Postprint of Observational Study on Daytime Spread-F-like Irregular Structures in Mid-latitude Regions

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Abstract

Based on high-frequency Doppler observations, this study demonstrates that spread echo traces characterizing spread F phenomena appeared during daytime in mid-latitude regions, while other ionospheric disturbances that accompany, precede, or follow them were also recorded. The results indicate that daytime spread F-like phenomena possess the following characteristics: 1) Their occurrence time covers almost the entire daytime period: morning hours, late morning to noon, and afternoon hours; 2) Morphological characteristics manifest as echo spreading (similar to nighttime spread F), with frequency shifts of the spread echoes tending toward positive offsets, sometimes accompanied by traveling ionospheric disturbances (TIDs), though these TIDs do not exhibit the characteristics of typhoon-generated TIDs reported previously; cases without TID accompaniment also exist, yet the spreading magnitude can still be substantial; 3) The duration is relatively long, with the maximum lasting approximately 5 hours; 4) They appear concurrently with other ionospheric disturbances (such as TIDs, solar flares, etc.). These characteristics demonstrate that high-frequency Doppler observations are effective for studying daytime spread F-like phenomena. Although the echo spreading phenomenon occurring during daytime is a sporadic event with an extremely low occurrence rate, its extensive temporal and spatial coverage fully demonstrates the non-negligible importance of this phenomenon for space weather.

Full Text

Preamble

Observational Study of Daytime Spread-F-Like Irregularities in the Mid-Latitude Region

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Abstract

Based on HF Doppler observations, this study investigates daytime blurred echo traces characteristic of spread-F phenomena at mid-latitudes, simultaneously recording associated ionospheric disturbances that appear concurrently with, or immediately before or after, these events. The results reveal several key characteristics of daytime spread-F-like phenomena: (1) occurrence times span nearly the entire daytime period, including morning, late morning to noon, and afternoon; (2) morphological features exhibit echo spreading (similar to nighttime spread-F) with predominantly positive frequency offsets, sometimes accompanied by traveling ionospheric disturbances (TIDs) that lack the characteristics previously reported for typhoon-generated TIDs, while in other cases substantial spreading occurs without TID accompaniment; (3) durations are relatively long, with the longest lasting approximately five hours; and (4) events often appear in conjunction with other ionospheric disturbances such as TIDs and solar flares. These characteristics demonstrate that HF Doppler sounding is an effective tool for observing and studying daytime spread-F-like phenomena. Although daytime spread echoes occur sporadically with extremely low occurrence rates, their extensive temporal and spatial distribution underscores their non-negligible importance for space weather effects.

Keywords: Ionospheric disturbance, ionospheric irregularities, mid-latitude ionosphere, daytime spread-F

Introduction

Spread-F represents a significant ionospheric disturbance phenomenon that substantially impacts radio wave propagation. Typically, due to the disappearance of the E-layer after sunset, steep electron density gradients create favorable background conditions for spread-F generation, leading most research to focus on nighttime periods, particularly in equatorial regions. Comprehensive investigations combining observations, theory, and numerical simulations have yielded consistent results and established widely accepted physical mechanisms for nighttime equatorial spread-F. In contrast, mid-latitude spread-F requires further observational analysis and mechanistic exploration.

Only a limited number of studies have reported ionospheric spread-F during daytime. Dyson [1] noted a small but significant occurrence rate of spread-F between sunrise and noon in topside equatorial observations from Alouette I. Subsequent Jicamarca radar studies by Woodman et al. [2] and Chau and Woodman [3] revealed topside spread-F extending from 600 km to 1400 km between 14:00-16:00 LT, with these irregularities enhancing radar echo intensity by 1–2 orders of magnitude. Weaker irregularities were later detected in the bottomside F-region during noon-to-afternoon periods [4]. More recently, Fukao et al. [5] reported a sunrise-associated plume structure observed by the 47 MHz Equatorial Atmosphere Radar (EAR) in West Sumatra, Indonesia (0.20°S, 100.32°E; dip latitude 10.36°N). This plume occurred at 200–250 km altitude, first appearing before solar illumination reached the E-region, but persisted for nearly two hours after E-region sunrise, expanding upward from the F-layer bottomside to the topside ionosphere. While these reports primarily concern equatorial and low-latitude regions, daytime spread-F at mid-latitudes has also been documented, notably by Bowman and colleagues.

Based on ionosonde observations, Bowman [6] first identified occasional unknown spread-F traces in one-hop reflections during daytime in 1964, noting very low occurrence rates. Bowman et al. [7] subsequently reported a strong relationship between daytime two-hop spread and subsequent nighttime spread-F occurrences, with weaker daytime one-hop spread also observed when two-hop events occurred [8]. Later research linked daytime spread-F to traveling ionospheric disturbances (TIDs) [9]. More recently, Xiao et al. [10] observed daytime spread-F phenomena during intense tropical storm activity using HF Doppler techniques. Collectively, these studies from equatorial, low-latitude, and mid-latitude regions demonstrate that daytime spread-F occurs infrequently but represents a significant phenomenon.

Physical mechanisms for daytime spread-F-like phenomena remain largely unexplored. Fukao et al. [5] attributed the upward-extending plume structure to field-aligned integrated Pedersen conductivity, proposing that plasma bubble generation and growth initiate in the bottomside F-region where Pedersen conductivity is low. While post-sunrise E-region development can inhibit plume growth, once plasma bubbles develop and reach the F-peak, the field-aligned integrated conductivity in the F-region may exceed that in the E-region, enabling continued plume development. At mid-latitudes, Bowman [9] suggested that acoustic-gravity wave-generated TIDs play a central role in both daytime and nighttime spread-F formation.

Given the extremely low occurrence rate of daytime spread-F-like phenomena, current understanding relies primarily on sporadic case studies. Synthesizing previous reports reveals that daytime spread-F in equatorial regions occurs throughout the ionosphere (bottomside, topside, and bottom-to-top) and across all daytime periods (sunrise-to-noon, noon-to-afternoon, and 14:00–16:00 LT). Although uncommon, the extensive temporal and spatial distribution of these events underscores their broad impact and significance. Therefore, accumulating observational evidence and investigating potential triggering factors for daytime spread-F-like phenomena are urgently needed to provide a scientific foundation for understanding their characteristics and physical mechanisms. This study leverages HF Doppler observations, capitalizing on their convenience, high temporal resolution, and sensitivity to various ionospheric disturbances. By selecting distinct sporadic cases from long-term data archives, we avoid limitations of single-case analysis while revealing the breadth and systematic nature of these rare events, focusing on observational characteristics of daytime spread-F-like irregularities at mid-latitudes.

2. Data Sources

The data used in this study were obtained from the Peking University HF Doppler observation station, established in 1986 with nearly three decades of operational history. As a single-frequency station, it receives 10 MHz radio signals broadcast by the National Time Service Center. We selected several years of high-quality data for analysis.

Spread-F was originally discovered and defined through ionosonde observations, which operate over a wide frequency band and characterize spread-F as echo spreading. This phenomenon is further classified into frequency-type and range-type spread-F based on spreading characteristics. HF Doppler sounding represents another typical ionospheric detection method; when irregular structures exist in the ionosphere, Doppler echo traces also exhibit spreading. The Peking University HF Doppler station receives 10 MHz signals with a horizontal distance of approximately 700 km between the transmitter (35.0°N, 109.5°E) and receiver (39.4°N, 116.2°E). As an oblique incidence system, received signals represent one-hop reflections from altitudes of approximately 140–180 km for 10 MHz signals. The spreading of these Doppler traces reflects F-layer characteristics, and their temporal patterns generally correspond to spread-F echo spreading observed by ionosondes. Thus, spread-F phenomena manifest as echo spreading in Doppler observations.

Since ionospheric reflections of 10 MHz radio signals typically produce Doppler frequency shifts within ± 1 Hz, the vertical axis in our results represents frequency shift, with upper and lower lines marking +1 Hz and -1 Hz, respectively. A quiescent ionosphere with zero Doppler shift appears at the midpoint between these lines, while the horizontal axis denotes Beijing local time (LT).

3. Observational Results

In HF Doppler observations, spread-F manifests as spreading of echo frequency shifts, appearing as diffuse traces in frequency shift versus time plots. While such spreading typically occurs after sunset, long-term observations reveal rare daytime occurrences. The following sections detail these observational results for this sporadic phenomenon.

[Figure 1: see original paper] Figure 1 presents observations from July 15, 1990, between 07:33–17:10 LT. Beginning shortly after sunrise, the records show that following the sunrise effect, the echo frequency shift does not simply decrease but exhibits clear wave-like disturbances during its descent. Around 08:10 LT, these fluctuations are replaced by diffuse echo traces, indicating typical spread-F phenomena with predominantly positive frequency offsets. This spreading persists for over an hour before clear wave fluctuations reappear, though they are soon obscured again by spreading echoes. The spreading continues, reaching maximum intensity around 10:40 LT and weakening noticeably after 11:30 LT. Distinct wave-like disturbances emerge around 13:00 LT and continue for several hours. The July 15, 1990, event is characterized by diffuse echo traces during morning hours (08:10–11:30 LT) with predominantly positive frequency shifts superimposed on wave-like disturbances.

Figure 2 shows observations from September 3, 1989. As the sudden positive frequency shift from the sunrise effect gradually subsides (essentially a monotonic decrease), obvious echo spreading begins around 08:35 LT. The spreading amplitude is significantly stronger than in the previous example, lasting over two hours with predominantly positive frequency shifts. As the diffusion weakens, the ionosphere gradually returns to a stable state. Notably, no wave disturbances appear before, during, or after the spread-F event on September 3, 1989, yet the echo frequency shift spreading is substantial and almost entirely positively offset.

[Figure 2: see original paper] Figure 3 displays HF Doppler echo frequency shifts from July 10, 1988, between 07:55–17:32 LT. The record begins before 08:00 LT, with the sunrise effect fully dissipated and no other ionospheric disturbances such as wave-like fluctuations present, indicating a very stable ionosphere near the reflection surface. Around 08:40 LT, echoes suddenly spread with large amplitude, exceeding 1 Hz at maximum. The spreading persists from morning through noon into afternoon, weakening noticeably only after approximately 13:30 LT, after which clear wave-like disturbances appear. Similar to Figure 1, diffuse echo traces are clearly superimposed with wave-like disturbances (09:45–11:00 LT) and exhibit predominantly positive frequency offsets. However, the spreading duration is longer (lasting five hours) and extends from morning through afternoon (08:40–13:30 LT).

[Figure 3: see original paper] Figure 4 presents HF Doppler observations from June 29, 1988, showing persistent echo spreading accompanied by solar flare events. The spreading occurs from noon to afternoon (approximately 11:40–16:30 LT). Unlike previous cases, multiple solar flare events appear before and after the daytime echo diffusion, such as around 10:50 LT at the record’ s start, between 11:15–11:20 LT, and during 16:30–16:35 LT. While the spreading initially shows predominantly positive frequency offsets, it later shifts to negative offsets. Additionally, spread-F appears during the afternoon period, and after sunset evolves into clear, strong wave-like disturbances without nighttime spread-F occurring until 20:00 LT.

[Figure 4: see original paper] Figure 5 shows Kp and Dst indices from 07:00–18:00 LT for three events (July 15, 1990; September 3, 1989; and July 10, 1988, from left to right). The indices remain very low during all three events.

4. Conclusions and Discussion

The high temporal resolution and sensitivity of HF Doppler sounding to rapid ionospheric disturbances enabled us to observe not only daytime spread-F phenomena but also associated disturbances appearing concurrently with, or immediately before or after, these events. Based on our analysis, the characteristics of daytime spreading echoes are summarized as follows:

(1) **Occurrence Time**: The events cover broad daytime periods, including morning (Figures 1 and 2), late morning to noon (Figure 3), and noon to afternoon (Figure 4).

(2) **Morphological Features**: The spreading echoes resemble nighttime spread-F, but predominantly exhibit positive offsets (Figures 1–4). They sometimes accompany TIDs (Figures 1, 3, and 4), though these TIDs lack the characteristics of typhoon-generated waves. Substantial spreading can also occur without TID accompaniment (Figure 2).

(3) **Duration**: All events exceed one hour, with the longest lasting approximately five hours (Figure 3).

(4) **Association with Other Disturbances**: Some events accompany TIDs (Figures 1, 3, and 4), while others show large spreading amplitudes without TIDs (Figure 2). Solar flares also appear, with multiple events occurring before and after echo spreading (Figure 4).

Our HF Doppler observations of daytime spread-F-like irregularities share similarities with but also differ from previous studies. At mid-latitudes, Bowman et al. [6–9] have focused considerable attention on daytime spread-F, with ionosonde analyses revealing both one-hop and two-hop spreading primarily during morning hours. Our results demonstrate that in the Northern Hemisphere mid-latitudes, events also occur at noon and in the afternoon, consistent with comprehensive observations from equatorial regions. Thus, daytime echo spreading at mid-latitudes is broadly distributed throughout the day. Additionally, durations are comparable to equatorial observations, with Woodman et al. [2] reporting 1–2 hour events and our cases all exceeding one hour.

Furthermore, our observations show wave-like disturbances accompanying the diffuse echoes, with clear fluctuations appearing before spreading and evolving into distinct waves as diffusion weakens, predominantly medium-scale fluctuations.

Bowman et al. [9] proposed that acoustic-gravity wave-generated TIDs play a central role in both daytime and nighttime spread-F formation. Studies of ionospheric responses to intense lower-atmospheric activity indicate that typhoon-excited acoustic-gravity waves can readily trigger nighttime spread-F when amplitudes are large after sunset [11]. Research on seeding factors for spread-F has also revealed close relationships between large-amplitude acoustic-gravity waves and mid-latitude nighttime spread-F [12]. In our records, wave-like disturbances (TIDs) appear to varying degrees before, during, and after daytime spread-F (Figures 1, 3, and 4). Based on Doppler frequency shift variations, these TIDs appear to be medium-scale acoustic-gravity waves, but their periods and amplitudes show no clear evolutionary patterns, particularly lacking the frequency characteristics of typhoon-excited waves [11]. Moreover, pre-spreading fluctuations are far weaker than those closely associated with nighttime spread-F [12]. This raises important questions: Do acoustic-gravity waves play equally important roles in daytime spread-F? What is the relationship between daytime spread-F generation and waves of different amplitudes? Do larger-amplitude waves more readily trigger daytime spread-F, as with nighttime events? These questions urgently require additional observational analysis and statistical studies, representing important directions for future research.

Daytime spreading echoes observed by the Peking University HF Doppler station lack corroboration from other ionospheric instruments near the reflection point. To address this limitation, we preliminarily examined ionosonde observations from the mid-latitude Urumqi station. Although not from the same period, hourly values from Urumqi also recorded daytime spread-F with very low occurrence rates, covering morning, noon, and afternoon periods.

Studies of nighttime spread-F relationships with geomagnetic and solar activity demonstrate clear influences [13]. In Figure 4, besides prominent daytime spreading echoes, multiple significant solar flare events occur, yet subsequent nighttime observations show no spread-F, consistent with established results. However, the appearance of strong spreading echoes during daytime despite intense solar flares suggests different physical mechanisms from nighttime events. Although spread-F was originally discovered and defined for nighttime conditions—and is commonly regarded as a nighttime phenomenon—the distinct differences between daytime and nighttime events underscore the important scientific significance of daytime spread-F research. Given the complexity shown in Figure 4, we specifically examined Kp and Dst indices for three other daytime events (Figure 5), which remain very low throughout all events. This demonstrates that daytime spread-F cannot be simply treated as equivalent to its nighttime counterpart.

Although daytime spreading echoes are sporadic with extremely low occurrence rates, HF Doppler observations reveal they can appear during any daytime period and may accompany other ionospheric disturbances, with distribution characteristics clearly differing from typical nighttime spread-F. Due to observational limitations, the spatial distribution of these daytime diffuse echoes remains unresolved, necessitating comprehensive multi-instrument observations and mechanistic investigations.

To date, research on daytime spread-F-like irregularities has been limited to a few reported cases. Despite the lack of clear physical explanations, their characteristics share many similarities with nighttime spread-F, particularly in morphology and wave relationships. However, important questions remain: What differences exist between daytime and nighttime spread-F? Do daytime events share the close relationship with acoustic-gravity waves seen in nighttime spread-F? Are daytime spread-F-like irregularities connected to intense activities such as typhoons or major earthquakes? Addressing these questions through further research and observational analysis is crucial for understanding the ionospheric conditions required for these unusual daytime phenomena and for gaining deeper insight into the physical mechanisms behind the observed diffuse echoes.

[Figure 5: see original paper]

Acknowledgments

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Note: Figure translations are in progress. See original paper for figures.