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A minimum in the latitude variation of spread-F at March equinox

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Abstract

This short paper presents the statistics of spread-F occurrence at four low-mid latitude locations (17.0° N, 21.2° N, 26.5° N and 36.5° N mag. lat.) in Japan longitude sector (~135° E) in March to April 2002, 2003 and 2006 (high, medium and low solar activity). The location of a spread-F minimum predicted by theoretical models is identified for the first time. The spread-F minimum occurs at the poleward side of the equatorial ionisation anomaly crest and shifts equatorward from ~25° N mag. lat. at high solar activity to below 17° N at low solar activity. The corresponding spread-F maximum occurring on the poleward side of the minimum also shifts equatorward from ~35° N (or beyond) at medium solar activity to 20°–25° N at low solar activity. The spread-F occurrence increases with decreasing solar activity at all locations especially at higher latitudes (> ~25° N) where there is almost no occurrence at high solar activity.

Keywords: Low-mid latitude spread-F, Minimum and maximum in spread-F

Introduction

Earth's ionosphere has a smooth density distribution during daytime when there is production of ionisation. In other words, during daytime when the E-region conductivity is strong, the ionospheric drivers such as electric fields and neutral winds and their fluctuations cannot destabilise the ionosphere. But after sunset when the E-region conductivity becomes weak, the drivers can destabilise the ionosphere and generate plasma irregularities of various scale sizes that manifest as spread-F (Booker and Wells 1938) and plasma bubbles (Woodman and La Hoz 1976) causing scintillations in communication signals (Aarons 1993). The irregularities occurring at low and mid latitudes have been studied widely using various experimental and theoretical modelling techniques for over 75 years to understand their science and variability and for mitigating their adverse effects on communication and navigation; for recent reviews, see Bowman (1990), Aarons (1993), Patra 2008, Woodman (2009), Kelley et al. (2011), and Yokoyama and Stolle (2017). The studies are to be continued for a better understanding of the generation

and growth of the irregularities and their day-to-day variability to reach a level of forecasting capability.

The spread-F and plasma bubbles at equatorial latitudes where the geomagnetic field lines are horizontal are thought to originate through the Rayleigh-Taylor (RT) instability mechanism (Dungey 1956; Scannapieco and Ossakow 1976; Jayachandran et al. 1993). The main driver that destabilises the ionosphere at post-sunset hours is the pre-reversal strengthening of the eastward electric field (e.g. Heelis et al. 1974; Eccles et al. 2015), which causes the pre-reversal enhancement of the vertical upward $E \times B$ plasma drift velocity V_z referred as PRE (e.g. Fejer et al. 1979; Nambathiri et al. 1989; Balan et al. 1992; Huang and Hairston 2015). The irregularities have a linear growth rate (Ossakow 1981):

$$\gamma = (1/H)(g/v_{in} + Vz) - \beta \quad (1)$$

The first and second terms are the gravitational and cross-field instability growth rates, β is the recombination rate, H is the electron density scale height, g is the acceleration due to gravity, and v_{in} is ion-neutral collision frequency. The irregularities originating at the equatorial bottom-side F-region rise to the topside as plasma bubbles (Scannapieco and Ossakow 1976) and extend along the field lines to higher latitudes especially at high solar activity when PRE is strong.

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Modelling studies of the growth rate have predicted a low latitude minimum. For example, Maruyama (1990) who modelled the growth rate of both the gravitational and cross-field ($E \times B$) instability modes using flux tube integrated values (without neutral wind) showed that the net instability growth rate at March equinox under medium solar activity ($F10.7 = 120$) is negative in a narrow latitude region near 18° mag. lat. At lower and higher latitudes, the ionosphere becomes unstable.

The neutral wind fluctuations known as waves especially gravity waves which are always present and cause fluctuations in the $E \times B$ drift velocity (Balachandran et al. 1992; Abdu et al. 2015) are thought to act as the seed for the onset of the plasma irregularities (e.g. Osaakow, 1981; Sekar et al. 1995). The background neutral wind can also directly influence the growth of the irregularities (e.g. Maruyama and Matuura 1984). At low solar activity and when PRE is absent, the plasma irregularities generally occur at around midnight (e.g. Nishioka et al. 2012). They are thought to be caused mainly by the electric field fluctuations due to atmospheric gravity waves propagating to ionospheric heights easily at low solar activity (e.g. Tsunoda et al. 2010; Patra et al. 2013; Tulasiram et al. 2014; Narayanan et al. 2014a).

Plasma irregularities have also been observed at low and mid latitudes where PRE is absent due to inclined geomagnetic field lines (Bowman 1990 and references therein). Whalen (2002) studied the spread-F occurrence at a chain of stations up to 20° mag. lat. in American sector. Fukao et al. (1991) and Kelley and Fukao (1991) studied the F-region plasma irregularities observed by the MU (middle and upper atmosphere) radar. Otsuka et al. (2002), for the first time, observed an identical optical structure at conjugate stations beyond the EIA crests.

The mid latitude plasma irregularities were first thought to be associated with atmospheric gravity waves (e.g. Bowman 1990; Kelley and Fukao 1991) and later with medium-scale travelling ionospheric (atmospheric) disturbances (MSTIDs) (e.g. Saito et al. 2001; Makela and Otsuka 2012). The mechanism that relates the mid latitude plasma irregularities to its source (e.g. MSTID) is the so-called Perkins instability (Perkins 1973; Miller 1997) which takes the form of rising and falling sheets of ionisation when a north-south electric field is present in addition to the east-west field. Hamza (1999) updated the Perkins equations by adding neutral wind. Recent understanding is that the electro-dynamical coupling between the E- and F-regions plays an important role in enhancing the growth rate of Perkins instability (e.g. Tsunoda and Cosgrove 2001; Yokoyama et al. 2008). The instability has a linear growth rate (Tsunoda 2006; Yokoyama and Stolle 2017):

$$\gamma = (|E| \cos I)[\sin(\theta - \alpha) \sin \alpha] / BH \quad (2)$$

where $E = E_0 + U^F \times B$ is total effective electric field with E_0 being the background field; U^F is F-region neutral wind, B is geomagnetic field of magnitude B , I is magnetic inclination angle, H is atmospheric scale height including ion-neutral collision frequency, θ is the angle between E and east direction, and α is the angle between the direction normal to the frontal structure and east direction. A maximum of the growth rate γ is expected to occur at the location where $\alpha = \theta/2$.

As introduced, theoretical models have predicted a low-latitude minimum (e.g. Maruyama 1990) and a mid-latitude maximum (e.g. Tsunoda 2006) for the occurrence of plasma irregularities manifested as spread-F in ionograms. The possibility of the minimum has also been indicated by optical observations of MSTIDs (Shio-kawa et al. 2002, 2003), which shows a low-latitude limit for their propagation at $\sim 18^\circ$ N mag. lat. at high solar activity (1999), and the limit is found to extend to further lower latitudes at low solar activity (e.g. Narayanan et al. 2014b). However, to our knowledge, the expected minimum and maximum in the occurrence of plasma irregularities have not yet been identified.

This short paper identifies the spread-F minimum and maximum for the first time by analysing the ionosonde data during the March equinox season when the minimum was predicted. The data used are collected at four low- to mid-latitude locations (17.0° N, 21.2° N, 26.5° N and 36.5° N mag. lat.), referred as low-mid latitudes, in Japan longitude sector ($\sim 135^\circ$ E) in March to April (or equatorial spread-F season (Aarons 1993) at high, medium and low solar activity (2002, 2003 and 2006). The locations of the spread-F minimum and maximum are found to shift equatorward with decreasing solar activity.

Methods/Experimental

The study uses the ionosonde data collected at Okinawa (26.7° N, 128.2° E; 17.0° N mag. lat.), Yamagawa (31° N, 131° E; 21.2° N mag. lat.), Kokubunji (35.7° N, 139.5° E; 26.5° N mag. lat.) and Wakkanai (45.4° N, 141.7° E; 36.5° N mag. lat.) in Japan during March to April 2002, 2003 and 2006. The periods cover high, medium and low solar activity (mean $F10.7 = 185, 129$ and 82) when typical post-sunset EIA crests reach up to $\sim \pm 22^\circ, \pm 18^\circ$ and $\pm 15^\circ$ mag. lat. as shown by model calculations (Balan and Bailey 1995; Balan et al. 1997, 2012). The ionosondes at Yamagawa (21.2° N mag. lat.) and Okinawa (17.0° N mag. lat.) might have fallen at around the northern EIA crest during the evening-night hours in 2002 and 2003, and the crest might not have reached Okinawa (lowest latitude) in 2006.

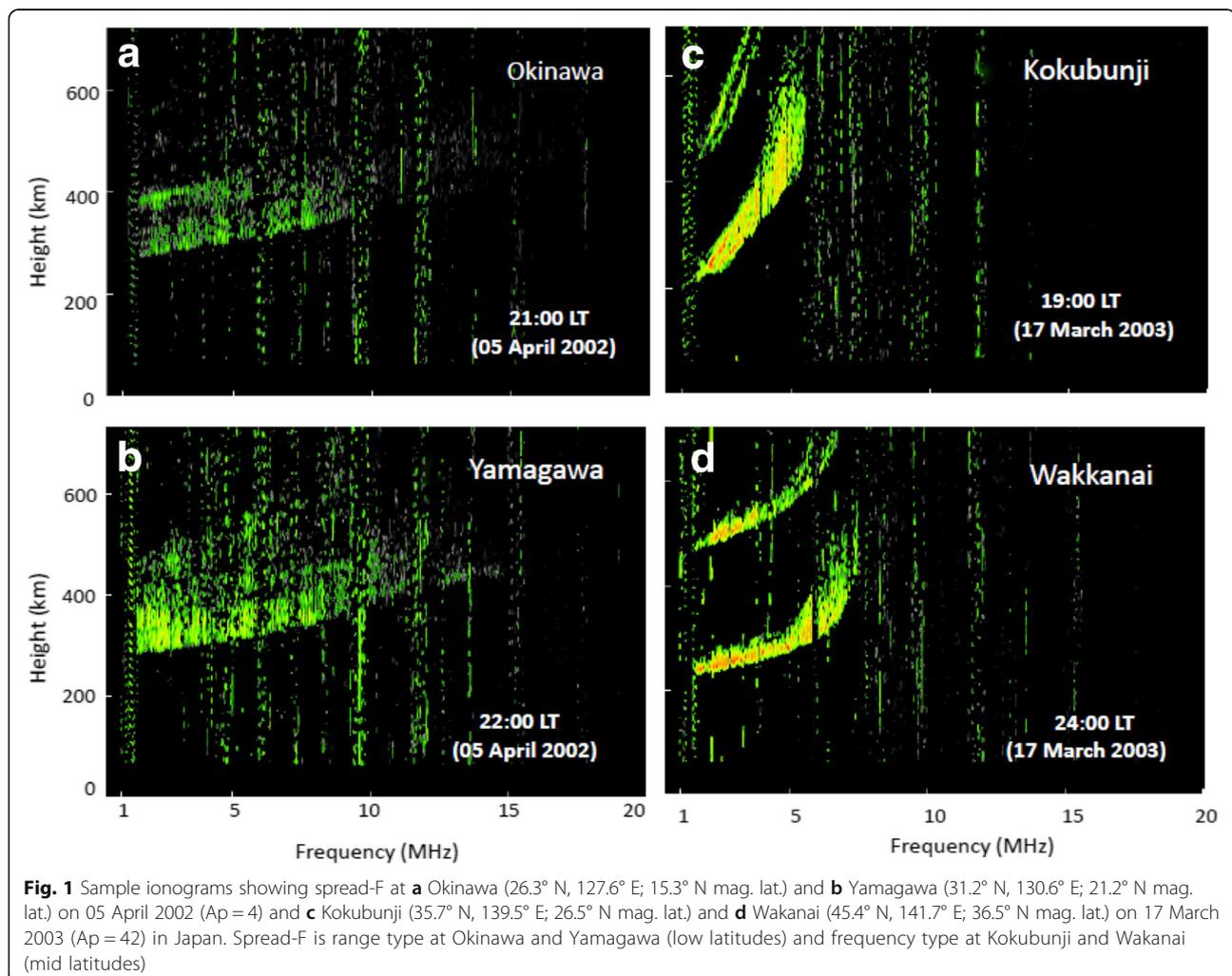
The ionograms collected at 15-min intervals are analysed for the occurrence, onset time and duration of spread-F. As shown by the sample ionograms (Fig. 1), the spread-F at Okinawa and Yamagawa is range type and that at Kokubunji and Wakanai is frequency type. The spread-F in these stations are found to be of the same type at all levels of solar activity except for a few cases which are not distinguished in the analysis. Figure 2 shows the statistics of occurrence, onset time and duration of spread-F at all locations in March to April 2002. Figures 3 and 4 are similar to Fig. 2 but for 2003 and 2006. The data are available for all days at all locations except for a gap of 7 days at Wakkanai (02–08 April 2002).

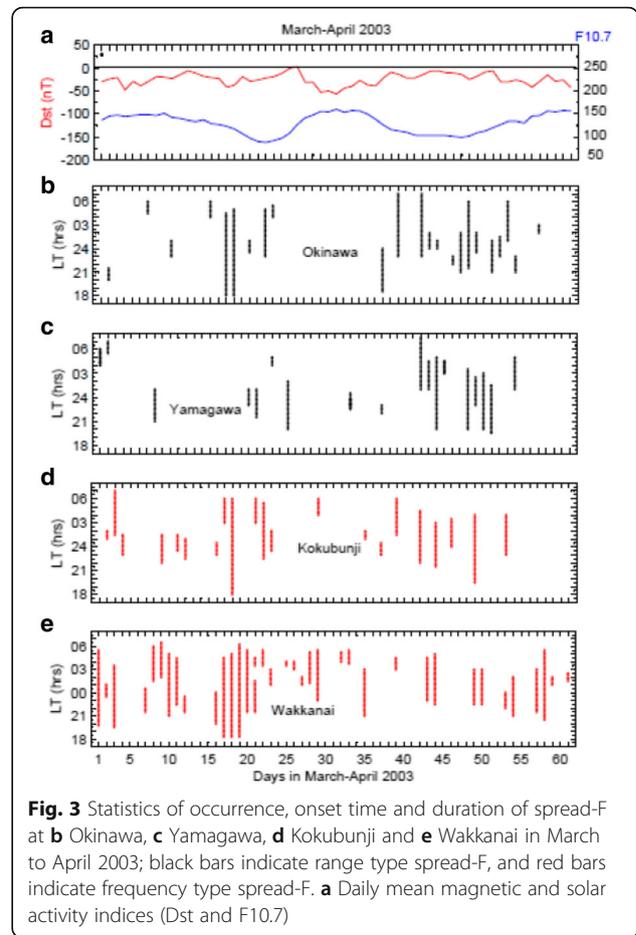
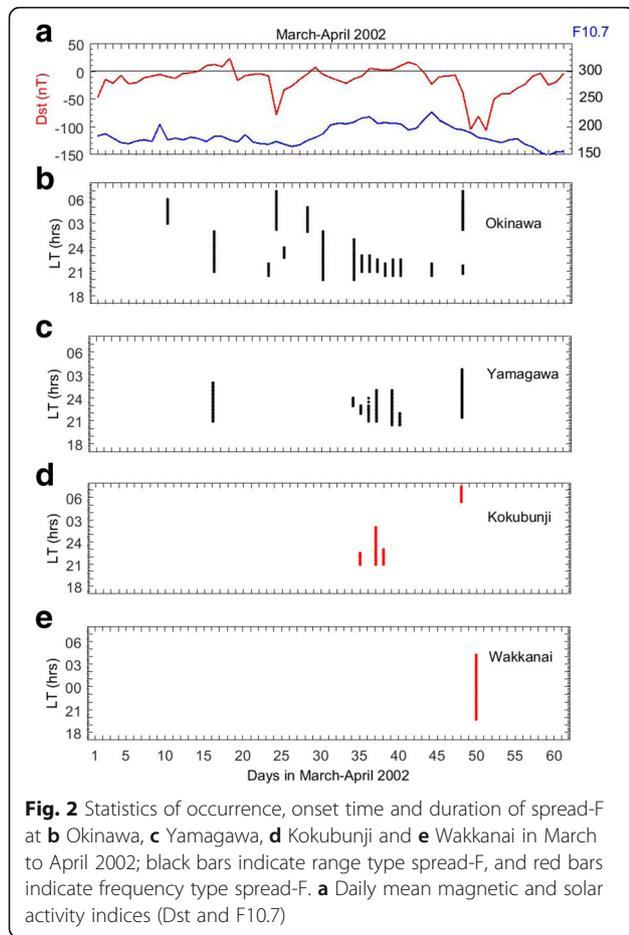
Results

High solar activity

The spread-F occurrence in the low-mid latitude region at high solar activity (2002; Fig. 2) is not so frequent.

The occurrence also decreases steadily with increasing latitude from $\sim 26\%$ at Okinawa to $\sim 2\%$ at Wakkanai, and there is almost no occurrence at latitudes beyond 26.5° N (Kokubunji). No spread-F occurred at higher latitudes without a corresponding spread-F at lower latitudes (Okinawa) except for the lone case at the highest latitude (Wakkanai). The spread-F onset at all locations is generally at post-sunset hours ($\sim 21\text{--}23$ LT) except at Okinawa where some cases occurred at post-midnight hours also. On common days of spread-F, the occurrence at higher latitudes in general started at around the same time or slightly after its start at the lowest latitude, and the duration of spread-F is generally longer at lower latitudes (Okinawa and Yamagawa) and shorter at higher latitudes except for the lone case at the highest latitude. The observations therefore indicate that at high solar activity when typical post-sunset EIA crest reaches up to $\sim 22^\circ$ N mag. lat. (Balan et al. 1997), the low latitude minimum of spread-F is located at the poleward side of the EIA





crest at magnetic latitudes near 25° N in Japan longitudes; spread-F at the equatorward side of the minimum is mainly of equatorial origin, and at the poleward side of the minimum, there is almost no spread-F, discussed below.

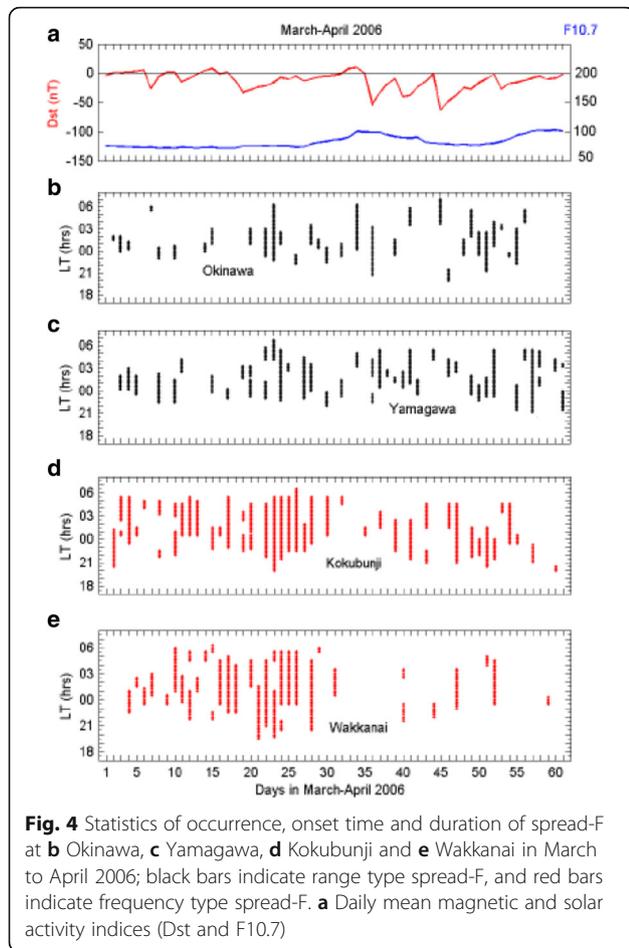
Medium solar activity

Spread-F occurs more frequently at medium solar activity (2003; Fig. 3) than at high solar activity at all locations especially at higher latitudes. Compared to high solar activity while the occurrence increases by about 12% at low latitudes (17.0° N, Okinawa), the increase is over 55% at mid latitudes (36.5° N, Wakkanai) and the increase at the latitudes in between is 15% at 21.2° N and 30% at 26.5° N. More importantly, in 2003 (Fig. 3), the occurrence shows a clear minimum near Yamagawa (21.2° N) while it was near Kokubunji (26.5° N) in 2002. The occurrence also indicates a possible maximum near or beyond Wakkanai (36.5° N) while there was almost no spread-F beyond the minimum in 2002. The onset time of spread-F varies from as early as 18:00 LT to as late as 04:30 LT with over half of the onsets being after 21–22 LT at all locations. The duration of spread F varies from as short as 30 min to as long as 11 h with about half of the cases lasting over 5 h.

The observations therefore indicate that at medium solar activity, there is a clear spread-F minimum located at ~20° N mag. lat. at the poleward side of the typical EIA crest that reaches as far as ~18° N (Balan and Bailey 1995). There is also indication of a spread-F maximum at ~35° N mag. lat. (Wakkanai) or beyond as expected (Eq. 2), and the spread-F at the poleward side of the minimum (Kokubunji and Wakkanai) is mainly of mid-latitude mechanism.

Low solar activity

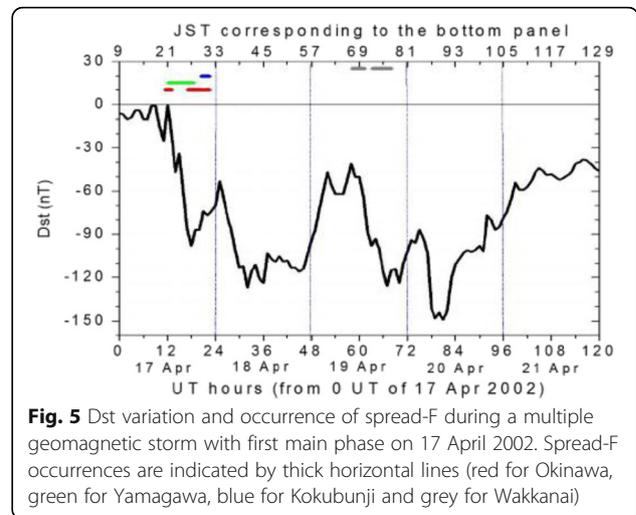
The spread-F occurrence is most frequent at low solar activity (2006; Fig. 4) at all locations except at the highest latitude (Wakkanai) where it slightly decreases by 8% compared to medium solar activity. With respect to medium solar activity, while the occurrence increases by 20% at Okinawa, the increase is 36% each at Yamagawa and Kokubunji. It is interesting to note that the occurrence in 2006 is least frequent at Okinawa (17.0° N) and most frequent and almost equally at Yamagawa and Kokubunji (21.2° N and 26.5° N). The onset time is generally after 22 LT at all locations except at Wakkanai where some cases started before 22 LT. The duration of spread-F is generally



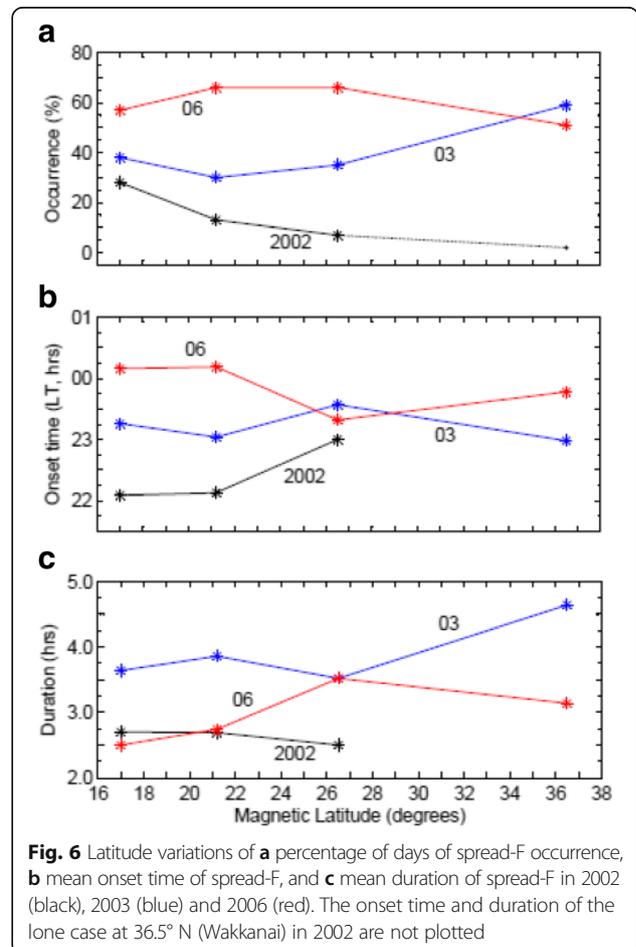
longer at higher latitudes. These observations indicate that the spread-F minimum at low solar activity might be located at latitudes below 17° N when a weak EIA crest reaches up to ~ 15° N (Balan et al. 2012). There is also a clear spread-F maximum located at ~ 20°–25° N mag. lat., and the spread-F at all locations (now on the poleward of the minimum) is mainly of mid-latitude mechanism.

Magnetic activity

The data under magnetically active conditions in the selected periods are not sufficient for statistical study. At high solar activity (Fig. 2), an intense magnetic storm (DstMin up to -149 nT) with multiple dips in Dst occurred. Spread-F occurred during the first main phase at all three lower latitude locations with earlier onset at lower latitudes as shown by the horizontal bars in Fig. 5. The characteristics of the spread-F indicate that the irregularity might have been caused by the eastward electric field penetrated from high to low latitudes. Several moderate storms occurred both at medium and low solar activities (Figs. 3 and 4), though no storm-related spread-F can be identified. It is interesting to note that the lone spread-F observed at the highest latitude location (Wakkanai) at



high solar activity (Fig. 2) occurred during the middle of the long storm (Fig. 5) with no spread-F at lower latitudes. The strong spread-F started at ~ 19.5 LT and lasted for over 9 h which could most probably be due to storm-related MSTIDs originated at high latitudes.



Discussion

The statistics of occurrence, onset time and duration of spread-F are summarised in Fig. 6. As shown, the spread-F occurrence (Fig. 6a) at all locations increases with decreasing solar activity particularly at higher latitudes (26.5° – 36.5° N) where the occurrence increases from a low of $\sim 2\%$ at high solar activity to a high of over 65% at low solar activity. The onset time of spread-F (Fig. 6b) at low latitudes ($< 25^{\circ}$ N mag. lat.) shifts from post-sunset at high solar activity to post-midnight at low solar activity, and at higher latitudes, the onset occurs at around the same time (before mid-night) at all levels of solar activity. The duration of spread-F (Fig. 6c) is long at medium solar activity. The latitude variation of spread-F occurrence is similar to that of night-time anomalous enhancement in total electron content that exhibits a distinct low latitude minimum bounded by maxima on either side (e.g. Balan and Rao 1987).

As described in the “Introduction” section, the plasma irregularities at March equinox manifesting as spread-F in ionograms are caused by separate mechanisms at equatorial (up to EIA crest) and higher latitudes, though there are overlaps at the latitude boundary. At equatorial latitudes, the irregularities originate in the bottomside F-layer mainly through the RT instability mechanism driven by PRE (e.g. Patra 2008; Yokoyama and Stolle 2017). At higher latitudes, the irregularities are known to be caused by the Perkins instability mechanism (Perkins 1973). Theoretical calculations of the latitude variation of the irregularities due to the RT mechanism have predicted a minimum at around 18° mag. lat. at March equinox at medium solar activity (e.g. Maruyama 1990). The ionosonde data at March equinox under three levels of solar activity analysed in this paper specifically to identify the expected minimum have brought out the minimum and showed that the minimum shifts to lower latitudes with decreasing solar activity. The analysis has also identified a spread-F maximum on the poleward side of the minimum expected from the Perkins mechanism (e.g. Tsunoda 2006); the maximum also shifts equatorward with decreasing solar activity.

In addition to the latitude variation of the RT mechanism that predicted the existence of the spread-F minimum (e.g. Maruyama 1990), the low latitude limit of the Perkins mechanism driven by MSTIDs (Shiokawa et al. 2002) also supports the existence of the spread-F minimum. The optical observations of MSTID propagation (Shiokawa et al. 2002) showed a low latitude limit for the propagation at around 18° N mag. lat. The spread-F observations (Fig. 3) under similar conditions (March equinox at medium solar activity) indicate the minimum occurring at $\sim 20^{\circ}$ N mag. lat. at the poleward side of the EIA crest. The spread-F minimum shifts from $\sim 25^{\circ}$ N mag. lat. at high solar activity to below 17° N at low solar activity (Figs. 2, 3, 4, 5 and 6)

when the typical location of the EIA crest shifts from $\sim 22^{\circ}$ N to 15° N. The spread-F maximum occurring on the poleward side of the minimum (under medium and low solar activities) also shifts equatorward with decreasing solar activity. There is almost no spread-F on the poleward side of the minimum at high solar activity.

As mentioned, the spread-F occurrence (Figs. 2, 3, 4, 5 and 6) on the poleward side of the minimum seems mainly of local origin. The local origin believed to be due to Perkins mechanism (Perkins 1973) is associated well with nighttime MSTIDs because (1) like spread-F, MSTIDs also occur most frequently at low solar activity and least frequently at high solar activity (Shiokawa et al. 2002, 2003), and (2) the low latitude limit of MSTIDs extends to further lower latitudes with decreasing solar activity (Narayanan et al. 2014b). These features of MSTIDs agree well with the observed spread-F occurrence on the poleward side of its minimum. Shiokawa et al. (2003) who studied the spread-F at mid latitudes reported $\sim 10\%$ occurrence of spread-F during the high solar activity period spanning 4 years (1979–1982), which also agrees with the present observations of $\sim 2\%$ at the peak of solar activity (1982).

Since the purpose of the present paper is to identify the latitude of the spread-F minimum expected at March equinox, we used the data at same equinox season. It will be interesting to do a similar study at solstices as well, which we plan to undertake in the near future. Earlier, Shiokawa et al. (2003) presented the monthly variation of spread-F occurrence at the four locations under high and low solar activity conditions. They showed that the spread-F occurrence reaches a maximum in summer months.

Conclusions

The short paper has presented the statistics of spread-F occurrence at four low-mid latitude locations (17.0° N, 21.2° N, 26.5° N and 36.5° N mag. lat.) in Japan ($\sim 135^{\circ}$ E) in March to April 2002, 2003 and 2006. The important observations are listed.

- The spread-F occurrence increases with decreasing solar activity especially at latitudes greater than $\sim 25^{\circ}$ N mag. lat.
- The location of a spread-F minimum predicted by theoretical models is identified for the first time.
- The spread-F minimum occurs at the poleward side of the EIA crest and shifts from $\sim 25^{\circ}$ N at high solar activity to below 17° N at low solar activity.
- The corresponding spread-F maximum occurring on the poleward side of the minimum (at low and medium solar activities) also shifts equatorward from $\sim 35^{\circ}$ N (or beyond) to 20° – 25° N.
- There is almost no spread-F on the poleward side of the minimum at high solar activity.

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Availability of data and materials

The data used are obtained using the ionosondes in Japan, which are available at http://wdc.nict.go.jp/ionog/js_viewer/js_01.html.

Authors' contributions

NB took the initiative, analysed the data and prepared the paper. TM provided the data. AKP has been involved in the discussions. VLN did some data analysis and participated in the discussions. All authors read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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