# Preliminary Results from 3-D Approach to Ionospheric Conductivities in the Equatorial Region.

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## ABSTRACT

A 3-D approach to ionospheric conductivities in the equatorial region has yielded new results. The hourly variation of horizontal and vertical components of geomagnetic field data of IEEY of the African sector of 1993 was employed. The hourly dip angles derived from electrojet indices were used as input data in the implementation of appropriate program developed to obtain hourly variations of ionospheric conductivities. These new results reveal that the ionosphere is a 3-dimensional structure having real values of vertical ionospheric conductivities, as opposed the usual 2- D approach, which assumed the ionosphere to be a thin layer.

(Keywords: ionosphere, ionospheric conductivities, electrojet, equatorial region, geomagnetic elements)

## INTRODUCTION

Ionospheric conductivities caused by the presence of charged particles in the ionosphere are used in describing the components of current in the ionosphere. This current causes part of the geomagnetic field variations that affect communication, navigational equipment, changes in the environment, and electrical properties of the earth. The ionosphere, as part of the upper atmosphere, is influenced by the earth's magnetic field and over the equatorial region the ionosphere can have far greater impact on the signals (Rycroft, 2005), because the geomagnetic field runs horizontally over the magnetic equator. This effect causes the electrical conductivity to be abnormally large over the equator.

Researchers have consistently continued to work on the conductivity of the ionosphere for the past several years, owing to its great importance to long distance radio communications as well as its intrinsic scientific interest.

Since Balfour Stewart's postulation of the daily oscillations in ground magnetic records originate from dynamo action in the upper atmosphere, the existence of the requisite ionospheric conductivities has been actively researched. Ionospheric research is believed to have started later in 1930 when the first experimental evidence of the E–region of the ionosphere was obtained in India on establishment of an ionospheric radio sounding station at Kodaikanal in 1952 (Chandra, et al., 2000).

Forbes and Lindzen (1976a) used a two–dimensional (2-D) model to calculate the specific equatorial, equinox and average solar conditions. Onwumechili (1992), from the work of Forbes and Lindzen, calculated the appropriate values of ionospheric conductivities at certain altitudes.

Several studies of the ionosphere have always regarded the ionosphere, especially in the equatorial region, as a thin layer. This, in effect, neglects the vertical components of the ionospheric conductivity. In our approach we regard the ionosphere as three-dimensional (3-D) thick layered structure, hence the vertical component of the ionospheric conductivities will not be neglected.

## DATA AND ANALYSIS

The geomagnetic data set used in this study consists of hourly mean values of geomagnetic elements (HDZ) of International Equatorial Electrojet Year (IEEY) record in the West African sub-sector. The data were collected during the intensive, coordinated, and pluridisplinary investigation of ionospheric dynamics in the equatorial region of the African sector (Vassal et al., 1998; Cohen, 1998). The network consists of ten stations which were operated and recorded by ORSTOM geophysical laboratory from November 1992 to November 1994 along a 1200 km long North-South profile across the magnetic equator. The sites are numbered from site 1 (Tombouctou) northward, with approximately 150 km space between sites. The ten stations involved are Tombouctou (TOM), Mopti (MOP), San (SAN), Koutiala (KOU), Sikasso (SIK), Nielle NIE), Korhogo (KOR), Katiola (KAT), Tiebissou (TIE) and Lamto (LAM). They are sites located between Ivory Coast in the south and Mali in the North. Figure 1 shows the geographic location of the stations.

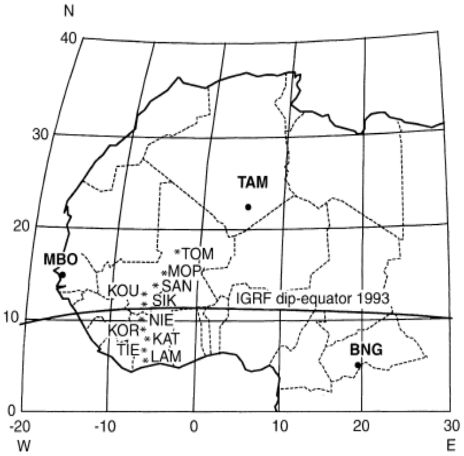

**Figure 1:** Geographic Location of the IEEY Stations and Three Permanent African Magnetic Observatories (Vassal et al., 1998).

Figure 1 also includes stations from three permanent African magnetic observatories: Mbour (MBO), Bangui (BNG) and Tamanrasset (TAM). Although ten stations are available, four of the ten stations were chosen for the purpose of our study and analysis. This is based on the consistency of the recorded data and on the year of interest, 1993. In addition to the four stations a permanent observatory also in the African sector and outside the Equatorial Electrojet (EEJ) influence was chosen. This is to enable us obtain the electrojet indices of the geomagnetic elements since all the stations in the IEEY data are all under the influence of equatorial electrojet.

Table 1 shows the name, code, geographic location, and altitude of the stations that are used in our analysis.

**Table 1:** The Names, Codes, Geographic Location, and Altitude of the IEEY Magnetic Stations.

| S / N | Station | Code | Lat. (N) | Long (E) | Dip Lat. (N) |
|---|---|---|---|---|---|
| 1 | Katiola | KAT | 08.183 | -5.044 | -3.82 |
| 2 | Korhogo | KOR | 09.336 | -5.427 | -2.30 |
| 3 | San | SAN | 13.237 | -4.879 | 2.50 |
| 4 | Mopti | MOP | 14.508 | -4.087 | 4.03 |
| 5 | Tamanrasset | TAM | 22.792 | 5.527 | 12.50 |

The year 1993 is chosen because it has recorded HDZ hourly mean values from January to December.

## DATA SELECTION AND DEDUCTION

The IEEY geomagnetic data is not a continuous dataset as measured values were not reported in all the days of the months nor at all of the stations due to meteorological causes and battery discharges, and the delay to repair technical problems can take up to two months. These factors led to the selection of data. After thorough data inspection of all the months in 1993 and quiet days in the months of the year 1993 based on magnetic activity index, it was observed that the following months, April, June, July, September, October, and November, were available for all the stations of interest already shown in Table 1. These months were also selected to represent different seasons in the year. In our analysis, only international quiet days in a month were considered to ensure absolute quietness of record data.

## BASIC THEORY

The microscopic Ohm's law is given by:

$$\vec{J} = \sigma\vec{E} \qquad \textbf{(1)}$$

where $\vec{J}$ = current density, $\vec{E}$ = electric field vector, and $\sigma$ = medium conductivity.

The flow of current in the ionosphere follows Ohm's Law of Equation 1, but the electric conductivity is anisotropic owing to the effect of geomagnetic field. In this work, we regard the ionosphere as a three dimensional layer with *X* the magnetic south, *Y* the magnetic eas,t and *Z* the upwards with unit vectors, respectively as i, j, and k in each of the axes.

The effective or layer conductivities can be obtained following Onwumechili (1967, 1997). The detail of the development is given in Onwumechili (1997). Taking the magnetic meridian plane with the coordinates *X* and *Y* axes defined above and *Z* upward the electric field vector in an arbitrary direction is written as:

$$\vec{\mathrm{E}} = \vec{\mathrm{E}}_{\mathrm{x}}\mathrm{i} + \vec{\mathrm{E}}_{\mathrm{y}}\mathrm{j} + \vec{\mathrm{E}}_{\mathrm{z}}k \qquad \textbf{(2)}$$

The current density expression is therefore given as:

$$\begin{aligned}\vec{\mathbf{J}} = &\left\{\left(\sigma_{\mathbf{o}}A^2 + \sigma_1 B^2\right)\mathrm{E}_{\mathrm{x}} + \sigma_2 B\mathrm{E}_{\mathrm{y}} + (\sigma_o - \sigma_1)AB\mathrm{E}_{\mathrm{z}}\right\}\mathbf{i} + \left\{-\sigma_2 B\mathrm{E}_{\mathrm{x}} + \sigma_1\mathrm{E}_{\mathrm{y}} + \sigma_2 A\mathrm{E}_{\mathrm{z}}\right\}\mathbf{j} \\ &+ \left\{(\sigma_o - \sigma_1)AB\mathrm{E}_{\mathrm{x}} - \sigma_2 A\mathrm{E}_{\mathrm{y}} + \left(\sigma_o B^2 + \sigma_1 A^2\right)\mathrm{E}_{\mathrm{z}}\right\}\mathbf{k}\end{aligned} \qquad \textbf{(3)}$$

It has been observed from the literature that the ionosphere has been regarded as a thin layer by several authors (Baker and Martyn, 1953; Ownumehili, 1997) and as such, a two dimensional model which neglected the vertical component of current density has been employed in determining ionospheric conductivity. This, in turn, leaves some gaps in understanding the ionosphere, hence our consideration of 3-dimensional model in which case the vertical component of the current density is not neglected so as to completely describe the various ionospheric conductivities.

## 2-Dimensional Approach

In two dimensions, the conductivity components are

$$\sigma_{xx} = \sigma_o\sigma_1 / (\sigma_o \sin^2 I + \sigma_1 \cos^2 I)$$

$$\sigma_{xy} = \sigma_o\sigma_2 \sin I / (\sigma_o \sin^2 I + \sigma_1 \cos^2 I) = -\sigma_{yx}$$

$$\sigma_{yy} = \frac{\{\sigma_o\sigma_1 \sin^2 I + (\sigma_1^2 + \sigma_2^2)\cos^2 I\}}{(\sigma_o \sin^2 I + \sigma_1 \cos^2 I)}$$

## 3-Dimensional Approach

In this study, no restrictions of the vertical current density flow were made hence the conductivity in 3-dimensions are:

$$\sigma_{xx} = \sigma_o Cos^2 I + \sigma_1 Sin^2 I$$

$$\sigma_{yy} = \sigma_1$$

$$\sigma_{xy} = -\sigma_{yx} = \sigma_2 SinI$$

$$\sigma_{yz} = -\sigma_{zy} = \sigma_2 CosI$$

$$\sigma_{xz} = \sigma_{zx} = (\sigma_o - \sigma_1) CosISinI$$

$$\sigma_{zz} = \sigma_o Sin^2 I + \sigma_1 Cos^2 I$$

The conductivity components in addition to the specific conductivities show that ionospheric conductivities are function of dip angle, ***I***.

## METHOD OF ANALYSIS

Hourly magnetic dip angle variations were calculated from the hourly variation of Z and H components of the magnetic field and set of four simultaneous hourly variations of the dip angles were obtained at every hour in the four equatorial electroject stations.

These values of ***I*** were substituted into model equation of the form: f(x) = 0 to yield a set of four non-linear simultaneous equations were underdetermined. A software implementation of Mathlab® optimization techniques for solving non-linear optimization algorithm was used. This technique is an advanced, but most widely used method for solving non-linear optimization algorithm.

## ANALYSIS AND DISCUSSION OF RESULT

Owing to the complex nature of the ionosphere, the ionosphere has been regarded as a horizontally stratified layer in two dimensions usually referred as the thin shell model (Baker and Martyn, 1953; Ownumehili, 1997; Tsunomura, 1999).

In our approach we regard the ionosphere as a simple model structure in three dimensions in which the vertical ionospheric conductivity $\sigma_{zz}$ and its related components $\sigma_{xz}$ and $\sigma_{yz}$ were considered. The results of the three-dimensional consideration of the ionosphere are given in Table 2 as sample result.

It is strikingly interesting to observe that the results of Table 2 show real values of all the tensor elements that describe the ionospheric conductivities in three dimensions. It, therefore, proves that ionospheric conductivities are in three-dimensions - a new result. The results in Table 2 also show that the values of ionospheric conductivities are high during the daytime hours and low during night-time hours. This result now stands to agree and be the practical proof of the theoretical assumption made by Yagova, et al. (1999) that ionospheric conductivities are high in the daytime hours and low at night-time hours.

The fact that ionospheric conductivities are high during the daytime as observed in Table 2 signifies high electro-dynamic interactions in the ionosphere and can lead to various and complex phenomena in the ionosphere such as ionospheric instabilities. It may be that the high ionospheric conductivities are as a result of the high solar activity during the daytime hours. This result supports the results of Fujii et al. (1981), Fujii and Iijima (1987), Ohtani et al. (2000, 2005), Christiansen et al (2002) and Haraguchi et al. (2004) that solar illumination contributes much more to high daytime values of ionospheric conductivities.

**Table 2:** Conductivity Tensors in Units of ($Sm^{-1}$) in October, 1993.

| Time (Hours) | $\sigma_{xx}$ | $\sigma_{yy}$ | $\sigma_{zz}$ | $\sigma_{xy}$ | $\sigma_{yz}$ | $\sigma_{XZ} = \sigma_{ZX}$ | $\sigma_o$ | $\sigma_2$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.003005 | 0.00000084 | 0.000351 | 0.0000010 | 0.0000048 | 0.000523 | 0.003351 | 0.00000520 |
| 2 | 0.003283 | 0.00000085 | 9.19E-05 | 0.0000007 | 0.0000050 | 0.000418 | 3.37E-03 | 0.00000522 |
| 3 | 0.002321 | 0.00000087 | 0.001157 | 0.0000024 | 0.0000036 | 0.000675 | 0.003475 | 0.00000526 |
| 4 | 0.002336 | 0.00000093 | 0.001462 | 0.0000030 | 0.0000040 | 0.00147 | 0.003805 | 0.00000538 |
| 5 | 0.004208 | 0.00000109 | 0.000477 | 0.0000016 | 0.0000052 | 0.001225 | 0.004719 | 0.00000565 |
| 6 | 0.007429 | 0.00000151 | 0.000341 | 0.0000010 | 0.0000063 | 0.001182 | 0.007315 | 0.00000620 |
| 7 | 0.133052 | 0.00003028 | 0.017458 | 0.0000220 | 0.0000626 | 0.04567 | 0.160584 | 0.00006815 |
| 8 | 0.136987 | 0.00009009 | 0.248838 | 0.0001449 | 0.0001035 | 0.096592 | 0.380744 | 0.00020823 |
| 9 | 0.288875 | 0.00012584 | 0.206277 | 0.0001672 | 0.0002116 | 0.11831 | 0.485954 | 0.00032037 |
| 10 | 0.229655 | 0.00014606 | 0.313751 | 0.0002822 | 0.0002351 | 0.216087 | 0.53784 | 0.00039910 |
| 11 | 0.190425 | 0.00016209 | 0.385911 | 0.0003504 | 0.0002337 | 0.234518 | 0.579222 | 0.00045130 |
| 12 | 0.148232 | 0.00017196 | 0.449428 | 0.0003969 | 0.0001980 | 0.202704 | 0.601769 | 0.00048078 |
| 13 | 0.191339 | 0.00017423 | 0.406838 | 0.0003810 | 0.0002436 | 0.235852 | 0.602677 | 0.00048763 |
| 14 | 0.471081 | 0.00016868 | 0.107208 | 0.0001718 | 0.0004071 | 0.186263 | 0.582157 | 0.00047175 |
| 15 | 0.328135 | 0.00015469 | 0.205499 | 0.0002098 | 0.0003083 | 0.154474 | 0.5375 | 0.00043176 |
| 16 | 0.325937 | 0.00013189 | 0.150976 | 0.0001818 | 0.0002914 | 0.190487 | 0.466881 | 0.00036436 |
| 17 | 0.29769 | 0.00009953 | 0.078022 | 0.0000949 | 0.0002285 | 0.118177 | 0.366056 | 0.00026247 |
| 18 | 0.169721 | 0.00005306 | 0.047912 | 0.0000525 | 0.0001201 | 0.070055 | 0.211494 | 0.00013862 |
| 19 | 0.030741 | 0.00000640 | 0.000574 | 0.0000025 | 0.0000210 | 0.003654 | 0.029379 | 0.00002061 |
| 20 | 0.00495 | 0.00000127 | 0.000541 | 0.0000015 | 0.0000054 | 0.001288 | 0.005554 | 0.00000592 |
| 21 | 0.002714 | 0.00000100 | 0.001385 | 0.0000027 | 0.0000041 | 0.00121 | 0.00412 | 0.00000551 |
| 22 | 0.002808 | 0.00000090 | 0.000817 | 0.0000022 | 0.0000045 | 0.001223 | 0.003632 | 0.00000532 |
| 23 | 0.002529 | 0.00000086 | 0.000929 | 0.0000019 | 0.0000040 | 0.000641 | 0.00346 | 0.00000524 |
| 24 | 0.003035 | 0.00000084 | 0.000354 | 0.0000010 | 0.0000048 | 0.000528 | 0.003388 | 0.00000521 |

It has been reported that increases in electron content (Ratcliffe, 1972) in the equator cause wind in the neutral air to blow from the poles toward the equator so as to move ionization upwards. Since the ionospheric conductivities are in three-dimensions it is expected that ionization must move upwards. From our result (Table 2) it is obvious that equatorial ionosphere is in three-dimensions and has vertical ionospheric conductivities. Due to this vertical ionospheric conductivity there is an associated vertical current flow, hence, it is erroneous to assume that the ionosphere is only two-dimensional.

To substantiate this fact we compared the values of two- dimensional ionospheric conductivities ($\sigma_{xx} = 4.08 \times 10^{-3}$ $Sm^{-1}$, $\sigma_{yy} = 6.00 \times 10^{-5}$ $Sm^{-1}$, $\sigma_{xy} = 1.20 \times 10^{-5}$ $Sm^{-1}$) to that due to three-dimensions($\sigma_{xx} = 2.03 \times 10^{-1}$ $Sm^{-1}$, $\sigma_{yy} = 5.92 \times 10^{-5}$ $Sm^{-1}$, $\sigma_{zz} = 1.48 \times 10^{-2}$ $Sm^{-1}$, $\sigma_{xy} = 1.80 \times 10^{-5}$ $Sm^{-1}$, $\sigma_{yz} = 2.43 \times 10^{-4}$ $Sm^{-1}$, $\sigma_{xz} = 7.64 \times 10^{-3}$ $Sm^{-1}$) and observed that the two-dimensional ionospheric conductivities is less than the three-dimensional ionospheric conductivity values. Following this observation it may be seen that the influence of the vertical ionospheric conductivities is a contributor to the cause of damage to communication systems above and below ionospheric regions. For these reasons ionospheric warnings systems can be built and predictions of its effect can be useful.

It is evident from Table 2 that the components of vertical conductivity, as obtained in the three-dimensional ionosphere, have reasonable values. Based on this result the vertical components of current density should not be assumed to be zero, as most previous researchers have assumed. This result negates the idea of several authors (Baker and Martyn, 1953; Tsunomura, 1999) that there is zero or a negligible vertical component of current density in determining ionospheric conductivity. We therefore suggest that results from these previous workers be re-visited so as to account for the vertical ionospheric conductivities arising from the consideration of three-dimensional ionosphere.

It is evident from our results that there is a high value of daytime ionospheric conductivities. This high value of ionospheric conductivities corresponds to high electron density. It is known that current flow is associated with conductivity and the action of solar activity on electrons in the equatorial region causes a corresponding effect of the ionospheric region being highly conductive. These ionospheric conductivities then cause the flow of ionospheric current which in turn cause magnetic disturbances that can be measured by magnetometers on the ground. The dangerous effect of the high ionospheric currents is the damage caused to communication and navigational systems, changes occurring during ionospheric storm, ion composition changes and space weather effects on telecommunication systems.

## CONCLUSIONS

Many studies of ionospheric conductivity analysis have been based on a 2-D approach. Occasionally, these conductivities are studied at a particular hour of the day, at noon, and zero hour time. A good reference is that of Maeda and Matsumoto (1962), Forbes and Lindzen (1976), and Onwumechili (1997). All of these studies have been based on the assumption of 2-D ionosphere considering the vertical current to be zero. On the contrary, our findings from this work have disproved this, we therefore conclude the following:

- The ionosphere should be regarded as a 3-dimensional structure of real physical dynamic system.
- This three-dimensional structure of the ionosphere reveals that vertical ionospheric conductivity component can be determined by a simple modeling process.
- The existence of these vertical ionospheric components disproves that there is no vertical ionospheric current based on the assumption of two-dimensional ionosphere. This suggests that prediction of solar and ionospheric events might have been erroneously predicted, because of the improper account of the vertical ionospheric conductivity component whose contribution to 3-D ionospheric current density is much greater than to 2-D ionospheric current density.

It is strikingly obvious that besides the contributions from the 2-D ionosphere, the thick ionosphere is equally subjected to effective contribution from the 3-D ionosphere. Hence, the modification of the model 2-D ionosphere to 3-D ionosphere has a direct effect on the plasma density, plasma irregularities, and dynamic processes in the ionosphere. A detailed and further understanding of this modification will yield a better understanding of interactions between geomagnetism and the ionosphere, and hence will enhance understanding of complex phenomenon. The contributions due to 3-D ionosphere can never be neglected, if a more robust result is be expected. As the electron density maximum, enhancement of Sq(H) equinoctial maxima, etc., all are attributed to large Hall polarization and hence large Cowling conductivity even at equatorial region, the consideration of 3-D ionosphere becomes very crucial and pertinent.

We therefore, suggest that, all future works and research place a 3-D approach into consideration for more robust results.

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