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Key Points:

- Analysis of Digisonde, High Frequency Doppler receiver, and Global Navigation Satellite System data was undertaken
- Use of low-cost High Frequency Doppler equipment for reliable diagnostic of the equatorial ionosphere is demonstrated
- Daytime equatorial spread F is associated with traveling ionospheric disturbances

Supporting Information:
Supporting Information may be found in the online version of this article.

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Abstract

Daytime equatorial spread F (ESF) is not as common as nighttime ESF due to the presence of a highly conducting E-layer during the daytime which counteracts the development of F-layer plasma irregularities. This study presents two rare daytime ESF-like events which occurred over an interval ~2 h and were detected by the HF Doppler receiver located in Lagos (LAG: geographic: 3.27°E, 6.48°N; dip latitude −1.72°) and the Lowell Digisonde at Ilorin (ILR: 4.68°E, 8.50°N; dip latitude −1.25°), managed by Lowell GIRO Data Center (LGDC). Analysis of the first event revealed ~30 min periodic oscillations in iso-heights of ionospheric electron density. Shorter period (~15 min) oscillations appeared simultaneously in HF Doppler measurements and these oscillations lasted nearly 3 h. Close inspection of the ionograms from ILR during this interval (1500–1800 UT) showed the occurrence of small-scale spreading in the F-layer trace which varied in altitude as the disturbance progressed. Computation of the linear growth rate of the collisional Rayleigh-Taylor instability showed that the plasma instability was seeded by a traveling ionospheric disturbance (TID). The characteristics of the second event suggest that horizontal stratifications in plasma density distribution at the reflecting ionospheric layer were responsible for the spread F traces in the ionograms. Analysis of GPS TEC data from Nigeria during these events revealed the presence of wave structures consistent with TIDs.

1. Introduction

The ionosphere is an indispensable medium for the propagation of communication and navigation signals. It has been extensively studied over the years to understand its properties and variability under different conditions. Spread F (SF) is a common feature of the ionosphere that is caused by irregularities in electron density distribution in the F-layer. Radio signals incident on these irregular plasma structures are scattered, thereby causing diffuse scattering in the F-layer trace of ionograms. Bottomside spread F was first reported by Booker and Wells (1938) and a number of mechanisms are understood to be responsible for its occurrence and development. Post-sunset SF is most commonly attributed to increased upward vertical plasma drift (also known as the pre-reversal enhancement [PRE]) in response to an enhanced eastward electric field. Due to the absence of a highly conducting E-layer at night, plasma instabilities can develop more easily at elevated F-layer heights and can subsequently grow via the Rayleigh-Taylor instability (RTI). This phenomenon is even more common at equatorial latitudes because the geometry of the geomagnetic field at these latitudes facilitates \( E \times B \) plasma drifts (Sreehari et al., 2006). Apart from the PRE associated with post-sunset F-region electrodynamics, other mechanisms known to contribute to F-layer plasma instabilities include zonal winds, atmospheric gravity waves (AGWs) which manifest in the ionosphere as traveling ionospheric disturbances (TIDs), and trans-equatorial thermospheric winds (Abdu, 2012). The role of the RTI in the development of the equatorial spread F (ESF) was first suggested by Dungey (1956). The RTI develops when a heavy fluid rests on a lighter one. In such a state, gravity or other triggers can cause the heavier liquid to become unstable. Ossakow (1979) and references therein discussed the role of the F-layer peak and electron density scale length in the linear growth of the RTI. A higher F-layer peak and smaller electron density scale length are both favorable conditions for the linear growth of the RTI.

In the mathematical formulation by Huang et al. (1993), it was shown that AGWs can directly seed the RTI. Huang et al. (1993) showed that AGWs with speed 5–20 ms\(^{-1}\) and wavelength in the order of 100 km
can initiate the RTI in the F-region of the ionosphere. However, it was noted that the generated instabilities are more easily saturated when the amplitudes of the initiating AGW are small. Candido et al. (2011) analyzed ionograms from the Brazilian sector during solar cycle 23, from 2001 to 2010, for SF occurrence. They found that although the occurrence of spread F was high during the June solstice, equatorial plasma bubbles (EPBs) were rarely seen during this period. However, airglow images from an all-sky imager over the region showed that the SF events were associated with medium-scale TIDs (MSTIDs). Similarly, Pimenta et al. (2008) studied the effect of TIDs, observed over the southern crest of the equatorial ionization anomaly, on the nighttime ionosphere. They suggested that the TIDs were likely associated with plasma irregularities in the nighttime ionosphere. However, Abdu (2012) in his review noted that the exact nature of the control of AGWs on ESF variability was yet to be understood.

Although several reports of the occurrence of nighttime SF exist in the literature, there are far fewer reports, in comparison, of daytime SF. Bowman et al. (1987) noted that daytime occurrences of SF at midlatitudes were so low that they were regarded as completely absent. In Jiang et al. (2016), results from the analysis of a ~2 h long daytime spread F event at Puer (PUR; 22.7°N, 101.05°E; dip latitude 12.9°N) were presented. The event, which was not observed at a neighboring location with similar local time, but at a lower latitude, was also not associated with any extreme atmospheric disturbances such as a typhoon. However, iso-height plots of electron density variations indicated a downward movement of the phase velocity of TIDs in the ionosphere ~2 h before the SF event. They concluded that downward vertical neutral winds excited by TIDs were likely responsible for the downward movement of the ionosphere and triggered the SF event. Yang et al. (2018) reported three different SF events occurring from 0630 to 1130 LT on January 6, 2017 at a midlatitude station. They showed that local F-region electrodynamics were the most likely controlling factor for the first event while the other two events were associated with TID/AGW modulation of the overhead ionosphere. Li et al. (2018) observed daytime spread F-like irregularities in the topside F-layer from the Fuke VHF radar (19.3° N, 109.1° E; dip latitude 14° N). Shortly before the irregularities were observed, a GNSS receiver located ~120 km from the Fuke radar detected a depletion in total electron content (TEC) measurements. These observations were coincident with the passage of a rocket about 300 km in longitude away from the GNSS receiver. Li et al. (2018) suggested that the irregularities in the ionosphere were due to the RTI following the creation of a plasma hole induced by rocket exhaust.

Woodman et al. (1985) reported two daytime spread F-like disturbances recorded by the Jicamarca radar near the geomagnetic equator. These events were the only two seen out of the vast number of experiments with usable data available from the Jicamarca observatory. Chau and Woodman (2001) presented another rare daytime spread F-like disturbance seen in the range-time diagrams from the Jicamarca radar. Although no definite mechanism was established for the Jicamarca events, Woodman et al. (1985) suggested that they may be related to fossil bubbles. It is worthy of note that the daytime F-layer irregularities reported by Woodman et al. (1985) and Chau and Woodman (2001) could not be observed in ground-based ionosonde data because they occurred on the topside F-region (~600 km).

Kil et al. (2020) and Xie et al. (2020) provided more observational evidence of daytime plasma density irregularities in the low latitude F-layer. Kil et al. (2020) noted that the daytime ionospheric plasma irregularities observed by ROCsAT-1 satellite were closely associated with nighttime bubbles and suggested that the daytime events were fossils of the previous nighttime bubbles. However, it was observed that the nighttime events were concentrated near the magnetic equator whereas the daytime events tended to occur away from the magnetic equator. They associated this observation with the fountain effect. The results from VHF radar and satellite in situ measurements in the study by Xie et al. (2020) also showed that daytime F-region plasma density irregularities at low latitudes were due to remnants of EPBs from the previous night.

Although several studies have reported the occurrence of daytime SF at low and higher latitudes, daytime observations of equatorial SF are sparse. However, when these events occur, they adversely impact HF radio signals. Hence, an understanding of the conditions under which they occur will contribute to improving HF signal propagation at equatorial latitudes. In addition, the results presented herein provide an overview of the ionospheric diagnostic capabilities of the HF Doppler sounder installed in Nigeria, especially as there are few observational instruments and data available from this equatorial region.
2. Data and Methods

The HF Doppler instrument consists of a transmitter located at Abuja (ABU: geographic: 7.39°E, 8.99°N; dip latitude −1.37°) and a receiver stationed in Lagos (LAG: geographic: 3.27°E, 6.48°N; dip latitude −1.72°). The HF receiver consists of a digital receiver (WR-G313i), an external reference oscillator, an active loop antenna, and a personal computer. During the period of the study, the receiver was tuned to a frequency of 6.957 MHz, transmitting from ABU. Ionograms from the Digisonde at Ilorin (ILR: 4.68°E, 8.50°N; dip latitude −1.25°) were accessed from Lowell Global Ionospheric Radio Observatory (GIRO) Data Center (LGDC). The LGDC is a data-sharing facility where data providers submit ionogram and drift data, while the task of ensuring the quality of submitted records is undertaken by the LGDC (Reinisch & Galkin, 2011). In addition to providing quality control of submitted data, the LGDC provides services like cataloging data for queries, data safeguarding, and long-term preservation, software development for the derivation of secondary data products and displays, for example, Automatic Real-Time Ionogram Scaler with True height (ARTIST). Figure 1 shows the approximate locations of the HF Doppler receiver and transmitter, and Digisonde. The ionograms from ILR are available on the database at 15 min intervals. For the two events presented in this paper, the automatically scaled hmF2 was used. However, the data points with obvious disparities between the ionogram traces and scaled parameters were manually scaled using the interactive ionogram scaling software, SAO Explorer (v 3.5.3). Figure 2 shows an example of an ionogram during Event 1 (1500–1800 UT, September 30, 2019) where there is an obvious disparity between the ionogram trace and the automatically scaled parameters. For example, in Figure 2a, h'F2 was automatically scaled using the second hop signal trace instead of the main reflected signal trace. The ionograms at 0745, 0945, 1215, 1330, 1600, 2030, 2045, and 2230–2330 UT were also manually scaled. Comparison of automatically and manually scaled true height of the F2 layer (hmF2) during Event 1 is shown in Section 3.

To determine the occurrence of TIDs during these events, the time series of hmF2 and electron densities from the Digisonde, and TEC derived from GNSS data were visually inspected for variations. TIDs manifest as quasi-periodic oscillations in ionospheric plasma density and are characterized by a range of periodicities depending on the category of TID. Large-scale TIDs are reported to have periodicities of 50 min—3 h while medium-scale TIDs usually have periodicities of 15—60 min (Hocke & Schlegel, 1996). TIDs have been demonstrated to manifest in GNSS data as quasi-periodic oscillations in the slant TEC (sTEC) (Hernández-Pajares et al., 2006). GPS TEC from at least four different locations in Nigeria was processed to investigate the presence of TIDs during these events. To investigate the occurrence of large-scale wave structures (LSWS) during these events, the data from Malindi, Kenya (MAL: geographic: 40.19°E, 2.99°S; dip latitude −10.12°) and Yamoussoukro, Cote d’Ivoire (YKRO: geographic: 5.24°W, 6.87°N; dip latitude −0.90°) were also analyzed. MAL and YKRO were the closest locations to Nigeria from which GPS data were available during these events. The GPS Receiver Independent Exchange Format (RINEX) files for MAL and YKRO
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were downloaded from the University Navstar Consortium (UNAVCO) website while those from Nigeria were obtained from the Office of the Surveyor General of the Federation and TeroNet. The data were processed with the GPS-TEC analysis software developed by G. K. Seemala, Indian Institute of Geomagnetism, Navi Mumbai, India. The output sTEC from the software are returned at $\sim 30\, \text{s}$ intervals. To determine the presence of TIDs, the TEC data were smoothed using a 40 min running average, and then the low-passed data were subtracted from the original time series. This method is similar to the one used by other authors, for example, Azeem et al. (2017).

The gravity term in the linear growth rate of the RTI was computed using Equation 11 in Huang et al. (1993):

$$\gamma_g = \frac{g}{L v_{in}}$$

(1)

where $g$ is the acceleration due to gravity, $L$ is the electron density gradient scale length, and $v_{in}$ is the ion-neutral collision frequency. For horizontally propagating waves, the collisional RTI is predominantly dependent on gravity and the electron density gradient scale length (Ossakow, 1979); therefore, the wavelength term in Equation 11 in Huang et al. (1993) was ignored. The electron density gradient scale length $L$ is given as (Huang et al., 1993)

$$L = \left( \frac{1}{N} \frac{dN}{dZ} \right)^{-1}$$

(2)

where $N$ is the ionospheric electron density and $Z$ is the altitude in the ionosphere. The ion-neutral collision frequency $v_{in}$ was computed as given by Schunk and Nagy (1980):

$$v_{in} = C_{in} n_{n}$$

(3)

where $C_{in}$ is a numerical coefficient with values provided in Table 6 of Schunk and Nagy (1980), and $n_{n}$ is the number density of neutrals. Electron densities were obtained from the Digisonde while the neutral number densities were obtained from the NRLMSISE-00 Atmosphere Model (Picone et al., 2002), hosted by the Community Coordinated Modeling Center (CCMC).

3. Results

Details of the two daytime ESF-like events are presented.
3.1. Event 1 (1500–1800 UT, September 30, 2019)

This event occurred with clear signatures in the HF Doppler spectrograms and ionogram traces. Selected frames from the ionograms, showing the disturbances, are provided in Figures 3 and 4 while the corresponding HF Doppler spectrograms are shown in Figure 5. For comparison, an undisturbed interval in the HF Doppler spectrogram is shown in Figure 6. In Figure 3a, the disturbance first appeared in the ionograms at ~1500 UT and was localized at the bottom of the F-layer trace at a virtual height ~320–360 km. The altitude of the disturbance in the F-layer reached its peak at ~1600 UT (Figure 4a) at the F-layer critical frequency ~7–8 MHz, and virtual height of ~400–500 km. Close inspection of Figures 3a and 3b shows that the irregularity highlighted in blue ovals resembles range type spread F (RSF) while the irregularity highlighted in Figures 3d and 4a is a typical signature of TIDs, for example, Harris et al. (2012). Figures 4b–4d show the spread returning to the bottom of the trace. In Figure 5a, spreading in the Doppler signal starts at ~1515 UT, although the first appearance of oscillations (with a period of ~15 min) in the signal is at ~1454 UT. The oscillations and spreading in the Doppler signal continue until about 1750 UT while daytime F-region irregularities in the ionograms ceased by ~1715 UT. To further investigate whether the observed...
disturbances in the F-layer trace of the ionograms were the same as those detected by the HF signal, the equivalent vertical incident frequency of the oblique transmission frequency from ABU was computed using the secant law of HF radio wave propagation.

\[ f_{\text{oblique}} = f_{\text{vertical}} \sec \theta \]  

(4)

where \( f_{\text{oblique}} \) is the transmission frequency from ABU incident on the ionosphere at an angle \( \theta \), and \( f_{\text{vertical}} \) is the equivalent vertical incident transmission frequency of the signal from ABU, that is, \( f_{\text{oblique}} \). To compute \( \theta \), the distance from ABU–ILR was obtained from Figure 1 as 315 km while \( h_{\text{mF2}} \) was obtained from the ionogram at each epoch. The computed values at 15 min intervals (based on the time intervals of the ionograms) are shown in Table 1. Time intervals during which spreading was not evident in the ionogram F-layer trace are not included in the Table.

The calculated values of \( f_{\text{vertical}} \) fall within the range of Digisonde frequencies corresponding to the peak height of occurrence of the irregularity. The only exception occurred at 1645 UT. It should be noted that the

Figure 4. Selected ionograms from the Digisonde at ILR during the spread F event, September 30, 2019, 1600–1715 UT. The blue ovals in (a–d) show the location of the irregularities in the F-layer trace.
Figure 5. Selected spectrograms from the HF Doppler receiver during the spread F event, September 30, 2019. (a) The steady ~1 Hz Doppler shift, visible especially during 1454–1508 UT, is the signal reflected from the E-layer. (b) Spreading in the trace appears more severe at some points (e.g., blue oval) than at others (e.g., black oval). (c) Severe spreading continues ~1642–1722 UT.
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ionospheric reflection points of the HF signal and Digisonde signals are not coincident, as shown in Figure 1. An approximate distance of 135 km separates both locations; therefore, a time lag may exist between the events detected by the Digisonde and HF Doppler instrument. An interesting observation in Figure 5 is that the disturbance in the HF Doppler signal is not occurring with uniform severity during the whole period. The highest levels of disturbance occur around the time periods shown in Table 1 when $f_{\text{vertical}}$ falls within the range of Digisonde vertical incidence frequency at the height of the spread. The significant disturbance is also seen in the HF Doppler spectrogram at $\sim 1600$ UT when a TID signature appeared in the ionograms.

Figures 7a and 7c show the time series of $h_m F_2$ and $f_0 F_2$ obtained from the Lowell Digisonde at ILR. The automatically and manually scaled data are shown. Electron density contours and iso-height electron density variations from the manually scaled ionograms are shown in Figures 7b and 7d, respectively. Of particular interest are the $\sim 30$ min oscillations in Figure 7b, which are highlighted with black arrows. In Figure 7d, the same oscillations appear in the iso-heights of electron densities. However, it should be noted that the oscillations in electron densities occurring before noon were attenuated above 270 km as seen in Figure 7d. Another significant observation is that in Figure 7b, elevated values of electron density started to appear at about the same time that the highlighted oscillations in electron density appeared. This combination of oscillations in the ionospheric layer and increased electron density likely facilitated the development of the irregularities observed in the Digisonde and HF Doppler traces. The oscillations identified in Figures 7b and 7d can also be seen in Figures 7a and 7b. However, more information can be derived from Figures 7b and 7d. The TID signature highlighted in Figure 4a and the oscillations in electron density (Figures 7a and 7b) appear to be different signatures of the same disturbance which triggered the ESF-like event. The sTEC from selected PRNs with elevation angles $>20^\circ$ and visible over LAG during this event are shown in Figure 8. GPS TEC from other locations is provided in the supporting information. The interval of the ESF-like event is shown in the boxed area. However, the interval where oscillations in sTEC, similar to those seen in isodensity contours (Figure 7b), are present is highlighted by the double arrow. It should be noted that the sampling interval of the Digisonde data is 15 min while that of the HF Doppler data is 10 s. Therefore, higher frequency oscillations are evident in the HF Doppler data compared with the Digisonde data. Similarly, to emphasize higher frequency oscillations in the GPS TEC data, the filtered data using a 10 min sliding window are

Table 1

| Time (UT) | $h_m F_2$ (km) | Digisonde frequency corresponding to ESF altitude (MHz) | $f_{\text{vertical}}$ (MHz) |
|-----------|----------------|---------------------------------------------------|---------------------------|
| 1500      | 341.2          | 4.5–5.0                                           | 4.719                     |
| 1515      | 333.0          | 4.4–4.8                                           | 4.780                     |
| 1645      | 314.4          | 5.5–5.6                                           | 4.924                     |
| 1700      | 295.9          | 5.0–5.2                                           | 5.070                     |
| 1715      | 309.8          | 4.9–5.6                                           | 4.960                     |

Abbreviation: ESF, equatorial spread F.
The period of oscillations in the arrowed portion in Figure 8 is 256 s (≈4 min) while for ABU (Figure S2 in supporting information), the period of oscillation is 768 s (≈13 min). FFT of the data in this interval are provided in Figure S1 of the supporting information. The oscillations in Δ sTEC evident at LAG and ABU were not as distinct at the other locations.

The gravity term of the linear growth rate of the RTI, given by Equation 1, was computed for selected epochs during the occurrence of irregularities and is plotted in Figure 9. It should be mentioned here that when

**Figure 7.** (a) Peak height of the F2-layer (hmF2), (b) contour plot of the electron density profiles, (c) critical frequency of the F2-layer (foF2), and (d) iso-heights of electron densities obtained from the Digisonde at ILR September 30, 2019 (LT = UT + 1). The black arrows in (b) highlight oscillations in electron density during the interval of the event indicated by the dashed rectangle.

**Figure 8.** sTEC from PRN 7, visible over LAG during the ESF-like event September 30, 2019. The raw sTEC and satellite elevation angles are shown in the top panel. Variations in Δ sTEC are shown in the middle panel (the filtered data using a 10 and 40 min running mean are shown) while the IPP latitudes and longitudes are shown in the bottom panel. The red dashed rectangle indicates the interval of occurrence of the event, while the double arrow in the middle panel shows the interval where the oscillations of interest are most prominent.
the ionograms are automatically scaled, the electron density profile computed by the inversion program is provided at 5 km height intervals. However, when the ionograms are manually scaled, the electron density profile obtained is at 10 km height intervals. During the interval of this event, only the ionograms at 1600 UT and 1615 UT required manual scaling. Hence, the scale of the GRTI axis in Figure 9c is different from the scale for the rest of Figure 9. A distinct peak in the growth rate is evident at 1445 UT while another peak is evident at 1600 UT. Due to the different height intervals used in computing the electron density scale height in Figures 9a and 9c, it is not easy to make a direct comparison of the GRTI seen at these two epochs. However, it is obvious that a distinct increase in the GRTI occurs at both of these epochs. The peak in GRTI observed at 1445 UT can be attributed to the initial impact of the TID on the ionospheric layer, which was about the time that oscillations first appeared in the Doppler signal and isodensity contours. The second peak in GRTI at 1600 UT coincided with the appearance of the most prominent peak in isodensity contours during the interval of the event (Figure 7b). Beyond 1800 UT, the rise in hmF2 in Figure 7a (and the corresponding increase in the linear growth rate of the RTI in Figure 9f) is indicative of the evening pre-reversal enhancement. In addition, an increase in the linear growth of the RTI at two different ionospheric heights is noticeable from 1700 UT.

3.2. Event 2 (1445–1800 UT, July 23, 2019)

This event was accompanied by spread sporadic E (spread Es). Hence, the F-layer traces were occasionally, either blanketed by the Es layer or showed no spreading at all. However, the intervals during which irregularities were most evident in the ionograms are shown in Figure 10 (and Figure S6 in the supporting information) while the Doppler spectrograms are shown in Figure 11. Of importance is the distinct stratification of the Es layer in Figure 10a which can be observed in the height interval ~100–150 km. A similar stratification is also present in Figure S6a in the supporting information. Spreading in both range and frequency in the F-layer trace is visible in Figures 10b and 10c. Interference at the critical frequency of the main trace signal and the multiple hop signals can be seen in Figure 10d. The multiple hop Es layer trace also overlaps the bottom of the F-layer trace in Figure 10d. During the intervals at 1500, 1530, 1645, and 1715 UT, the F-layer trace was completely blanketed by the Es layer. Compared with Figure 6, the Doppler spectrograms in Figure 11 show spreading during these intervals. The fairly constant spread centered about 1 Hz in the Doppler signal, especially in Figure 11b, is an indication that the spread was due to the Es layer during this
interval. Long period variations (∼1 h) in ΔsTEC were present for most of the day at the locations shown in Figure 1. GPS TEC for this event is provided in Figures S8–S11 in the supporting information.

4. Discussion

The two events presented occurred during intervals of low geomagnetic activity. SYM-H for 48 h prior to, and during these events was ≥ -50 nT. The distinguishing characteristic of the event which occurred on September 30, 2019 was the localization of the spread in the F-layer trace and its variation with altitude as the disturbance progressed with time. Li et al. (2018) observed F-layer irregularities which gradually rose in altitude in the range-time intensity map of the Fuke VHF radar. Li et al. (2018) noted that such an occurrence could be produced by two mechanisms. One is that a disturbance occurring at the same ionospheric layer and traveling along a meridian across the field of view of the radar can produce such an effect. The other possibility is that the ionospheric layer in which the irregularity is occurring can be raised.
Figure 11. Selected spectrograms from the HF Doppler receiver during the spread F event, July 23, 2019. Spreading along the length of the trace is nearly uniform in (a and b). However, the disturbance in (c) is more diffuse than in the upper panels, possibly signifying a difference in the mechanism associated with the irregularities in (a and b) compared to (c).
in altitude. With regard to the first mechanism, there were no nearby stations on closely spaced meridians with ILR having ionosonde data with which to verify this mechanism. However, quasi-periodic ~30 min oscillations were observed in isodensity contours and iso-heights of ionospheric electron density from the ILR Digisonde during this event. Higher frequency (~4 min) oscillations in ΔsTEC were observed in the data from the GPS receiver at ABU during this interval, while ~13 min oscillations were observed in the ΔsTEC from LAG. These oscillations were not as distinct at any of the other GPS receiver locations included in the study. The oscillations in ΔsTEC from LAG more closely matched the observed oscillations in HF Doppler shift, both in frequency and timing of occurrence. However, a very interesting observation is that the oscillations in ΔsTEC from ABU (with a period of 256 s) were an exact harmonic of the oscillations observed in ΔsTEC from LAG (with a period of 768 s). Harris et al. (2012) investigated the occurrences of small spatial scale ionospheric disturbances that were localized to within a radius of 500 km. Although these disturbances were associated with TIDs, it was suggested that a spatial separation of less than 100 km for probing the ionosphere would be required to fully characterize the mechanisms for these disturbances. A distinguishing characteristic of Event 1 from those reported by Harris et al. (2012) is that Event 1 had a longer temporal scale (nearly 2 h) while the events reported by Harris et al. (2012) lasted ~10 min. The disturbances that characterized Event 1 appear to be small-scale disturbances which did not propagate over distances >800 km (i.e., the approximate distance from LAG–CBCR). Several authors have highlighted the role of AGWs/TIDs in the development of ESF. For instance, Ossakow (1979) noted that AGWs can provide the initial trigger for the linear growth of the RTI in ESF development. Huang et al. (1993) also noted that gravity waves are more likely to initiate the RTI in the nighttime compared with daytime due to the absence of a highly conducting E region at night. Abdu (2012) discussed the role of AGWs in directly seeding ESF. He noted that the role of AGWs appeared to be more prominent when the PRE was weaker. Although the scale on the GRTI axis in Figure 9(c) is different from that in the rest of the figure, a distinct peak in the growth rate of the RTI is noticeable at two different epochs. The peak which occurred at 1600 UT, about the time that the disturbance reached the peak height of the F-layer, is in agreement with findings by other authors, for example, Jayachandran et al. (1993). The other peak at 1445 UT can be attributed to the initial impact of the TID on the ionosphere. The increase in growth rates from 1645 UT is likely due to the gradual disappearance of the E-layer during these epochs.

Event 2 was mostly characterized by uniform spreading along with the entire extent of the F-layer trace as seen in Figures 10b and 10c. The disturbance in the HF Doppler signal during this event (Figures 11a and 11b) was also mostly uniform, compared with that during Event 1 (Figure 5). The feature in the ionograms in Figures 10b and 10c, called “satellite traces” by Bowman et al. (1987), was shown to be closely associated with TIDs and caused by reflections from replicas of the reflecting ionospheric layer. An ionospheric reflecting layer can become stratified or tilted by a TID for instance. When this occurs, the ionograms will register reflections from the stratified plasma density distribution as overlapping multiple echo traces like those in Figures 10b and 10c. Satellite traces can also be characterized by slightly different foF2 values (Bowman et al., 1987). The study by Tsunoda (2015) described ESF in the bottomside F-layer and EPBs within the F-layer as products of an upwelling of the ionospheric layer. An upwelling, which is described as an upward modulation of isodensity contours in the bottomside F-layer, can occur singly or in a group of several upwellings, in which case they are known as LSWS. LSWS also appear as variations in TEC with longitude. Three phases were associated with the development of these upwellings—the growth, onset, and structure phases. The growth phase, like the name suggests, is when amplification of the upwelling amplitude occurs. During the onset phase, the first EPB of the event is observed, while in the structure phase, EPB clusters and ESF patches become more developed and appear within each upwelling. Although the sources of LSWS remain a longstanding question, AGWs have been suggested as a very likely source.

Close examination of Figure 10a shows at least two distinct Es traces in the height interval ~100–150 km. Such horizontal stratification is also present in the Es layer in Figure 10d, although not quite as prominent as in Figure 10a. Earle et al. (2010) identified six distinct F-layer traces in the ionogram generated from the Dynasonde at Wallops Island during a mix spread F event. Due to improved height resolution of the Wallops Island Dynasonde over the regular Digisonde, the ionograms from the Dynasonde were able to resolve six distinct overlapping O-mode traces of the spread F-layer. Although the Digisonde at ILR does not possess the resolving capabilities of the Dynasonde, at least two distinct traces were evident in the Es traces. Bowman (1985) reported a close association of midlatitude spread Es and SF occurrences in their statistical
study. Therefore, it was suggested that both spread Es and SF at midlatitudes were triggered by the same or similar disturbance. Experimental evidence presented by Bowman (1985) showed that it was unlikely that the closely related spread Es and SF events were caused by small-scale irregularities arising from F-region electrodynamics. Therefore, more evidence pointed to the role of TIDs in producing the satellite traces. Yang et al. (2018) similarly observed the occurrence of midlatitude spread Es and SF during the daytime and suggested a contribution of TIDs in their occurrence. The Digisonde automatic scaler was unable to provide any output during the interval of this event (isodensity contours and iso-heights of the electron densities before this event are provided in Figure S7 in the supporting information). However, analysis of GPS TEC from the locations in Figure 1 (Figures S8–S11 in the supporting information) showed variations in ∆sTEC with longitude, especially over the locations in Nigeria. This is consistent with the signature of LSWS, which were likely to have triggered the satellite traces seen in the ionograms.

5. Summary and Conclusions

The results from analyses of two case study daytime ESF-like events have been presented in this study. Although daytime SF near the magnetic equator is a rare occurrence, these results show the characteristics and associated mechanisms of daytime bottomside ESF-like events. The first event was characterized by variations in ionospheric electron density from ILR and in ∆sTEC from ABU and LAG. Although the frequency of oscillations in ∆sTEC from ABU and LAG were different, the frequency of oscillations in ∆sTEC from ABU were harmonic of those from LAG. The appearance of harmonic frequencies at such closely spaced locations will require further investigation in a future study. The ∼15 min oscillations in the HF Doppler shift more closely matched the oscillations in ∆sTEC from LAG. The oscillations present in the electron densities obtained from the Digisonde at ILR had a periodicity of ∼30 min. Higher frequency oscillations could not be detected in these data due to the 15 min sampling interval of the data. Small-scale irregularities appeared on the bottomside F-layer following the impact of a TID. The progress of this event was marked by a gradual evolution in the height of the irregularities, which closely followed the modulation of the peak height of the F-layer by the TID. Computation of the growth rate of the RTI showed a peak in growth rate at the F-layer peak height, in agreement with previous studies. The event which lasted ∼2 h adversely impacted HF signal propagation through the ionosphere at the time of the event. The small scale disturbances which characterized Event 1 did not appear to propagate over distances >800 km. The variations in ∆sTEC with longitude which characterized Event 2 are consistent with the description of LSWS. The upward modulation of ionospheric electron density associated with LSWS is known to cause tilting of the reflecting ionospheric layer, thereby producing overlapping replicas of the F-layer trace (otherwise known as satellite traces).

The HF Doppler instrument provides continuous monitoring of the equatorial ionosphere over Nigeria. Observations of the Doppler spectograms show that small-scale irregularities are more visible or more easily detected in the Doppler than Digisonde signals. The results from this study are the first from simultaneous monitoring of this region of the equatorial ionosphere using both the Digisonde and the HF Doppler receiver, to the best of the knowledge of the authors.

Data Availability Statement

HF Doppler spectograms are available at the Department of Radiophysics of Geospace website (http://geospace.com.ua/en/index.html).

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