Occurrence of an Additional Layer in the Daytime F Region over Ilorin, Nigeria

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Abstract
An additional stratification in the daytime F region of the equatorial ionosphere within $\pm10°$ magnetic latitude, known as F3 layer, has been observed and reported for the South American and Asian sectors of the equatorial ionosphere. All the available ionograms recorded at Ilorin (Latitude 8.48° N, Longitude 4.67 °W, dip 3.3 °S) have been used to study the occurrence of the F3 layer. The study covers a period of 6 years (i.e., 2002, 2005–2008 and 2010). The results obtained showed a distinct F3 layer during low solar activity whereas the layer was not distinct during high solar activity. The duration of occurrence of the F3 layer ranges from about 15 minutes to 7 hours. The duration of occurrence seemed to be higher during low solar activity although no clear trend in solar activity was observed. The virtual peak height of the F3 layer (h'_mF3) as observed in Ilorin ranges from 484 km to 700 km, and the critical plasma frequency of the F3 layer (f_oF3) exceeds that of F2 layer (f_oF2) by 0.58 MHz to 1.01 MHz. The percentage of occurrence of the F3 layer seems to decrease with increase in solar activity.

Keywords: E×B drift, equatorial ionosphere, F3-layer, solar activity

Introduction

An additional stratification in the daytime F region of the equatorial ionosphere, known as F3 layer (Balan *et al.*, 1997), has been observed and reported by some authors in the South American sector (Balan *et al.* 1998, 1999, 2000; Jenkins *et al.*, 1997; Batista *et al.*, 2002, 2003), Asian sector (Zain *et al.*, 2008, Rama Rao *et al.*, 2005.) and in the Asia/South America/ African sector (Zhu *et al.*, 2013). The layer was formerly called G layer (Balan and Bailey, 1995).

This layer has been observed within the $\pm10°$ magnetic latitude centered around the magnetic equator. The formation mechanism of the F3 layer is believed to be the combined effect of the upward E×B drift and neutral wind, which provides a vertical upward plasma drift velocity at altitude near and above the F2 peak. This drift velocity causes the F2 peak to move upward thereby forming the F3 layer while the normal F2 layer develops at lower altitudes through the usual photochemical and dynamical process of the equatorial region (Balan *et al.*, 1997).

Previous studies have revealed that the F3 layer occurrence depends on the time of the day, season of the year, level of solar activity and geomagnetic storm effect (Balan *et al.* 1998, 1999, 2000; Zain *et al.*, 2008; Rama Rao *et al.*, 2005; Paznukhova *et al.*, 2007).

Also, latitudinal effect has been observed on the occurrence of F3 layer within the $\pm10°$ magnetic latitude (Zhao *et al.*, 2011; Karpachev *et al.*, 2013; Zhu *et al.*, 2013). For example, the study by Zhu *et al.* (2013) at 7 locations, which spanned the American, African and Asian sectors, focused on the formation pattern of the F3 layer in low and equatorial regions during geomagnetically quiet days. The stations used in that study included Ilorin, Nigeria; for which the April–October, 2010 data was utilised. Their result showed that the occurrence frequency of the F3 layer was highest at stations at magnetic low-latitude and lowest over the magnetic equator. The F3 layer occurrence has a significant effect on the performance of the ionospheric model especially in predicting the peak parameters of the F2 layer.

The well known global ionospheric models, such as IRI and NeQuick are currently not capable of predicting the occurrence of this layer. In fact, a study carried out by Batista *et al.* (2003) over Fortaleza in

Brazil revealed that the IRI model overestimates the observed critical frequency of the F2 layer by up to 3 MHz and underestimates the peak height of the F2 layer by up to 100 km when the F3 layer is present. This is in addition to the fact that the model can not predict the occurrence of F3 layer as observed in the ionograms for the period investigated.

This has a significant impact on applications that rely on the critical frequency and peak height of the F2 layer during the period that the F3 layer is present. Therefore, statistical occurrence distribution studies at different latitudes and longitudes over time are crucial in understanding the occurrence pattern of the F3 layer. The results of such studies could serve as a database into global models in the effort to improve the predicting capabilities of these models. Such a study is not available for Ilorin, Nigeria as the work by Zhu *et al*. (2013) only covered a period (April–October, 2010). The current study therefore focuses on the statistical occurrence of F3 layer in Ilorin, Nigeria. All the available ionograms at the Ilorin station were used for this study.

Materials and Methods

The Ilorin ionospheric station is a collaborative research effort facilitated by the T/ICT4D Laboratory, ICTP Italy (formerly known as Aeronomy and Radio Propagation Laboratory). Collaborators include the US Air Force Academy (USAFA) and University of Massachusetts Lowell Space Science Laboratory (UMLSSL). Ionograms available at Ilorin were recorded using two IPS-42 sounders from KEL Aerospace and one DPS_4 from UMLSSL. All the available ionograms were used for this study.

Table 1 shows the periods for which ionograms were available with the monthly average sunspot number. All the ionograms were manually checked for F3 layer occurrence and the periods of occurrence for each day as well as the duration of occurrence were recorded. The percentage occurrence was calculated using equation 1.

$$\%\ Occurrence = \frac{N_{Obs}}{N_{total}} \times 100\% \qquad (1)$$

where N_{obs} is the number of days F3 layer was observed while N_{total} is the total number of days for which ionograms are available for a particular month.

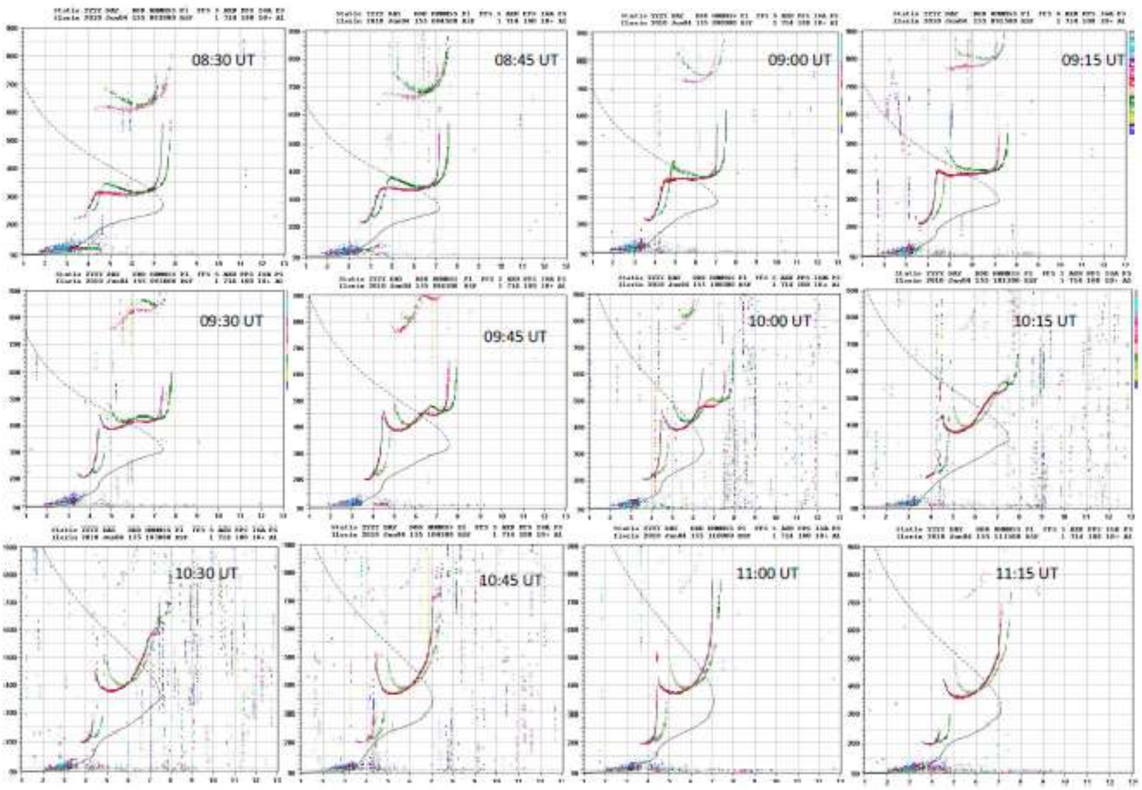
Results and Discussion

Figure 1 shows a sample of daytime ionograms at 15 min. intervals for June 4, 2010 from Ilorin. The ionograms shown are typical of daytime ionograms at this location during low solar activity periods when F3 layer is present. A distinct F3 layer was clearly seen between 9:30–10:15 UT, on this day. The F3 layer began to form around 09:00 UT and was fully formed by 9:30 UT. The layer stayed above the F2 layer through the period of occurrence as shown in all the ionograms in Figure 1. The layer persisted as a distinct additional stratification in the F-region until 10:30 UT and gradually disappeared thereafter.

Table 1: Periods of the Availability of the Ionograms

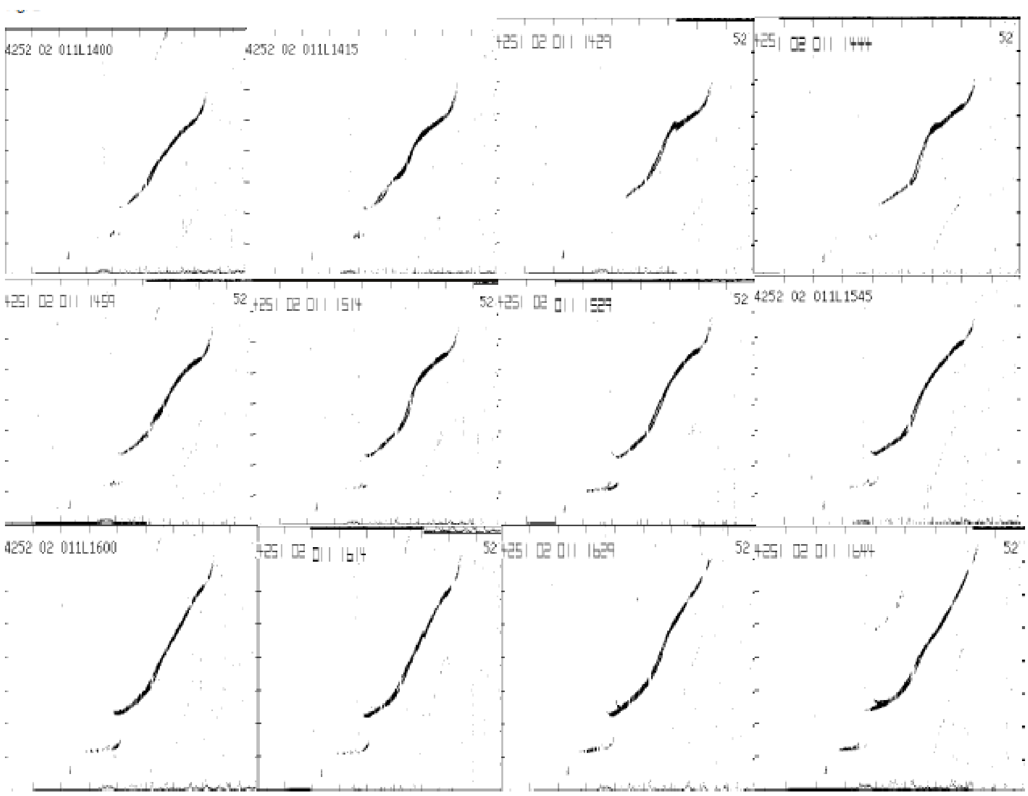
Year	Available Months	Monthly SSN
2002	January	114.1
	March	98.4
2005	November	18.0
	December	41.2
2006	January	15.4
	February	5.0
	March	10.8
	April	30.2
	May	22.2
2007	January	16.8
	February	10.7
	June	12.1
	July	9.7
	November	1.7
	December	10.1
2008	January	3.3
	February	2.1
	March	9.3
2010	March	15.4
	April	8.0
	May	8.7
	June	13.6
	July	16.1
	August	19.6
	September	25.2
	October	23.5
	November	21.5

One important feature that needs to be mentioned is the gradual movement of ionisation to higher altitude between the time of layer formation and layer disappearance. This is seen in the virtual peak height (h'_mF3) of the F3 layer of the ionograms in Figure 1. For example, h'_mF3 for this day at 9:30 UT was 500 km, which gradually increased to 650 km at 10:30 UT. Although the h'_mF3 gradually moved to higher altitude, the F3 critical frequency (f_oF3) was nearly constant. At 9:30 UT, on the first appearance of the F3 layer, *hmF1* (*h'F1*), *hmF2 (h'F2)*, *foF1* and *foF2* values were 184.5 km (300.0 km), 270 km (420 km), 4.42 MHz and 6.00 MHz, respectively, and at 10:30 UT, the values were 153.4 km (320.0 km), 320 km (580 km), 4.37 MHz and 7.00 MHz, respectively. It seemed that the effect of the lifting of ionisation was only on the F2 layer heights as *hmF2* and *h'F2* showed significant increases just like *h'F3*.



*A distinct F3 layer is seen between 9:30 UT and 10:15 UT.

Figure 1: Daytime Ionograms for Ilorin on June 4, 2010 at 15-Minute Intervals



*An F3 layer is seen between 14:00 UT and 16:14 UT. The layer is not as distinct as observed in Figure 1.

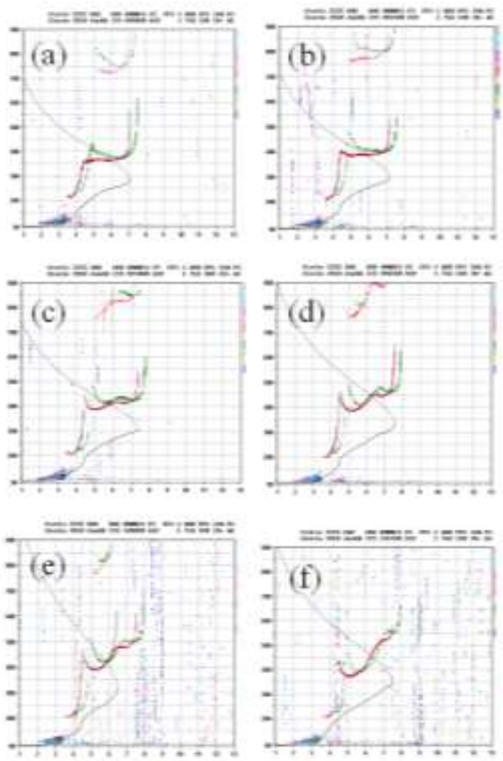
Figure 2: Daytime Ionograms for Ilorin on January 11, 2002 at 15-Minute Intervals

For the period investigated, there were instances when the layer reappeared in the afternoon after it had disappeared towards the local pre-noon hours. The F3 layer occurrence was more pronounced, in Ilorin, during the pre-noon hours; especially during low solar activity.

Figure 2 shows samples of daytime ionograms at 15-minute intervals for January 11, 2002 from Ilorin. The ionograms are typical of daytime ionograms in Ilorin during high solar activity periods when the F3 layer is present. Unlike what is observed during the low solar activity year, the F3 layer is not very distinct during high solar activity periods. However, one can still see the occurrence of F3 layers as shown in Figure 2 especially around 14:00 UT (15:00 LT). The layer can be seen till around 16:00 UT (17:00 LT). This could be likened to L-condition (160–190 km) that is normally a feature of the daytime F-region ionosphere during a high solar activity year at the Equator. As shown in the ionograms in Figure 2, there was no distinct F1 layer as the F1 was smoothly joined to the F2 layer (i.e., L-condition). Identifying the occurrence of F3 layer during high solar activity was quite challenging as a smooth joining of the F2 layer to the F3 layer, similar to that observed for the F1 layer with the F2 layer, was observed. As observed during the low solar activity, a gradual movement of ionisation to higher altitude between the time of formation and the time of layer disappearance was also observed during high solar activity. This is seen in the virtual peak height (h'_mF3) of the F3 layer of the ionograms in Figure 2 (e.g., h'_mF3 for this day at 14:00 UT was 600 km and this gradually increased to above 700 km at 16:00 UT).

Figure 3 shows selected ionograms from Figure 1. The auto scale profile is the solid curve line in each of the ionograms. The essence of this Figure is to show the behaviour of the auto scaling software for the Digisonde ionogram (Galkin *et al.*, 2008); for this particular day in the presence of F3 layer. There were instances when the F3 layer peak was scaled as the F2 layer peak even when the 2 layers were well-formed (Figures 3c, 3d & 3f) whereas in other ionograms, the F2 peak was scaled appropriately.

Figure 4 shows the plot of maximum daily duration of occurrence of the F3 layer within a month (in hours) for all the months/years investigated. The duration of occurrence of F3 layer at Ilorin ranged from 15 min. to 7 hrs for the period investigated. The month with the highest duration was June 2010. No clear solar activity dependency was observed, however, the duration of occurrence was highest in 2010, which was a period of low solar activity. Figure 5 shows the monthly percentage occurrence of the F3 layer for Ilorin. The monthly average value of sunspot number (SSN) for each of the months is also indicated. It is important to mention here that there were cases in which ionograms were not available for a few days within a month. However, in all cases, percentage occurrence was calculated based on the number of days for which ionograms were available (see equation 1). The F3 layer occurrence seemed to be more frequent during low solar activity periods than during high solar activity. Although no clear solar activity trend was observed in the occurrence of F3 layers at this station the highest value of percentage occurrence of 60% was observed in March 2010, which was a low solar activity period.



*F3 layer is present. Auto scale profile is shown as the smooth solid curve up to the peak of F2 layer and dotted line after the peak of F2 layer. Of interest is the behaviour of the auto scaling software as seen with the real height profile of frequency. F3 layer critical frequency *(foF3)* was scaled as F2 layer critical frequency *(foF2)* (see d & f) whereas in others *foF2* was scaled appropriately.

Figure 3: Selected Ionograms for Ilorin on June 4, 2010

As mentioned earlier, previous studies have shown the diurnal, seasonal and solar activity dependence of the F3 layer occurrence. The seasonal and solar activity trends also varied from one latitudinal/ longitudinal location to another. The study by Batistal *et al*. (2002) was on long term study of the occurrence of the F3 layer over Fortaleza, Brazil, South America.

Ionograms from 1975–2000 were used and the results of the studies showed that the occurrence of F3 layer was more frequent from December to February (local summer) and June to August (local winter).

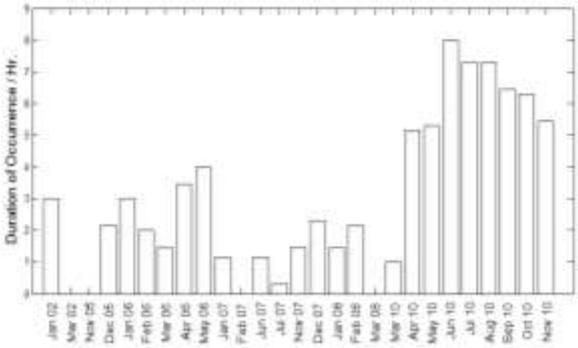


Figure 4: Plot of the Duration of F3 Layer Occurrence

Similarly, Zain *et al*. (2008) used a 1-year data (January–December 2005) to study the occurrence of the F3 layer over Parit Raja, Malaysia in the Asian Sector. Their results showed that the F3 layer was more frequent around local noon and that the occurrence was more pronounced during winter and equinoxes (i.e., October–February). It was also observed that *foF2* decreased with the appearance of the F3 layer.

The study by Rama Rao *et al.* (2005) was from the Indian sector and used half a solar cycle data (1997–2003) from Waltair to study the F3 layer occurrence. Their results showed that the occurrence of F3 layer was more frequent during summer solstice months at low solar activity and that the duration of occurrence was longer during these months compared to the equinox and winter solstice months. They also reported that the occurrence of the F3 layer does not depend on magnetic activity but that it decreases with increase in solar activity.

Just like previous studies, the current study shows that the occurrence of the F3 layer decreases with increase in solar activity and that its occurrence is more frequent during the pre-noon than the post-noon period. On the seasonal effects in Ilorin, it seems that the occurrence is more frequent during the equinox months. This can be deduced from the March–November, 2010 portion of the percentage occurrence plot (Figure 5).

By looking at the previous results and the current study in terms of the period of the year for which the occurrence of F3 layer was more frequent, it can be said that the occurrence of the F3 layer was more frequent from December to February and June to August at Fortaleza in Brazil, October to March at Parit Raja in Malaysia and from March to October at Waltair in India and Ilorin in Nigeria.

Our results seem to indicate solar activity effects on the occurrence of F3 layer at Ilorin, F3 layer occurrence seems to decrease with increase in solar activity. Similarly, the layer was very distinct during low solar activity but less distinct during moderate and high solar activities. This observation has been explained by Balan *et al.* (1998) in their study on the physical mechanism responsible for F3 layer occurrence. They modeled electron density (Ne) profiles under different solar activity conditions. Their results indicated that the morning–noon (i.e., morning towards noon hours) ionosphere becomes thicker and denser as the solar activity increases, whereas the corresponding E×B drift and neutral winds remain constant. The moderate and high solar activities period therefore brings about upward forcing from the E×B drift and wind, which is less efficient in lifting the morning F2 peak to the topside altitude where clear F3 layer could be formed.

As suggested by previous authors (Balan *et al.*, 1997) the lifting of ionisation by the combined effects of E×B drift and neutral wind as the mechanism responsible for the formation of the F3 layer was evident in the results obtained in the study. During both low and high solar activities for which F3 layer was present, the movement of ionisation to higher altitude was observed. This movement was seen around and above the F2 peak heights. The vertical drifting of ionisation started before the formation of the F3 layer and it continued till the layer completely disappeared, as observed in this study.

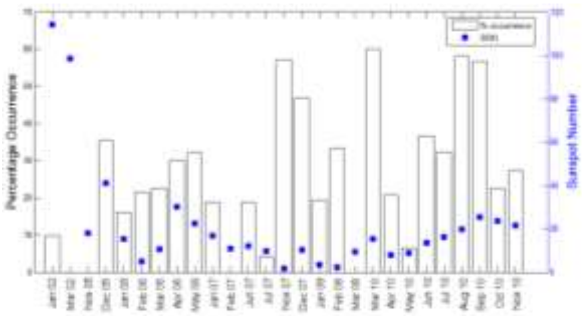


Figure 5: Plot of Percentage F3 Layer Occurrence and Average Sunspot Number

According to Balan *et al*. (1998), during the morning–noon period, when photoionisation dominates over loss of ionisation, the vertical velocity causes the F2 peak to drift upwards and form the F3 layer while the normal F2 layer develops at lower altitudes through the usual photochernical and dynamical processes of the equatorial region. The drifting of the F3 layer to higher altitude continues and the layer becomes thinner and thinner until it disappears while the new F2 layer continues to grow until it is fully formed because of the large production of ionisation at the F2 heights. This explains the observation during low solar activity. Balan *et al*. (1998) also predicted the solar activity dependence of the occurrence of the F3 layer and that it decreases with increase in solar activity though not supported with experimental data. Previous studies (Rama Rao *et al.*, 2005) presented experimental data to support the solar activity dependence of the F3 layer occurrence. The result obtained in the current study also supports this observation that F3 layer occurrence decreases with increase in solar activity.

Conclusion

Available ionograms recorded at Ilorin, which spans over 6 years, though not continuous, have been used to study the occurrence distribution of the F3 layer over Ilorin, Nigeria. Ilorin is located within the $\pm 10°$ magnetic latitude centered around the magnetic Equator for which an additional stratification known as F3 layer is expected to be formed.

Results obtained in this study can be summarised as follows:

- A distinct F3 layer was observed during low solar activity whereas the layer was not that distinct during high solar activity.
- The formation of the layer was associated with the lifting of ionisation to higher altitude before the formation of the layer and it continued until the layer completely disappeared.
- The duration of occurrence of the layer is between 15 min. to 7 hrs. While the duration of occurrence seemed to be higher during low solar activity, no clear solar activity trend was observed in the duration of occurrence. The result maybe due to scanty data.
- Virtual peak height of the F3 layer ($h'_m F3$) ranges from 484–700 km.
- Critical frequency of the F3 layer (f_oF3) exceeds that of F2 layer (f_oF2) by 0.58–1.00 MHz.
- The percentage of occurrence of the F3 layer decreased with increase in solar activity.

The presence of F3 layer in the equatorial F-region of the ionosphere could have significant implications on HF communication links. The occurrence of F3 layer will lead to reduction in hop distance and could lead to breakdown in communication links.

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