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Verifying the efficacy of F-region drift perturbation near the magnetic equator at sunrise

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Abstract

The efficacy of electron drift perturbation varying with height according to exponential variation of the form:

$$W=W_0 \exp(-bz)$$

has been verified for conditions at sunrise, applying data derived from ionosonde records at Ibadan, an African equatorial station. Results indicate that equatorial F-region drift stabilization is significantly enhanced if the value of the exponential constant is set at 0.21.

1.0 Introduction

Assessing the framework and concepts of the dynamical processes of the upper atmosphere has remained topical amongst workers across the globe in recent times. Babcock and Evans [1] had carried out a study on the effects of geomagnetic disturbances on neutral winds and temperature in the thermosphere at locations near the mid-latitude. Studies on modelling the low-latitude ionosphere over the Brazilian equatorial region was also reported by Batista el al [2].

Fejer et al [3, 4] presented some of the most comprehensive reports on seasonal, solar cycle and longitudinal effects on quiet time equatorial F- region vertical ion drifts using IDM data from the AE-E satellite. On the other hand, Somoye et al [5] gave a detailed review of the variability of

equatorial/low-latitude F-region characteristics with emphasis on the most general results reported in the literature.

Numerical modelling study of vertical and horizontal drift measurements have however, remained sparse at the African equatorial zone of the ionosphere. In this study, we intend to attempt testing the perturbation pattern of F-region drifts at sunrise, using data derived from the Ibadan (Nigeria) sector of the equatorial ionosphere.

2.0 Some relevant theoretical highlights.

There is abundant evidence of vertical drifts of electrons in the F region heights of the equatorial ionosphere at sunrise and also during the daytime. The electron drifts are generally believed to be upwards during the day and downwards during nighttime. The upward drifts imply that electrons are carried into a region of lower recombination coefficient. If the transport of ionisation is assumed to be due to vertical drift of electrons, then the effect of the transport term on the continuity equation at both sunrise and daytime periods is to cause a decrease in the rate of electron loss.

Drift of electrons which results in the transport of ionisation is caused by three major mechanisms.

(a) plasma diffusion
(b) drag due to neutral atmospheric gas motion
(c) drift motion due to applied electromagnetic action.

Following Ferraro [6], the electron density continuity equation for the case when transport of ionisation is caused by vertical diffusion in the Earth's magnetic field may be written as:

$$\frac{\partial N}{\partial t} = q - \beta N + \frac{b_0 e^z}{n_0 H^2} \sin^2 I \left[\frac{\partial^2 N}{\partial z^2} + \left(1 + \frac{H}{H_{(e)}}\right)\frac{\partial N}{\partial z} + \frac{HN}{H_{(e)}} \right]$$

Corresponding author: ***Ernest Emeagi Iheonu,*** E-mail: eeiheonu@yahoo.com, Tel.: +2348052329349 where $H_{(e)}$ is the scale height of the diffusing plasma and is the same as the electron density scale height, H is that of the ionisable constituent which is regarded as the medium in which the plasma is diffusing, n_0 is the number density of the ionisable constituent at the level of peak production for overhead sun. For a plasma of O$^+$ and electrons diffusing through O atoms, b may be written [6, 7] as:

$$b = 1.71\times10^{17}\,\frac{T^{3/2}}{T+187}$$

where T is the temperature which is assumed uniform everywhere. For an isothermal atmosphere, $H = \frac{1}{2}H_{(e)}$; so that:

$$\frac{\partial N}{\partial t} = q - \beta N + 1.71\times10^{17}\,\frac{T^{3/2}}{T+187}\,\frac{e^z}{n_0 H^2}\sin^2 I\left[\frac{\partial^2 N}{\partial z^2} + \frac{3}{2}\frac{\partial N}{\partial z} + \frac{N}{2}\right]$$

The conditions at Ibadan are however considerably simplified due to the small value of the magnetic dip $(\approx 6.0\ ^0\text{S})$. The diffusion term may be written following Iheonu and Oyekola[8] as:

$$D = d_0 e^z \sin^2 I\left(\frac{\partial^2 N}{\partial z^2} + 3\frac{\partial N}{\partial z} + \frac{N}{2}\right)$$

where the factor $d(z) = d_0 e^z$ is the plasma diffusion coefficient, which increases with the normalised height, z, d_0 is a constant, and I the geomagnetic dip. At low latitudes, vertical plasma diffusion is inhibited by geomagnetic fields; $\frac{\partial N}{\partial z}$ is approximately zero and for a Chapman layer, $\frac{\partial^2 N}{\partial z^2} \approx -\frac{1}{2}N$.

Numerically,sin^2 (I)=0.0076, [8], so that the effect due to the contributions of diffusion is very small, and hence the diffusion term, may be ignored generally, in treating transport of ionisation in the F-region near the magnetic equator.

The continuity equation may also be rewritten with a movement term M equal to the contribution from ambipolar diffusion of the ionisation, for an isothermal atmosphere (neglecting the variation of gravity with height). Thus,

$$\frac{dN}{dt} = q_0\exp(-z/H) - B_0 N_0 \exp(-kz/H)$$

$$+\ D_0\exp(z/H)\frac{d^2N}{dz^2} + \frac{3}{2h}\frac{dN}{dz} + \frac{N}{2H^2}$$

Here, it is assumed that the atmosphere is predominantly composed of an ionisable constituent with scale height H, the ion or electron production rate q and the vertical ambipolar diffusion coefficient D having values q_0 and D_0 at height $z = 0$.

The constant k, representing the rate of decrease with height of the ionisation loss coefficient β, must be greater than unity to give a layer in which the density increases with height from its lower segment. It is therefore probable that this is proportional to the density of some minor molecular constituent of the atmosphere.

3.0 Model fundamentals

Generally, the most fundamental equation for modelling the F-region is the continuity equation for electrons given by:

$$\frac{\partial N\,(h,t)}{\partial t} = q\,(\text{h},\chi) - L(N) - M \qquad (1)$$

where N(h, t) is the electron density at height h and at time t; q(h, x) is the rate of electron production per unit volume and is s function of both height and solar zenith distance x.

The electron production rate is estimated from "Chapman theory" (Chapman, [9, 10]; also Iheonu and Oyekola, [8]); the loss rate, L(N) is a function of electron density.

In an attempt to understand the behaviour of the F-region, it seems reasonable to suppose that the loss term is probably attachment – II type and may be written β(h)N [11], where the loss coefficient β(h) is a function of height but independent of N. The electron rate per unit volume denoted by the symbol M is normally outwards at sunrise.

It should however be pointed out that the transport term is quite a general one, covering the effects of diffusion, ionospheric winds, the change of temperature as well as electrodynamic drift, vertical or horizontal [12, 13].

Recall that primarily, the subject of our concern in this work is vertical electrodynamic forces which create drift irregularities at the F-region of the ionosphere. We thus consider testing an equation describing the existence of a drift velocity whose magnitude is height – dependent according to exponential variation at sunrise.

Basically, the electron density continuity equation expressed by equation (1) above may take the form:

$$\frac{\partial N\,(h,t)}{\partial t} = \mathrm{q}(\mathrm{h}, \chi) - \beta N(h,t) - div\ (Nw) \qquad (2)$$

where div. (Nw) is a function representing electron transport processes, with drift velocity vector. If we limit ourselves to the case of vertical transport, our basic equation (2) becomes

$$\frac{\partial N\,(h,t)}{\partial t} = q\ (h,\chi) - \ \beta N\ (h,t) - \frac{d}{dz}\ (Nw) \qquad (3)$$

where w is the vertical electron velocity and z, is the reduced height in the vertical coordinate. Since the vertical gradients in the electron densities typically exceed the horizontal gradients, the vertical gradient of electron drift is usually not more than 0.05 m/s/km. An estimation of vertical plasma velocity can be made if we assume that at equilibrium,

$$\frac{d}{dz}\,(Nw) \approx \frac{WdN(h,t)}{dz} \approx \frac{WdN(h,t)}{Hp(h)} \qquad (4)$$

where $\mathrm{H_p}$ (h) is the plasma scale height. At sunrise, away from the peak production, the loss and transport terms all tend to be non-negligible and larger than $\frac{\partial N}{\partial t}\ (h,t)$.

The continuity equation (3) after adopting equation (4), in the steady – state case becomes:

$$\frac{WN(h,t)}{H_p(h)} = q\ (h,\chi)\text{-}\ \beta N(h,t) \qquad (5)$$

The simplified vertical electromagnetic plasma drift velocity model, applicable in the vicinity of the geomagnetic equator may take the form:

$$\mathrm{W} = \frac{H_p(H)q(h,x)}{N(h,t)} - \mathrm{Vc} \qquad (6)$$

where Vc = $\mathrm{H_p}$ (h)$\beta(h)$ is the apparent vertical drift due to chemical recombination. The sign convention that could be adopted here is that a positive value of w denotes upward drift, while a negative value denotes downward drift.

Simplified treatment of the electron density continuity equation yields the approximations that ambipolar diffusion can be neglected at low latitudes, since vertical diffusion is inhibited by geomagnetic field.

Furthermore, ambipolar diffusion is much more important at greater heights above 600km height, because of the decrease of collision frequency. The smaller value of the magnetic dip near the magnetic equator also contributes to the neglect of the diffusion term; a factor which is very small in the diffusion formula. It is also assumed that neutral winds are significantly ineffective in producing vertical motion near the equator.

One major factor which cannot be neglected however is that near and/or within the sunrise period, the movement or transport term in the continuity equation must be included in all permutations and analysis. In order to determine the drift velocity w, the continuity equation as indicated above must be re-defined as follows:

$$\mathrm{W} = \frac{H_p}{N(h,t)}\left[\left(\frac{\partial N(h,t)}{\partial t} + \beta N(h,t) - q(h,\chi)\right)\right] \qquad (8)$$

where β is the attachment coefficient of electrons.

A detailed study of the behaviour of F-region drift velocity had been treated to a reasonable extent in earlier studies [8, 14]. In these literatures, it was shown that the simple theory developed by Chapman [9, 10] can be assumed to provide a fairly satisfactory explanation to F-region drift behaviour over time at Ibadan. We extend the solution of equation (8) by verifying the postulation that a vertical drift perturbation of the form:

$$\mathrm{W} = \mathrm{W_o}\ \exp\ (\text{-bz}) \qquad (9)$$

may exist at the equatorial F-region at sunrise.

4.0 Data base

Ground – based ionosonde data acquired at Ibadan have proved extremely useful in the analysis of several studies in the sector, particularly with those dealing with magnetically quiet periods. Except for very few spread – F visibility during sunrise, majority of the analyzed ionograms obtained during this period at Ibadan show distinct and unique features of the ordinary wave traces at different heights for peak electron density values comfortably well defined for theoretical modelling study of this nature.

Theoretical options have been used for several years to estimate drift motion of the ionosphere in the African, Indian and American equatorial sectors (see [2, 8, 15, 16, and 17]) and other references therein.

The maximum electron density, NmF values are derived from values of the mean critical ionosonde records, using the well-known equation of the form:

$$N_mF = 1.24 \times 10^4 (f_0F)^2 \; cm^{-3} \qquad (10)$$

where f_0F is in MHz.

We have adopted the 4-month seasonal groupings similar to those used in earlier studies [8, 17], including the distinctive packaging of solar cycle effects, namely 1958 IGY period (yearly average F10.7cm = 208 in units of 10_{-22} Wm $^{-2}$H., with R_z = 185) – year of high solar activity.

Thus, for mathematical expediency, we adopt values only for a typical period of high solar activity. It is expected that results obtained herein, will be complemented in similar computations for periods of low solar activity.

The Pearson's product moment correlation coefficient relationship is considered to represent a fair assessment index of the vertical electromagnetic drift velocity profiles near the geomagnetic equatorial F-region at sunrise and has been applied in this study.

5.0 Results and discussion

The seasonal dependence of the F-region vertical plasma drifts and fading rates of echoes over some equatorial stations have been discussed in several studies including those in the African equatorial zone, as demonstrated for instance, in the works of Iheonu and Oyekola [8] and Somoye [18]. Most of the studies have confined the scope of studies mainly to daytime analysis in the neighbourhood of 300km altitude.

Nighttime and/or sunrise ionograms make it imperative to take advantage of the distinctive profiles of the F-region at Ibadan for in-depth analysis of the region's behavioural trends, with respect to drift velocities at altitudes near, for instance, 350km. The results may be close to those obtained elsewhere but the modelling content of the deduction of electron velocity near sunrise may naturally provides a new dimension to F-region drift analysis at the equatorial region.

The drift speed models described by equations (8) and (9), have been used inclusively to carry out investigations into the behaviour of the equatorial F region of the ionosphere at sunrise. Equation (8) is a standard continuity equation for electron density while equation (9) is the proposed exponential version on the variability of drift whose magnitude is expected to conform with that expressed by the standard equation.

Figures 1, 2 and 3 represent drifts profiles for June Solstice, Equinox and December Solstice at 350km altitude. It is clearly shown that the drift results obtained using the electron density continuity equation and those estimated applying the model, are closely knit. For instance, at June solstice, near ground sunrise, when $\chi = 90^0$, the mean vertical drift value is approximately 22ms^{-1}, against model estimate of 24ms^{-1}, during the period of high solar activity. Similarly during the equinoctial period (Fig. 2) and December solstice (Fig. 3), the mean vertical drift values are approximately 22ms^{-1} and 24 ms^{-1} against 20ms^{-1} and 23ms^{-1}, respectively.

Although the mean velocity values at $\chi = 95^o$, show some visible disparity between the two equations during the equinoctial period (Fig. 2) namely 28ms^{-1} and 20ms^{-1} respectively, the average speed of 35ms^{-1} for December solstice (Fig. 3) also notwithstanding, the overall mean seasonal drift velocity is in the neighbourhood of 24ms^{-1} for the standard equation and 26ms^{-1} for the model estimates. In these respective seasonal instances, the coefficients of correlation are 0.9979, 0.9884 and 0.9916, thus confirming the close match between the two estimation models.

The model suggested in this report should thus provide a scientific alternative to drifts estimations in the strongly plasma influenced upper atmosphere at the African equatorial sector if basic information on drift values are available at lower ionospheric heights, particularly during sunrise periods and within the vicinity of the magnetic equator

6.0 Conclusion

In this paper, we have tested a model which applicability could provide quick and accurate evaluation of F-region drift estimates (probably at altitudes $\geq$ 350km) above any given threshold value (say 300km), near sunrise.

The model provides an alternative means to effect drift calculations to our advantage at the African sector of the equatorial ionosphere, if a threshold value is known. The use of the proposed model may however be treated with some caution beyond sunrise periods and probably up to 450km altitude at the African equatorial sector. In advanced economies, determination of diurnal and seasonal variations of electron drift velocities from about 300km and above, are feasible using HF radar, rocket probes and satellite-based instruments.

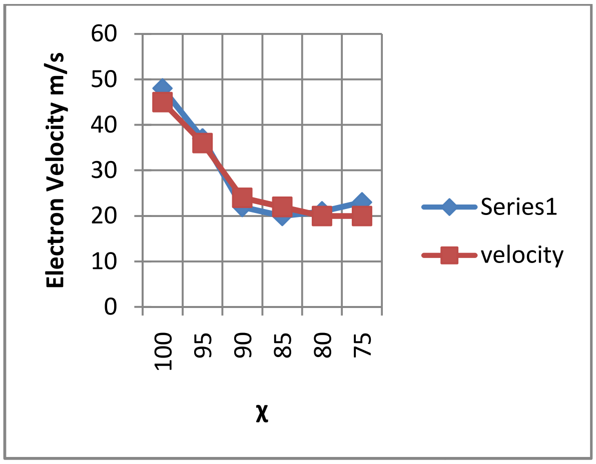

Fig. 1: Mean drift speed at 350km as a function of χ (June Solstice)

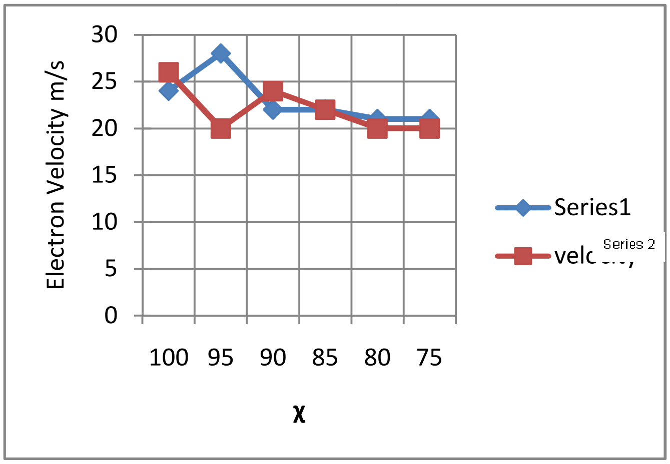

Fig. 2: Same as Figure 1 except for Equinox periods

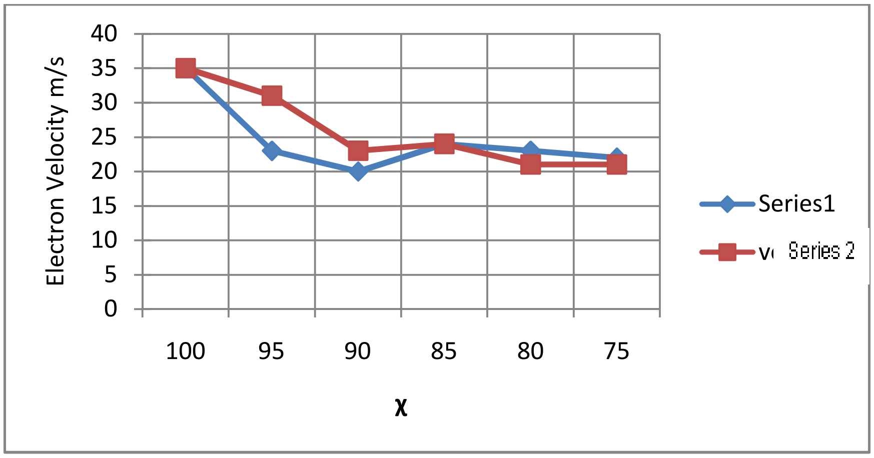

Fig. 3: Same as Figure 1 except for December Solstice Conditions

—◆— (Series 1 = Actual calculation as sunrise)

—■— (Series 2 = Model prediction using b = 0.21

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