Observations of Unusual Daytime Range Spread F at Middle Latitude During the Afternoon Hours

Lehui Wei¹, Chunhua Jiang¹, Ting Lan², Wenxuan Wang¹, Hua Shen¹, Ercha Aa³, Wengeng Huang¹, Jing Liu¹, Guobin Yang¹, Yaogai Hu¹, and Zhengyu Zhao¹

¹School of Electronic Information, Wuhan University, Wuhan, China, ²School of Computer, Huanggang Normal University, Huanggang, China, ³National Space Science Center, Chinese Academy of Sciences, Beijing, China, ⁴Haystack Observatory, Massachusetts Institute of Technology, Westford, MA, USA, ⁵Institute of Earthquake Forecasting, China Earthquake Administration, Beijing, China

Abstract In this study, an unusual daytime range spread F event recorded by the ionosonde installed at Zhangye (ZHY, 39.4°N, 100.13°E, dip latitude 29.65°N) station during the afternoon of December 23, 2016 was presented. Daytime spread F during the afternoon hours have seldom been reported at midlatitude regions. In addition, observations of daytime spread F are mostly the frequency spread F. In this case, daytime range spread F and spread Es in the midlatitude region were simultaneously observed during the afternoon hours (15:15-16:00 LT). Moreover, some distorted traces of the main traces occurred on ionograms during the morning. The result of these observations seems to indicate that these extra traces and daytime diffused echoes on ionograms might be attributed to the same ionospheric disturbances phenomenon. Analysis of the iso-frequency of ionospheric virtual height from ZHY ionosonde data during this event revealed the presence of wave-like disturbances consistent with traveling ionosphere disturbances (TIDs)/atmospheric gravity waves (AGWs). The periods of TIDs on this day are in a range of 20–70 min that can be roughly classified into MSTIDs. We found that the daytime range spread F might be induced by the passage of ionospheric wave-like structures caused by TIDs/AGWs. In addition, the seeding of TIDs/AGWs might be attributed to the stratospere gravity waves over the Qinghai-Tibetan Plateau, which causes the coupled of the atmosphere-ionosphere-thermosphere to significantly impact the ionosphere.

Plain Language Summary Spread F, as a manifestation of ionospheric irregularities in the F layer, has been widely regarded as a nighttime phenomenon. Recently, daytime spread F events/ ionospheric irregularities/plasma bubbles have also been reported by many researchers in the ionospheric community. Most of the daytime spread F events mainly occur in the sunrise and morning hours, and almost rarely occur in the afternoon, especially in midlatitude regions. Moreover, daytime spread F is mostly associated with frequency spread F. Range spread F or mixed spread F is seldom reported at daytime. Can the range spread F or mixed spread F occur during the daytime? In this study, an unexpected daytime range spread F was reported at middle latitudes (Zhangye station, 39.4°N, 100.13°E) during the afternoon hours. We think that the daytime range spread F might be due to the passage of ionospheric wave-like structures caused by traveling ionosphere disturbances/atmospheric gravity waves at Zhangye station, where the active stratospere gravity waves over the Qinghai-Tibetan Plateau could propagate upward to the ionosphere caused the coupled of the atmosphere-ionosphere-thermosphere.

1. Introduction

Spread F is a typical irregularity phenomenon in the F region of the ionosphere, which is manifested as the main F2 layer traces with spread or diffuse echoes on ionograms (Booker & Wells, 1938). A large number of observations and theory studies have indicated that ionospheric spread F mainly occurs in the nighttime (Aa, Zou, & Liu, 2020; Woodman, 2009), and its temporal and spatial characteristics and physical mechanism at nighttime have been already presented with mature results and conclusions. However, spread F occurred at daytime is seldom reported in the ionospheric community. Due to the striking differences in the ionospheric background state between nighttime and daytime, such as the ion-electron recombination rate and growth rate, electric field, neutral wind, etc., the triggering mechanism and characteristics of spread F during the daytime and nighttime might be quite different. The primary instability mechanism of nighttime spread F
in equatorial and low-latitude regions is Generalized Rayleigh-Taylor (GRT) instability (Abdu, 2001; Krall et al., 2013; Zhu et al., 2015). In the middle latitudes, the formation mechanism of the nighttime spread F is mainly due to two physical mechanism: Perkins instability (Perkins, 1973) and ionospheric wave structures (Bowman, 1990; Huang et al., 1994). In terms of GRT instability and Perkins instability, they both generate an electric field inside the ionospheric F layer, and then develop into ionospheric irregularity structures. However, this situation is difficult to happen in the daytime. Due to the dynamo effect of the E layer, the electric field in the E region can be mapped into the F region through the magnetic field lines, driving the plasma movement in the F region. In other words, the F layer acts as a load of the E layer dynamo in the daytime. The internal electric field in the F region could be shorted out by the E region electric field, and the electron density gradient at the bottom of the F layer at daytime is also smaller than nighttime (Kelley, 1989). Therefore, there is no favorable background condition for the generation of daytime spread F in the ionosphere. However, the physical mechanism of the wave-like structures of the ionosphere caused by TIDs is not limited by time, TIDs caused by geomagnetic storms or gravity waves in the lower and middle atmosphere may occur during the day and night (e.g., Aa, Zou, Eastes, et al., 2020; Hocke & Schlegel, 1996; Huang et al., 1993). On the other hand, under some special environments such as geomagnetic storms or extreme space weather phenomenon, ionospheric irregularities could also generate at dayside hours (e.g., Chau & Woodman, 2001; Huang et al., 2013; Li et al., 2012; Vats et al., 1978; Xiao et al., 2012).

During past several decades, daytime spread F has occasionally been observed by various observation tools, such as ionosondes, VHF radars, topside sounders, ground-based airglow measurements and satellite systems. As a result, daytime spread F has gradually attracted the attention of many scientists. Dyson (1977) analyzed Alouette I ionograms recorded at Singapore and found that the probability of daytime spread F in the topside ionosphere cannot be ignored. Aarons (1977) and Chandra et al. (1995) observed many daytime F-region scintillations at the equatorial and low latitude regions. Woodman et al. (1983) and Chau and Woodman (2001) also occasionally observed daytime spread F-like irregularities in the top of the ionosphere between 14:00 and 16:00 LT by the Jicamarca radar and suggested there is currently no clear physical mechanism to explain it. Huang et al. (2013) reported a long-lasting (~12 hr) daytime equatorial plasma bubbles from the post-midnight sector through the afternoon sector (~02:00-14:00 LT) and suggested that the overshielding electric field and the storm time disturbance dynamo might play an important role in forming daytime bubbles. Jiang et al. (2016) suggested that downward vertical winds caused by gravity waves might be important for the daytime spread F (08:30-10:45 LT) at low latitude during geomagnetic storms. Kil et al. (2019, 2020) observed daytime plasma bubbles in the equatorial F region and suggested that daytime irregularities developed on previous nights might be associated with the ionospheric fountain effect on the dayside. Xie et al. (2020) reported a high appearance of daytime F-region backscatter echoing structures over low latitude Sanya by VHF radar, and considered it was remnant of equatorial plasma bubble irregularities developed on the previous nights. Luo et al. (2020) reported the post-sunrise plasma irregularities at low latitude region during a moderate geomagnetic storm and considered that these plasma irregularities were not developed from the previous night, but were newly generated near sunrise hours due to the disturbance of the dynamo electric field. It is worthy to note that Olugbon et al. (2021) presented two daytime equatorial spread F events by the HF Doppler receiver and indicated that wave structures related to TIDs were responsible for the daytime ESF-like irregularities. In the middle latitude regions, Bowman et al. (1987) found that distorted traces of the main traces on daytime ionograms were caused by the passage of TIDs, and suggested these daytime distorted traces was a kind of the spread F-phenomenon. Li et al. (2012) presented long time existence of midlatitude plasma bubbles after sunrise by the Defense Meteorological Satellite Program in-situ measurements and suggested that an eastward electric field associated with the disturbance dynamo was responsible for the daytime irregularities. Park et al. (2015) reported a dayside plasma depletion (~10 LT) at low-altitude midlatitude ionospheric F-layer during a geomagnetically quiet periods. Yang et al. (2018) also showed three cases of daytime spread F (06:45-08:35 LT, 09:50-10:30 LT, 11:10-11:30 LT) at middle latitude during a geomagnetic storm and suggested the physical mechanisms of these cases might be different, one case was due to local F region electric field, the other two cases might be attributed to ionospheric wave-like structure caused by TIDs/AGWs.

Although the daytime spread F phenomenon occasionally occur and the occurrence rate is much lower than that at nighttime, the temporal and spatial distribution of the daytime ionospheric irregularities implies that its influence on the space weather is significantly important, and its physical mechanisms cannot
be replaced simply by that of spread F usually occurred at the nighttime. Therefore, the observational accumulation and study of the daytime spread F can provide more opportunities for further investigating its characteristics and physical mechanisms. This paper, is the first to report an unexpected daytime spread F phenomenon occurred during the afternoon hours in the midlatitude regions of northwestern China. Previous statistical studies have indicated that the occurrence time of daytime spread F in the equatorial and low latitude regions covers the entire daytime, including sunrise to noon (Dyson, 1977; Jiang et al., 2016), midday (Huang et al., 2013), and 14.00LT-16.00LT in the afternoon (Chau & Woodman, 2001). So far daytime spread F in midlatitude regions has been reported between early morning and noon (e.g., Li et al., 2012; Park et al., 2015; Yang et al., 2018), the occurrence time of daytime spread F during the afternoon hours is even unexpected. Moreover, mostly spread F occurred at daytime is associated with frequency spread F, Range spread F or mixed spread F is seldom reported at daytime. Can the range spread F or mixed spread F occur during the daytime? In this study, we report an extremely unusual feature of the daytime spread F at midlatitude during the local time mid-afternoon hours. It is associated with range spread F and mixed spread F. The purpose of this study is to investigate the morphological features of the daytime spread F at middle latitude regions and attempt to reveal possible physical mechanisms leading to the occurrence of daytime range spread F.

2. Data and Methodology

The data used in this study are from the records of the digital ionosonde, Wuhan Ionospheric Sounding System (Shi et al., 2017, and references therein) developed by the Ionosphere Laboratory Wuhan University, that was installed at Zhangye (ZHY, 39.4°N, 100.13°E, dip latitude 29.65°N) in the Northwest of China. Its operating frequency is 2–20 MHz, and it can obtain a vertical sounding ionograms every 5 min. The relevant software tool, ionoScaler, designed by Jiang et al. (2017) can implement automatic and manual scaling of the ionograms. As used herein, the ionospheric parameters data, foF2 (the critical frequency of the F2 layer), h′F2 (the base virtual height of the F2 layer) and hvEs (the base virtual height of the Es layer) from ZHY station ionosonde are manually scaled by using ionoScaler. In addition, the main trace of O mode wave is manually extracted from ionograms. The manual traces are smoothed to fit the recorded ionograms. Then, we can obtain the ionospheric parameters from the fitted traces.

The Vertical Total Electron Content (VTEC) derived from GNSS data and the amplitude scintillation index S4 data (only data with elevation>40° were chosen) at Zhangye station from the Space Environment Prediction Center (SPEC) are adapted in this study. The SPEC is affiliated to the National Space Science Center (NSSC) of the Chinese Academy of Sciences (CAS). Since 2005, SPEC has established an ionospheric GPS monitoring network near the Equatorial Ionospheric Anomaly (EIA) crest regions over Southern China. The monitoring network includes seven stations in Fuzhou (25.9°N, 119.3°E), Xiamen (24.3°N, 118.1°E), Guangzhou (23.0°N, 113.3°E), Nanning (22.7°N, 108.2°E), Hainan (19.4°N, 109.1°E), Kunming (24.7°N, 102.8°E), and Zhangye (39.2°N, 100.1°E), which can monitor ionospheric scintillation and regional GPS-TEC, with a time resolution of 1 min and 30 s, respectively. The amplitude scintillation index S4 has correlated with the size and structure of the ionospheric irregularities and been widely used in the study of the variations in plasma density and to predict the existence of ionospheric irregularities (Huang et al., 2014). In order to illustrate whether ionospheric irregularities appeared at ZHY station on December 23, 2016, the rate of change of TEC index (ROTI) was used to represent the presence of scintillation caused by ionospheric irregularities (Basu et al., 1999). The ROTI defined by Pi et al. (1997) is a good indicator of the existence of ionospheric irregularities and can be used to estimate the change characteristics of the structure of the ionospheric irregularities. Pi et al. (1997) suggested that the ROTI can be determined from the standard derivation of the rate of TEC(ROT) in a five-minute interval. In addition, the solar wind velocity (Vsw), geomagnetic indices (Dst and Kp) and interplanetary magnetic field (IMF) Bz component data are shown in this study. These data are respectively available from the following websites http://omniweb.gsfc.nasa.gov/ow_min.html, http://wdc.kugi.kyoto-u.ac.jp/ and www.srl.caltech.edu/ACE/ASC.
3. Results

Figure 1 shows (a) the solar wind velocity (Vsw), background geomagnetic indices of (b) Kp, (c) IMF Bz component, (d) Dst and ionospheric parameters at ZHY station (e) h'F2, (f) foF2 during December 20–26, 2016, respectively. The gray bars represent the occurrence times of daytime spread F at ZHY station.

Figure 1. Variations in different geophysical background (a) the solar wind velocity (Vsw), background geomagnetic indices of (b) Kp, (c) IMF Bz component, (d) Dst and ionospheric parameters at ZHY station (e) h'F2, (f) foF2 during December 20–26, 2016, respectively. The gray bars represent the occurrence times of daytime spread F at ZHY station.
21, 2016. The geomagnetic storm was in the recovery phase during December 23, 2016, and the ionosphere was relatively quiet at this time.

Figure 2 shows the evolutions of ionograms from 15:00 LT to 16:15 LT on December 23, 2016 over ZHY station, with a time interval of 5 min. The red ovals in Figure 2 represent the occurrence of daytime spread F on ionograms. It can be seen from the first three ionograms in Figure 2 that there is no spread phenomenon here. However, what is unusual is that at 15:05 LT, the F-layer echo seems to be modulated by some fluctuations, which makes the ionograms appear a cusp-like echo structure at the height of the F layer (∼270-300 km). Around at 15:10 LT, the cusp-like echo structure became blurred, it seems to show signs of spread. At 15:15 LT, the echoes of the F layer had also started to diffuse, accompanied with the slight range spreading on the F layer. After about 25 min, the intensity of range spread F gradually increased. At 15:45 LT, range spread F began to develop to mixed spread F with both range spread F and frequency spread F. Moreover, the second hop of the ionospheric F layer has been spread from 15:00 LT to 16:15 LT. At the same time, spread F was accompanied by the wide range spread Es which extend from about 110 km up to 200 km (Conventionally in the ionospheric community, spread Es is characterized by the Es traces spreading in a height range about 90–150 km, hereafter the spread Es indicates the wide range spread Es). The daytime
diffuse echo event in the ionospheric E and F layers lasts for ~45 min. At 16:00 LT, spread F and wide spread Es begin to fade over time, and then the ionograms return to its normal state at 16:05 LT.

To show diurnal variations of the ionosphere, the histogram (or image projection) technique (Jiang et al., 2013; Lynn, 2018) has been used to obtain the virtual height histogram from ionograms. Figure 3 shows the virtual height histogram of the ionograms. Yellow and red circles, respectively, indicate the presence of spread Es and spread F. It can be clearly seen from Figure 3 that the bottom of ionospheric F layer is undergoing significant and periodic wave-like disturbances. During the spreading, the strength ranges of the Es and F layers overlapped together. Interestingly, at ~11:00 LT, the downward movement of F1 layer and normal Es layer merged together at a height of ~120 km, and then the intensity of Es layer increased and lasted for ~3h. At around 15:15 LT, the spread Es layer and spread F layer appeared at the same time, as shown by the yellow and red circles. The spreading echoes lasted for about 45 min. After 16:00 LT, the spreading echoes and Es layer disappeared.

Figure 4 shows the variations of VTEC and ROTI at ZHY station on December 23, 2016. The shaded gray bars in Figure 4 indicate the onset time of daytime spread F. It can be seen from Figure 4 that the amplitude disturbances of VTEC and ROTI were small within the presence of the daytime spread F. The maximum value of ROTI was ~0.05 TECU (Total Electron Content Unit)/min during the presence of the daytime spread F.

Figure 5 shows the S4 index data at ZHY station obtained from different GPS (G) and Beidou (C) receivers from SPEC on December 23, 2016. The gray bar represents the duration of daytime spread F. As shown in Figure 5, during the daytime spread F, Only Beidou receivers (C02, C03) and GPS receiver (G17) recorded S4 scintillation data, and the maximum values of S4 index were ~0.09, ~0.07 and ~0.07 during the occurrence of daytime spread F, respectively.

4. Discussion

In the previous study, observational evidences showed that the seed sources of triggering daytime spread F/ionospheric irregularities at midlatitude regions can generally be summarized as the following: the remain of the plasma irregularities generated at the previous night (e.g., Huang et al., 2013; Li et al., 2012),
Figure 4. Variations in VTEC and ROTI on December 23, 2016 at ZHY station. The gray bars represent the duration of daytime spread F.

Figure 5. The variations of S4 parameter at ZHY station obtained by different GPS(G) and Beidou (C) receivers from SPEC on December 23, 2016. The gray bar represents the duration of daytime spread F.
Results and Discussion

Ionospheric irregularities newly generated at dayside hours (e.g., Xiao et al., 2012; Yang et al., 2018) and the passage of the wave-like disturbances in the ionosphere (e.g., Bowman et al., 1987; Jiang et al., 2019; Yang et al., 2018). In most cases, daytime spread F/ionospheric irregularities is due to the existence of long-lasting nighttime spread F. However, there was no spread F observed at ZHY station on the previous night, and the occurrence time of spread F is the afternoon hours. Thus, it might not be possible that daytime spread F in this event is associated with the remnant of the ionospheric irregularities on previous night. It is more likely to be freshly generated at afternoon hours. Furthermore, during magnetically disturbed conditions, it is suggested that the eastward electric field associated with the disturbance dynamo or the overshielding electric field might play an important role in developing daytime bubbles generated on previous night, which can last for a long time from low latitudes to middle latitudes (Huang et al., 2013; Li et al., 2012). As shown in Figure 1, the lightly uplift of h’F2 appeared before the onset time of daytime spread F indicated that the ionosphere was moving upwards at this time. And there was a minor geomagnetic storm occurred in the present event. It is reasonable to consider the prompt penetration electric field might be attributed to the generation of daytime spread F (Huang et al., 2013; Li et al., 2012). However, the IMF Bz component did not undergo an obvious southward reversal during the uplift of h’F2, and the occurrence time of daytime spread F is at the afternoon and no spread echoes phenomena were observed on the previous night on December 22, 2016. Therefore, it seems unlikely that the daytime spread F at midlatitude region is triggered by the eastward electric field caused by the minor geomagnetic storm.

It is obvious seen from Figure 2 that spreading echoes occurred on the E and F layers. The result for spreading echoes on the E and F layers reveal that it might have common mechanism source to develop. Similar observation presented by Yang et al. (2018) showed that the occurrence of midlatitude spread Es and spread F during the daytime is the contribution of TIDs caused by gravity waves passing in the ionosphere. As illustrated by Wei et al. (2021) and Bowman. (1985), that the passage of TIDs may play a significant role in influencing spread Es and spread F. Specifically, Wei et al. (2021) reported a similar phenomenon that midlatitude spread F and Es also occurred at ZHY station during the recovery phase of a geomagnetic storm and considered that the TIDs might play a significant role in forming satellite traces and spread F at middle latitudes. However, compared to the study reported by Wei et al. (2021), the former is during the night and this event herein is during the daytime. It should be noted that the appearance of TIDs is not limited by time, once it is beneficial to the trigger source of appearance, it may occur at any time.

To determine the possible occurrence of TIDs/AGWs during this event, the virtual height variations of (a) F layer and (b) Es layer at various iso-frequency were plotted in Figure 6. It should be noted that the uncertainty on the virtual height values is about ±3.84 km (height resolution). The virtual height data were smoothed in Figure 6b. Gray shaded area indicates the occurred time of the daytime spread F. The gaps in Figure 6b mean that there is no Es layer or no data. The oblique black lines in Figures 6a and 6b show that there is a downward movement of the phase velocity in Es layer and F layer of the ionosphere. It is the characteristic of the AGWs propagation in the ionosphere (Pezzopane et al., 2011). It is well known that TIDs manifest as quasi-periodic oscillations in ionospheric plasma density, which are generally considered as plasma manifestations of AGWs propagating in the ionosphere (Hines, 1960). And TIDs are characterized by different periodicities, depending on different types of TIDs. Therefore, it is clearly seen that TIDs/AGWs propagation indeed exist during this event. Wavelike structures associated with TIDs have reasonable support as the primary cause of the daytime spread F at midlatitudes. This also verified that the wavelike perturbations in the ionosphere manifested as TIDs also could cause the height rise of h’F2 which precedes spread F and spread Es occurrence, as shown in Figure 1e. Furthermore, using iso-frequency curves shown in Figure 6a, it is possible to estimate the TIDs period. Of particular interests are the period of TIDs in this event, which are highlighted with red double arrows in Figure 6. It can be qualitatively inferred that the periods of TIDs are around 20–70 min. According to the typical medium-scale TIDs (MSTIDs) period (20–60 min), the TIDs in this event could primary be classified as MSTIDs. Previous works of midlatitude spread F done by Bowman (1990), the author indicated that the ionospheric tilts associated with MSTIDs can be expected to be significantly greater than those associated with large-scale TIDs, since they have about an order of magnitude difference in speeds due to the dispersion equation of AGWs. It is known that the magnitude of TIDs has a positive correlation with the variations of the virtual height on ionograms. Figure 6a shows that there are two large magnitude of TIDs during 09:00 LT and 16:00 LT (the terminator was ignored). The first is between 11:00 LT and 12:00 LT, and the second is before the occurrence of daytime spread F (around...
15:00 LT). The response of the ionosphere to TIDs, is usually observed as two morphological characteristics on the ionograms, one is spread F, and the other is the F2 layer cusp or stratification (Jiang et al., 2019, and references therein). Obviously, the second large magnitude of TIDs exactly caused the formation of range spread F and spread Es as shown in Figure 2. So what effect would the first TIDs during 11:00 LT and 12:00 LT have on the ionosphere?

In order to see the impact of the TIDs on the ionosphere more intuitively in this case, Figure 7 shows the daytime ionograms recorded at 5 min intervals are taken from 10:30 to 11:45 LT (LT = UT + 7h). It is necessary to mention that similar ionospheric disturbances have occurred within a few hours before the time in Figure 7, which are not presented in this paper. In Figure 7, the red and yellow ovals respectively indicate unusual traces at the F2 layer trace and E layer caused by disturbances. In Figure 7, the main trace of the ionospheric F2 layer is subdivided into some discrete traces at 10:45 LT, 11:10 LT, 11:15 LT, 11:25 LT, and 11:30 LT, respectively. The branches of the main trace of the ionospheric F2 layer attempt to move to near the top frequency of F2 layer and then develop into discrete traces, until it disappears on ionograms. Thus,
the result of the first TIDs between 11:00 LT and 12:00 LT on the ionosphere was multibranch structures attached on the main traces of F layer, termed as F2 layer cusp or stratification on ionograms. It is well-known that a passing TIDs wavelike structures can cause some expected extra traces of the main traces on daytime ionograms (e.g., Munro, 1953). Moreover, Jiang et al. (2019) studied the F2 Layer stratification on ionograms caused by AGWs/TIDs using a ray tracing method and found that the vertical and horizontal gradients caused by AGWs/TIDs might respectively control the appearance of the F2 stratification and spread F on ionograms. As shown by the red ovals in Figure 7, some extra traces of main traces on the F2 layer are obviously observed on the ionograms that indicate these bifurcated traces are likely to be caused by the vertical gradient induced by AGWs/TIDs. This hypothesis is also verified in Figure 2. It can be clearly seen from Figure 2 that there is indeed spread F and spread Es which might be caused by the horizontal gradient induced by AGWs/TIDs. Based on the above observations and analysis, it further verified that there were indeed TIDs, and the passage of AGWs/TIDs resulting in the ionospheric tilts could lead to these distorted traces similar to the F2 stratification structures and daytime spread F on December 23, 2016.

In addition, a cusp starts to develop at the E layer trace in Figure 7, as marked by yellow ovals. At 10:50 LT, it can be clearly seen that a “cusp” is visible near 2.6 MHz of the E layer trace. And the “cusp” frequency is slightly below foE. Subsequently, the frequency of the “cusp” is gradually approaching the foE, and, at
10:55 LT, a comparatively symmetrical structure evolves at about Es layer height. As illustrated by Wakai et al. (1987), this type of Es is termed C (cusp) type Es, which could be observed up to higher frequencies in the daytime, being connected to the thick E layer trace. The authors noted that the cusp formed at a frequency at or below $f_{oE}$ occurred mostly during daytime. The $f_{oE}$ of the C type Es gradually increases over time, reaching the maximum frequency (4.2 MHz) at 11:25 LT, and then begin to fade away until 11:45 LT, the C type Es is completely invisible. According to Szuszczewicz et al. (1995), the cusp (c) type Es is attributed to the intermediate layers. Back to Figure 6b, the virtual height of Es layer is decreasing between 10:30 LT and 14:00 LT. At 2.75 MHz frequency, Es layer appears at 10:30 LT at a virtual height of 140 km and moves down to a height of 100 km until 12:00 LT. Using the method of calculating the intermediate descending layer (IDLs) mentioned by Niranjan et al. (2010), from the ionograms on this day, a weak descending Es layer was first observed at 10:55 LT at an altitude of about 160 km, which gradually descended to an altitude of 110 km at around 13:30 LT and merged with the normal E layer. During the descent, the descending rate of the layer is roughly 14 km/hr. The day-to-day variability of the formation of the IDLs might be influenced by atmospheric tides, electric fields, metallic ion populations and gravity waves (Niranjan et al., 2010, and references therein). The mainly control tides of IDLs is the semi-diurnal model tides, most of the times, which can cause the descent rates of IDLs were between 7 and 11 km/hr (Williams, 1996). However, the downward moving velocity of Es layer associated with gravity wave could cause enormously speed up. That is to say the common modulation of gravity waves and tidal waves can increase the descent rate of IDLs (Niranjan et al., 2010, and references therein). Considering the descent rate of IDLs is ~14 km/hr and the ionospheric Es layer is modulated by AGWs, the IDLs in this event might be caused by a mixture modulation waves of tide waves and gravity waves.

Furthermore, Ma and Maruyama (2006) suggested that $\text{ROTI} \geq 0.5$ indicates the existence of ionospheric irregularities at scale lengths of a few kilometers relevant to ionospheric scintillation. Liu et al. (2016) further pointed out that $\text{ROTI} < 0.25$ indicates no ionospheric TEC fluctuations. In addition, $S4 \geq 0.2$ is typically considered as the condition for judging the occurrence of ionospheric scintillation events (Zou & Wang, 2009). As illustrated in Figures 4 and 5, during the time of daytime spread F, the TEC perturbations and scintillation index were both lower than the above-mentioned values. As we all know, the size of the ionospheric plasma irregularities responsible for the amplitude scintillation of satellite beacon signal is about First Fresnel radius. For GPS L1 signal, this size is roughly 1 km. However, in addition to kilometer-scale irregularities, a wealth of meter-scale plasma irregularities embedded in sporadic E layer and spread F associated with MSTID are also concurrently present, which are responsible for the echoes of coherent scatter radar (Lin et al., 2016). Given all that, there might be some small-scale ionospheric scintillation and plasma irregularities. Furthermore, Bowman (1990) stated that small-scale structures have little impact on the extra traces (termed as spread-F traces) on ionograms, and the primary contribution to those extras is the larger scale structures. Considering that the duration of daytime spread F is less than 1h (~45 min) and the periods of TIDs are around 20~70 min, it seems possible to further infer that the characteristic of ionospheric irregularities associated with daytime spread F in this event should mainly be medium-scale ionospheric plasma irregularities structures.

TIDs caused by AGWs play a significant role in forming spread F during the day and night (Bowman, 1992). However, what is the seed source of TIDs in this daytime spread F event? The impact of AGWs in the ionosphere is very significant and can result a variety of ionospheric disturbances, that is usually termed as TIDs. AGWs had been paid much attention because it can propagate from the lower atmosphere to the thermosphere, and various experimental studies confirmed that AGWs is a powerful source to influence the diurnal variations of the ionosphere. There are diverse sources in the lower atmosphere that can trigger AGWs, such as earthquakes, typhoon, geomagnetic storms, the meteorological disturbances, solar terminator and solar eclipse, turbulence and convection in the mesoscale, and orography effects (Borchevkina et al., 2020, and references therein). Although the wavelike perturbations here are mostly mesoscale, they would not have the characteristics of wavelike structure disturbances related to tropical storms. Interestingly, Xu et al. (2016) reported the stratosphere gravity waves over the Qinghai-Tibetan Plateau (TP) were active in each season and suggested that the topography and wind speed are important factors in forming the majority of gravity wave activities over TP. Coincidentally, the southwest of ZHY station is the Qilian mountain (located on the edge of the TP). There is a Heli mountain in the northeast, and the middle region is an inclined plain of 1,410~2,230 m above sea level to form the Zhangye Basin. Fritts and Nastrom (1992)
and Fritts and Alexander (2003) also suggested that gravity waves associated with topography effects are a considerable source of AGWs. Gavrilov and Koval, (2013) studied the stationary orographic waves caused by surface airstreams flowing over a mountain and concluded that orographic waves in the atmosphere can propagate from the ground to the height of the lower thermosphere. Hoffmann et al. (2013) studied gravity waves activities in global hotspots and showed that the majority of gravity wave sources in gravity wave active areas are related to mountains or convective activities. When the airflow in the atmosphere flows through the mountains, the mechanical obstruction of the mountains will stimulate the generation of gravity waves (that is, mountain gravity waves). Mountain gravity waves are mainly produced in stratified atmosphere, formed by topography effect. Therefore, the topography effects resulting in AGWs might be reasonably responsible for the TIDs, which then lead to the midlatitude daytime spread F during the afternoon hours in this event. The topography effect event might be considered as a part of the coupled atmospheric-ionosphere-thermosphere phenomenon that gravity wave sources in the lower atmosphere potentially impact the ionosphere. Furthermore, the correlation between spread F and spread Es could be explained by the time-delay between the passage of upward propagating gravity waves in the F layer and in the Es layer (Bourdillon et al., 1997). However, in the upper atmosphere, AGWs will break when wave reaches saturation in the development of its upward propagation, and the breaking of AGWs is intimately associated with in the development of midlatitude spread F structures (Bowman, 1990). Therefore, the characteristics of propagation of wavelike structures in forming midlatitude daytime spread F are hard to precisely determine, this requires further research and more observational data analysis to reveal it.

5. Conclusions

This paper reports an extremely unusual daytime range spread F observed by the ZHY ionosonde over midlatitude region during the afternoon hours (15:15-16:00 LT) on December 23, 2016. Compared with the previous statistic studies on daytime midlatitude plasma irregularities, the occurrence time of daytime spread F at the afternoon is even rarely reported. The observation results show that spread Es accompanied with daytime spread F was also observed on the ionograms obtained at ZHY station during this event. Analysis of the iso-frequency of ionospheric virtual heights from ZHY ionosonde data during this event reveals the presence of wave-like disturbances consistent with TIDs/AGWs. The periods of TIDs in this event are in a range of 20–70 min that can be roughly classified into MSTIDs. The TIDs might be due to the orography/topography effects in the lower atmosphere, which is a part of the coupling atmospheric-ionosphere-thermosphere phenomenon that gravity wave sources in the lower atmosphere potentially impact the ionosphere.

Data Availability Statement

The IMF Bz data was downloaded from the website www.srl.caltech.edu/ACE/ASC. Dip latitudes and Magnetic latitudes were calculated by IGRF-12 in this study. The ionosonde and GNSS data at ZHY station used in this study are available from Zenodo: https://zenodo.org/record/5176166 (DOI: 10.5281/zenodo.5176166, the section: daytime range spread F at middle latitudes).

References

Aa, E., Zou, S., Eastes, R., Karan, D. K., Zhang, S. R., Erickson, P. J., & Coster, A. J. (2020). Coordinated ground-based and space-based observations of equatorial plasma bubbles. Journal of Geophysical Research: Space Physics, 125(1), e2019JA027569. https://doi.org/10.1029/2019JA027569

Aa, E., Zou, S., & Liu, S. (2020). Statistical analysis of equatorial plasma irregularities retrieved from Swarm 2013–2019 observations. Journal of Geophysical Research: Space Physics, 125(4), e2019JA027022. https://doi.org/10.1029/2019ja027022

Aarons, J. (1977). Equatorial scintillations: A review. IEEE Transactions on Antennas and Propagation, 25(5), 729–736. https://doi.org/10.1109/TAP.1977.1141649

Abdu, M. A. (2001). Outstanding problems in the equatorial ionosphere–thermosphere electrodynamics relevant to spread F. Journal of Atmospheric and Solar-Terrestrial Physics, 63(9), 869–884. https://doi.org/10.1016/S1364-6826(00)00201-7

Basu, S., Groves, K. M., Quinn, J. M., & Doherty, P. (1999). A comparison of TEC fluctuations and scintillations at Ascension Island. Journal of Atmospheric and Solar-Terrestrial Physics, 61(16), 1219–1226.

Booher, H. G., & Wells, H. W. (1938). Scattering of radio waves by the F-region of the ionosphere. Terrestrial Magnatism and Atmospheric Electricity, 48(3), 249–256. https://doi.org/10.1029/te048i003p00249

Borchevkina, O., Karpov, I., & Karpov, M. (2020). Meteorological storm influence on the ionosphere parameters. Atmosphere, 11(9), 1017. https://doi.org/10.3390/atmos11091017

Acknowledgments

This work was supported by the National Natural Science Foundation of China (NSFC 42074184, 41604133, 41727804 and 41974184) and Science and Technology Research Project of Education Commission of Hubei Province of China (Q20202906). We acknowledge the open data policy ofDst index and Kp index through WDC, Kyoto University, Japan (http://wdc.kugi.kyoto-u.ac.jp/) and ACE solar wind parameters through SPDF, NASA, USA (http://omniweb.gsfc.nasa.gov/ow_min.html). The authors are grateful to two anonymous reviewers for their assistance in evaluating this paper.
Olugbon, B., Oyeyemi, E. O., Kascheyev, A., Rabiu, A. B., Obafaye, A. A., Odeyemi, O. O., & Adewale, A. O. (2021). Daytime equatorial spread F-like irregularities detected by HF Doppler receiver and digisonde. *Space Weather, 19*(4), e2020SW002676. https://doi.org/10.1029/2020sw002676

Park, J., Stolle, C., Xiong, C., Lühr, H., Pfaff, R. F., Buchert, S., & Martinis, C. R. (2015). A dayside plasma depletion observed at midlatitudes during quiet geomagnetic conditions. *Geophysical Research Letters, 42*(4), 967–974. https://doi.org/10.1002/2014GL062655

Perkins, F. (1973). Spread F and ionospheric currents. *Journal of Geophysical Research, 78*(1), 218–226. https://doi.org/10.1029/JA078i001p00218

Pezzopane, M., Fagundes, P. R., Ciraolo, L., Correia, E., Cabrera, M. A., & Esquer, R. G. (2011). Unusual nighttime impulsive foF2 enhancement below the southern anomaly crest under geomagnetically quiet conditions. *Journal of Geophysical Research, 116*, A12314. https://doi.org/10.1029/2011JA016593

Pi, X., Mannucci, A. J., Lindqwister, U. J., & Ho, C. M. (1997). Monitoring of global ionospheric irregularities using the worldwide GPS network. *Geophysical Research Letters, 24*(18), 2283–2286. https://doi.org/10.1029/97GL02800

Shi, S., Yang, G., Jiang, C., Zhang, Y., & Zhao, Z. (2017). Wuhan ionospheric oblique backscattering sounding system and its applications—A review. *Sensors, 17*(6), 1430.

Szuszczewicz, E. P., Roble, R. G., Wilkinson, P. J., & Hanababa, R. (1995). Coupling mechanisms in the lower ionospheric-thermospheric system and manifestations in the formation and dynamics of intermediate and descending layers. *Journal of Atmospheric and Terrestrial Physics, 57*(12), 1483–1496.

Vats, H. O., Chandra, H., Deshpande, M. R., Rastogi, R. G., Murthy, B. S., Janve, A. V., et al. (1978). Equatorial irregularity belt and its movement during a magnetic storm. *Nature, 272*(5651), 345–346. https://doi.org/10.1038/272345a0

Woodman, R. F. (2009). Spread F—An old equatorial aeronomy problem finally resolved? *Annales Geophysicae, 27*, 1915–1934. https://doi.org/10.3390/s17061430

Woodman, R. F., Pingree, J. E., & Swartz, W. E. (1985). Spread-F-like irregularities observed by the Jicamarca radar during the day-time. *Journal of Atmospheric and Terrestrial Physics, 47*(8–10), 867–874. https://doi.org/10.1016/0021-9169(94)00145-e

Xie, H., Yang, S., Zhao, X., Hu, L., Sun, W., Wu, Z., & Li, G. (2020). Unexpected high occurrence of daytime F-Region backscatter plume structures over low latitude Sanya and their possible origin. *Geophysical Research Letters, 47*(22), e2020GL090517. https://doi.org/10.1029/2020GL090517

Xu, X. H., Guo, J. C., & Luo, J. (2016). Analysis of the active characteristics of stratosphere gravity waves over the Qinghai-Tibetan Plateau using COSMIC radio occultation data. *Chinese Journal of Geophysical s, 59*(4), 1199–1210. https://doi.org/10.6038/cjg20160403

Zhu, Z., Lan, J., Luo, W., Sun, F., Chen, K., & Chang, S. (2015). Statistical characteristics of ionogram spread-F and satellite traces over a Chinese low-latitude station Sanya. *Advances in Space Research, 56*(9), 1911–1921. https://doi.org/10.1016/j.asr.2015.03.038

Zou, Y., & Wang, D. (2009). A study of GPS ionospheric scintillations observed at Gulin. *Journal of Atmospheric and Solar-Terrestrial Physics, 71*(17–18), 1948–1958.