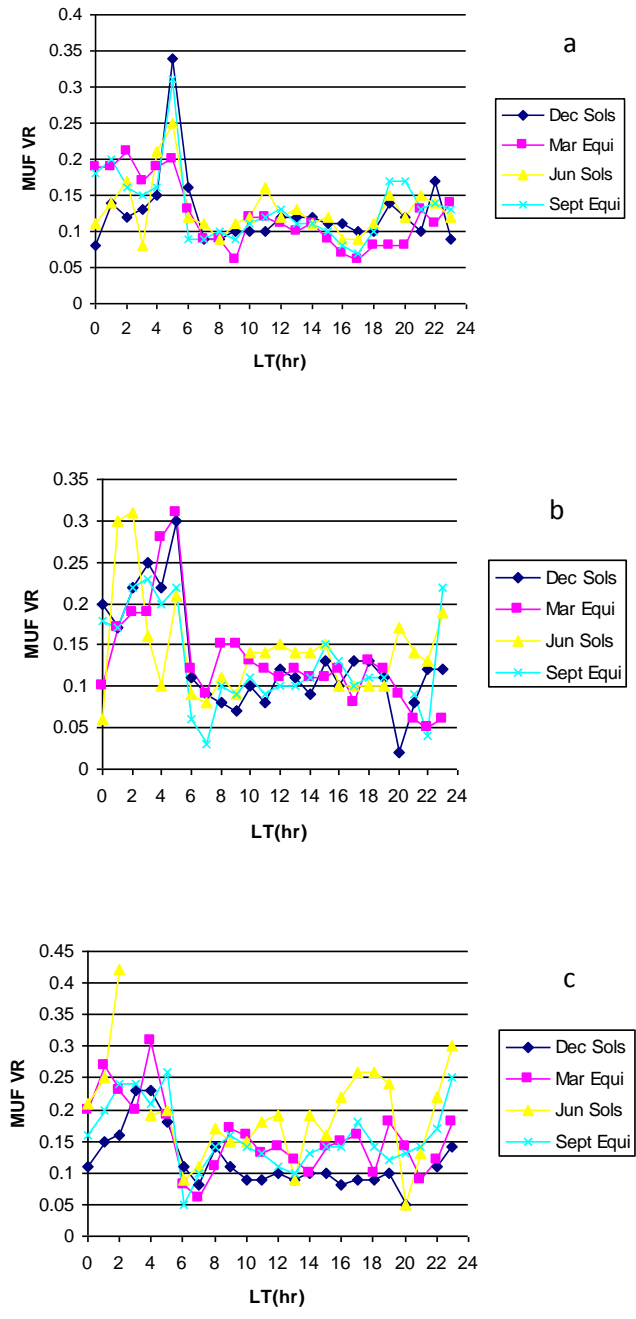


Figure 22: Diurnal MUF VR during (a) High Solar Activity, (b) Moderate solar Activity (c) Low Solar Activity. (After Somoye and Akala, 2011)

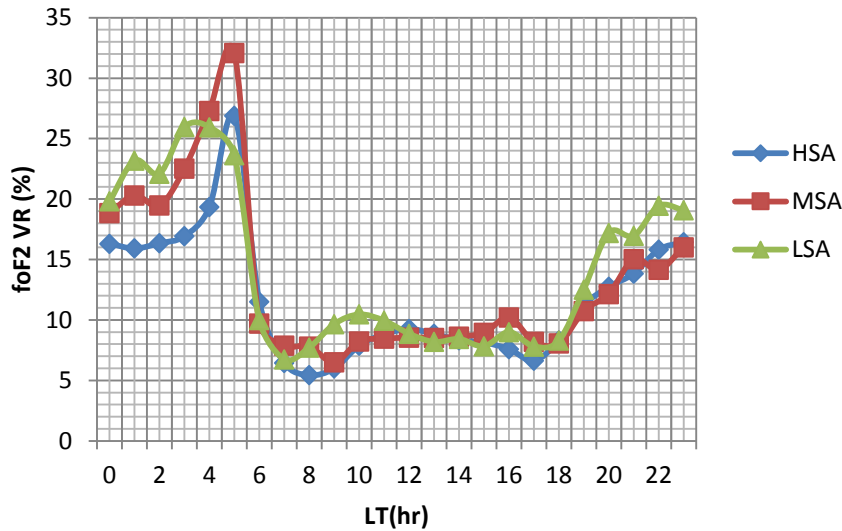


Figure 23: Diurnal plot of annual foF2 VR during HSA, MSA and LSA at Ibadan (after Somoye et al., 2013b)

For foE, the characteristic peaks occurred at post-sunrise and pre-sunset as illustrated in Figure 24 while for M(3000)F2 characteristic peaks are not obvious implying there is no diurnal trend in the M(3000)F2 VR. Worth mentioning is the observation that the VR peaks around the sunrise is more often than not greater than the one in the neighbourhood of sunset. The characteristic VR peaks near sunrise and sunset have been explained in terms of the low mean values at these hours of the day by Bilitza et al. (2004). Somoye (2009), however, pointed out that another factor that results in these peaks is the decay suffered by ionospheric parameters at these times. The decay not only leads to reduction but also to irregularity in their mean values since ionospheric parameters known to decrease irregularly at night (Rishbeth and Garriot, 1969). Somoye (2009) showed that it is not only the relative variability of these parameters that were high at night as their absolute variability were also found to be high. This is evident in Figure 25 which shows both the absolute and relative VR of NmF2 during equinox of a high solar activity year.

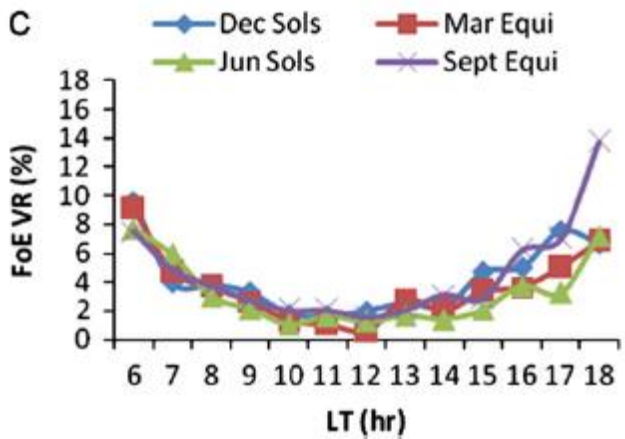
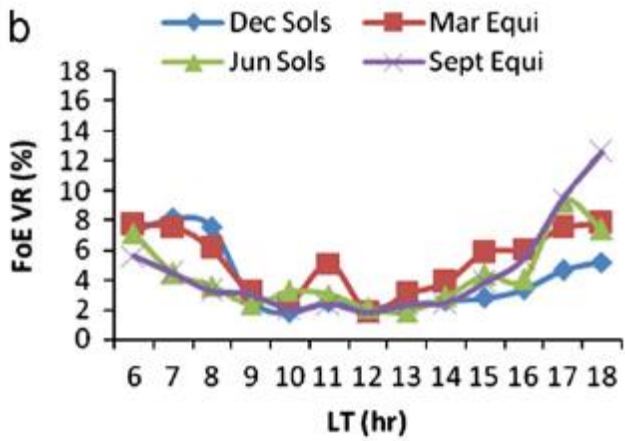
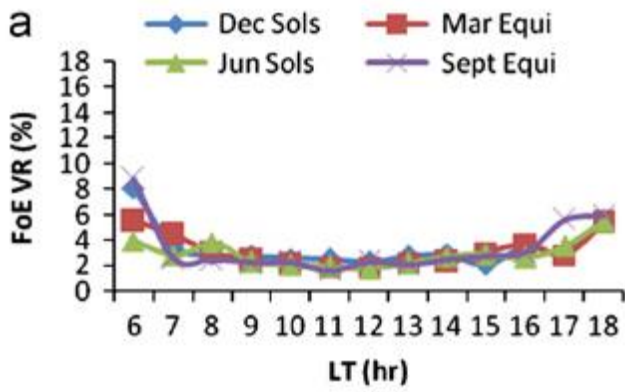


Figure 24: Diurnal foE VR during (a) high (b) Moderate and (c) Low solar activity at the Ibadan station.

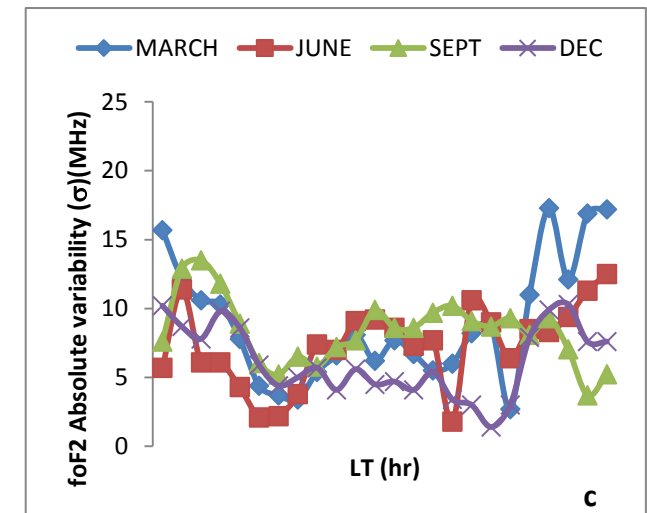
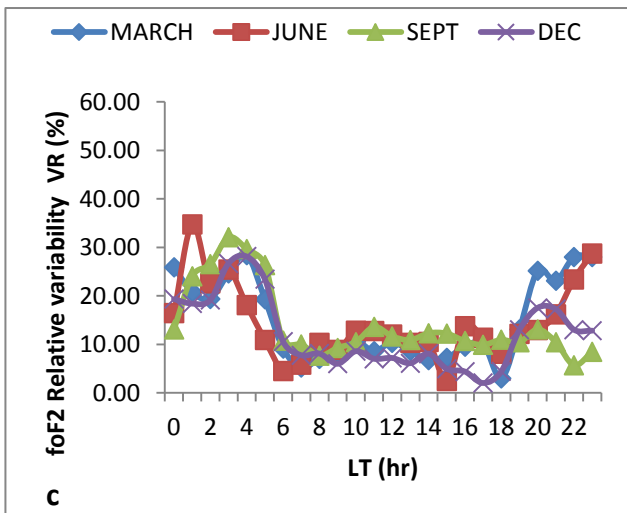
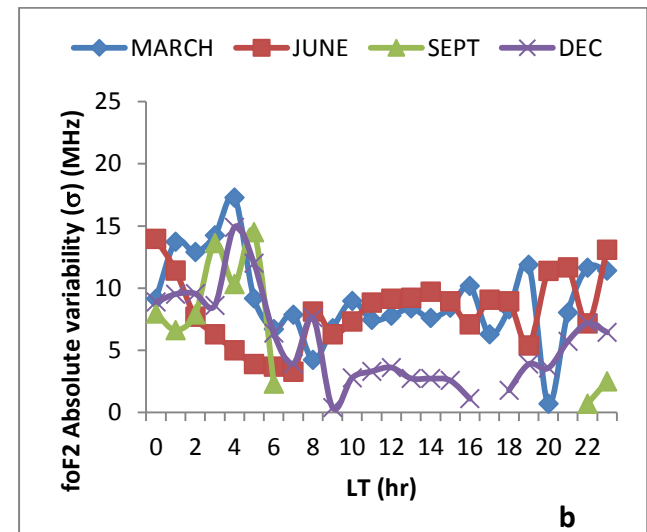
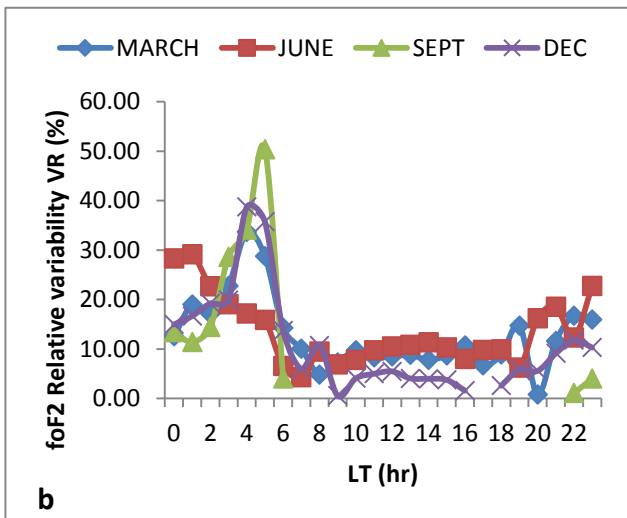
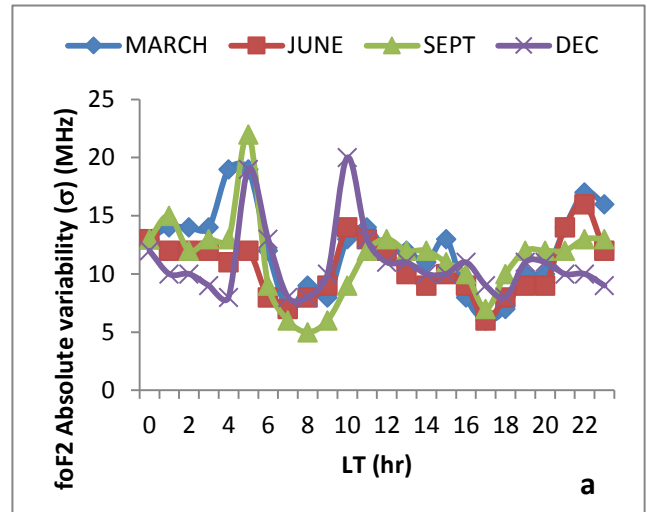
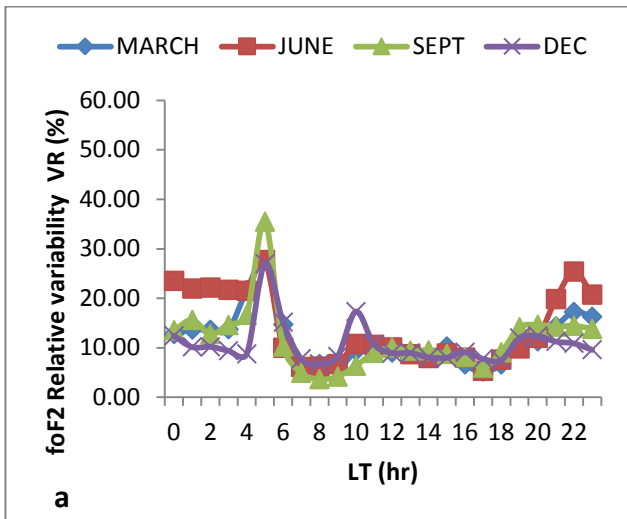
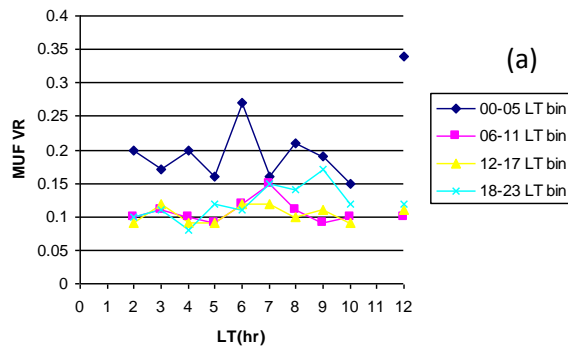


Figure 25: Comparison of Absolute and Relative variability of foF2 during (a) High Solar Activity (HSA) (b) Moderate solar Activity (MSA) (c) Low Solar Activity (LSA) (after Onori et al, 2012)

### 4.3.2 Seasonal effect of ionospheric day-to-day variability

Seasonal difference in the mean values of ionospheric parameters is a common phenomenon. Rishbeth and Garriot (1969) mentioned the existence of an annual variation of peak electron density of F2 layer, NmF2, which is about 20% greater in December Solstice than in June Solstice. This is, possibly, due to the 6% variation of solar ionizing flux greater in December Solstice than in June Solstice as a result of the variation of sun-earth distance. This seasonal effect is expected to extend to the day-to-day variability of these parameters. We observed that pre-sunrise VR of ionospheric parameters show more seasonal influence than post-sunset and daytime VR. Figure 26, in which MUF VR for different local time (LT) bins is plotted with the months of the year shows this clearly. Somoye (2009) reported that NmF2 pre-sunrise VR is greater in June Solstice and September Equinox during high solar activity (HSA). He found nighttime (pre-sunrise and post-sunset) NmF2 VR greater at the equinoxes than other seasons during low solar activity (LSA) and moderate activity (MSA). Somoye et al. (2011) also reported greater nighttime VR of F2 layer critical frequency, foF2 and VR of virtual height of F layer, h'F during June Solstice and September Equinox for the equatorial station of Ibadan. Greater nighttime VR in foF2 was equally observed at the equatorial stations of Dakar (14.8°N, 17.4°W, dip: 11.4°N), Ouagadougou (12.4°N, 1.5°W, dip: 2.8°N) and Djibouti (11.5°N, 42.8°E, dip: 7.2°N) and reported by Akala et al. (2010). In the equatorial American station of Huancayo (12°S, 284.7°E, dip: 1.9°), Akala et al. (2011) reported that peak nighttime foF2 VR occurred in March Equinox while for Asian low latitude of Vanimo (2.7°S, 141.3°E, dip: 22.5°S), it was observed in June Solstice. Somoye and Akala (2011) observed that peak nighttime Maximum Useable Frequency (MUF) VR at Ibadan occurred at different seasons depending on the epoch of solar cycle considered. Maximum pre-sunrise critical frequency of E layer (foE) VR was found to occur during December Solstice and the Equinoxes during HSA and LSA by Somoye et al. (2013). The maximum pre-sunrise foE VR during MSA was observed, by them, to occur in June Solstice.

I should mention that the daytime (i.e. 06h – 17h) VR of ionospheric parameters were found independent of seasons (Somoye et al., 2013; Rishbeth and Mendillo, 2001).



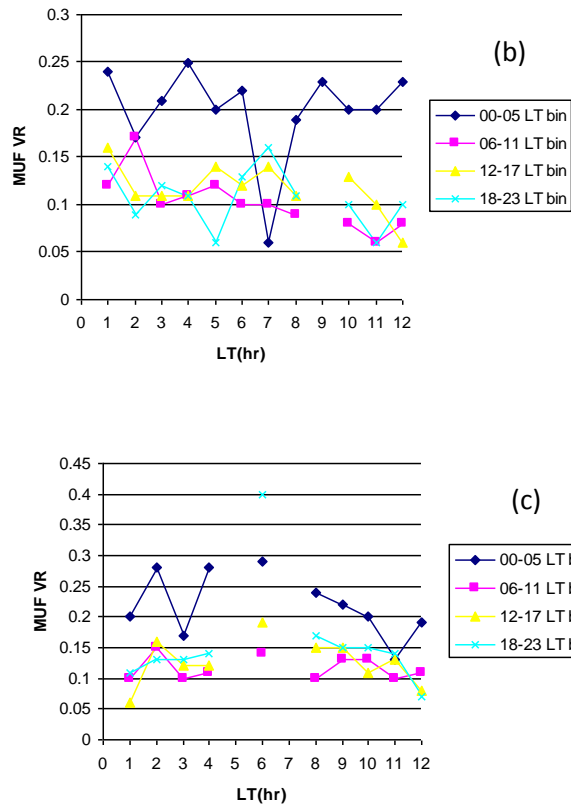


Figure 26: Annual MUF relative VR of different LT bins for (a) HSA (b) MSA and (c) LSA. (After Somoye and Akala, 2011)

#### 4.3.3 Solar cycle influence of day-to-day variability

The periodicity of solar activity cycle (here after, solar cycle) is taken to be 11 years by researchers. Using the annual average sunspot number, Rz12, one of the indices of solar activity, Somoye (2009b) found that at some hours of the day the periodicity is as low as 8 years while at others, it is as high as 14 years (see Figure 27). Some features of the diurnal variation of foF2 were found to consistently give a solar periodicity of 11 years. These features are ionization build up rate (BUR) which is the difference in the values of pre-noon peak and pre-sunrise depression. The second feature is the difference in values between pre-noon and post noon peaks as shown in Figure 28. Both the relative variability and the absolute variability of ionospheric parameters are also known to change with solar cycle. We, however, observed that it is only the nighttime relative variability (VR) of ionospheric parameters like F2 layer electron density, NmF2, F2 layer critical frequency, foF2, maximum useable frequency (MUF) that vary with solar cycle. Somoye (2009c), Somoye and Akala (2011), Akala et al. (2010, 2011), Bilitza et al. (2004) and Ezquer et al. (2004) reported that nighttime VR of ionospheric parameters decrease with increase in Rz12. This is evident in Figure 29 which illustrates the diurnal variation of annual foF2 VR during high solar activity (HSA), moderate solar activity (MSA) and low solar activity (LSA) for Huancayo, Ouagadougou and Vanimo. In the same Figure, it is discernible that solar cycle effect on daytime VR is little or nil except at Vanimo possibly due to the variable electrodynamic at Vanimo, Vanimo being on the flank of equatorial ionization anomaly crest.

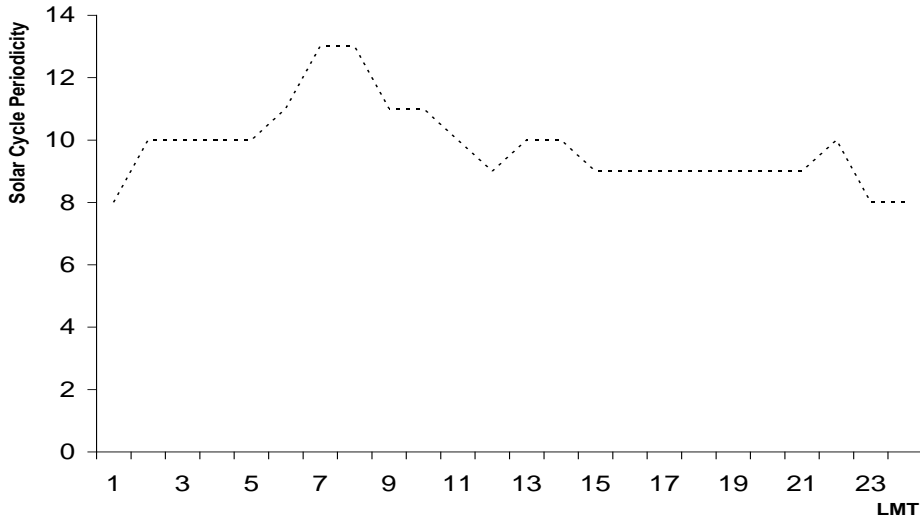


Figure 27a: Illustrating variation of solar cycle periodicity

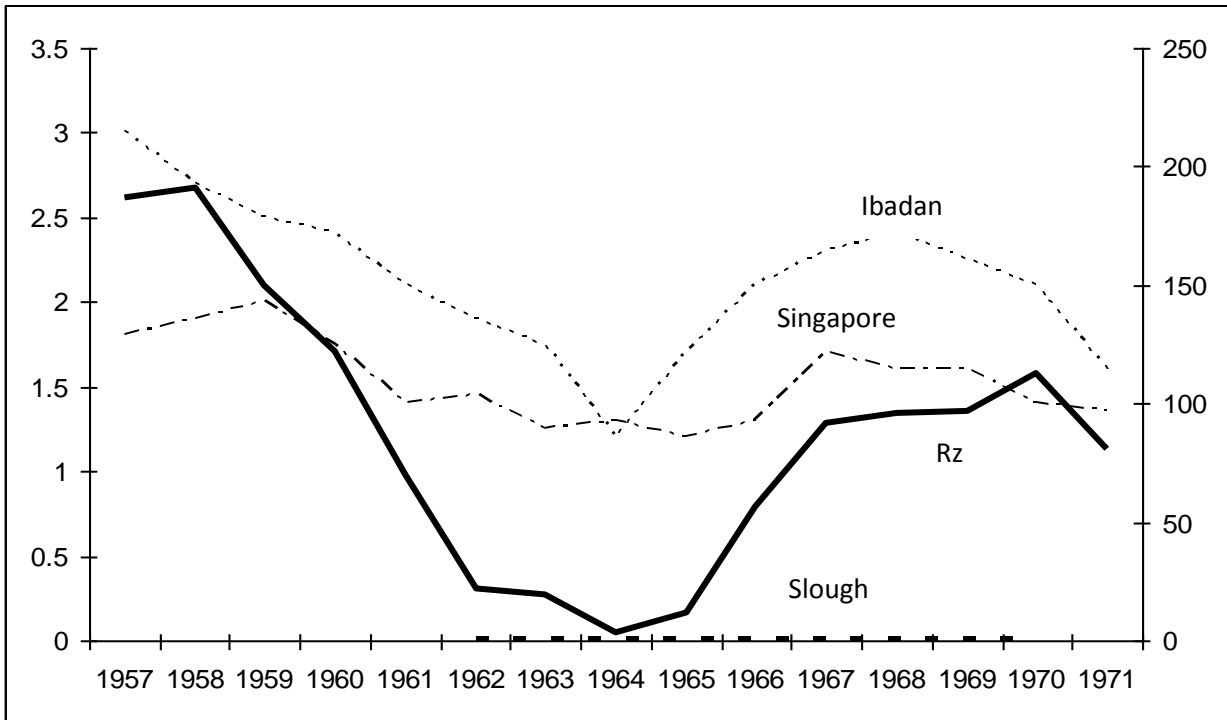


Figure 27b: Illustrating build-up rate of ionization and sunspot number, Rz.

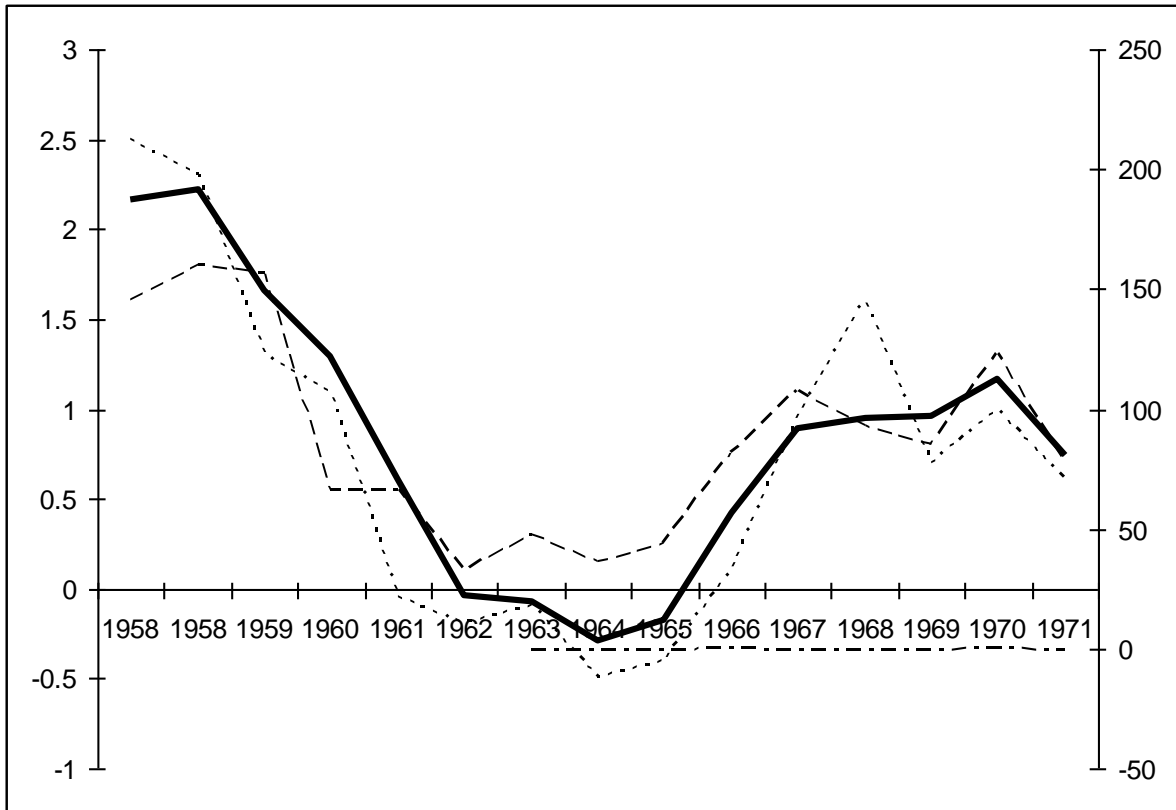


Figure 27c: Illustrating difference in pre-noon peak and post-noon peak of ionization and sunspot number, Rz. (After Somoye,2009)

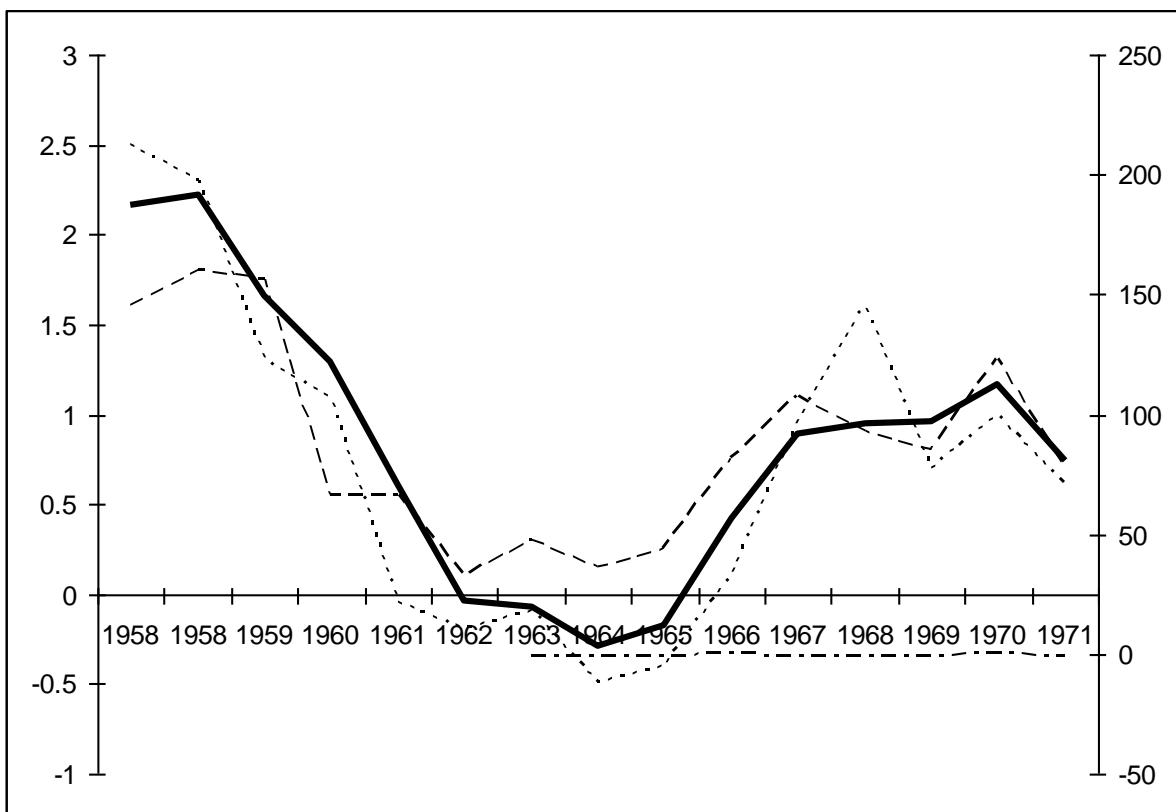


Figure 29: Pre-noon and post-noon peaks of ionization and sunspot number, Rz at Ibadan Singapore and Slough. (After Somoye, 2009)

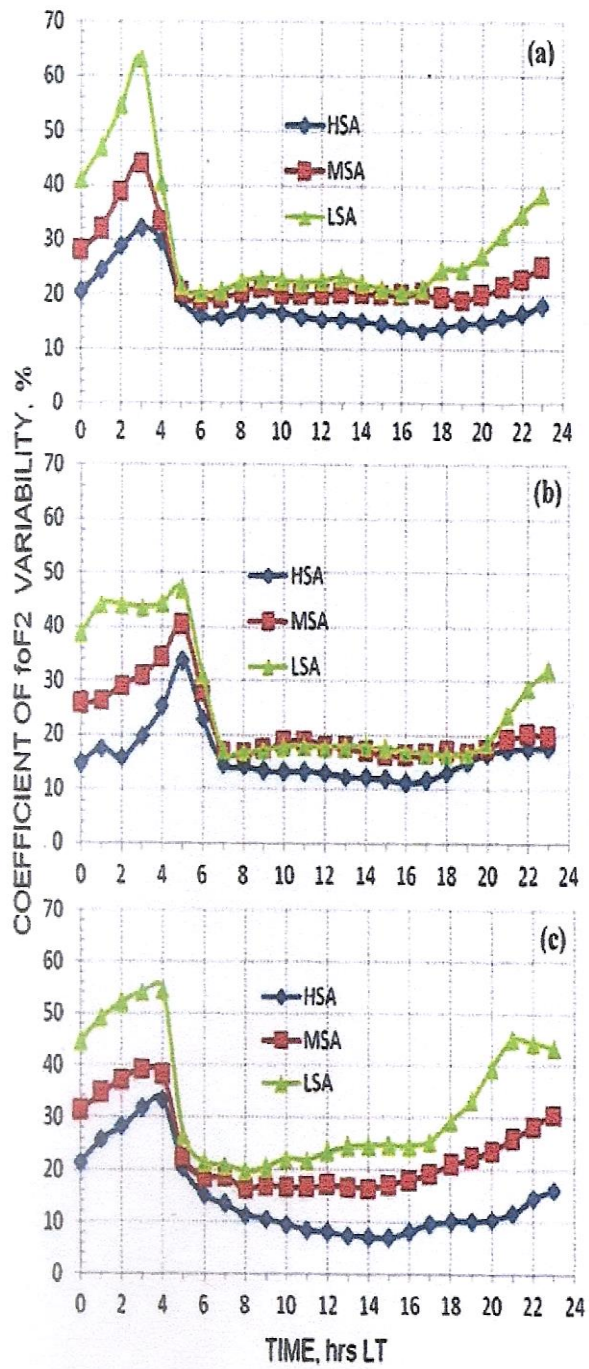


Figure 29: Diurnal variation of coefficient of foF2 variability of mean values for all seasons during low activity (LSA), moderate solar activity (MSA) and high solar activity (HSA) for (a) Haucanyo (b) Ouagadougou and (c) Vanimo. (after Akala et al. (2011)).

#### 4.3.4 Latitudinal dependence of day-to-day variability

As mentioned in Section 3.4.1, the ionosphere over different latitudes, vary as a result of the variation of sun's zenith angle. The parameters of the ionosphere, therefore, depends on the latitude of the observing ionospheric station. We investigated the effect of latitude on the relative variability of some ionospheric parameters. While nighttime VR of NmF2, foF2, MUF and  $h'F$  decreased with increase in latitude (Rishbeth and Mendillo, 2001; Araujo-Pradere et al, 2004; Rawer et al., 2003; Somoye, 2009c), the daytime NmF2 VR and foF2 VR were found to increase with latitude (Somoye, 2009c). The daytime VR of MUF and that of  $h'F$  did not show latitudinal dependence (Somoye and Akala, 2011). Figure 30 shows the day-to-day variability of Maximum Useable Frequency (MUF) for Ibadan – an equatorial station, Singapore – a low latitude station and Slough – a mid-latitude station during moderate solar activity. MUF VR was found greater at Singapore and Ibadan than at Slough (Somoye and Akala, 2010).

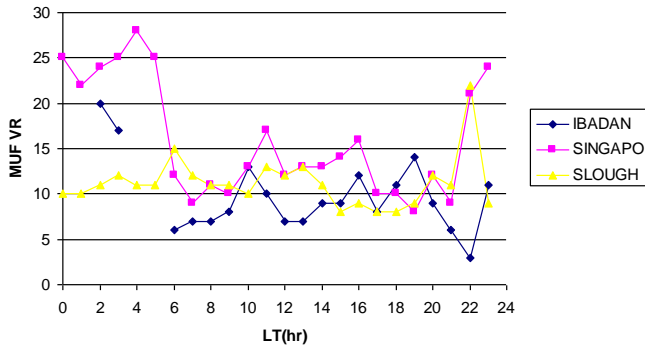


Figure 30: Diurnal MUF relative VR for IBADAN, SINGAPORE and SLOUGH for Moderate Solar Activity (MSA). (Somoye and Akala, 2011)

#### 4.3.5 Longitudinal dependence of day-to-day variability

Recent development in ionospheric research has brought the effect of longitude on ionospheric variations to the fore. The vertical  $E \times B$  drift of ionization due to the interaction of equatorial electrojet current and horizontal earth's magnetic field is now known to exhibit longitudinal variation (Pedatella et al. 2011). The  $E \times B$  upward force is responsible for three important phenomena in the equatorial ionosphere. These phenomena are (i) increased F2 layer height (ii) decreased ionization between 0900hr and 1500hr known as noon bite-out of ionization (iii) peaks of ionization at  $\pm 20^\circ$  dip latitude instead of at the equator, referred to as equatorial ionization anomaly (EIA) (Rajaram, 1977). In the American Geophysical Union (AGU) Conference at Adiss Ababa, Ethiopia that I was privileged to attend in 2012, the theme of the conference was Longitudinal and Hemispheric Dependence of Space Weather. The major longitudinal sectors of the globe are the American sector, west of the Greenwich Meridian (GM), the Euro-African sector, neighbourhood of GM and the Asian sector, east of GM. Investigation of longitudinal effect on variability we embarked upon indicated that the variability of propagation factor, M(3000)F2 VR is dependent on longitude (Somoye et al., 2013). Significant dependence of Maximum Useable Frequency (MUF) VR was observed by Fotiadis et al. (2004). Akala et al. (2011) also reported that the variability of F2 layer critical frequency (foF2) was greater for the equatorial station of Huancayo in the American sector, west of GM, followed by foF2 VR of Vanimo in the Asian sector, east of GM. We found foF2 VR least for Ouagadougou, a low latitude station in the Euro-African sector in the neighbourhood of GM. We also found similar result for the relative variability of maximum electron density of F2 layer (NmF2 VR). NmF2 VR of Huancayo, west of GM was 78%. That of Vanimo, east of GM was 70% while those of Ouagadougou and Dakar, stations in the neighbourhood of GM was 62% and 78% respectively (Ogwala et al., 2015; Onori et al. 2015). While pre-sunrise VR occurred at stations, west of GM between ----- and at stations east of GM between 02 – 04 hr. It occurred between 05 – 07hr at stations neighbourhood of GM. Ogwala et al. (2015) reported the occurrence of early morning depression of NmF2 earlier at west and east of GM than in the neighbourhood of GM. It is worth

mentioning that greater VR found at the American and Asian longitudinal sectors than in the Euro-African sector is possibly due to greater declination at the former than at the latter.

#### 4.3.6 Relationship between day-to-day variability of ionospheric parameters

Some of the outstanding results obtained in the course of my research work are the report of relationships observed between the day-to-day variability of ionospheric parameters.

- (a) Somoye et al. (2011) reported that the nighttime relative variability (VR) of the peak electron density of F2 layer (NmF2) was found to be twice that of the critical frequency (foF2). Figure 31 shows this clearly. Theoretically, if a quantity  $U = KX^n$ , where X is another quantity, then the deviation of  $U = dU$ , while the deviation of  $X = dx$ . We can therefore write

$$\frac{\Delta U}{U} = nk \frac{\Delta x}{x} \quad (*)$$

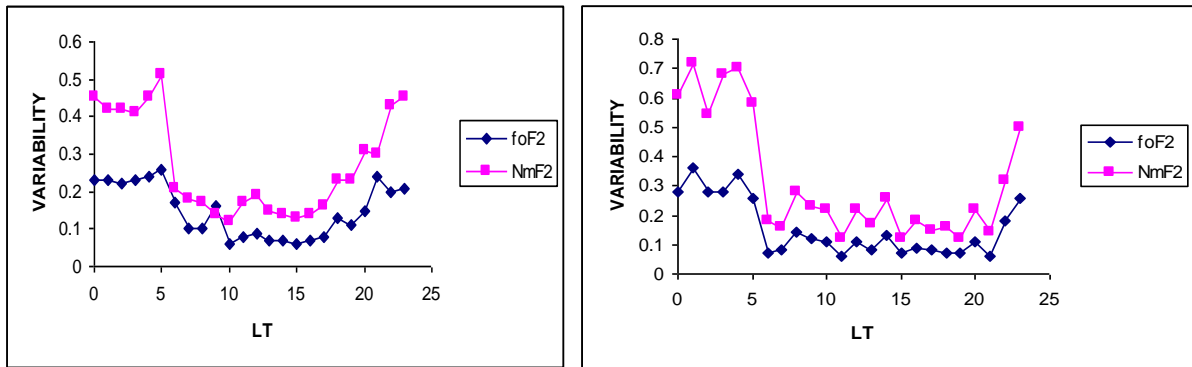


Figure 31: Nighttime relative variability of NmF2 and foF2 during HSA and LSA (After Somoye and Akala, 2010).

The electron density of the F2 layer,  $NmF2 = k(foF2)^2$ , foF2 being the critical frequency of F2 layer.

By equation (\*),  $\frac{\partial(NmF2)}{NmF2} = \frac{2k\partial(foF2)}{foF2}$  or  $NmF2 VR = 2foF2 VR$ .

The interesting part of this result obtained by Somoye et al. (2011) is that it is not always that theory and experiment agree (Ratcliffe, 1970) as it is in this case.

- (b) The maximum useable frequency (MUF) is taken as the product of the critical frequency of F2 layers, foF2, and the propagation factor, M(3000)F2 (Fotiadis et al., 2004). The relative variability of nighttime MUF is found to be the same order of magnitude as that of foF2 (Somoye and Akala, 2011), see Figure 32. We also reported that nighttime variability of MUF was found to be half that of NmF2 as revealed in Figure 33.

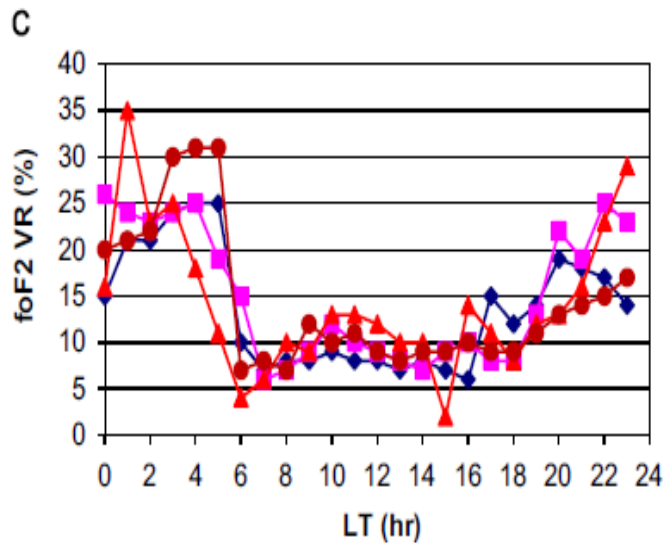
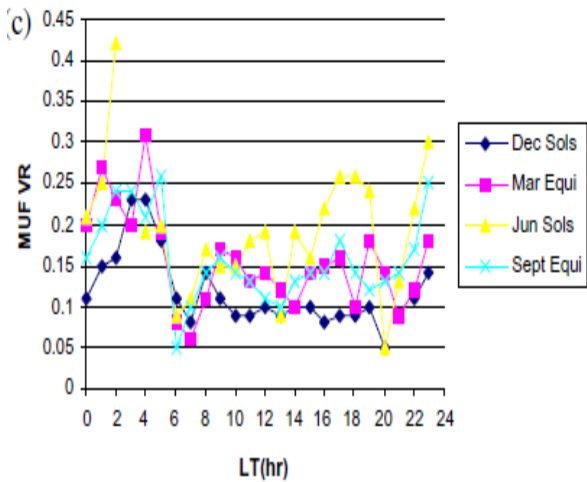
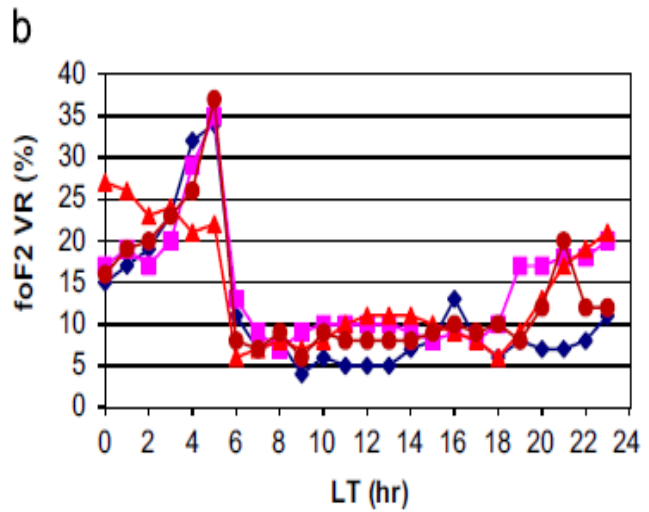
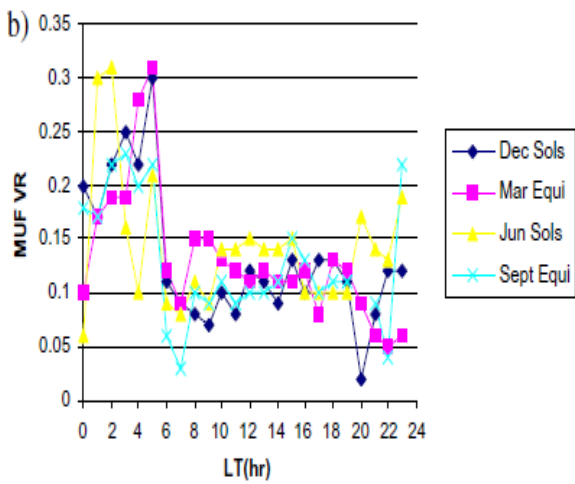
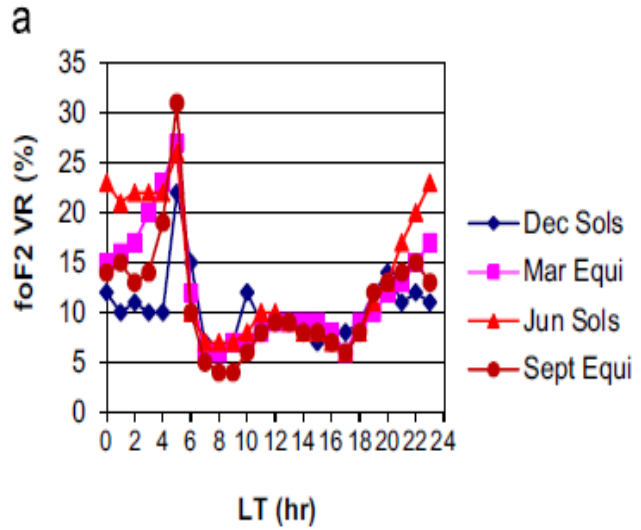
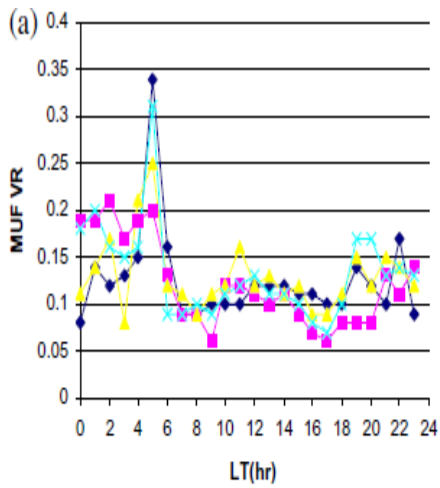


Figure 32: Nighttime diurnal MUF VR and foF2 VR for all seasons during (a) HSA (b) MSA (c) LSA (Somoye and Akala, 2011, Somoye et al., 2011)

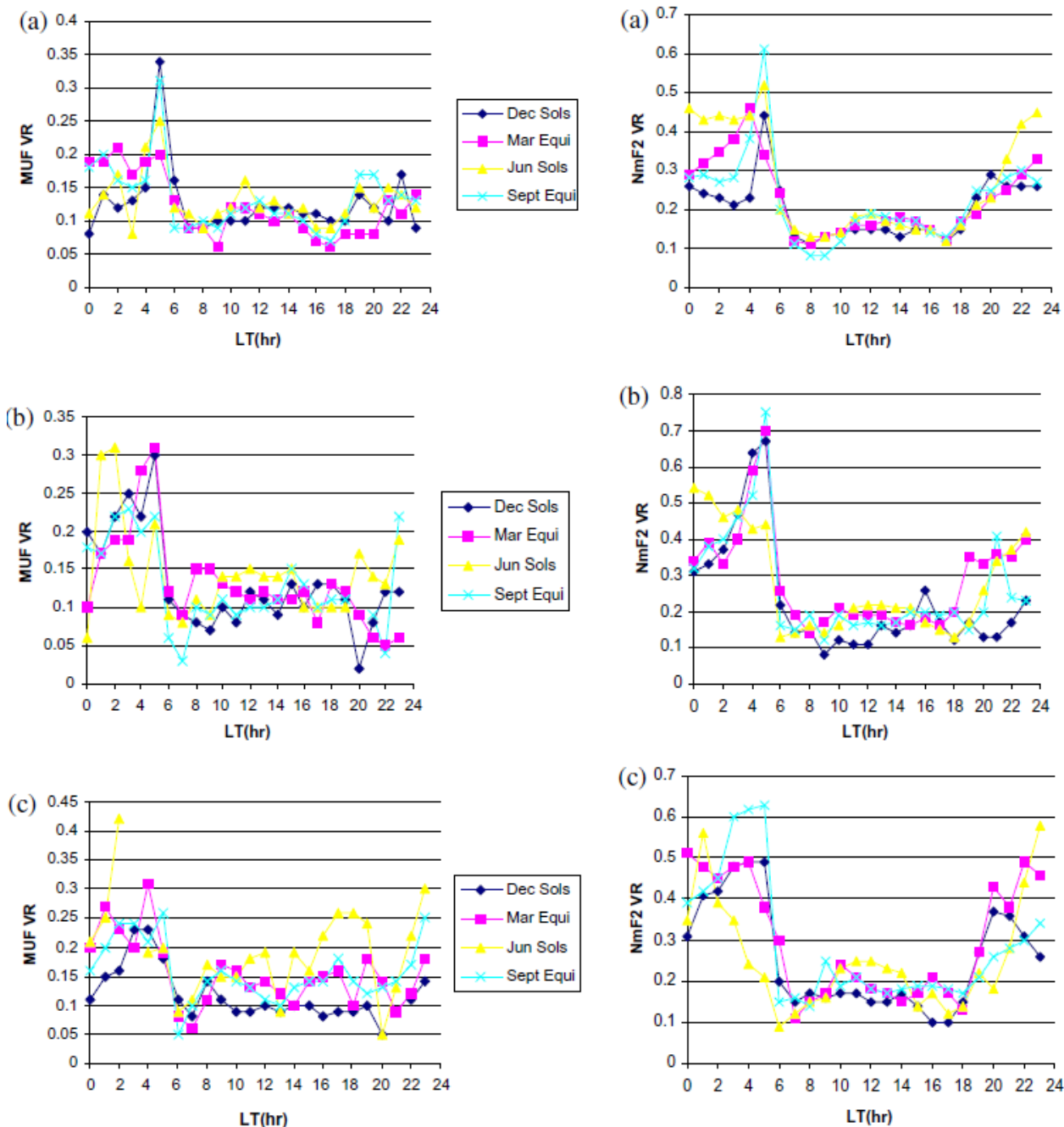


Figure 33: Nighttime diurnal MUF VR and NmF2 VR for all seasons during (a) HSA (b) MSA (c) LSA (After Somoye and Akala, 2011)

(c) Somoye et al. (2013) found that the nighttime relative variability of the propagation factor,  $M(3000)F_2$  was found to be half that of the critical frequency ( $f_oF_2$ ) at the equatorial station of Ibadan. See Figure 34.

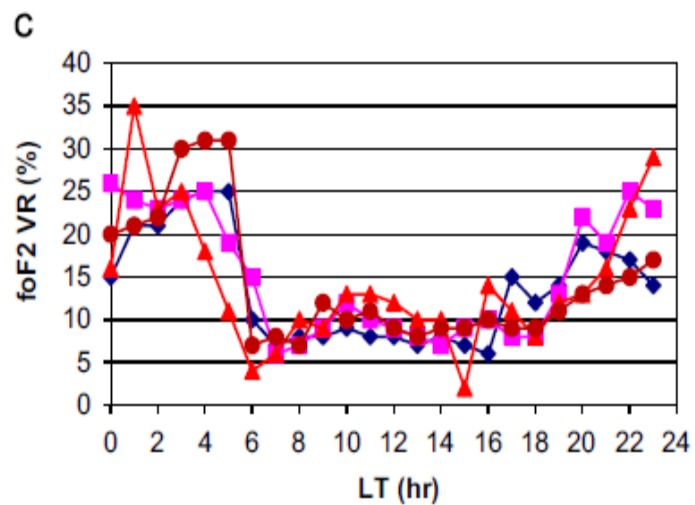
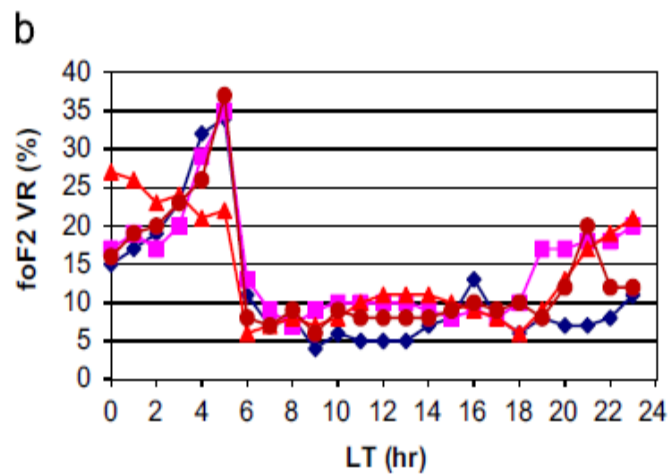
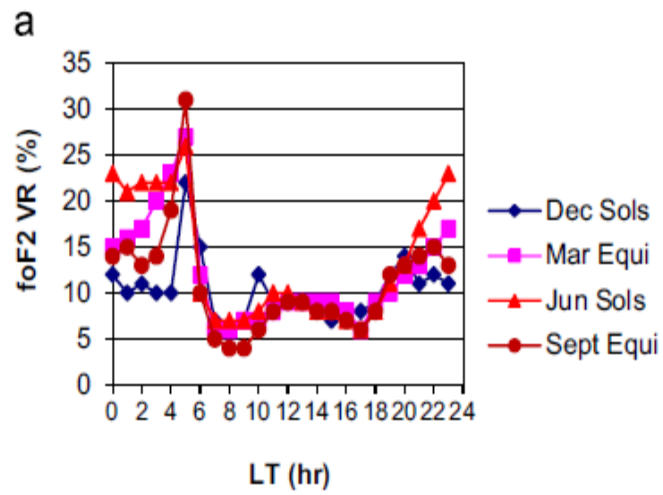
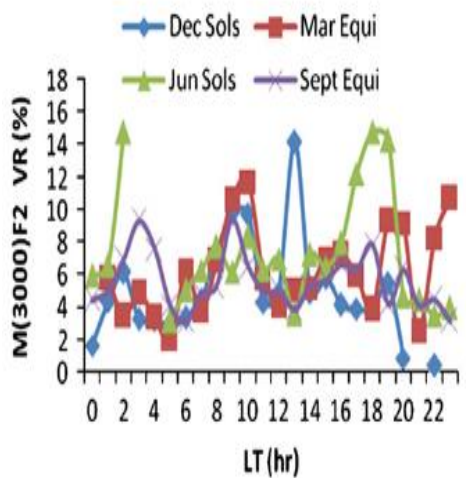
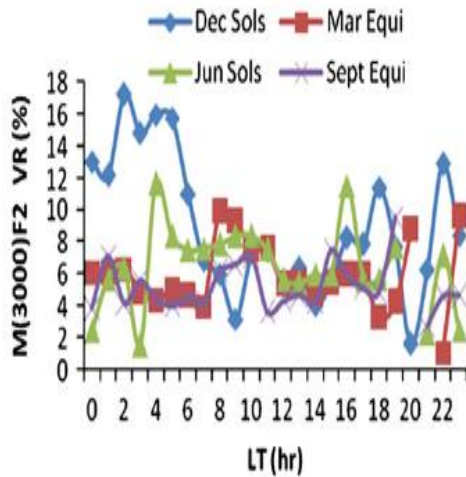
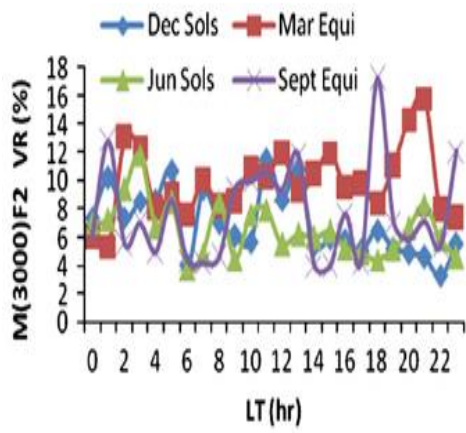


Figure 34: Diurnal M(3000)F2 VR and foF2 VR for all seasons during (a) HSA (b) MSA (c) LSA, (after Somoye et al. 2013 and Somoye et al., 2011)

(d) Olatunji (1966) mentioned that the combination of the observed variations of critical frequency, foF2, and peak height of echoes of F2 layers, h<sub>m</sub>F2, provides a basis for qualitative interpretation of the behaviour (i.e. climatology) of the equatorial ionosphere. We carried out a comparison of the relative variability (i.e. weather) of both parameters and found that the variability of foF2 (foF2 VR) was greater than that of h'F (h'F VR) at all hours and during all epochs of solar cycle except for nighttime h'F VR, which is about equal as nighttime foF2 VR during high solar activity (HSA) (Somoye et al., 2011). See Figure 35. This is due to pre-reversal enhancement (PRE) of height of reflection of echoes that occurs just after sunset at equatorial ionosphere which is more prominent during HSA. When the ionospheric plasma is raised high and the bottomside gradient steep enough, plasma density depletions grow via the collisional Rayleigh-Taylor (RTI) or possibly the gradient drift instability (GDI) and rise non-linearly by  $E \times B$  motion through the peak to the topside of the F region (Oyekola et al., 2007; Oyekola and Oluwafemi, 2008; Chen et al., 2006; Abdu et al., 2009; Ossakow, 1981; Rottger, 1981).

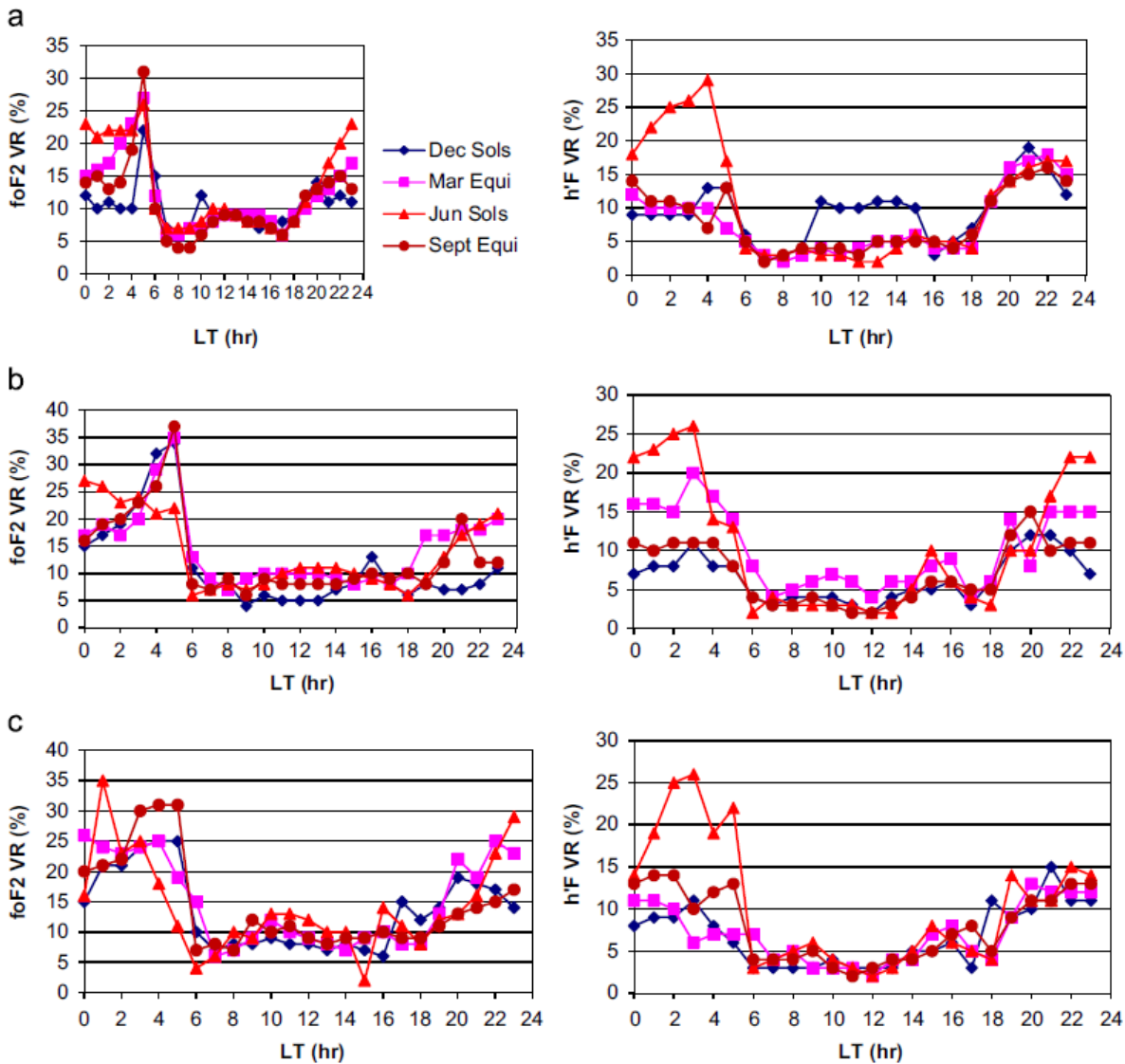


Figure 35: Diurnal foF2 VR and h'F VR for all seasons during (a) HSA (b) MSA (c) LSA, Somoye et al., 2011)

(e) The relative variability of the critical frequency of equatorial sporadic E layer, foEsq VR deserves special mention. The sporadic E layer sometimes permits unexpectedly good reception (Kennedy and Davies, 1990) of radio signals because of its abnormal increase of ionization. Though it occupies the same height (~ 100km) as the normal E layer, the relative variability of the critical frequency of sporadic E layer is not found to follow the same trend as the relative

variability of other ionospheric parameters including that of the critical frequency of the normal E layer, foE. This is possibly because the behaviour of this layer is highly irregular. For instance while relative variability is higher during low solar activity than during high solar activity for other parameters, the reverse is the case for foEsq. This is evident in Figure 36 in which is illustrated the foEsq of HSA, MSA and LSA. Also, foEsq VR was characterised by pre-sunrise and post-sunset peaks only during high solar activity. We did not observe any diurnal trend of nighttime foEsq VR during low and moderate solar activities. This was not the case for foE VR which though is a daytime phenomenon, the sunrise and sunset peaks are obvious from the Figure during all epochs of solar activity (Somoye et al., 2013).

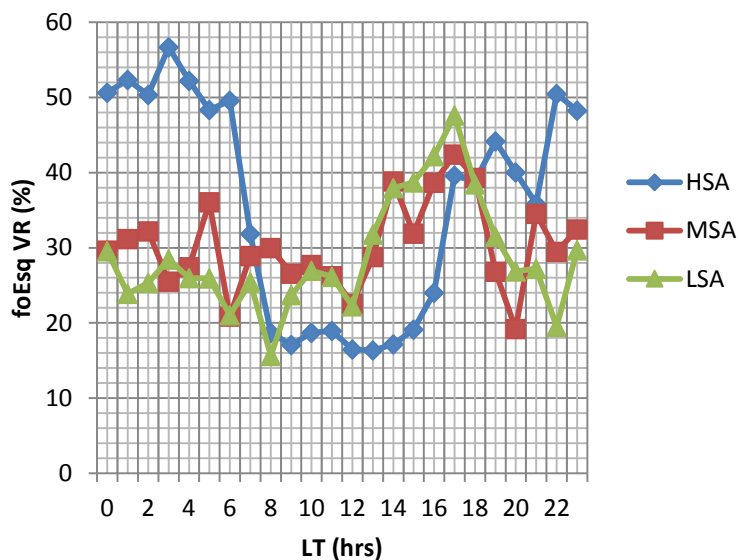


Figure 36: Diurnal plot of annual foEsq VR during HSA, MSA and LSA at Ibadan (after Somoye et al., 2013b)

- (f) It is pertinent to mention that daytime relative variability of ionospheric parameters were found to be, more often than not, much lower than nighttime VR and can be taken as negligible for all interest and purposes. Two factors responsible for low daytime VR are (i) greater daytime mean values than nighttime mean values due to greater ionization during the day as a result of increasing ionization in the intensity of solar radiation (Bilitza et al., 2004). (ii) irregularity in the reduction of nighttime values of ionospheric parameters (Rishbeth and Garriot, 1969) which leads to decay (Somoye, 2009). This results in greater nighttime absolute variability than that of daytime. Figure 25 shows that nighttime absolute variability is greater than that of daytime.

#### 4.3.7 Application of Space Weather

Ionospheric variations form a significant aspect of the complex subject of space weather (Rishbeth and Mendillo, 2001) which is itself a substantial part of space physics. According to Moldwin (2012), space physics is the part of space science that studies the structure and dynamics of the sun's atmosphere and its interaction with everything inside the solar system (from planetary atmosphere and magnetosphere to asteroids, comets and dust) as well as its interaction with the local interstellar----tion medium. Space science, defined as the knowledge of the region beyond the terrestrial earth (Somoye et al., 2014) is said to be an important driver for scientific enquiry, knowledge creation, technology development, human capital development and a vehicle for stimulating interest, awareness, understanding and appreciation of science among the youth and the general public (Mckinnel, 2012). Space weather effects which describe variations in the sun, solar wind, magnetosphere, ionosphere and thermosphere can influence the performance and reliability of a variety of space-borne and ground-based technological systems and can also endanger human health and safety (Koons et al., 1999, Royal Academy Engineering, 2013). Meehan

and Kunches (2012) reported that Delta Airline in United States of America had an unprecedented experience in 2011. One of its flights was rerouted because of space-weather activity. They further reported that the aviation industry is becoming more aware of the impacts that space weather can have on operations, communication and navigation as well as the issue of increased radiation exposure for passengers and flight crew on board.

In reviewing the book written by Delores Knipp and titled, “Understanding Space Weather and the Physics behind it”, Moldwin (2012) said our increased reliance on space technology, global communication and navigation system and continental scale power grids has bought the realisation that the sun significantly influences the earth’s space environment with societal technological implications. Showstack (2012) made mention of how increased solar activity is increasingly affecting technology. He pointed out that the focus of researchers and government agencies should be on how to prevent or mitigate threats to electricity grids, GPS and other potentially vulnerable technological soft spot space weather effects.

## 5.0 CONCLUDING REMARKS

Space science is beneficial for:

- (i) Exploration of the unknown.
- (ii) Expansion of knowledge.
- (iii) Providing a driving force for technological advancement.
- (iv) Development and occupation of new frontiers with access to extra-terrestrial resources and unlimited pd energy.
- (v) Providing opportunity for international cooperation and understanding.

## 6.0 RECOMMENDATIONS

The following are my recommendations:

- (i) Inclusion of space science especially space Physics in the curriculum of undergraduates Physics students.
- (ii) Provision of ionospheric observatories to be equipped with in the six-geopolitical zones of the country.
- (iii) Training of professionals in space science and related fields.

## 6.0 ACKNOWLEDGEMENT

I give all the glory, honour, majesty, dominion and power to the Lord God of Heaven and earth, the creator and the possessor of heaven and earth, the source of knowledge. He is the one that has made this day a reality.

I am grateful for the sacrifice made by my father, Pa Joseph Olufunso Mofoluwaso Somoye who retired from Railways Corporation in 1971 when I was just finishing form one. His gratuity and pension was used to sponsor my secondary school education. He refused the advice given to him that I should be asked to learn “Mechanic”, otherwise I would have ended up in “Fehingbole Grammar School”. When I finished my secondary school education at Offa and was to proceed to the University, it was my mother that gave me ₦50 in 1976. That ₦50, by the exchange rate of today is about ₦25,000 which is LASU’s school fee for a session, actually the money sustained me for one session. God used bursary award by Ogun State tokeep me in school for the remaining sessions. Unfortunately, my mother, Mrs Emily Ayoka Oluwaremilekun Somoye died when I was in final year. Known onto God are the mysteries of death.

I am grateful to Late Professor (Emeritus) Oluwamuyiwa Awe who was my B.Sc, M.Sc and P.hD supervisor at the University of Ibadan. Even after retirement, he continued to correct my write-ups. On

one of such occasions, it was Professor (Mrs) Bolanle Awe that I gave the draft. On giving her the draft, she asked if it was long-hand (i.e. untyped) that I normally submitted. She wondered why her husband was collecting untyped manuscript and going through such pains.

I appreciate my teachers at United Native Authority (UNA) Primary School, Odunfa Street, Ebutte-Metta, Lagos (1964-1967). This is despite the fact that I was not allowed to start school a year earlier because my left hand could not touch my right ear. My teachers at United Missionary Church Authority (UMCA), Jebba, where I completed primary school were so committed to teaching and preparing us for the First Leaving School certificate that I made the school proud by coming first in the Ilorin division of that time. As a result, my school was given 18 desks and 18 benches. I thought that I should have been given scholarship to secondary school.

I cannot forget the efforts of my teachers at Offa Grammar School where Science was made fascinating to me by Mr Adelowo, arguably one of the best principals of that era, and the other teachers. It was also in this school that I received the Lord Jesus Christ into my heart.

I thank Justice B.O. Babalakin for giving me his daughter, a very courageous and kind-hearted woman, Mrs Oyinlola Abosede Somoye, as my wife. Her presence in my life was so wonderful that words cannot express.

My gratitude also goes to all my colleagues in the Faculty of Science. I Three senior colleagues deserve special appreciation as they have been my referees for close to 10 years. Prof. Oyedamola Oke is instrumental to the title of today's inaugural. Just before our interview in April, I asked him to give me some tips on likely questions and one of the tips he gave me was "What could be the title of your inaugural lecture". This really got me thinking and the result is what we are witnessing today. Professor Babajide Elemo believes so much in me. In 2004, when he became the Dean of Faculty of Science, he was told by some people not to make me Acting Head of Department of Physics. My only offence being that I was too rigid and principled. Thank you so much, Sir, for believing in me. The encouragement of Professor Adeleke Adeniyi at a time when research was a little tough remains invaluable.

My colleagues, Prof.Boyo, Drs Ogabi, Idowu, Ogungbe, Adegbola, Messrs Umar, Adewusi, Onori, Adejo, Bamidele, Ahimere, Oguniyi, Amosun, Mrs Ometan, Mrs Olaoye, Mrs Fayemi, Mrs Adesuyi, Mrs Akprese and Mrs Amosun have been wonderful.

The first opportunity I had to supervise Ph. D Physics was when I was made a co-Supervisor of Dr Andrew Ovie-Akala who was a Ph. D candidate in the Department of Physics, University of Lagos. Since then we have published many articles together. May God continue to elevate you, Dr A.O. Akala.

I cannot but appreciate members of our research team, the LASU Ionospheric Research Group (LIRG), most of whom were my M.Sc and Ph.D students (past and present). I appreciate Dr C.O. Ogabi, Dr E.E. Iheonu, Mr R.A. Adeniji-Adele, Mr E.O Onori, Mr T.A. Sode, Mr K.S. Oluyo, Mrs O. Ometan, and Mr A. Ogwala. Mr A. Ogwala helped in typing the draft while Messrs Oluyo and Onori helped with figures and references. May God bless you abundantly. I also appreciate Messrs Ajape, Padonu, Aseja, Olatunde, Karimu,Falowo,Chikeleze and Mrs Akinyelure for being my wonderful student both in LASU and UNILAG.

Prof Wale Okunuga, my “twin” brother (we were the only foundation lecturer of the then Physical and Mathematical Sc. Dept. apart from late Prof F.B.A. Giwa, the foundation Dean) left me here for Unilag. Thank you for your concern about my elevation.

My siblings have stood by me through thick and thin. I appreciate Dr Akintoye Somoye who attended Offa Grammar School about fifteen years before me, Mr Kola Somoye who taught the art of beating drum, Mr Michael Ayotunde Somoye, a very great and courageous brother, Mrs Dorcas T. Opunsunju who with her husband, Mr Goddy Opunsunju hosted me throughout my Ph. D programme, Dr Mrs Esther T. Ojo, my running mate and the last but not the least, my kid brother, Mr Afolabi A. Somoye who shared the same place of birth with me. I thank you all.

I am grateful for the support of all my in-laws, Mrs O. Akinsanya, Dr B.O. Babalakin, Arch. Tayo Babalakin, Dr (Mrs) A. Adewumi, Barr. B. Are, Mama Lucy Ajedegba, Mr. H Ajedegba, Mr John Ajedegba, Mr Matthew Ajedegba, Mr Victor Ajedegba, Mr Johnson Ajedegba, Mrs J. Akukwata, Cornelius, Bartholomew and Peter.

EXCO members of Christian Evangelical Social Movement (CESM) are much appreciated for their prayers. I am grateful to all the members of Chapel of Light (Non Denominational), LASU, especially the Men of Light who prayed for my promotion at our monthly meetings.

I thank old students of Offa Grammar School, Offa who are here. May God honour you all in Jesus name.

One of the persons who joined in praying for me is my friend Dr. Ope Oyedeji who came from South Africa with his wife, Prof. (Mrs) Oyedeji. Dr Ope Oyedeji did not start with praying for my promotion. When I had to wait for 21 months, after submission, before I could defend my Ph. D thesis, we prayed together. It was after he left for South Africa that my “aburo” Dr M.A Akanbi became my prayer partner.

I appreciate my wonderful and great children: Arch. Emmanuel Oluwapelumi Olufemi Somoye (Pearloomi), Mr Nathaniel Fiyinfoluwa Somoye (FANS), Abigail Ifeoluwa Temiloluwa wa Somoye (Somzy Brown), Miss Rachael Boluwatife Somoye (Bolulu) and Master Joel David Oluwaseun Somoye (our small doctor) for their prayers, loyalty and support.

As it is said, what concerns us shall be served last, I want to say that I acknowledge and appreciate the support, love and loyalty of the closest person to me after the trinity – Mrs Glory Oke Somoye, a peace-loving and multi-talented woman. May our glorious God reward your labour of love.

What can I say? Without the University Multimedia Centre led by Dr Bose Amoo, my sister, this evening would not have been worthwhile. Thank you UMC.

## 7.0 REFERENCES

Adeniyi, J. O. (1980), A study of some features of the equatorial ionosphere on magnetically quiet and disturbed days, Ph. D thesis, University of Ibadan, Ibadan, Nigeria.

Adeniyi, J. O., D. Bilitza, S.M. Radicella, and A.A. Willoughby (2003), Equatorial F2 Peak parameter in the IRI model, *Advances in Space Research*, 3: 507 – 512

Ahrens, C. D. (2000), *Meteorology today*, chapter 23. Brooks/Cole, USA

- Awe, O. (1960), Studies of ionospheric irregularities, Ph. D thesis, University of Cambridge, Cambridge.
- Akala A. O., E.O. Oyeyemi, E.O. Somoye, A. B. Adeloye, A. O. Adewale (2010), Variability of foF2 in the African Equatorial Ionosphere , *Advances in Space Research*, 45: 1311 – 1314
- Akala, A. O., Adeloye, A. B. and Somoye, E. O. (2010), Ionospheric F0F2 Variability Over the Southeast Asian Sector, *Journal of Geophysics Research* 115, A09329, doi:10.1029/2010JA15250
- Akala, A. O., E. O. Somoye, A.B. Adeloye, and A.B. Rabiou (2011), Comparison of Diurnal, Seasonal and Latitudinal Effect of MUF Variability and NmF2 Variability during Some Solar Cycle Epochs, *Advance Space Research*, 47: 2182 – 2187
- Akinyelure, M. R., E. O. Somoye, and E. O. Onori (2010), “Seasonal Effect of Noon Burn-Out over a Solar Cycle”, *Nigeria Union of Radio Science (NURS), 2010 Conference Proceeding*: 46 – 50.
- Appleton, E. V. and M. A. F. Barnett (1925), On some direct evidence for downward atmospheric reflection of electric ray, *Proc. Roy. Soc. (London)* A100: 621 – 641.
- Araujo-Pradere, E. A., J.J. Fuller-Rowell, and D. Bilitza (2004), Ionospheric Variability for Quiet and Perturbed Conditions, *Adv. Space Research (UK)*, 34: 1923 – 1921
- Awe, O. (1971), Studies of Nighttime  $E_s$  at Ibadan Near the Magnetic Equator, *Journal of Atmos. Terrestrial Physics* 33: 1209 – 1222.
- Awe, O. (1975), Some Aspects of the behavior of the Nighttime Ionosphere F Layer at Low Latitudes, *Journal of Atmos. Terrestrial Physics* 37: 181 – 183.
- Bilitza, D. (2000), Report from 33<sup>rd</sup> COSPAR Scientific Assembly, Warsaw, Poland, 16 – 23, July 2000, *IRI News Letter*, Volume 7, Nos. 3/4: 1 – 4.
- Bilitza, D. (2001), International Reference Ionosphere 2000, *Radio Science*, 36: 261 – 275.
- Bilitza, D., A.K. Obrou, J.O. Adeniyi, and O. Oladipo (2004), Variability of foF2 in the Equatorial Ionosphere, *Advances in Space Research (UK)*, 34: 1901 – 1906.
- Bilitza, D., M. Sheikh, and R. Eyfrig (1979), A Global Model for the Height of the F-peak Using M3000 Values from CCIR, *Telecom Journal*, 46: 549 – 553.
- Bamgboye, D. K. (1969), Horizontal Ionospheric Drifts in the Neighbourhood Magnetic Equator, Ph. D thesis, University of Ibadan, Ibadan, Nigeria.
- Bowhill, S. A. (1956), The fading of Radio Waves of Frequencies between 16 and 2400kHz, *Journal of Atmosphere Solar Terrestrial Physics*, 8: 129 – 145

- Bradley, P. A. and J.R. Dudeney (1973), A Simple Model of the Vertical Distribution of Electron Concentration in the Ionosphere, *Journal of Atmospheric and Terrestrial Physics* 35: 2131 – 2146.
- Breit, D., and M.A. Tuve (1926), A Radio Method of Estimating the Height of Conducting Layer, *Physics Review*, 28: 254
- Briggs, A. B. and G. J. Philips (1950), A Study of Horizontal Irregularities of the Ionosphere, *Proceedings of Physics Society*, 633 – 907
- Chen, W. S., C.C. Lee, J.Y. Liu, F.D. Chu, and B.W. Reinich (2006), Digisonde Spread F and GPS Phase Fluctuation on the Equatorial Ionosphere during Solar Maximum, *Journal of Geophysics (USA)*, 11, AJ2305, doi:10.1029/2006JA011688
- Chikeleze, P. C., E.O. Somoye, and E.O. Onori (2004), Comparison of the response of NmE and NmF2 to variation in sunspot number at different Latitude, *Nigerian Union of Radio Science (NURS)*: 57 – 64
- Craig, R. A. (1965), *The Upper Atmosphere*, Chapter 9. Academic Press, New York
- Duncan, R. A. (1960), The Equatorial F Region of the Ionosphere, *Journal of Atmospheric and Terrestrial Physics*, 18: 89 – 100.
- de Paula<sup>1</sup>, E.R., E.A. Kherani<sup>1</sup>, M.A. Abdu, I.S. Batista, J.H.A. Sobral, I.J. Kantor, H. Takahashi, L.F.C. de Rezende, M.T.A.H. Muella, F.S. Rodrigues, P.M. Kintner, B.M. Ledvina, C. Mitchel, K.M. Groves (2007), Characteristics of the F region plasma irregularities over Brazilian longitudinal sector, *Indian Journal of Radio and Space Physics*, 36, 268 – 277.
- Eyfrig, R. (1973), *Eine Bemerkung Zur Bradley-Dudeney's Chen Modell Ionosphaere, Kleinheubacher Berichte* 17: 199 – 202.
- Forbes, J. M., S.E. Palo, and X. Zhang (2000), Variability of the Ionosphere, *Journal of Atmospheric and Solar Physics*, 62: 685 – 693.
- Fotiadis, D. N., G.M. Baziakos, and S.S. Kouris (2004), On the global behaviour of day-to-day MUF Variation, *Advances in Space Research*, 33 (6): 893 – 901.
- Friedman, H. (1960), The Sun's Ionizing Radiations, in "Physics of the Upper Atmosphere" (J.A. Ratcliffe, ed.), pp 133 – 208, Academic Press New York.
- Iheonu, E. E. and E.O. Somoye (2013), The relationship between electron density and electron temperature near the magnetic equator", *Journal of Nigeria Association of Mathematical Phys.* 25 (2): 337 – 344.
- ITU, R. (1997), HF propagation prediction method, Recommendation of International Telecommunication Union, Geneva.

Kisons, H. C., J.E. Mazur, R.S. Selesnick, B.J. Fennell, J.L. Roeder, and P.C. Anderson (1999), The Impact of the Space Environment on Space Systems, Rep. Tr-99 (1670) – 1, Aerospace Corporation, El Segundo, USA.

Kolawole, L. B. (1974), Studies of the nighttime E-region of the Ionosphere, Ph.D. Thesis, University of Ibadan, Ibadan, Nigeria.

Marconi, G. (1901), The Story of Ionosphere, Chapter 3, Hulton Educational Publications London.

Mckinnell, L. A. (2012), An Overview of the South African National Space Agency (SANSA), AGU CHAPMAN Conference on Longitudinal Hemispheric Dependence of Space Weather, Addis – Ababa, Ethiopia, 12 – 16 November, 2012.

Meehan, J. and J. Kunches (2012), Workshop Addresses Aviation Communication, Space Weather, 10, S08011, doi: 10.1029/2012SW000828

Moldwin, M. (2012), Book Review: Delores knipp's Understanding Space Weather and the Physics Behind it, Space Weather, 10, S08004 doi:10.1029/2012SW00823.

Obrou, O. K., D. Bilitza, J.O. Adeniyi, and S.M. Radicella, (2003), Equatorial F2 Layer Peak Height and Correlation with Vertical Ion Drift and M(3000), Advance in Space Research, 31: 513 – 520.

Ogabi, C. O. and E.O. Somoye (2001), E-layer at Ibadan – A Chapman Layer, Journal of Res. and Review 2, 48 – 50.

Ogwala, A., E.O. Somoye, E.O. Onori and R.A. Adeniyi-Adele (2015), Characterizing the Maximum Electron Density of the F2 Layer (NmF2) in the Equatorial Ionosphere, Physics Journal, 1 (2): 137 – 152.

Olatunji, E. O. (1996), Ionospheric Diurnal Variation in the F-Layer at Ibadan over a Sunspot Cycle, Journal of Geophysics (Germany), 2 (3): 393 – 395.

Onolaja, G. B. (1977), Studies of Ionospheric Drifts at Ibadan, Ph. D thesis, University of Ibadan, Ibadan, Nigeria.

Onori, E. O., E.O. Somoye, A.S. Ogungbe, and A. Ogwala (2015), Longitudinal Influence of NmF2 Variability on the Equatorial Ionosphere during High Solar Activity, Physics Journal 1 (3): 388 – 392.

Onori, E. O. and E.O. Somoye (2010), Comparison of the Response of E – and F2 Layer to Solar Activity at Ibadan, Nigerian Union of Radio Science (NURS), 2010 Conference Proceedings, 207 – 210.

Oyekola, O. S. and C.O. Oluwafemi (2008), Solar and Geomagnetic Trends of Equatorial Evening and Nighttime F-Layer Vertical Ion Drift, Journal of Geophysics Research (USA) 113: A12318.

Oyekola, O. S., A. Ojo, A. Akinrinmisi, E.R. de Paula (2007), Seasonal and Solar Cycle Variability in F Region Vertical Plasma Drift Over Ouagadougou, Journal of Geophysics Research (USA), A12306, doi:10.1029/2007.

Pedatella, N. M., J.M. Forbes, A. Marte, A.D. Richmond, T.W. Fang, K.M. Lawson, and G. Millward (2011), Longitude Variation in the F-Region Ionosphere and the Topside Ionosphere-Plasma: Observations and Model Simulation, Journal of Geophysics Research, 116, A12309.

Philips, G. J. and M. Spencer (1955), The Effect of Anisometric Amplitude Pattern in the Measurement of Ionospheric Drifts, Proceedings of Physics Society (London), B68: 481 – 492.

Rajaram, G. (1977), Structure of the Equatorial F-Region topside and bottomside: A Review, Journal of Atmospheric and Terrestrial Physics, 39: 1125 – 1144.

Rajaram, G. and R.G. Rastogi (1977), Equatorial electron densities – Seasonal and Solar Cycle Changes, Journal of Atmospheric and Terrestrial Physics, 39: 1175 – 1182

Ratcliffe, J. A. (1979), Sun, Earth and Radio: an Introduction to the Ionosphere and Magnetosphere, World University Library, London.

Rawer, K. and R. Eyfri (2004), Improving the M3000 – hmF2 Relation, Advances in Space Research, 33: 878 – 879.

Rawer, K., S. Kuris, and D.N. Fotiadis (2003), Variability of the F2 Parameter Depending on Modip, Advance Space Research, 31(3): 537 – 541

Rishbeth, H. and M. Meridillo, (2001), Pattern of F2-Layer Variability, Journal of Atmospheric and Terrestrial Physics, 63: 1661 – 1680.

Roltger, J. (1981), Equatorial Spread F by Electric Fields and Atmospheric Gravity Waves Generated by the Thunderstorm, Journal of Atmospheric and Terrestrial Physics (UK), 43: 453 – 462.

Royal Academy of Engineering (2013), Extreme Space Weather Impact on Engineered Systems and Infrastructure, Royal Academic of Engineering, London

Rishbeth, H., and O. Garriot (1969), Introduction to Ionospheric Physics. Academic Press, New York and London.

Schuster, A. (1889), The Diurnal Variation of Terrestrial Magnetism”, Phil, Trans. Roy. Soc, A180: 467 – 518.

Shimazaki, T. (1955), World – Wide daily Variations in the Height of the Maximum Electron Density of the Ionospheric F2 – Layer, Space Radio Research Laboratory 2: 85 – 97.

- Showstoc, R. (2012), Space Weather Forum includes Broad Range of Discussion, Space Weather, 10, S008013, doi: 10.1029/2012SW000845.
- Sode, A. T. and E.O. Somoye (2010), Diurnal and Seasonal Variation of  $N_{MAX}$  (1958 - 1965), Nigerian Union of Radio Science (NURS) Conference Proceedings: 211 – 217
- Somoye, E. O. (2005), Shape and Size of F2 Layer Ionospheric Irregularities at Ibadan, Refreed Conference Proceedings Science Faculty, Lagos State University, Lagos, Nigeria, 4: 112 – 113
- Somoye, E. O. (1996), Some Aspect of the behaviour and Characteristic of Ionospheric Irregularities at Ibadan, University of Ibadan, Ibadan, Nigeria
- Somoye, E. O. (2009a), Comparison of NmF2 Variability at Ibadan, Singapore and Slough during Different Epochs of Solar Cycle, Asian Journal of Scientific Research, 2 (3): 155 – 160.
- Somoye, E. O. (2009b), Comparison of Results of Drift Measurement of E and F region Irregularities at Ibadan, International Journal of Physical Sciences 4 (3): 107 – 110.
- Somoye, E. O. (2009c), Periodicity of Solar Cycle from Diurnal Variation of foF2 at Ibadan, International Journal of Physical Sciences 4 (3): 111 – 114.
- Somoye, E. O. (2010a), Appropriate Film Speed for Ionospheric Fading Records from Winds Equipment, Asian Journal of Scientific Research 3 (1): 31 – 38.
- Somoye, E. O. (2010b), Diurnal and Seasonal Variation of Fading Rate of E- and F- Region Echoes During IGY and IQSY at the Equatorial Station of Ibadan, Indian Journal of Radio and Space Physics, 38: 194 – 202.
- Somoye, E. O. and A.O. Akala (2010), NmF2 Variability at Equatorial and Low Latitude Stations - a review, Research Journal of Physics, 4 (2), 50 – 55.
- Somoye, E. O., A.O. Akala, R.A. Adeniji-Adele, E.E. Iheonu, E.O. Onori, and A. Ogwala, (2012), Solar Cycle and Seasonal Variation of F2 Layer Nighttime/Daytime ionization Ratio at the Equatorial Station of Ibadan, Nigerian Union of Radio Science (NURS) 5<sup>th</sup> Annual Conference Proceeding.
- Somoye, E. O., A.O. Akala, and A. Ogwala (2011), Day-to-day Variability of h'F and foF2 during Some Solar Cycle Epochs, Journal of Atmospheric and Solar Physics, 73 (2011): 1915 – 1922.
- Somoye, E. O., A.O. Akala, R.A. Adeniji-Adele, E.O. Onori, A. Ogwala, and A.O. Karimu (2013), Day to Day Variability of h'E in the Equatorial Ionosphere, Radio Science, 48, doi: 10.1002/rds.20057.

Somoye, E. O., A.O. Akala, R.A. Adeniji-Adele, E.E. Iheonu, E.O. Onori, and A. Ogwala (2013), "Equatorial F2 Characteristics Variability: A Review of Recent Observations", *Advances in Space Research*, 52 (2013): 1261 – 1266.

Somoye, E. O., A.O. Akala, R.A. Adeniji-Adele, E.E. Iheonu, E.O. Onori, and A. Ogwala (2012), "Solar Cycle and Seasonal Variation of F2 Layer Nighttime/Daytime Ionization Ratio at the Equatorial Station of Ibadan, Nigeria Union of Radio Science (NURS), 5<sup>th</sup> Conference Proceedings.

Somoye, E. O., A.O. Akala, A. Ogwala, R.A. Adeniji-Adele, E.E. Iheonu, and E.O. Onori (2014), "Space Science and Astronomy Awareness, Latin American Journal of Physics Education, 8 (2): 374 – 396.

Somoye, E. O., E.O. Onori, and A.O. Akala, (2013), "Comparison of h'E and M(3000)F2 Variability at Ibadan, Singapore and Slough, 92: 18 – 22.

Somoye, E. O., A.T. Sode, and K.S. Oluyo (2011), "The Annual Influence of the Diurnal Variation Nm (1958/1965) against hour at different month, International Journal of Science and Soc, Yabatech, 1 (1): 48 – 56.

Somoye, E.O. (2006), "Impact of Physics On Humanity, In General Studies Book Of Readings: Philosophy of Science and Technology Vol. 3, ed. D.F. Asaju, pp 328-330, Lagos State University Press, Lagos, Nigeria.

Stewart, B. (1882), *Terrestrial Magnetism Encyclopedia Britannica*, London and New York, 9<sup>th</sup> Edition.

Stubb, P. (1968), "Theory of Nighttime F layer, *Journal of Atmospheric and Terrestrial Physics*, 30: 243 – 263.