Annual Behavior of Electron Density and Critical Frequency Parameters During Maximum and Minimum Years of Solar Cycles 22, 23 and 24

Asma'a A. Hamied, Khalid A. Hadi
Department of Astronomy & Space, College of Science, University of Baghdad, Iraq.

Correspondent Email: Khalid.Hadi@sc.uobaghdad.edu.iq

Abstract: In this work, the annual behavior of critical frequency and electron density parameters of the ionosphere have been studied for the years (1989, 2001 and 2014) and (1986, 1996 and 2008) which represent the maximum and minimum of years in the solar cycles (22, 23 and 24) respectively. The annual behavior of (Ne, f_o) parameters have been investigated for different heights of Ionosphere layer (100-1000) Km. The dataset was created both of critical frequency and electron density parameters by using the international reference ionosphere model (IRI-2016 model). This study showed result that during the maximum solar cycles the values of the (Ne) parameter change with altitude. Where the electron density increases with altitude, and its highest value reaches 400 km during the maximum solar cycles and 300 km during the minimum solar cycles, whereas the critical frequency indicates differences in values over different years and locations.

Keywords: Electron Density (Ne), Critical Frequency (f_o), Ionosphere, IRI Model.

1. Introduction
The ionosphere is a region of electrically charged gases and ions in the Earth's atmosphere, upwards from 50 km to 600 km [1]. The region is assessed into many regions consistent with the electron density profile like (D, E and F) layers. The D layer is that the lowest portion of the region approximate altitude varies 50–90 km [2]. The E-layer is the middle layer that extended from the altitude range from 90–130 km [3]. The F-layer is that the maximum and most heavily ionizing of the ionized regions, and typically the altitude ranges from concerning 140 km to about 500 km. This layer is separation into two layers F_1 layer and F_2 layer [4].

2. Critical Frequency
The ionosphere of critical frequency can be described with various descriptions but the most commonly used term is the so-called "critical frequencies". Critical frequency is a well-defined, commonly measured quantity. The critical frequency of the ionosphere layer is the highest plasma frequency of a given layer for example: the critical frequencies of the layers (D, E, F_1, F_2) are (f_oD, f_oE, f_oF_1, f_oF_2), when there is a standard daily stratification f_oF_2 values are used for the total analysis. This data is the most complete and compatible for the use of
various measuring tools. The plasma frequency is directly related to the electron concentration by the equation:

\[ f_{oF_2} = 9\sqrt{\text{Ne}_{\text{max}}} \]  

(1)

where

\( f_{oF_2} \) denotes critical frequency of F2 layer, \( \text{Ne} \) denotes electron density (e/cm³)

3. **Electron Density**

The way to explore the ionosphere is through the flow of the radio wave from Earth. The main reason of the elevated density of free electrons and positively charged ions and molecules is photo-ionization from UV radiation coming from space and in special from the Sun. Taking into consideration that the density of neutral atoms with altitude is decreased and because of absorption the ionization convert to weaker because of absorption. The behavior of electron density versus height is an important criterion describing different regions in the ionosphere. Relative maximum and minimum limits are used to distinguish between the ionosphere layers. The relationship between frequency and electron density there is relationship can be illustrated in the following equation:

\[ \text{Ne} = 1.24 \times 10^4 f_{N_2} \]  

(2)

Where:

\( f_{N_2} \) = plasma frequency (MHz).

The ionospheric electron density vary with different conditions, like altitude, longitude, latitude, solar cycle and local time. For this variation a very vital role to understanding the lower as well as the upper atmosphere. The increase in electron density can give rise to great disorders in radio-wave propagation conditions (reflection, absorption, and scatter) [6].

4. **The International Reference Ionosphere Model (IRI-Model)**

The International Reference Ionosphere (IRI) is an international project sponsored by the International Union of Radio Science (URSI) and the Committee on Space Research (COSPAR). For given location, time and date, IRI provides monthly averages of electron temperature, electron density, ion composition and ion temperature ... etc in the ionospheric altitude range [8].

5. **Test and Results**

This project presented a study of the effect of solar activity on the ionosphere for the maximum in the following years (1989, 2001, 2014) and minimum years (1986, 1996, 2008) and solar cycles (22, 23, 24) in the Iraqi region and the values were adopted Observed number of sunspots and solar flux (F10.7) at the monthly time of the years tested.
Table (1) shows the monthly-observed data for sunspot count and solar flux (F10.7) that max and min years of solar cycles (22, 23, 24) [9].

| Smoothed sunspot number (SSN) | Month | 1986 | 1989 | 1996 | 2001 | 2008 | 2014 |
|-------------------------------|-------|------|------|------|------|------|------|
| Jan | 15.2 | 210.1 | 16.8 | 158.3 | 6.6 | 109.3 |
| Feb | 14.3 | 208.7 | 16.2 | 152.5 | 5.6 | 110.5 |
| Mar | 14.3 | 170.4 | 15.4 | 155.1 | 5.1 | 114.3 |
| Apr | 15.1 | 166.3 | 13.6 | 160.7 | 5.1 | 116.4 |
| May | 15.8 | 195.4 | 12.9 | 163.7 | 5.3 | 115.0 |
| Jun | 15.2 | 284.5 | 13.5 | 167.4 | 4.8 | 114.1 |
| Jul | 15.1 | 180.5 | 13.4 | 172.0 | 4.0 | 112.6 |
| Aug | 14.4 | 232.0 | 13.1 | 175.8 | 3.8 | 108.3 |
| Sep | 13.5 | 225.1 | 13.3 | 177.1 | 3.2 | 101.9 |
| Oct | 14.7 | 212.2 | 14.0 | 177.3 | 2.4 | 97.7 |
| Nov | 16.6 | 238.2 | 15.4 | 180.3 | 2.3 | 94.7 |
| Dec | 18.3 | 211.4 | 16.2 | 179.1 | 2.2 | 92.2 |

| Solar flux (F10.7 cm) | Month | 1986 | 1989 | 1996 | 2001 | 2008 | 2014 |
|-----------------------|-------|------|------|------|------|------|------|
| Jan | 73.25 | 235.38 | 74.52 | 167.50 | 74.02 | 162.69 |
| Feb | 83.58 | 222.39 | 71.83 | 146.72 | 71.03 | 170.13 |
| Mar | 77.02 | 205.07 | 70.67 | 178.14 | 72.99 | 150.50 |
| Apr | 75.06 | 189.56 | 69.42 | 192.46 | 70.15 | 143.94 |
| May | 72.61 | 190.14 | 70.13 | 147.52 | 68.32 | 130.11 |
| Jun | 67.59 | 239.58 | 69.86 | 174.11 | 65.85 | 122.37 |
| Jul | 70.21 | 181.86 | 71.36 | 131.72 | 65.67 | 137.90 |
| Aug | 68.37 | 217.09 | 72.48 | 166.85 | 66.17 | 124.56 |
| Sep | 68.71 | 225.90 | 69.45 | 134.08 | 67.00 | 146.57 |
| Oct | 82.95 | 208.68 | 69.23 | 210.54 | 68.21 | 154.99 |
| Nov | 77.14 | 235.13 | 79.06 | 214.57 | 68.53 | 155.74 |
| Dec | 72.64 | 2013.00 | 75.69 | 241.16 | 69.05 | 159.02 |

The International Reference Ionosphere (IRI) is the internationally recognized and recommended standard for specification of plasma parameters in the Earth’s ionosphere, the most recent version of IRI-2016 was chosen this model represents the latest updated version and one of the most accurate HF communication models. Figure (1) showed the input screen of IRI-2016 model.
Figure 1. Interface of the input screen of IRI-2016 model.

Figure (2) illustrate sample of the output file of the IRI-2016 model that consist the calculated results of the electron density and critical frequency of different ionospheric layers (Ne, $f_{o}F_2$, $f_{o}F_1$, $f_oE$).

| Selected parameters are: |
|---------------------------|
| 1. Height, km             |
| 2. Electron_density_Ne, m^-3 |
| 3. $f_{o}F_2$, MHz        |
| 4. $f_{o}F_1$, MHz        |
| 5. $f_oE$, MHz            |

| Height (km) | Ne (m^-3) | $f_{o}F_2$ (MHz) | $f_{o}F_1$ (MHz) | $f_oE$ (MHz) |
|-------------|-----------|------------------|------------------|--------------|
| 100.00      | 0.30890E+10 | 3.125            | 0.000            | 0.540        |
| 150.00      | 0.12536E+10 | 3.125            | 0.000            | 0.540        |
| 200.00      | 0.5082E+10  | 3.125            | 0.000            | 0.540        |
| 250.00      | 0.25523E+11 | 3.125            | 0.000            | 0.540        |
| 300.00      | 0.12791E+11 | 3.125            | 0.000            | 0.540        |
| 350.00      | 0.63450E+11 | 3.125            | 0.000            | 0.540        |
| 400.00      | 0.32973E+12 | 3.125            | 0.000            | 0.540        |
| 450.00      | 0.16704E+12 | 3.125            | 0.000            | 0.540        |
| 500.00      | 0.80135E+11 | 3.125            | 0.000            | 0.540        |
| 550.00      | 0.53306E+11 | 3.125            | 0.000            | 0.540        |
| 600.00      | 0.32912E+11 | 3.125            | 0.000            | 0.540        |
| 650.00      | 0.23086E+11 | 3.125            | 0.000            | 0.540        |
| 700.00      | 0.13331E+11 | 3.125            | 0.000            | 0.540        |
| 750.00      | 0.74374E+11 | 3.125            | 0.000            | 0.540        |
| 800.00      | 0.41506E+11 | 3.125            | 0.000            | 0.540        |
| 850.00      | 0.23468E+10 | 3.125            | 0.000            | 0.540        |
| 900.00      | 0.13802E+10 | 3.125            | 0.000            | 0.540        |
| 950.00      | 0.65520E+10 | 3.125            | 0.000            | 0.540        |
| 1000.00     | 0.35592E+10 | 3.125            | 0.000            | 0.540        |
| 1050.00     | 0.18257E+10 | 3.125            | 0.000            | 0.540        |
| 1100.00     | 0.90909E+10 | 3.125            | 0.000            | 0.540        |
| 1150.00     | 0.45455E+10 | 3.125            | 0.000            | 0.540        |
| 1200.00     | 0.22727E+10 | 3.125            | 0.000            | 0.540        |
| 1250.00     | 0.11363E+10 | 3.125            | 0.000            | 0.540        |
| 1300.00     | 0.56855E+10 | 3.125            | 0.000            | 0.540        |
| 1350.00     | 0.28428E+10 | 3.125            | 0.000            | 0.540        |
| 1400.00     | 0.14296E+10 | 3.125            | 0.000            | 0.540        |
| 1450.00     | 0.71483E+10 | 3.125            | 0.000            | 0.540        |
| 1500.00     | 0.35746E+10 | 3.125            | 0.000            | 0.540        |
| 1550.00     | 0.17346E+10 | 3.125            | 0.000            | 0.540        |
| 1600.00     | 0.86923E+10 | 3.125            | 0.000            | 0.540        |

Figure 2. The output file of IRI-2016 model.

Samples for the results the annual variation of electron density (Ne) parameter to the heights (100, 200, 300 .., 1000) km at a specific monthly medium time (12 pm) the minimum and maximum years to the solar cycles (22, 23 and 24) have been shown in figure (3).

Figure 3. Specimens of the annual electron density (Ne) parameter variation for the heights (100-1000 km) at (12 pm) for the Max. and Min. years of Solar cycles (22, 23 and 24).
Samples for the results of the annual behavior of critical frequency (foE, foF1 and foF2) parameter for the heights (100, 200, 300… 1000) km at specific monthly medium time (12 pm) for the minimum years (1986, 1996 and 2008) and the maximum years (1989, 2001, and 2014) of the three solar cycles (22, 23 and 24) respectively have been shown in figures (4) and (5) respectively.

Figure 4. Samples of the annual behavior of critical frequency parameter (foE, foF1and foF2) for the heights (100-1000 km) at (12 pm) for the Max. years of Solar cycles (22, 23 and 24).

Figure 5. Samples of the annual behavior of critical frequency parameter (foE, foF1 and foF2) for the heights (100-1000 km) at (12 pm) for the Min. years of Solar cycles (22,23 and 24).
6. Discussion and Conclusions

An analytical study was conducted on the datasets that were established using the IRI-2016 model of electron density (Ne) and critical-frequency ionosphere parameters (fo) over the Iraqi region by considering the city of Baghdad as a transmitter station and there are many other sites that are distributed around the transmitting station as receiving stations. The behavior of ionospheric parameters has been studied in maximum and minimum years of the last three solar cycles (22, 23 and 24). The behavior of the critical frequency and electron density parameters have been studied for a specific monthly medium time (12 pm) of the annual variation for the heights (100, 200, 300 ... 1000) km.

From the results it can be noticed the Ne parameter values for the maximum years (1989, 2001 and 2014) of the solar cycles (22, 23 and 24) are directly proportional to the maximum altitude values, where they increase with increasing altitude until they reach their maximum value at 400 km then they start to decline with increasing height up to reach a semi-stable value at the height of 1000 km. Also, it has been noticed that during the minimum years (1986, 1996 and 2008) of the tested solar cycles, the values of the Ne parameter are increase with altitude till they reach their maximum value at 300 km then they start to decrease with increasing height and this decrement might due to the presence of the free electrons after sunset during the minimum solar cycles. As well, it had been noticed that the Ne values in the southern region (i.e. al-khidhir) showed more variation in behavior and values than the middle (i.e. Baghdad) and northern (i.e. Nineveh) regions, which means that the variation of Ne parameter is depending on the latitudes parameter. In addition the calculations of Ne parameter showed that their values were higher in solar cycle 22 than solar cycle 23 and 24, and that’s maybe due to the impact of the high solar activity represented by the high sunspots number.

The results of the analytical study for the behavior of the Ne parameter during the selected years showed that there was an obvious anomaly in the behavior of the electron density during these years on the heights (200 and 300) km then it’s back to its normal stable behavior when its reach to an altitude of 400 km and higher.

The results of the annual variance study of the critical frequency parameter of the E, F$_1$ and F$_2$ layers (f$_o$E, f$_o$F$_1$ and f$_o$F$_2$) for the years (1989, 2001, and 2014) showed that the variance values were semi-stable (almost constant) for all altitudes but they were differing from region to another, where the southern regions showed higher values than the mid and northern regions.

For the E-layer, the variations for the tested years showed vary slight differences between them where, the higher values were during the maximum years of solar cycles (i.e. higher values were in and lower values were in 2014), while the year 1986 presented 1989 the higher value during the minimum years of the solar cycles with less value in 2008.

Form the study of the critical frequency behavior of F$_1$-layer (f$_o$F$_1$), it had been noticed that the values were invariant for all heights for the tested locations. Also, it had showed that the behavior of f$_o$F$_1$ is changeable from region to another and year to another.

The calculations of (f$_o$F$_1$) for the minimum solar cycles years exhibited that their values in 2008 were higher than the other years in Baghdad and al-khidhir regions whereas the highest value was in Nineveh was in 1986. These results present a clear anomaly behavior between the selected regions, which may due to the differences in latitudes.

The behavior study of (f$_o$F$_2$) for ionospheric F$_2$-layer showed that the values of (f$_o$F$_2$) for the maximum years of the studied solar cycles (1989, 2001, and 2014) had the same behavior at all tested regions. The values of (f$_o$F$_2$) for the tested year vary with altitude, where
it showed their highest value in (1989) whereas the lowest value was at (2014). Also, the calculated results of the \( f_{0}F_{2} \) parameter showed that their values in the southern region were more than the values of the mid and northern regions. As for the minimum years (1986, 1996, and 2008) of the studied solar cycles, the behavior of \( f_{0}F_{2} \) present the same behavior for the all selected regions and years with very slight differences in the values between regions and years.

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