VHF radar observations of post-midnight F-region field-aligned irregularities over Indonesia during solar minimum

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A VHF backscatter radar with operating frequency 30.8 MHz has been operated at Kototabang (0.20°S, 100.32°E; dip latitude 10.4°S), Indonesia since February 2006. The F-region field-aligned irregularities (FAIs) observed by this radar from February 2006 to December 2010 during a solar minimum period have been analyzed and found that FAIs appeared frequently at the post-midnight sector between May and August every year from 2006 to 2010. Five-beam measurements by the radar revealed zonal propagation of the F-region FAIs. The present paper reports, for the first time, statistics of the zonal propagation velocity of the post-midnight FAIs. Between May and August, 46% (14%) of the post-midnight FAIs propagated westward (eastward), and zonal propagation was not discernible for 40% of the post-midnight FAIs. Average velocity was approximately 50 m s⁻¹ westward. The post-midnight FAIs were likely associated with either plasma bubbles or medium-scale traveling ionospheric disturbances (MSTIDs).

Keywords: F-region irregularities, Field-aligned irregularities (FAIs), Plasma bubbles, Traveling ionospheric disturbances

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1 Introduction

VHF, UHF, and L-band radars are used for observations of Bragg scatter echo from field-aligned irregularities (FAIs) with a spatial scale of one half the radar wavelength1-5. Tsunoda6 performed simultaneous incoherent and coherent measurements with the ALTAIR radar in the Kwajalein in the Central Pacific and showed that FAIs are collocated with plasma-depleted regions caused by plasma bubbles generated by the Rayleigh-Taylor instability7. Seasonal and longitudinal variations of plasma bubble occurrence can be theoretically explained in terms of geomagnetic field declination8-9. Plasma bubble occurrence rates obtained from plasma density measurements on defense meteorological satellite program (DMSP) satellites increase with solar activity10. Ground-based scintillation measurements also show remarkable solar activity dependence11. These solar activity dependences could be attributed to increase in the evening enhancement of eastward electric fields. On the other hand, ionosonde observations in India show that the spread-F occurrence rates during solar minimum are high at post-midnight around the June solstice12,13. Heelis et al.14 analyzed plasma density data obtained with the Communication/Navigation Outage Forecasting System (C/NOFS) satellite and suggested that seeding from tropospheric sources influences post-midnight irregularities. Patra et al.15 observed post-midnight FAIs in summers in low solar activity conditions by using the Gadanki radar in India. Miller et al.16 performed coordinated optical and 50 MHz radar measurements from 2002 to 2010 in the Pacific sector and showed that plasma bubbles and FAIs, indeed, occurred at a high rate during low solar activity conditions.

FAIs in the nighttime F-region have been studied using the Equatorial Atmosphere Radar (EAR) at an operating frequency of 47 MHz at Kototabang (0.20° S, 100.32°E; dip latitude 10.4°S), Indonesia which is located at magnetically low latitudes17-18. Because the EAR mainly performed tropospheric and stratospheric measurements until July 2010, another VHF radar has been installed with an operating frequency of 30.8 MHz at the EAR site to make continuous FAI observations over Indonesia. Otsuka et al.19 reported seasonal and local time variations of the nighttime F-region FAIs observed
with the 30.8 MHz radar from February 2006 to November 2007, and showed that post-midnight FAIs appeared frequently between May and August. Statistical results show that most post-midnight FAI regions did not show propagation, but that some propagated westward. Based on these results, they argued that post-midnight FAIs are similar to mid-latitude FAIs detected by the middle and upper atmosphere (MU) radar and two VHF radars in the Caribbean sector. Mid-latitude FAIs are accompanied by medium-scale traveling ionospheric disturbances (MSTIDs) with wavelengths of several hundred kilometers. Both MSTIDs and FAIs over Japan frequently occur during the nighttime in summer, and have wavelike structures stretching from northwest to southeast and propagating southwestward.

Yokoyama et al., who have compared observations of post-midnight irregularities by the C/NOFS satellite and the EAR, showed that westward-propagating post-midnight irregularities could be associated with either plasma bubbles or MSTIDs.

In the present paper, F-region FAI data, obtained with the 30.8 MHz radar at Kototabang during a solar minimum period in 2006–2010, has been analyzed and statistical results of the FAI propagation velocity has been shown. Based on these results, possible mechanisms for generating the post-midnight FAIs has been discussed.

2 Observations

A VHF backscatter radar with 30.8 MHz operating frequency has been operated since February 2006 at the EAR site in Kototabang, Indonesia. Basic parameters were reported by Otsuka et al. Peak and average transmitting power are 20 and 1.5 kW, respectively. The antenna is composed of a linear array of 18 three-element Yagi antennas. The radar beam can be steered in nine directions between ±54° azimuth around geographic south (125.8°–234.2°). Zenith angle of all radar beams is 20°. Half-power full beam widths are 12° azimuth and 40° zenith. As shown by Fukao et al., perpendicularity between the radar beam and the geomagnetic field line over Kototabang can be achieved at beam zenith angle of 24° due south and 35° at azimuth ±54° from due south. Within the half-power full beam width of 40° zenith, perpendicularity is achieved in all nine VHF radar beam directions.

Since February 2006, the VHF radar has been operated in a mode consisting of E and F-region FAI measurements. To reveal spatial and temporal variations of the FAI echoes, five beams were allocated for F-region FAI measurements on 125.8°, 153.0°, 180.0°, 207.0°, and 234.2° azimuths from February 2006 to January 2008; and 153.0°, 166.4°, 180.0°, 193.6°, and 207.0° since February 2008. Beam coverage was approximately 300 km (between February 2006 and January 2008) and 150 km (from February 2008) at an altitude of 300 km. Single pulses of 128 µs width were transmitted, yielding a range resolution of 19.2 km. Echoes were sampled at 2.4 km intervals in a range of 122–544 km. Time resolution was approximately 4 min.

3 Results

Figure 1 shows range-time-intensity (RTI) plots of the F-region FAI echoes observed on the five beams on 11 June 2009. The vertical axis at the right of each figure shows the altitude at which the radar beam is perpendicular to the geomagnetic field. On this night, the echo region appeared first on the eastern most beam (azimuth 153.0°) at an altitude of 240 km at 0150 hrs LT, and then was sequentially observed on beams with azimuth 166.4°, 180.0°, 193.6°, and 207.0°. From the time delay of the echo appearance between the eastern most and western most beams, propagation velocity of the FAI echo region in the zonal direction was approximately 140 m s⁻¹ westward.

Figure 2 shows RTI plots of the F-region FAI echoes observed on 8 June 2008. FAI echoes were observed first at around altitude of 230 km at 0115 hrs LT on all five radar beams. No time delay of the FAI echo appearance was discernible among the beams, indicating that the FAIs appeared simultaneously within the beam’s field of view.

The F-region FAI data obtained with the VHF radar at Kototabang from 23 February 2006 to 31 December 2010 has been analyzed by using the procedure reported by Otsuka et al. to reveal seasonal and local time variations of the FAI echo occurrence rate. In this study, radar backscatter echoes with signal-to-noise ratio larger than 0 dB and extending more than 50 km are adopted to exclude non-FAI echoes. The signal-to-noise ratio was integrated from 200 to 540 km in range to investigate the FAI occurrence rate. Figure 3 shows seasonal and local time variations of FAI echo intensity observed on the southward beam (azimuth 180°). The black portion in the figure represents no observation due to instrumental problems. From the figure, it is found that post-sunset FAIs were frequently observed between March and May in 2006, and that the
post-midnight FAI occurrence rate was high between May and August during the years 2006–2010. The occurrence rate in 2010 is relatively small as compared to that in other years, indicating negative correlation between the post-midnight FAI occurrence rate and solar activity.

FAI zonal propagation velocities were investigated by comparing FAI echoes among the different five beams. Some FAI echo regions changed their structures on the RTI plots during their passage through the radar’s field of view, making it difficult to determine the time delay between beams. In this study, therefore, data has been used in which an echo time delay can be seen among at least four different beams. Post-midnight FAIs appearing between 0000 and 0500 hrs LT were observed on 253 out of the 448 nights for which F-region FAI measurements were performed between May and August during 2006–2010. Figure 4 shows a histogram of zonal velocity of the post-midnight FAIs for those observations. FAIs propagated eastward on 35 nights (14%) and westward on 116 nights (46%). FAI propagation was not discernible on 102 nights (40%). The average of the zonal propagation velocity is approximately 50 m s\(^{-1}\) westward.

To investigate local time variation of the zonal propagation velocity of the post-midnight F-region FAIs, the velocity data has been divided into 30-minute interval bin and averaged the data in each bin. Figure 5 shows the local time variation of averaged zonal propagation velocity of the post-midnight F-region FAIs observed between May and August during 2006–2010. Error bar in the figure indicates standard deviation of the propagation velocity.
velocity in each bin. The local time variation of the averaged propagation velocity is not distinct whereas the standard deviations exceed 100 m s$^{-1}$.

4 Discussion

Analysis of FAI data obtained by the 30.8 MHz radar at Kototabang, Indonesia, from February 2006 to December 2010 revealed that post-midnight FAIs are frequently observed between May and August during solar minimum periods, in contrast to post-sunset FAIs, which frequently occur at equinox during solar maximum periods. Seasonal and solar activity dependences of the post-midnight FAIs observed at Kototabang are consistent with those observed by VHF coherent radars in India and Hawaii$^{15,16}$. Tsunoda et al.$^{23}$ have suggested that plasma bubbles at solstices could be generated mainly by seeding of gravity waves launched from the inter-tropical convergence zone (ITCZ), and that seasonal migration of the ITCZ in latitude could account for the seasonal variation of the post-midnight plasma bubbles. The present results are consistent with this hypothesis.

Figure 2—Range-time-intensity plot of the field-aligned irregularity (FAI) in the F-region observed on beams with azimuth 153.0°, 166.4°, 180.0°, 193.6°, and 207.0° (top to bottom panels) with 30.8 MHz radar at Kototabang, Indonesia on 8 June 2008 [left vertical axis shows the range from the radar and the right axis shows the altitude at which the radar beam is perpendicular to the geomagnetic field].

Five-beam measurements by the VHF radar at Kototabang allows to estimate apparent zonal velocity of the FAI propagation. Statistical analysis shows that post-midnight FAIs prefer to propagate westward rather than eastward, which is inconsistent with the propagation direction of plasma bubbles that occur at the sunset terminator. The plasma bubbles propagate at the same velocity as ambient plasma, and the nighttime F-region plasma moves by $E 	imes B$ drift. Fejer et al.$^{24}$ reported that seasonally averaged plasma drift measured by the Jicamarca incoherent scatter radar at...
the magnetic equator is eastward through nighttime in all seasons for both low and high solar activity conditions. Fejer\textsuperscript{25} performed statistical study of the plasma drift observed with the Arecibo incoherent scatter radar at middle latitude (magnetic latitude of 30°), and showed that the zonal plasma drift velocities turn from eastward to westward around midnight during low solar activity periods. These results suggest that the zonal plasma drift velocity decreases with altitude/latitude and reverses direction from eastward to westward in some cases. Such altitude/latitude variation of the zonal drift velocities is responsible for the inverted-C shape of plasma bubble structures.\textsuperscript{26} Yokoyama \textit{et al.}\textsuperscript{21,22} suggested that at Kototabang, which is located at a low magnetic latitude (10°S), westward motion of the F-region plasma and plasma bubble may occur and showed that plasma drift measured with the C/NOFS satellite was westward during post-midnight FAIs observed with the EAR. Consequently, the post-midnight plasma drift over Kototabang could be westward in some cases during solar minimum.

Next, it has been considered whether the seasonally-averaged plasma drift velocity at post-midnight over Kototabang is westward, based on the statistical results of zonal plasma drift velocities over Jicamarca and Arecibo as reported by Fejer \textit{et al.}\textsuperscript{23} and Fejer\textsuperscript{24}, respectively. The seasonally-averaged post-midnight velocities for low solar activity conditions are approximately 30 m s\textsuperscript{-1} eastward over Jicamarca and 0–50 m s\textsuperscript{-1} westward over Arecibo. Assuming zonal plasma drift velocity
linearly decreases with latitude from the magnetic equator to the magnetic latitude of Arecibo (30°N). The zonal plasma drift velocity at Kototabang (magnetic latitude of 10°S) is estimated to be approximately 0–20 ms⁻¹ eastward. Since the post-midnight plasma drift over Kototabang is eastward on average, a high occurrence (46%) of the westward propagating FAIs at post-midnight cannot be explained by post-midnight FAI coexisting with plasma bubbles. Furthermore, the plasma drift velocity at equatorial and mid-latitude regions tends to increase its westward component with time during nighttime. However, averaged zonal propagation velocity of the post-midnight FAI does not show distinct local time dependence, indicating that the FAI propagation velocity may not follow the plasma drift velocity. It is, therefore, suggested that not all post-midnight FAIs are associated with plasma bubbles, although some might coexist with them.

The westward plasma motion, in general, can be caused by the disturbance dynamo electric fields. During geomagnetically disturbed conditions, the thermosphere at the auroral region is heated by the Joule and/or frictional heating. The resulting pressure gradient toward higher latitude drives equatorward thermospheric winds. By the Coriolis force, westward component of the thermospheric winds are generated. Because the westward winds traverse the geomagnetic field lines, ions move downward due to the Lorentz force and collisions with neutral particles. On the other hand, electrons do not move, resulting in generating upward electric fields, which cause westward plasma motion through the \( E \times B \) drift. In the present study, the geomagnetic activity dependence of the post-midnight FAI propagation direction has been investigated. It is defined geomagnetically quiet (disturbed) day as sigma Kp index (integration of 3-hour Kp index over a day) less than or equal to 24 (greater than 24). Table 1 shows number of events of the eastward and westward propagating post-midnight FAIs for the geomagnetically quiet and disturbed days. It has been found that westward propagation of the post-midnight FAIs is observed frequently even in the quiet conditions. This result indicates that major cause of the westward propagation of the post-midnight FAIs is not the disturbance dynamo electric fields. On the disturbed day, on the other hand, eastward propagating FAIs were not observed, indicating that the disturbance dynamo mechanism may be operating.

It may be noted that some researchers report difference between the ambient F-region plasma drift and movement of the plasma bubbles. Huang et al. have shown that, in most cases, the zonal plasma drift velocity inside the plasma bubbles is westward relative to the ambient plasma velocity, and explained that the plasma drift inside the plasma bubbles could be caused by polarization electric fields. This westward plasma drift relative to the ambient plasma may make the plasma bubble motion slower than the ambient plasma drift. Furthermore, Huang et al. have reported that electric field in the plasma depletion at the post-midnight sector is stronger than that of the ambient plasma and suggested that the post-midnight plasma depletion is plasma bubble in the growth phase.

**Fig. 4**—Histogram of zonal propagation velocity (positive eastward) of the post-midnight F-region FAIs observed during 0000–0500 hrs LT between May and August 2006–2010

**Fig. 5**—Local time variation of averaged zonal propagation velocity (positive eastward) of the post-midnight F-region FAIs observed between May and August 2006–2010. [error bar indicates standard deviation of the zonal propagation velocity in each 30-minute bin]
Fukao et al.\textsuperscript{18} and Yokoyama et al.\textsuperscript{21,22} suggested that some post-midnight FAIs over Kototabang are mid-latitude-type FAIs accompanied by nighttime MSTIDs, which have mirrored structures in the northern and southern hemispheres connected by the geomagnetic field at mid-latitude and prefer to propagate northwestward (southwestward) with a wavefront elongated from northeast to southwest (northwest to southeast) in the southern (northern) hemisphere\textsuperscript{31,32}. The horizontal propagation velocities of mid-latitude MSTIDs are mostly 40–120 ms\(^{-1}\) (Refs \textsuperscript{33,34}), and mid-latitude FAIs often coexist with MSTIDs. Both FAIs and MSTIDs have structures elongated from northwest to southeast and propagate in identical directions\textsuperscript{20,35}. Mid-latitude MSTIDs are accompanied by polarization electric fields\textsuperscript{36}, which could generate the mid-latitude FAIs through gradient-drift instability\textsuperscript{35}. In light of this generation mechanism, the FAIs could have structure similar to the MSTIDs and propagate in the same direction. The above results indicate that FAIs over Kototabang have a structure elongated from northeast to southwest and propagate northwestward. The results of the present study show that FAIs prefer to propagate westward at an average velocity of 50 m s\(^{-1}\) in the zonal direction, consistent with mid-latitude FAIs that are associated with the MSTIDs.

In the current study, FAI propagation velocity could not be determined for 40\% of the post-midnight FAIs, including events such as those shown in Fig. 2 in which FAIs were observed almost simultaneously on different five beams. Yokoyama et al.\textsuperscript{21,22} reported that post-midnight FAIs observed at the EAR coexisted with plasma density depletion and electric field perturbations observed with \textit{in situ} measurements by the C/NOFS satellite. They, furthermore, showed that plasma density and electric field irregularities were observed at post-midnight sectors for every satellite orbit and suggested that post-midnight FAIs could be generated at a fixed local time one after another. Ground-based measurements should, therefore, indicate FAIs propagating westward at a velocity of approximately 500 m s\(^{-1}\) over the equator. The time resolution and radar beam coverage of the current VHF radar measurements do not allow to detect such fast propagation, meaning FAIs might seemingly appear simultaneously on all radar beams. Such events may be included among those post-midnight FAIs without propagation features.

### 5 Summary and Conclusions

The F-region FAI data observed with 30.8 MHz Doppler radar at Kototabang, Indonesia from 23 February 2006 to 31 December 2010 during a solar minimum period has been analyzed. Post-midnight FAIs were frequently observed between May and August during 2006—2010, and seasonal variation was consistent with observations at India and Hawaii. This paper presents, for the first time, statistical results regarding the FAI propagation velocity in the zonal direction. Of the observed post-midnight FAIs, 46\% propagated westward, whereas 16\% propagated eastward. Average propagation velocity in the zonal direction was approximately 50 ms\(^{-1}\) westward. Although the post-midnight FAIs could be associated with plasma bubbles, the high occurrence rate of westward propagating post-midnight FAIs over Kototabang is not explained by the average plasma drift velocities observed at Jicamarca and Arecibo, indicating that not all post-midnight FAIs are associated with plasma bubbles. Some post-midnight FAIs over Kototabang could be mid-latitude FAIs coexisting with MSTIDs, because the zonal propagation velocity of the post-midnight FAIs is comparable to the MSTIDs observed at mid-latitudes.

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### References


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| Table 1—Number of events of the post-midnight FAIs propagating toward different directions for the magnetically quiet and disturbed days |
|----------------|----------------|
|                | Quiet | Disturbed |
| Westward propagation | 110   | 6         |
| Eastward propagation  | 35    | 0         |
| No propagation         | 181   | 13        |

*Geomagnetically quiet (disturbed) day is defined as sigma Kp index less than or equal to 24 (greater than 24), respectively.*
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