Comparison of observed $h_mF_2$ and IRI 2007 model with $M(3000)F_2$ estimation of $h_mF_2$ during high solar activity for an equatorial station

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In this paper, the ways of improving the equatorial F2 layer peak heights estimated from M(3000)F2 ionosonde data measured using the Ionospheric Prediction Service (IPS-42) sounder at Ouagadougou, Burkina Faso (geog lat +12.4°N, geog long +1.5°W, magnetic dip +5.9°N) during high solar activity year (1991) was investigated. For this purpose, the observed height of maximum electron density of F2 region ($h_mF_2$), deduced using an algorithm from scaled virtual heights of quiet day ionograms; and the predicted $h_mF_2$ values, which is given by the IRI 2007 model ($h_mF_2_{IRI2007}$) have been compared with the ionosonde measured $M(3000)F_2$ estimation of the $h_mF_2$ values ($h_mF_2_{obs}$), respectively. A strong correlation with its coefficients $R^2$ for all the seasons ranging 0.562 - 0.857 for $h_mF_2_{obs}$ values, and ranging 0.876 - 0.968 for the $h_mF_2_{IRI2007}$ Values was observed in the linear regressions of $h_mF_2_{obs}$ and $h_mF_2_{IRI2007}$ with M(3000)F2 inverse. During the nighttime, estimated $h_mF_2$ ($h_mF_2_{est}$) was found to be positively correlated with the $h_mF_2_{obs}$ values by the post-sunset peak representation, which is not represented by the $h_mF_2_{IRI2007}$ values. Also, the validity of the $h_mF_2_{est}$ values has been investigated by finding the percentage deviations when compared with the $h_mF_2_{obs}$ and $h_mF_2_{IRI2007}$.

**Keywords:** F2 layer peak height, F2 region electron density, High solar activity

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1 Introduction

The International Reference Ionosphere (IRI) 2007 model, which has incorporated the topside electron density, electron density changes in the lower ionosphere, plasma temperatures, ion composition and spread-F have been used in the present study. Though, some years ago, the IRI 2000 model and the ones before, which are based on experimental data, has been widely used for predictions$^{1-7}$. The IRI 2007 model did not have any modification on the electron density height when compared with the IRI 2000 model$^8$. The estimated F2 peak height based on ionosonde measured propagation factor [M(3000)F2] at equatorial latitude$^{7}$, which is studied in this work, depends on several factors such as the hourly mean value of F2 peak critical frequency (f0F2), E peak critical frequency (foE ) and M(3000)F2 (Refs 10,11). It has been noted that post-sunset peak is rarely seen or observed when using the IRI 2007 predicted $h_mF_2$ ($h_mF_2_{IRI2007}$) for an equatorial station. In order to improve the accuracy of the predictions obtained for an equatorial $h_mF_2_{IRI2007}$, comparison is made between the $h_mF_2_{est}$ obtained from ionosonde data and the observed $h_mF_2$ ($h_mF_2_{obs}$) deduced using an algorithm from scaled virtual heights of quiet day ionograms. From comparison with the measurements of $h_mF_2$, that is $h_mF_2_{est}$, it was shown that IRI 2007 did not predict the equatorial $h_mF_2$ quite well, particularly the post-sunset peak, which is a prominent feature in the equatorial region$^{12}$. Several researchers have introduced correction factor (∆M) in a bid to improve the performance of the estimated $h_mF_2$ (Refs 13-15). Their correction factor formulations have been used by Berkey & Stonehoecker$^{16}$ for a mid-latitude station, Logan in Utah (41.6°N, 111.6°W). However, in the present study, the use of the $h_mF_2_{est}$ with the aid of the Bilitza et al.$^{15}$ formulation of the correction factor (∆$M_{est}$) has been explored with the intent to overcome the observed post-sunset anomaly of the IRI 2000 model.

Shimazaki$^{17}$ had established a strong anti-correlation between the height of F2 layer ($h_mF_2$) and the transmission factors M(3000)F2, however, Bilitza et al.$^{15}$ formulated a model that not only established a strong anti-correlation between the height of F2 layer ($h_mF_2$) and the transmission factors M(3000)F2 but also introduced a correction factor ∆$M_{est}$, expressed as:
\[ h_m F_2^{\text{est}} / \text{Km} = \frac{1490}{M(3000)F2 + \Delta M_{\text{est}}} - 176 \quad \text{(1)} \]

This factor \( \Delta M_{\text{est}} \) was introduced to account for the underlying E-layer and it is, therefore, a function of \( f_0E \) given by:

\[ \Delta M_{\text{est}} = \frac{F_1 F_4}{f_0 F_2} - F_3 \quad \text{(2)} \]

where, \( F_1 = 0.0023 R_s - 0.222 \quad \text{(2.1)} \)
\( F_2 = 1.2 - 0.0116 \exp(0.00239 R_s) \quad \text{(2.2)} \)
\( F_3 = 0.00064 R_s - 0.016 \quad \text{(2.3)} \)
\( F_4 = 1 - \frac{R_s}{150} \exp \left[ -\left( \frac{\theta}{40} \right)^2 \right] \quad \text{(2.4)} \]

where, \( R_s \) is the monthly mean sunspot number for each month in question; \( \theta \) the latitudinal angle in degrees; and \( f_0F_2 \) and \( f_0E \), the F2 and E-peak critical frequencies. Bilitza et al.\(^ {15} \) model was derived based on data from incoherent scatter radar measurement at Millstone Hill, Arecibo and Jicamarca.

2 Data analysis

The data used is from the ionosonde station located in Ouagadougou, Burkina Faso (geographic latitude 12.4°N, longitude 1.5°W, magnetic inclination 5.9°N). The data covers all hours for magnetically quiet days in January representing December solstice, April representing March equinox, July representing June solstice and October representing September equinox of a high solar activity year (1991). The monthly mean sunspot number \( R_s \) for the four seasons under study are: January – 136.9, April – 140.0, July – 173.7 and October – 144.1.

\( M(3000)F2 \) is expressed as \( M(3000)F2 = \text{MUF}/f_0F_2 \), where MUF is the maximum usable frequency that can be received at a distance of 3000 km when reflected by the ionosphere. This factor \( M(3000)F2 \) is routinely scaled from ionograms. The hourly mean value of \( M(3000)F2 \), \( f_0F_2 \) and \( f_0E \) were calculated and used to obtain the \( h_m F_2^{\text{est}} \) values from Eq. (1). The \( h_m F_2^{\text{obs}} \) was obtained from scaled virtual heights of quiet day ionograms using Automatic Real Time Ionogram Scaler with True Height (ARTIST) program NHPC (a program for inversion of scaled ionogram traces into electron density profiles), developed by Huang & Reinisch\(^ {18} \). For validation of IRI, the IRI 2007 model was used to generate \( h_m F_2^{\text{IRI2007}} \) values for each hour of the 15th (middle day) of each month during the year 1991. These hourly values are taken to be representative of the monthly hourly means for the days of that month. The hourly means obtained in this way were compared with the corresponding ones obtained for the observed \( h_m F_2^{\text{obs}} \). The percentage deviation of the \( h_m F_2^{\text{est}} \) from the \( h_m F_2^{\text{obs}} \) and the \( h_m F_2^{\text{IRI2007}} \) was also computed. The inverse of the \( M(3000)F2 \) value was also computed and correlated with \( h_m F_2^{\text{IRI2007}} \) and \( h_m F_2^{\text{obs}} \). The error bars indicated on the \( h_m F_2^{\text{obs}} \) is to determine if the percentage deviations between the observed \( h_m F_2^{\text{obs}} \) and the IRI 2007 model \( h_m F_2^{\text{IRI2007}} \) is significant or not.

3 Results and Discussion

Figure 1(a-d) shows the diurnal variation of the \( h_m F_2^{\text{est}} \), the \( h_m F_2^{\text{obs}} \) and the \( h_m F_2^{\text{IRI2007}} \) for the four seasons based on four different months of the year: January representing December solstice, April standing for March equinox, July representing June solstice and October standing for September equinox. The graphs of \( h_m F_2^{\text{est}} \) as compared with \( h_m F_2^{\text{obs}} \) exhibit one characteristics peak just after sunset both during the solstices and equinoxes of the year. But this peak is not clearly seen with \( h_m F_2^{\text{obs}} \). The post-sunset peak for \( h_m F_2^{\text{est}} \) observed to have a pronounced diurnal feature during the solstice months, especially January as compared with \( h_m F_2^{\text{obs}} \). The post-sunset peak for \( h_m F_2^{\text{obs}} \) is also prominent during the September equinox. The \( h_m F_2^{\text{est}} \) noon time peak for \( h_m F_2^{\text{est}} \) is only pronounced in June solstice (July) as compared with \( h_m F_2^{\text{IRI2007}} \). The \( h_m F_2^{\text{IRI2007}} \) post-sunset peaks usually occur between 0700 and 0800 hrs LT and this is also very sharp as compared to the post-sunset peaks, which are in agreement with Radicella & Adeniyi\(^ {19} \) for the diurnal, seasonal and solar cycle effects.

The nighttime morphological variation in the observed \( h_m F_2 \) values are generally quite close with estimated \( h_m F_2 \) values, except in equinoxes where the variation in the \( h_m F_2^{\text{est}} \), as compared with the \( h_m F_2^{\text{obs}} \), are greatly dispersed from each other. For predicted \( h_m F_2 \) values, the nighttime morphological variation of \( h_m F_2^{\text{IRI2007}} \) are not quite close with estimated \( h_m F_2 \) values, especially in July between 2000 and 0300 hrs LT. There is a general drop in the values of the \( h_m F_2 \) (estimated, observed and predicted) before and after the post-sunset peak. This may be as a result
of the electron density profile, which is determined by electron gain and loss as well as transport processes during the daytime; whereas at nighttime, transport processes alone play the dominant role. The sharp drop in the $h_mF_2$ values before the post-sunset peak most especially in the $h_mF_2_{obs}$, is likely to be due to the onset of solar ionization and the resulting increase in electron density at lower altitudes. These observations are in agreement with Ehinlafa et al.\textsuperscript{20} for the diurnal variation noticed during low solar activity, and also, in a fairly good agreement with Jesus et al.\textsuperscript{21} during the nighttime in all the seasons.

The linear regressions of $h_mF_2_{obs}$ and $h_mF_2_{IRI2007}$ with M(3000)F2 inverse for each season are plotted in Figs 2(a–d) and 3(a–d), respectively in order to validate the M(3000)F2 values used. The regression coefficients, $R^2$, obtained are in the range of 0.562-0.852 and 0.776-0.857 for solstices and equinoxes, respectively. The strong correlation of the inverse M(3000)F2 with both $h_mF_2_{obs}$ and $h_mF_2_{IRI2007}$ are quite significant both during the solstices and the equinoxes. This shows that the inverse M(3000)F2 used is of greater reliability for all the seasons under consideration. This is in a fairly good agreement with Kouris et al.\textsuperscript{22} and Ouattara et al.\textsuperscript{23,24} for F2 layer peak height based on M(3000)F2 during all the seasons.

Figure 4(a–d) shows the percentage deviation in equatorial $h_mF_2$ between $h_mF_2_{est}$ and the $h_mF_2_{obs}$ values for the four months. The post-sunset peaks of the $h_mF_2$ percentage deviation are observed between 1900 and 2100 hrs LT. The $h_mF_2$ positive percentage deviation of March equinox value of ~18% (April) occurred at 2100 hrs LT. The $h_mF_2$ positive percentage deviation of March equinox value of 11.0% (July) occurred at 2000 hrs LT. Likewise, the negative percentage deviations in $h_mF_2$ for equinoxes are very high compared to that of solstices, especially in the month of October with negative value of ~38% occurring at 0200 hrs LT.
Fig. 2 – Regression plots of the $h_m F_2 \text{obs}$ against $M(3000)F_2$ inverse at high solar activity during 1991 for: (a) December solstice; (b) March equinox; (c) June solstice; and (d) September equinox.

Fig. 3 – Regression plots of the $h_m F_2 \text{IRI2007}$ against $M(3000)F_2$ inverse at high solar activity during 1991 for: (a) December solstice; (b) March equinox; (c) June solstice; and (d) September equinox.
A very large negative trough spread in the $h_mF_2$ percentage deviation is observed during solstices, especially in the month of January as compared with that of equinoxes. A negative sunrise peak of $h_mF_2$ percentage deviation is noticed only for October (equinox) at 0700 hrs LT. There are more negative trough spreads in the $h_mF_2$ percentage deviation in the equinoxes than the solstices. These observations are in good agreement with Ouattara et al.\textsuperscript{25} for the seasonal, diurnal and solar cycle variations of electron density.

Figure 5(a-d), similarly, shows percentage deviation in equatorial $h_mF_2$ between the $h_mF_2_{\text{est}}$ and the $h_mF_2_{\text{obs}}$. The post-sunset peak of $h_mF_2$ percentage deviation between $h_mF_2_{\text{est}}$ and $h_mF_2_{\text{IRI2007}}$ have positive peak value of ~ 3% for all seasons, except in June solstice where there is no positive peak observed, and the negative peak value ranges from ~ 14% for January (solstice) to ~ 42% in April (equinox). There is a negative noontime peak of $h_mF_2$ percentage deviation at 1200 hrs LT for January (solstice). There are very large negative trough spreads in the $h_mF_2$ percentage deviation both in the equinoxes and the solstices. These observations show a better agreement with Fagundes et al.\textsuperscript{26} for a typical F2 layer peak height during a low solar activity.

The post-sunset peaks of the positive $h_mF_2$ percentage deviation for both the observed and the IRI values are, generally, higher in the equinoxes than the solstices between 1900 and 2100 hrs LT. Also, during nighttime, $h_mF_2$ percentage deviation of negative values for both the observed and the IRI

Fig. 4 — Percentage deviations between equatorial $h_mF_2_{\text{est}}$ and $h_mF_2_{\text{obs}}$ at high solar activity during 1991 for: (a) December solstice; (b) March equinox; (c) June solstice; and (d) September equinox.
values are generally higher in the equinoxes than the solstices as compared with the daytime.

4 Conclusion

Generally, during high solar activity, the diurnal variation of the values of the \( h_mF_2 \) (estimated and predicted) are represented well with the noontime peak, but \( h_mF_2_{\text{obs}} \) is over estimated during the solstices, especially July. Also, the variation in the \( h_mF_2_{\text{est}} \) and the \( h_mF_2_{\text{obs}} \) are closely related with the post-sunset peak being prominent in equinoxes, especially in the month of October. But, the variation in \( h_mF_2_{\text{IRI2007}} \) is not represented well with the post-sunset peak as compared with the \( h_mF_2_{\text{est}} \). A discrepancy of dispersion of the \( h_mF_2_{\text{est}} \) from the \( h_mF_2_{\text{obs}} \) as observed in the months of the equinoxes during the nighttime is due to insufficient data because of the limitations of the underlying database at high solar activities. This is in a good agreement with Jesus et al.\(^{21}\) during all the seasons as observed in the observed \( h_mF_2 \) and modeled \( h_mF_2 \).

Also, the correlation of the \( h_mF_2_{\text{IRI2007}} \) with inverse M(3000)F2 for all of the seasons are found to be positively higher in value than with the \( h_mF_2_{\text{obs}} \). The percentage deviation between the \( h_mF_2_{\text{est}} \) and the \( h_mF_2_{\text{obs}} \) gives a better representation of post-sunset peak for all of the seasons when compared \( h_mF_2_{\text{est}} \) with \( h_mF_2_{\text{IRI2007}} \). A slight but consistent over estimation which does not seem to be significant judging by the percentage deviations about the predicted \( h_mF_2 \) is still present at night.

The result, in this study, demonstrates to a large extent that the hourly values of \( h_mF_2_{\text{est}} \) and \( h_mF_2_{\text{obs}} \) compared with \( h_mF_2_{\text{IRI2007}} \) shows a good representation...
of both pre-sunset and post-sunset peaks indicating that the \(M(3000)F2\) is of greater reliability for all of the seasons\(^{23,24}\).

The results from this study along with previous work by Radicella & Adeniyi\(^{19}\) should help in the description of determining the height of maximum electron density of \(F2\) region profiles in IRI model at least for the equatorial regions. There is need, however, to conduct similar investigations for other latitudinal regions during other periods of solar cycle.

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References