Modelling the Diurnal Electron Density Variation over the Equatorial region

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Abstract - **The ionosphere is a region at the atmosphere that contains high concentration of free electrons which is termed as electron density (*Ne*). In this work, the *Ne* was modelled for latitude from 0 to 50° and longitude from 100 to 120°, and the *Ne* was obtained from International Reference Ionosphere (IRI). IRI is the international standard for the climatologically specification of ionospheric parameters. Altitude of 350km was chosen to do this modelling as this has been presumed as the altitude where the content of the *Ne* is maximum over the equatorial region. The *Ne* was taken at four different local times (LT). They are 8.00am, 1.30pm, 6.30pm and 11.30pm from 1st June 2009 to 7th June 2009. This *Ne* values were modelled in 2 dimensions (latitude and longitude) using Table Curve 3D (TC3D). TC3D is software that can generate a mathematical equation for given latitude, longitude and *Ne*. Then, the *Ne* from IRI will be compared with TC3D and from MATLAB. However, due the variation in the solar activity, it is very hard to obtain the same mathematical model for the ionospheric formation at different time of a day and on different days.**

Index Terms - **IRI, Ne, latitude, longitude, ionosphere modelling, diurnal variation**

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I. INTRODUCTION

The Earth's atmosphere is a thin layer of gases that surrounds the Earth. The present composition of the atmosphere is 79% nitrogen, 20% oxygen, and 1% other gases such as argon and carbon dioxide. This thin gaseous layer insulates the Earth from extreme temperatures; keeps heat inside the atmosphere and also blocks the Earth from the Sun's incoming ultraviolet radiation. The atmosphere of the Earth may be divided into several distinct layers, as shown Figure 1. The ionosphere contains up to four layers of free electrons, which is found from the altitude of about 60km to about 700km [1], making long-distance radio communication possible.
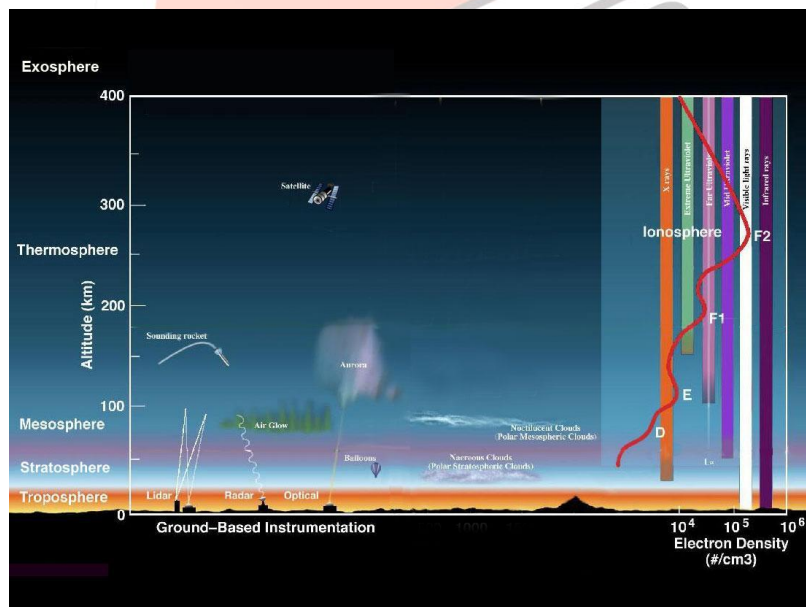

Figure 1 Earth's atmosphere Layer [2]

Ionosphere was formed when extreme ultraviolet (EUV) light from the Sun; strips the electrons from the neutral atoms of the Earth atmosphere. When EUV light that is photon hits a neutral atom such as oxygen atom, its energy it is transferred to an electron in the neutral atom that can then escape from the atom and dart freely around [3]. This neutral atom becomes positively ion because it has lost a negative charged electron and is known as positive ion. The rate at which ionization occurs depends on the density of atoms in the atmosphere and the intensity of the EUV, which varies with the activity of the Sun. The density of the

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ionized layer depends on the elevation angle of the Sun, known as the zenith angle. Since the zenith angle changes continuously, the height and thickness of the ionized layers vary depending on the time of the day and season of the year. Recombination is the reverse of photoionization [4].

During late afternoon and early evening hours, the rate of recombination exceeds the rate of ionization. Due to this, the density of the ionized layers normally begins to decrease in the D, E and F_1 layers at this time. However, the F_2 layer behaves differently. The electron density in the F_2 layer reaches its lowest value just before dawn. Then, once the Sun rises, photoionization takes place which causes the content of electron density to increase again in the F_2 layer. That is the reason the ionosphere can still be used at night time for HF or ionospheric reflected radio wave propagation. Other than recombination, the protonosphere also plays a role here where the protonosphere acts like a reservoir as there is no plasma production in the protonosphere [5]. It takes plasma from the ionosphere by day, stores it in a loss-free environment and returns it to the ionosphere at night, which helps to maintain the night time F layer.

In general, the electron density in ionosphere is greatest in summer, in the middle of day, and near the equator. The equatorial region is more or less the same as the mid-latitude F layer, which have 2 higher critical frequencies. It is because the Sun is more directly overhead [4]. The season between summer and winter are not much different. The ionosphere also varies with significantly with solar activity, the amount of EUV radiation from the sun waxes and waves every 11 years or so. The word 'diurnal' simply means 'throughout the day'. The diurnal variations of f_oE and f_oF_1 are more or less what we would expect, the critical frequencies reaching their greatest values at noon. The diurnal variation of f_oF_2 is often rather complicated makes the F_2 layer the most important layer as far as HF communications are concerned [4]. The UV radiation from the Sun is influenced by the number of *sunspots* on the Sun's "surface", which shows a cycle of about 11 years (see Figure 2).
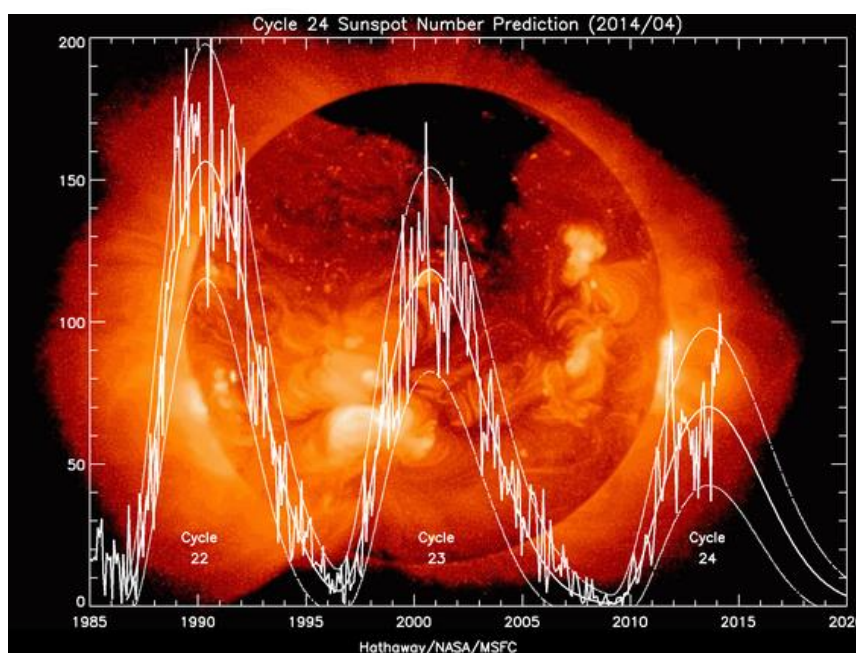

Figure 2 Cycle 24 Sunspot Number Prediction [6]

The sunspot number clearly goes up and down every 11 years or so, it has a cycle of about 11 years. Virtually everything associated with the sun of relevance to the ionosphere occurs with an approximately 11 year cycle, hence the name solar cycle. The previous solar cycle (solar cycle 23) starts in about 1998 and ends in 2009. So, that is why 2009 has the lowest solar cycle. Currently, we are in a solar maximum period (year 2014). According to NOAA and NASA, the sunspot cycle hit an unusually deep bottom from 2007 to 2009. In fact, in 2008 and 2009, there were almost no sunspots, a very unusual situation that had not happened for almost a century [7]. The sunspot number is used as a parameter to compare the values of critical frequency at high sunspot and low sunspot numbers for the day. Although sunspots themselves produce only minor effects on solar emissions, the magnetic activity that accompanies the sunspots can produce dramatic changes in the ultraviolet and soft x-ray emission levels [8]. Solar variation causes changes in space weather and to some degree weather and climate and have important consequences for the Earth's upper atmosphere on Earth. It causes a periodic change in the amount of irradiation from the Sun that is experienced on Earth. The years of high solar activities correspond to high electron density, while the years of low solar activities are also years of low electron density [9].

The equator is the intersection of the Earth's surface with the plan perpendicular to the Earth's surface axis of rotation and containing the center of mass. The equatorial regions are the geographic region of the Earth centered on the Equator (0˚ latitude).
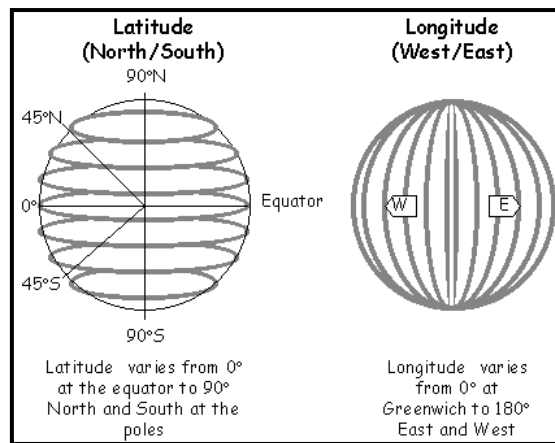
Figure 3 Latitude, longitude and equator lines [10]

Latitude lines are lines which run east-west on the globe. Lines of latitude are measured in degrees north (N) or south (S) of the Equator, 0° latitude. Latitude measurements can only go from 0° to 90° [11]. Longitude lines are lines which run North-South on the globe. These lines all converge and meet at the North and South Poles. Because of this convergence the distance from one line of longitude to the next is not constant. As one moves towards the poles from the equator the East-West distance between lines decreases. Line of longitude is measured in degrees east (E) or west (W) of the Prime Meridian. Half way around the globe from the Prime Meridian is 180°. Longitude measurements can only go from 0° to 180° [11].

II. METHODOLOGY

In this part, the methods of project implementation, including the description and software development, has been given. As for the software, International Reference Ionosphere [12] is used to obtain *Ne*, and TC3D for calculation and viewing the 3D graph.

The International Reference Ionosphere (IRI) is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). IRI is updated yearly. For a given location, time and date, IRI describes the electron density, electron temperature, ion temperature, and ion composition in the altitude range from about 50 km to about 2000 km, and also the electron content. This model is an accurate in describing the variations of the electron density from bottom of the ionosphere to the altitude of maximum density than in describing the total electron content (TEC) [12].

Table Curve 3D gives scientists and engineers the knowledge to find the ideal model for even the most complex data including equations that might never have been considered. In addition to standard least squares minimization, Table Curve 3D's nonlinear engine is capable of three different robust estimations: least absolute deviation, Lorentzian minimization and Pearson VII Limit minimization. On systems that support multi-threading, Table Curve 3D's Background Thread processing option allows fitting to occur without any form of user input [13].

The plots from TC3D show that the software does give a very good fitting to the given input data. In this context, the input data is the *Ne* taken from IRI. The accuracy of the fitting can be defined by parameters like r^2 (coefficient of determination) and SSE (sum of squared errors). These two values need to be adjusted to get better fitting.

For this work, assume the input data are x, y and z and they represent the values of longitude, latitude and electron density respectively, where the values of *Ne* are taken from IRI. By using an excel document, these values can be imported into the T3CD software. Once this has been done, TC3D will determine an equation that can best represent the given input data. In this work, the form of an equation that can consists of only sine and cosine terms or their combinations was used to model the electron density. The sine and cosine functions are primarily chosen because (like the exponential) their derivatives are always continuous. This is in line with the requirement by the numerical ray tracing program where the electron density equation and its spatial derivatives must be continuous with respect to altitude, latitude and longitude.

III. RESULTS AND DISCUSSIONS

A. Validation of the *Ne* Model from IRI and TC3D using Matlab

Comparison plots presented in Figure 4 and 5 show that the equation number 539 can fit well the input data that was taken from IRI. It shows the plots on 1st June 2009 at 8am LT.
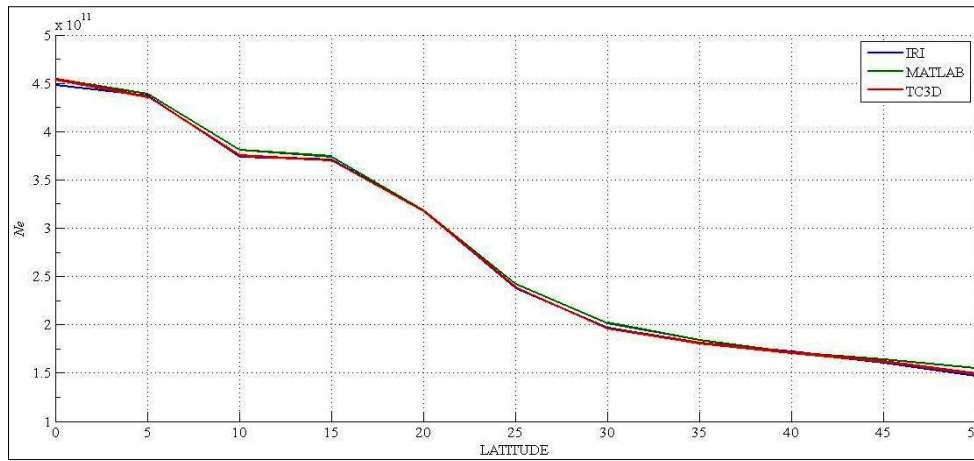
Figure 4 The fitted values (from equation 539) and the values of the *Ne* from IRI at longitude of 100° and for the region of latitude from 0 to 50°
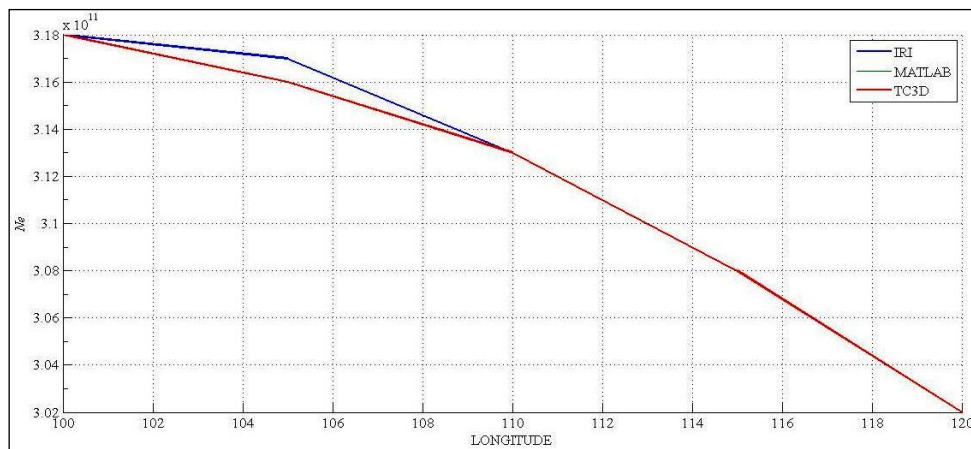

Figure 5 The fitted values (from equation 539) and the values of the *Ne* from IRI at latitude of 20° and for the region of longitude from 100 to 120°

As can be seen above, IRI refers to the predicted variation of *Ne* from IRI website. TC3D is the value of *Ne* that is given by the software being known as the predicted value while Matlab is the value of *Ne* when the equation is implemented using Matlab.

$$Z(x,y) = (a)+(b*\cos(X))+(c*\cos(Y))+(d*\cos(2*X))+(e*\cos(X)*\cos(Y))+(f*\cos(2*Y))+(g*\cos(3*X))+(h*\cos(2*X)*\cos(Y))+$$
$$(i*\cos(X)*\cos(2*Y))+(j*\cos(3*Y))+(k*\cos(4*X))+(l*\cos(3*X)*\cos(Y))+(m*\cos(2*X)*\cos(2*Y))+(n*\cos(X)*\cos(3*Y))$$
$$+(o*\cos(4*Y))+(p*\cos(5*X))+(q*\cos(4*X)*\cos(Y))+(r*\cos(3*X)*\cos(2*Y))+(s*\cos(2*X)*\cos(3*Y))+(t*\cos(X)*\cos(4*Y))+(u*\cos(5*Y))+(v*\cos(6*X))+(aa*\cos(5*X)*\cos(Y))+(ab*\cos(4*X)*\cos(2*Y))+(ac*\cos(3*X)*\cos(3*Y))+(ad*\cos(2*X)*\cos(4*Y))+(ae*\cos(X))+(\cos(5*Y))+(af*\cos(6*Y))+(ag*\cos(7*X))+(ah*\cos(6*X)*\cos(Y))+(ai*\cos(5*X)*\cos(2*Y))+(aj*\cos(4*X)*\cos(3*Y))+(ak*\cos(3*X)*\cos(4*Y))+(al*\cos(2*X)*\cos(5*Y))+(am*\cos(X)*\cos(6*Y))+(an*\cos(7*Y))+(ao*\cos(8*X))+(ap*\cos(7*X)*\cos(Y))+(aq*\cos(6*X)*\cos(2*Y))+(ar*\cos(5*X)*\cos(3*Y))+(as*\cos(4*X)*\cos(4*Y))+(at*\cos(3*X)*\cos(5*Y))+(au*\cos(2*X)*\cos(6*Y))+(av*\cos(X)*\cos(7*Y))+(ba*\cos(8*Y))+(bb*\cos(9*X))+(bc*\cos(8*X)*\cos(Y))+(bd*\cos(7*X)*\cos(2*Y))+(be*\cos(6*X)*\cos(3*Y))+(bf*\cos(5*X)*\cos(4*Y))+(bg*\cos(4*X)*\cos(5*Y))+(bh*\cos(3*X)*\cos(6*Y))+(bi*\cos(2*X)*\cos(7*Y))+(bj*\cos(X)*\cos(8*Y))+(bk*\cos(9*Y))+(bl*\cos(10*X))+(bm*\cos(9*X)*\cos(Y))+(bn*\cos(8*X)*\cos(2*Y))+(bo*\cos(7*X)*\cos(3*Y))+(bp*\cos(6*X)*\cos(4*Y))+(bq*\cos(5*X)*\cos(5*Y))+(br*\cos(4*X)*\cos(6*Y))+(bs*\cos(3*X)*\cos(7*Y))+(bt*\cos(2*X)*\cos(8*Y))+(bu*\cos(X)*\cos(9*Y))+(bv*\cos(10*Y))$$

where;
a,b,c…..bq are the value of parameters which are obtained from 3D curve fitting software.
X, Y = scaled 0 to π (180º).

In this task, the equation above show that Cosine Series Bivariate Polynomials is the best equation compared to all another equation (the equation with first rank). The accuracy of the mesh plot can be defined by parameters like r^2 (coefficient of determination) which it have to be approach 1 (100%) and the SSE (Sum of Squared Errors) will approach 0 for all the plots that were done. Approaching these figures will signify the best fitting.

The TC3D will use the given x (longitude), y (latitude) and z (*Ne*) values to 'calculate' another set of z (*Ne*) values; called the predicted z (*Ne*) value. These predicted z values together with the x and y values will be used to find an equation. The calculations can be done in Matlab by manipulating the equation in Matlab to confirm that TC3D does give a very precise equation with only small residuals, when this depends on the input data compared with the original data (from IRI).

The z value (represent the *Ne*) from the equation above must be same or near the all value in z-parameters. It shows exactly the value of parameter are correct with the numerical mathematical model. It can be proven when the new calculation will be made in MATLAB with the certain scaled. From Table 1, it shows quite different *Ne* between Table Curve 3D compared to MATLAB. In another scaled, the value of z parameter is not far from the original electron density in Table Curve 3D. In MATLAB, all the scaled should be used in radian that make a more decimal point value.

Table 1 The comparison value of electron density, *Ne* from IRI, TC3D and MATLAB

X		Y		*Ne*		
longitude	scaled	latitude	scaled	IRI	MATLAB	TC3D
100	0	0	0	4.48E+11	4.54E+11	4.54E+11
100	0	10	$\pi/5$	3.74E+11	3.81E+11	3.75E+11
100	0	20	$4\pi/10$	3.18E+11	3.18E+11	3.18E+11
100	0	30	$6\pi/10$	1.97E+11	2.02E+11	1.96E+11
100	0	40	$8\pi/10$	1.72E+11	1.71E+11	1.71E+11
100	0	50	Π	1.47E+11	1.55E+11	1.49E+11
105	$\pi/4$	0	0	4.37E+11	4.44E+11	4.44E+11
105	$\pi/4$	10	$\pi/5$	3.73E+11	3.78E+11	3.73E+11
105	$\pi/4$	20	$4\pi/10$	3.17E+11	3.16E+11	3.16E+11
105	$\pi/4$	30	$6\pi/10$	1.95E+11	1.99E+11	1.94E+11
105	$\pi/4$	40	$8\pi/10$	1.67E+11	1.66E+11	1.67E+11
105	$\pi/4$	50	Π	1.44E+11	1.49E+11	1.45E+11
110	$\pi/2$	0	0	4.24E+11	4.31E+11	4.31E+11
110	$\pi/2$	10	$\pi/5$	3.72E+11	3.72E+11	3.72E+11
110	$\pi/2$	20	$4\pi/10$	3.13E+11	3.13E+11	3.13E+11
110	$\pi/2$	30	$6\pi/10$	1.93E+11	1.92E+11	1.92E+11
110	$\pi/2$	40	$8\pi/10$	1.63E+11	1.62E+11	1.62E+11
110	$\pi/2$	50	Π	1.40E+11	1.41E+11	1.41E+11
115	$3\pi/4$	0	0	4.10E+11	4.16E+11	4.16E+11
115	$3\pi/4$	10	$\pi/5$	3.70E+11	3.65E+11	3.70E+11
115	$3\pi/4$	20	$4\pi/10$	3.08E+11	3.08E+11	3.08E+11
115	$3\pi/4$	30	$6\pi/10$	1.91E+11	1.85E+11	1.90E+11
115	$3\pi/4$	40	$8\pi/10$	1.58E+11	1.57E+11	1.57E+11
115	$3\pi/4$	50	Π	1.36E+11	1.32E+11	1.37E+11
120	π	0	0	3.92E+11	4.01E+11	4.01E+11
120	π	10	$\pi/5$	3.66E+11	3.59E+11	3.66E+11
120	π	20	$4\pi/10$	3.02E+11	3.02E+11	3.02E+11
120	π	30	$6\pi/10$	1.90E+11	1.82E+11	1.89E+11
120	π	40	$8\pi/10$	1.54E+11	1.52E+11	1.53E+11
120	π	50	Π	1.32E+11	1.26E+11	1.33E+11

B. Modelling the Diurnal Variation of Ionosphere in Longitude and Latitude over the Equatorial Region

Altitude of 350km was chosen to do this modelling as this has been presumed as the altitude where the content of the *Ne* is maximum over the equatorial region. Then the *Ne* was taken at four different local time; 8.00am, 1.30pm, 6.30pm and 11.30pm from 1st June 2009 to 7th June 2009. This *Ne* then modeled in 2 dimensions (latitude and longitude) using Table Curve 3D (TC3D). Then, the *Ne* from IRI will be compared with TC3D and from MATLAB.

Figures 6, 7 and 8 show the plot of *Ne* using TC3D from 5th June 2009 to 7th June 2009 at 4 different times. The range of latitude and longitude chosen are from 0-50º and 100-120º respectively.
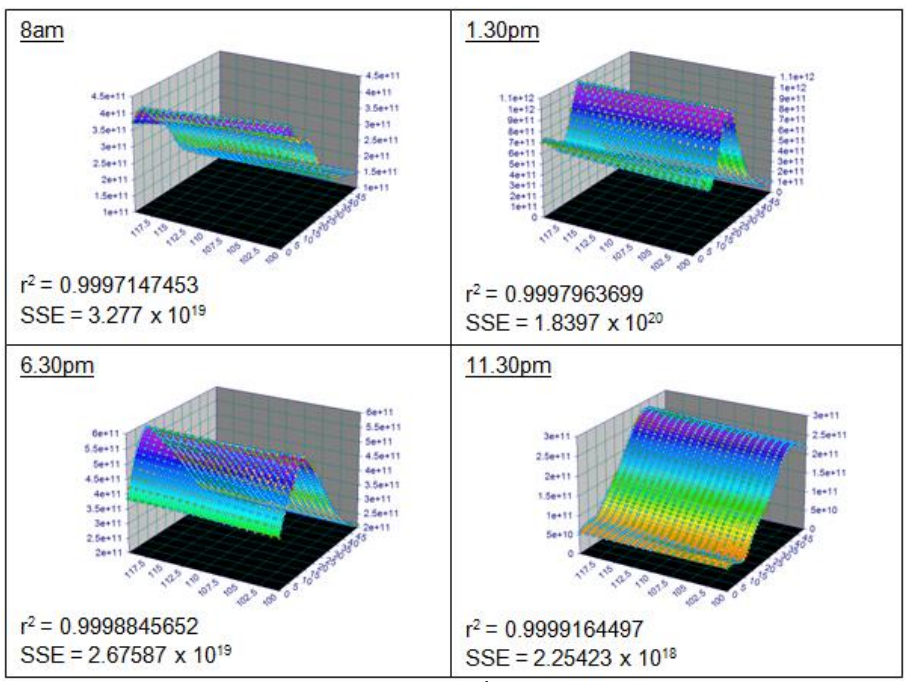
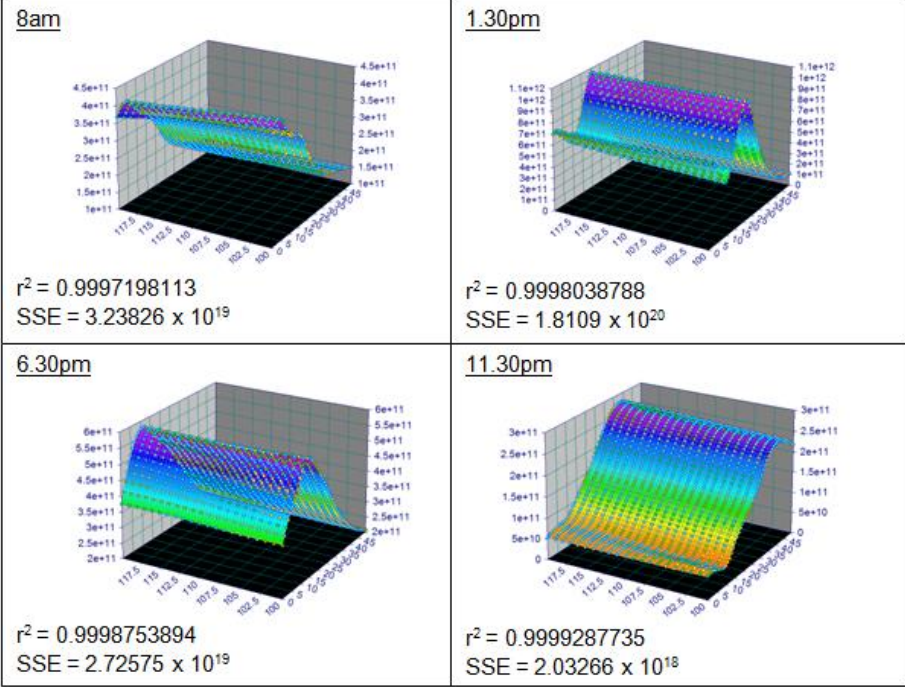Figure 6 The contour plot of *Ne* on 5th June 2009 at 4 different times

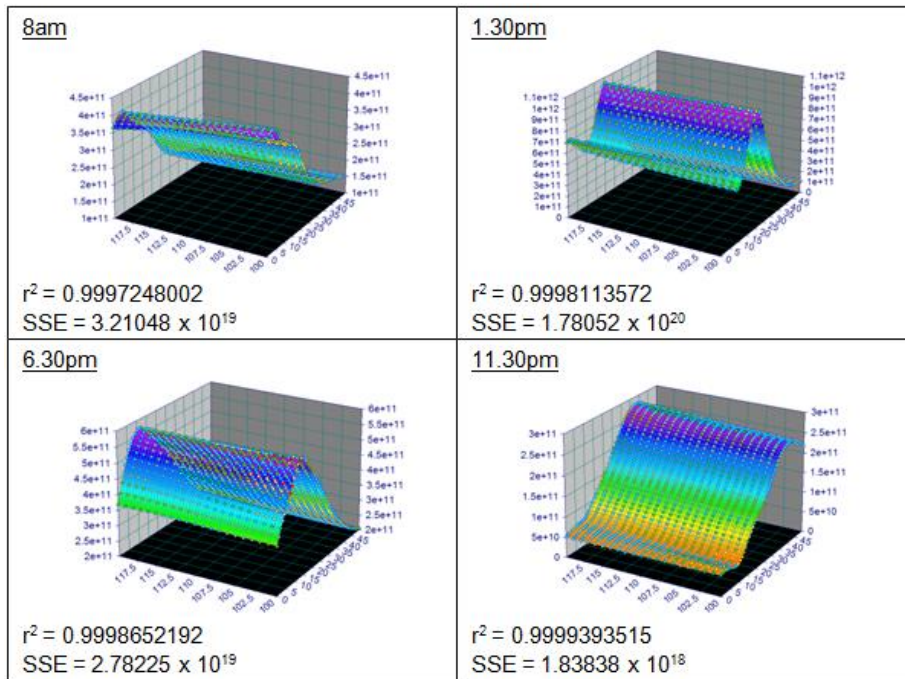Figure 7 The contour plot of *Ne* on 6th June 2009 at 4 different times

Figure 8 The contour plot of *Ne* on 7th June 2009 at 4 different times

Large numbers of different equations were used to fit the *Ne* model. However, the equation (Fourier Series Bivariate Polynomials) shown below found to be the optimum.

Z(x,y) = (a)+(b*cos(X))+(c*cos(Y))+(d*sin(X))+(e*sin(Y))+(f*cos(2*X))+(g*cos(2*Y))+(h*sin(2*X))+(i*sin(2*Y))+(j*cos (3*X))+(k*cos(3*Y))+(l*sin(3*X))+(m*sin(3*Y))+(n*cos(4*X))+(o*cos(4*Y))+(p*sin(4*X))+(q*sin(4*Y))+(r*cos(5* X))+(s*cos(5*Y))+(t*sin(5*X))+(u*sin(5*Y))+(v*cos(X)*cos(Y))+(a*a*cos(X)*sin(Y))+(a*b*sinX)*cos(Y))+(a*c*cos (X)*cos(2*Y))+(a*d*cos(2*X)*cos(Y))+(a*e*cos(X)*sin(2*Y))+(a*f*sin(2*X)*cos(Y))+(a*g*cos(X)*cos(3*Y))+(a*h *cos(3*X)*cos(Y))+(a*i*cos(X)*sin(3*Y))+(a*j*sin(3*X)*cos(Y))+(a*k*cos(X)*cos(4*Y))+(a*l*cos(4*X)*cos(Y))+(a *m*cos(X)*sin(4*Y))+(a*n*sin(4*X)*cos(Y))+(a*o*sin(X)*sin(Y))+(a*p*sin(X)*cos(2*Y))+(a*q*cos(2*X)*sin(Y))+(a*r*sin(X)*sin(2*Y))+(a*s*sin(2*X)*sin(Y))+(a*t*sin(X)*cos(3*Y))+(a*u*cos(3*X)*sin(Y))+(a*v*sin(X)*sin(3*Y))+ (b*a*sin(3*X)*sin(Y))+(b*b*sin(X)*cos(4*Y))+(b*c*cos(4*X)*sin(Y))+(b*d*sin(X)*sin(4*Y))+(b*e*sin(4*X)*sin(Y))+(b*f*cos(2*X)*cos(2*Y))+(b*g*cos(2*X)*sin(2*Y))+(b*h*sin(2*X)*cos(2*Y))+(b*i*cos(2*X)*cos(3*Y))+(b*j*cos(3*X)*cos(2*Y))+(b*k*cos(2*X)*sin(3*Y))+(b*l*sin(3*X)*cos(2*Y))+(b*m*sin(2*X)*sin(2*Y))+(b*n*sin(2*X)*cos(3 *Y))+(b*o*cos(3*X)*sin(2*Y))+(b*p*sin(2*X)*sin(3*Y))+(b*q*sin(3*X)*sin(2*Y))

where;
a,b,c…..bq are the value of parameters which are obtained from TC3D curve fitting software.
X, Y = scaled 0 to π (180º).

As was mentioned in Section 3.1 above, the fitted done so that the value of z will be nearer to the actual value of Ne. However, the difference in *Ne* between TC3D and MATLAB is shown in Table 2 below.

Table 2 The comparison value of electron density, *Ne* from IRI, TC3D and MATLAB

X		Y		*Ne*		
longitude	scaled	latitude	Scaled	IRI	MATLAB	TC3D
100	0	0	0	4.48E+11	4.54E+11	4.54E+11
100	0	10	$\pi/5$	3.74E+11	3.81E+11	3.75E+11
100	0	20	$4\pi/10$	3.18E+11	3.18E+11	3.18E+11
100	0	30	$6\pi/10$	1.97E+11	2.02E+11	1.96E+11
100	0	40	$8\pi/10$	1.72E+11	1.71E+11	1.71E+11
100	0	50	Π	1.47E+11	1.55E+11	1.49E+11
105	$\pi/4$	0	0	4.37E+11	4.44E+11	4.44E+11
105	$\pi/4$	10	$\pi/5$	3.73E+11	3.78E+11	3.73E+11
105	$\pi/4$	20	$4\pi/10$	3.17E+11	3.16E+11	3.16E+11
105	$\pi/4$	30	$6\pi/10$	1.95E+11	1.99E+11	1.94E+11
105	$\pi/4$	40	$8\pi/10$	1.67E+11	1.66E+11	1.67E+11
105	$\pi/4$	50	Π	1.44E+11	1.49E+11	1.45E+11
110	$\pi/2$	0	0	4.24E+11	4.31E+11	4.31E+11
110	$\pi/2$	10	$\pi/5$	3.72E+11	3.72E+11	3.72E+11
110	$\pi/2$	20	$4\pi/10$	3.13E+11	3.13E+11	3.13E+11
110	$\pi/2$	30	$6\pi/10$	1.93E+11	1.92E+11	1.92E+11
110	$\pi/2$	40	$8\pi/10$	1.63E+11	1.62E+11	1.62E+11
110	$\pi/2$	50	Π	1.40E+11	1.41E+11	1.41E+11
115	$3\pi/4$	0	0	4.10E+11	4.16E+11	4.16E+11
115	$3\pi/4$	10	$\pi/5$	3.70E+11	3.65E+11	3.70E+11
115	$3\pi/4$	20	$4\pi/10$	3.08E+11	3.08E+11	3.08E+11
115	$3\pi/4$	30	$6\pi/10$	1.91E+11	1.85E+11	1.90E+11
115	$3\pi/4$	40	$8\pi/10$	1.58E+11	1.57E+11	1.57E+11
115	$3\pi/4$	50	Π	1.36E+11	1.32E+11	1.37E+11
120	π	0	0	3.92E+11	4.01E+11	4.01E+11
120	π	10	$\pi/5$	3.66E+11	3.59E+11	3.66E+11
120	π	20	$4\pi/10$	3.02E+11	3.02E+11	3.02E+11
120	π	30	$6\pi/10$	1.90E+11	1.82E+11	1.89E+11
120	π	40	$8\pi/10$	1.54E+11	1.52E+11	1.53E+11
120	π	50	Π	1.32E+11	1.26E+11	1.33E+11

IV. CONCLUSIONS

The variation of the ionosphere over the equatorial region was obtained (IRI). According to the results and analysis, it is very hard to obtain the same mathematical model for the ionospheric formation at different time of a day due the variation in the solar activity. The entire layer in ionospheric will be calculated using software like TC3D. There are so many numerical mathematical that can be chosen but the one that fit well will be chosen. In this work the polynomial mathematical (Cosine/Fourier Series Bivariate Polynomials) will be chosen because this is the best mathematical model which gives the least residual for the fitting. From the Table Curve 3D, it will give all the important data like z-parameter, z-residual, or z-predictor that needed to be as a reference this model than will be compared with MATLAB to prove the fitting is done well. Equations that obtained from TC3D can determined the variation of electron density with latitude, longitude and altitude. This is the form of *Ne* equation that is required to do the ray tracing using Jones 3-D ray tracing program using realistic 3-D ionospheric model.

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