Characteristics of the *E*- and *F*-region field-aligned irregularities in middle latitudes: Initial results obtained from the Daejeon 40.8 MHz VHF radar in South Korea

Young-Sil Kwak^{1,2†}, Tae-Yong Yang^{1,2}, Hoysub Kil³, Devulapalli Venkata Phanikumar⁴, Bok-Haeng Heo⁵, Jae-Jin Lee¹, Junga Hwang¹, Seong-Hwan Choi¹, Young-Deuk Park¹, Ho-Seong Choi⁶

¹Division of Space Science, Korea Astronomy and Space Science Institute, Daejeon 305-348, Korea

²University of Science and Technology, Daejeon 305-350, Korea

³Space Department, The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA

⁴Aryabhata Research Institute of Observational Sciences (ARIES), Nainital, India

⁵Korea Meteorological Administration, Seoul 156-720, Korea

⁶Republic of Korea Air Force, Gyeryong-si, Korea

We present preliminary observations of the field-aligned-irregularities (FAIs) in the *E* and *F* regions during the solar minimum (2009 - 2010) using the 40.8 MHz coherent backscatter radar at Daejeon (36.18°N, 127.14°E, 26.7°N dip latitude) in South Korea. The radar, which consists of 24 Yagi antennas, observes the FAIs using a single beam with a peak power of 24 kW. The radar has been continuously operated since December 2009. Depending on the manner of occurrence of the backscatter echoes, the *E*-region echoes are largely divided into two types: quasi-periodic (QP) and continuous echoes. Our observations show that the QP echoes occur frequently above an altitude of 105 km in the post-sunset period and continuous echoes occur preferentially around an altitude of 105 km in the post-sunrise period. QP echoes appear as striated discrete echoes for a period of about 10 - 20 min. The QP-type echoes occur more frequently than the continuous-type echoes do and the echo intensity of the QP type is stronger than that of the continuous type. In the *F* region, the FAIs occur at night at an altitude interval of 250 - 450 km. As time proceeds, the occurrence height of the FAIs gradually increases until early in the morning and then decreases. The duration of the *F*-region FAIs is typically a few hours at night, although, in rare cases, FAIs persist throughout the night or appear even after sunrise. We discuss the similarities and differences of the FAIs observed by the Daejeon radar in comparison with other radar observations.

Keywords: VHF coherent backscatter radar, ionospheric irregularities, mid-latitude

1. INTRODUCTION

The electron density irregularities in the ionosphere cause diffraction of the radio waves that can be responsible for scintillation, fading, and disruption of the propagating signals. For this practical importance, significant efforts have been made to establish information on the occurrence climatology of such irregularities, to understand the onset conditions of such irregularities, and to predict or avoid

the impact of these irregularities on the society. While the irregularities occur in all latitudes, less attention has been paid to irregularities in the middle latitudes. This may be because irregularities in the middle latitudes are not as severe as those in other latitude regions. However, the middle latitudes are also the place where various forms of irregularities cause radio scintillations.

During the last five decades, coherent backscatter radars have been widely used to probe electron density

© This is an open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/3.0/>) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Received Jan 27, 2014 Revised Feb 18, 2014 Accepted Feb 19, 2014

†Corresponding Author

E-mail: yskwak@kasi.re.kr

Tel: +82-42-865-2039, Fax: +82-42-865-3272

irregularities in the equatorial region (e.g., Ragharavao et al. 2002, and references therein), in middle latitudes (e.g., Yamamoto et al. 2005, and references therein), and in the auroral region (e.g., Haldoupis et al. 1993, and references therein). A mono-static coherent scatter radars detect the radio waves that are scattered by the medium under observation. These backscattered signals correspond to the Bragg wavelength component of the fluctuations in the refractive index of the medium caused by the ionospheric electron density irregularities. In a mono-static radar, the Bragg wavelength is half of the radar wavelength. The properties of the irregularities are assessed according to the strength, Doppler velocity, and spectral width of the echoes. Anisotropic motions of plasmas associated with magnetic field cause the elongation of the irregularities along the magnetic field lines. For this reason, ionospheric electron density irregularities are often called Field-Aligned-Irregularities (FAIs). Very High Frequency (VHF) radars have been used to detect meter-scale FAIs in the *E* and *F* regions.

In middle latitudes, radar probing of FAIs started with the observation of sporadic *E* (*Es*) at an altitude of ~105 km with a portable 50-MHz radar on the island of Guadeloupe in French West Indies (Ecklund et al. 1981). Our understanding of the middle-latitude irregularity phenomenon was enriched by the observations of the Middle and Upper atmosphere (MU) radar at Shigaraki (34.89°N, 136.10°E, 29.3°N dip latitude) in Japan (Fukao et al. 1985a,b). From MU radar observations, Yamamoto et al. (1991) identified the existence of two types of echoes in the middle-latitude *E* region: “quasi-periodic (QP)” and “continuous” echoes. QP echoes occur intermittently with periods of 5–10 min above 100 km altitude in the post-sunset period. Continuous echoes indicate continuous echoes in time and appear in the altitude interval of 90–100 km in the post-sunrise period. The occurrence rate of QP echoes shows a distinct seasonal variation, with a maximum during the northern summer months. Normally, the occurrence rate of QP echoes increases abruptly after sunset and decreases after midnight (Yamamoto et al. 1992).

Woodman et al. (1991) suggested that *E*-region QP echoes can be created by the modulation of the *Es* layer by atmospheric gravity waves. Tsunoda et al. (1994) extended the theory of Woodman et al. (1991) and suggested that polarized electric fields produced by spatial modulation of the *Es* layer by gravity waves are responsible for the QP echoes. The Sporadic-*E* Experiment over Kyushu (SEEK) (e.g., Fukao et al. 1998, Yamamoto et al. 1998) and SEEK-2 (e.g., Saito et al. 2005, Yamamoto et al. 2005) were conducted at Kyushu in Japan to investigate the relationship

between QP echoes and *Es* layers. The campaign results showed that polarization electric fields and QP echoes were induced in association with the *Es* layer. In addition, the whole set of *E*-region structures were seen to be controlled by polarization electric fields mapped upward along geomagnetic field lines. Otsuka et al. (2007) reported that the electric fields associated with the *F*-region medium-scale traveling ionospheric disturbances (MSTIDs) could be closely coupled to the electric fields associated with QP echoes in the *E* region.

Several studies have investigated *F*-region irregularities in middle latitudes using radars in Japan (Fukao et al. 1988, 1991, Otsuka et al. 2009, Saito et al. 1998, 2002, 2008) and Puerto Rico (Swartz et al. 2000). Because the investigation of the *F*-region FAIs has been done as an event or on a campaign basis, the characteristics and distribution of the *F*-region FAIs have not yet been established. QP-type variation of the echo intensity has also been observed in the *F* region (Fukao et al. 1988), but we do not know yet how frequently QP-type echoes occur in the *F* region. Perkins instability is suggested as the source of the FAIs in the middle-latitude *F* region (Behnke 1979, Perkins 1973). However, Kelley & Fukao (1991) argued that the growth rate of the Perkins instability is too small to explain the observed FAI strength and suggested that seeding by gravity waves is necessary. From the observations of FAIs and the 630 nm airglow intensity over Arecibo in Puerto Rico, Miller et al. (1997) identified the development of *F*-region FAIs in association with gravity wave seeding. Fukao et al. (1991) noticed the occurrence of *F*-region FAIs accompanied by MSTIDs whose wavelength was of several hundred kilometers. Both MSTIDs and FAIs frequently occur over Japan at nighttime during summer (Saito et al. 2002). Otsuka et al. (2009) reported simultaneous observations of MSTIDs and FAIs in the *F* region using an all-sky imager and MU radar. Spatial modulation of plasma density by MSTIDs induces polarization electric fields, by which plasmas drift vertically and develop FAIs (Otsuka et al. 2009).

MU radar is the major data source of the FAIs in middle latitude, but the radar has been operated on a campaign basis. Intermittent radar observations are not sufficient for the investigation of the characteristics, occurrence climatology, and driving mechanisms of middle-latitude FAIs. A 40.8 MHz VHF radar was built at Daejeon (36.18°N, 127.14°E, 26.7°N dip latitude) in South Korea aiming at continuous monitoring of middle-latitude FAIs in the Far East Asian sector. The radar has been continuously operated since December 2009. For the purpose of introducing the Daejeon VHF radar and its capability to the community, we report initial results obtained between 29 December 2009

Table 1. Specifications of the VHF ionospheric radar at Daejeon.

Parameter	Value
Latitude	36.2°N
Longitude	127.1°E
Magnetic latitude	26.7°N
Antenna	12×2 array of 5-element Yagi antennas
Frequency	40.8 MHz
Peak power	24 kW
Band width	170 kHz
Beam direction	48°N
Beam width	10° horizontally, 22° vertically

Table 2. Observational modes for *E*- and *F*-region FAIs.

Parameter	<i>E</i> -region FAIs	<i>F</i> -region FAIs
Pulse repetition frequency (Hz)	400	150
Interpulse period (ms)	2.5	6.6
Pulse width (μs)	6	32
Range resolution (km)	0.9	4.8

and 28 June 2010. This period corresponds to the period of the solar minimum. We present various forms of echoes in the *E* and *F* regions observed by the Daejeon radar and discuss the similarities and differences between the *E*- and *F*-region FAIs observed by the Daejeon and MU radars.

2. EXPERIMENT DESCRIPTION

The Daejeon VHF radar is operated at a frequency of 40.8 MHz and with a peak transmitting power of 24 kW. The basic parameters and the technical specifications of the radar are listed in Table 1. The antenna system, occupying an area of 85 × 40 m, is a phased array of 12 × 2 five-element Yagi antennas. To detect the coherent backscatter from the *E*- and *F*-region irregularities, the radar beam is oriented at a 48° zenith angle due magnetic north, which satisfies the field perpendicularity condition at the *E*- and *F*-region heights. Half-power full beam widths in azimuth and zenith directions are 10° and 22°, respectively. Table 2 lists the observational modes for the *E*- and *F*-region FAIs. The radar has been operating on a routine basis, sampling the *E* and *F* regions for one minute. The inter-pulse periods for the *E*- and *F*-region experiments are 2.5 and 6.6 ms, respectively, and the pulse widths are 6 and 32 μs, respectively. The range resolutions of the VHF radar measurements for the *E* and *F* regions are 900 m and 4.8 km, respectively. The *E*- and *F*-region FAIs detected by the 40.8 MHz radar correspond to a scale size of 3.68 m (half wavelength of the transmitted pulse).

Our VHF radar consists of a transmitter, transceiver, and two-computers for analysis and acquisition. Raw data is acquired at 14 bit sampling resolution and ±2V

Fig. 1. The view of the Daejeon 40.8 MHz VHF radar site. **Fig. 2.** Schematic representation of our Daejeon coherent scatter radar experiments in South Korea. The small circle represents the location of the radar. The horizontal curves are the loci where the radar ray paths are perpendicular to the geomagnetic field at *E*- and *F*-region altitudes.

input range. The complex time series of the decoded and integrated raw data signal samples are subjected to the process of fast Fourier transform for on-line computation of the Doppler power spectra for each range bin of the selected range window. The processing of these Doppler power spectra involves the removal of DC, the estimation of the average noise levels, the removal of interference, incoherent integration, and the computation of the three low-order moments. As a method of post-analysis for the raw data, Ionospheric Doppler Beam Steering (IDBS) analysis provides estimates of the Doppler velocity, spectral width, signal-to-noise ratio (SNR), and power for a number

of transmitted beam directions. IDBS analyzed data are written to a Solid State Drive disk in a binary format. During continuous data acquisition, each analyzed data file begins at 00:00 universal time (UT).

Fig. 1 shows the view of the radar site. Fig. 2 illustrates the geometry of the radar experiment. The location of the radar is marked with a small circle. The horizontal curves with vertical height information show the loci where the radar ray paths are perpendicular to the geomagnetic field at various *E*- and *F*-region altitudes, assuming straight-line ray propagation paths.

3. *E*-REGION FAIS

Using During the initial observations from 29 December 2009 to 28 June 2010, intense echoes frequently occurred between 17:00 and 24:00 local time (LT) above 105 km height (155 km range). Fig. 3 shows the power spectra of the Doppler velocity in the *E* region at 19:00 LT on 24 February 2010. Positive (negative) velocity corresponds to motion away from (towards) the radar or upward (downward) motion. Strong echoes appear at the 165 - 195 km range (110 - 130 km in height). The mean Doppler velocity is well below the ion acoustic velocity (350 - 400 ms⁻¹). Type II spectra, which are often observed in the middle latitudes, are characterized by broad Doppler spectral width (300 - 800 ms⁻¹) and small mean Doppler velocity (Schlegel 1996). Owing to the narrow Doppler spectral width of the echoes, most of the echoes observed at Daejeon are categorized as narrow Type II spectra.

Fig. 4 presents sample observations of the (a) signal-to-noise ratio (SNR), (b) Doppler velocity, and (c) spectral width between 16:00 and 23:00 LT on 24 February 2010. The plots are presented in the range-time-intensity (RTI) format with height on the right side. Strong echoes appear at an altitude interval of 115 - 130 km just after sunset (18:40 LT) and persist until midnight at an altitude interval of 105 - 120 km. The heights of the *E*-region QP echoes observed by the Daejeon radar are higher by about 5 km than those observed by the MU radar (e.g., Yamamoto et al. 1991, 1992). From Fig. 4a, one may notice the quasi-periodic variation of the echo intensity as a function of time, with a period of 10 - 20 min. This sample observation may explain why those echoes are named QP echoes. The other interesting features are the descent of the echo height with time and the vertical striation of the echoes. These are also the characteristics of middle-latitude *E*-region QP echoes. The descending rate of the echo altitude is ~3 km per hour. The gradual descent of the QP echo altitude in the *E* region is seen to be

Fig. 3. Doppler spectra associated with the *E*-region FAIs observed at 19:00 LT on 24 February 2010.

Fig. 4. Range-time variation of (a) SNR, (b) Doppler velocity, and (c) spectral width of the *E*-region QP echoes observed on 24 February 2010. 'S' denotes the sunset time.

a common behavior in the low and middle latitudes. This phenomenon is observed in the middle latitudes by the MU radar (e.g., Ogawa et al. 1995, Yamamoto et al. 1992), near the equatorial ionization anomaly region by VHF radar at Chung-Li (24.91°N, 121.24°E, 13.3°N dip latitude) in Taiwan (Pan et al. 1994), and near the magnetic equator

Fig. 5. Range-time variation of (a) SNR, (b) Doppler velocity, and (c) spectral width of the *E*-region continuous echoes observed on 2 June 2010. 'R' denotes the sunrise time.

by the MST Radar at Gadanki (13.45°N, 79.17°E, 6.4°N dip latitude) in India (Choudary et al. 1996). The striation of the echoes is similar to the observations by the MU radar (Fukao et al. 1998, Yamamoto et al. 1991) and to those of the radar at Tanegashima (30.75°N, 131.03°E, 43.2°N dip latitude) (Tsunoda et al. 1998). One of the characteristics of the striations in the middle latitudes is the negative slope of the striations in the frame of time and height. That is, the echoes move downward as time progresses. However, the striations in the lower latitudes, as observed at Chung-Li (Pan & Tsunoda 1998) and Gadanki (Patra et al. 2002), show a positive slope. The reason for the opposite behavior of the striations in different latitudes has not yet been clearly understood. The Doppler velocities shown in Fig. 4b verify the downward motion of the *E*-region QP echoes. A positive (negative) value of Doppler velocity indicates motion away from (toward) the radar or upward (downward) velocity. Since the Doppler velocity of the FAI echoes is the phase velocity of the plasma irregularities, the Doppler velocities above 100 km altitude correspond to a line-of-sight component of the $E \times B$ plasma drift (Tanaka & Venkateswaran 1982). The Doppler velocities for the QP

echoes above 105 km are mostly more than 30 ms⁻¹ and their signs are mostly negative, indicating the movement of the FAIs toward the radar (or the downward motion of the FAIs). The negative Doppler velocities of the QP echoes are consistent with the decrease of the echo height with time and with the negative slopes of the striations observed in Fig. 4a. The full spectral width of the Doppler velocity shown in Fig. 4c represents the level of turbulence in the medium. The spectral width ranges between 20 ms⁻¹ and 100 ms⁻¹ and varies with time and spatial. In comparison with the Doppler velocity shown in Fig. 4b, the spectral widths near the regions of positive/upward velocities are greater than those near the regions of negative/downward velocities. However, the behavior of the spectral width is variable day to day and the observation in Fig. 4c is not a general feature.

The characteristics of the *E*-region echoes observed in the post-sunrise period are quite different from those of the QP echoes. In the post-sunrise period, the weak echoes (SNR ≤ 15 dB) that show a quasi-stable behavior occur frequently at an altitude interval of 100 - 110 km. These echoes are of the continuous type in nature in both space and time. Fig. 5 presents an example of continuous echoes observed on 2 June 2010. The format is the same as that used in Fig. 4. In Fig. 5a, continuous echoes start to appear with sunrise (05:10 LT) around an altitude of 105 km and the echoes are seen to persistent for several hours. The SNR of the echo is less than 15 dB, which is smaller than the SNR of the QP echoes shown in Fig. 4a. Fig. 5b shows the line-of-sight Doppler velocities for the same time period. The mean Doppler velocities around 105 km altitude are mostly less than 30 ms⁻¹. The Doppler velocity is positive between 05:10 and 07:00 LT, indicating that FAIs are moving away from the radar (or upward velocities). Observations of both the positive and negative Doppler velocities after 07:00 LT may indicate a merger of two different FAI layers. Fig. 5c shows the full Doppler spectral width. The full spectral widths are less than 50 ms⁻¹. Formation of a narrow spectral width (< 100 ms⁻¹) is explained by the gradient drift instability (Ogawa et al. 1995). For MU radar observations, continuous echoes (Yamamoto et al. 1991, 1992, 1994, Ogawa et al. 1995, 2002) appear around a height of 90 - 100 km, about 5 km lower than the height shown in Fig. 5. Because the echo height is variable day to day, comparison of the simultaneous observations at Daejeon and Shigaraki and values from statistical analysis are necessary in order to verify the existence of any latitudinal and longitudinal variations of the echo height. Ogawa et al. (2002) suggested that continuous echoes have no relation with *Es* activity, but the driving mechanism of the continuous echoes remains a widely open question.

Fig. 6. Range-time variation of (a-c) SNR and (d-f) Doppler velocity of *F*-region FAIs observed on 30-31 December 2009 and 1 January 2010.

4. *F*-REGION FAIS

F-region FAIs appear after sunset and disappear just before sunrise. Following the seasonal variation of the sunset and sunrise times, the occurrence LT of the FAIs also varies with season. The majority of FAIs in the *F* region appear like sparsely distributed patches. Infrequently, FAIs are persistent throughout the night. Here we present examples of those two types.

Patch type FAIs were observed at early morning for three consecutive days. Fig. 6 shows the RTI plots of (a-c) SNR and (d-f) Doppler velocity during the period 30 December 2009–1 January 2010. Figs. 6a-c show the existence of a mixture of weak (~ -10 dB) and strong (~ -20 dB) echoes during those three days. The echoes appear between the heights of 230 and 430 km. The echo height shows a tendency to decrease with time. The strong echoes in Figs. 6a and 6b show negative height rate, i.e., decrease of the echo height with time. On the other hand, the strong echoes in Fig. 6c show upward movement between 02:00 and 03:00 LT, reaching to a height of 330 km altitude and then exhibiting downward movement after 04:00 LT. The Doppler velocities shown in Figs. 6d-f are consistent with the movement of echoes shown in Figs. 6a-c. The Doppler velocities during the three days are mostly negative, with a maximum velocity of 66 ms^{-1} . At the locations of the echoes that show positive height rates (the echoes between 02:00 and 03:00 LT in Fig. 6c), the Doppler velocity is about 50 ms^{-1} . The striations of the negative height rates (the slope of the striation on the time and height frame) show negative Doppler velocities (moving toward the radar or downward velocities) and the striations of positive height rates show positive Doppler velocities

(moving away from the radar or upward velocities). The striation of the *F*-region echoes and the variation of the observed Doppler velocities, depending on the height rate of the striation, were similar to those observed by the MU radar in Japan (Fukao et al. 1991, Saito et al. 2008).

Fig. 7 shows an example of persistent *F*-region FAIs observed on the night of 23-24 February 2010. In Fig. 7a, strong echoes appear around 290 km height at about 20:00 LT, move upward to around 380 km height at about 23:00 LT, and echoes then descend until 01:30 LT. Abrupt upward movements of the echoes are observed between 01:30 and 02:00 LT and the peak height of the echoes reaches 450 km. Then, strong echoes gradually descend and persist until 07:00 LT. After 07:00 LT, the echo height abruptly drops from 280 km to below 230 km. The echoes observed at 07:00 LT persist until 09:00 LT. The persistence of the *F*-region FAIs throughout the night rarely happens in middle latitude, and the *F*-region FAIs after sunrise have not yet been reported in previous studies. The *F*-region echoes show striations whose slope on the time and altitude frame varies with time. The slope is negative at 20:00 - 23:30 LT, positive at 23:30 - 00:00 LT, negative at 00:00 - 02:00 LT, etc. The property of the striation is more clearly visible by looking at the Doppler velocity shown in Fig. 7b. Striations with negative height rates have negative Doppler velocities (moving toward the radar or downward velocities) and those with positive slopes have positive Doppler velocities (moving away from the radar or upward velocities). The Doppler velocity is negative in the pre-midnight period, whereas the direction of the Doppler velocity varies quasi-periodically after midnight. At the locations of the FAIs after sunrise, the Doppler velocity is positive. The quasi-periodic variation of the striation

Fig. 7. Range-time variation of (a) SNR, (b) Doppler velocity, and (c) spectral width of *F*-region FAIs observed on 23-24 February 2010.

(or Doppler velocity) was also identified from persistent echoes observed during other days. The spectral widths of the Doppler velocity shown in Fig. 7c are mostly less than 15 ms^{-1} , which is smaller by about a factor of 2 compared with those of the *E*-region FAIs. We leave further specification of the *F*-region echoes and investigation of their association with MSTIDs to future studies.

5. SUMMARY

In this paper, we introduce initial observations of *E*- and *F*-region FAIs during the solar minimum (2009-2010) using the 40.8 MHz coherent backscatter radar at Daejeon (36.18°N , 127.14°E , 26.7°N dip latitude) in South Korea. In the *E* region, QP-type echoes appear in the post-sunset period above an altitude of 105 km and continuous-type echoes appear in post-sunrise period around an altitude of 105 km. The QP echoes occur intermittently with a quasi-period of 10-20 min and descend to lower altitudes as time progresses. The striations in the QP echoes show negative slopes on the time and altitude frame. While most of the characteristics of the *E*-region QP and continuous echoes

observed at Daejeon are consistent with those observed by the MU radar in Japan, the height of the *E*-region QP and continuous echoes observed by the Daejeon radar is seen to be higher by about 5 km than that observed by the MU radar.

In the *F* region, FAIs appear mostly at night in the altitude range of 250 - 450 km. Most of these echoes look like patches that last for a few hours. In general, the height of the FAIs increases during pre-midnight and decreases during post-midnight. The duration of the *F*-region FAIs is typically a few hours at night, although, in rare cases, FAIs persist throughout the night. The *F*-region FAIs after sunrise are a new finding by the Daejeon radar. Striation and periodic variation of the striation direction of the FAIs are observed in the *F* region. The striations of negative and positive slopes on the time-height frame are consistent with observations of negative and positive Doppler velocities, respectively. The striation of the *F*-region echoes and the periodic variation of the Doppler velocity, depending on the direction of the striation, were also identified by the MU radar in Japan.

The Daejeon radar has been operated continuously since December 2009. Initially (December 2009 -January 2010), the operation time intervals of the *E*- and *F*-region modes were 00:00 - 24:00 LT and 18:00 - 06:00 LT, respectively. For the period of February 2010 - January 2011, the operation time interval of the *F*-region mode was changed to 18:00 - 09:00 LT. Since February 2011, the *E*- and *F*-region modes have been operated for 24 hours. Other observational facilities such as an all-sky imager, ionosonde, global positioning system, scintillation monitor, total electron content meter, and magnetometer are available near the Daejeon radar observatory. Combining those observations, the continuous and long-term observations of the Daejeon radar are expected to enrich our understanding of the characteristics, climatology, and driving mechanisms of middle-latitude irregularities.

ACKNOWLEDGMENTS

This paper is based on research sponsored by the Air Force Research Laboratory, under agreement number FA 2386-14-1-4004. Y.-S. Kwak was also supported by the “Study of near-Earth effects by CME/HSS” project and basic research funding from Korea Astronomy and Space Science Institute (KASI). The Daejeon VHF radar was developed and installed with the support of the “Development of Korean Space Weather Center”, a project of the KASI. H. Kil acknowledges support from National Science Foundation Aeronomy program (AGS-1237276). We are grateful for

the helpful advice offered by D. L. Hysell. We also thank the members of ATRAD for their kind support of the construction and continuous operation of our radar.

REFERENCES

- Behnke RA, *F*-layer height bands in the nocturnal ionosphere over Arecibo, JGR, 84, 974-978 (1979). <http://dx.doi.org/10.1029/JA084iA03p00974>
- Choudary RK, Mahajan KK, Singh S, Kumar K, Anandan VK, First VHF radar observations of tropical latitude *E*-region field-aligned irregularities, GRL, 23, 3683-3686 (1996). <http://dx.doi.org/10.1029/96GL02625>
- Ecklund WL, Carter DA, Balsley BB, Gradient drift irregularities in mid-latitude sporadic E, JGR, 86, 858-862 (1981). <http://dx.doi.org/10.1029/JA086iA02p00858>
- Fukao S, Kelley MC, Shirakawa T, Takami T, Yamamoto M, et al., Turbulent upwelling of the mid-latitude ionosphere: 1. Observational results by the MU radar, JGR, 96, 3725-3746 (1991). <http://dx.doi.org/10.1029/90JA02253>
- Fukao S, McClure JP, Ito A, Sato T, Kimura I, et al., First VHF radar observation of mid-latitude F-region field-aligned irregularities, GRL, 15, 768-771 (1988). <http://dx.doi.org/10.1029/GL015i008p00768>
- Fukao S, Sato T, Tsuda T, Kato S, Wakasugi K, et al., The MU radar with an active phased array system, 1. Antenna and power amplifiers, Radio Sci., 20, 1158-1168 (1985a). <http://dx.doi.org/10.1029/RS020i006p01155>
- Fukao S, Tsuda T, Sato T, Kato S, Wakasugi K, et al., The MU radar with an active phased array system, 2. In-house equipment, Radio Sci., 20, 1169-1176 (1985b). <http://dx.doi.org/10.1029/RS020i006p01169>
- Fukao S, Yamamoto M, Tsunoda RT, Hayakawa H, The SEEK (Sporadic E Experiment over Kyushu) Campaign, GRL, 25, 1761-1764 (1998). <http://dx.doi.org/10.1029/98GL00932>
- Haldoupis C, Koehler J, Sofko G, Danskin D, McKibben M, André D, Preferential phase velocities for type 4 Irregularities in the auroral E-region plasma, JGR, 98, 6173-6179 (1993). <http://dx.doi.org/10.1029/92JA02652>
- Kelley MC, Fukao S, Turbulent upwelling of the mid-latitude ionosphere: 2. Theoretical framework, JGR, 96, 3725-3746 (1991). <http://dx.doi.org/10.1029/90JA02252>
- Miller CA, Swartz WE, Kelley MC, Mendillo M, Nottingham D, Scali J, Reinisch B, Electrodynamics of mid-latitude spread *F*: 1. Observations of unstable, gravity wave-induced ionospheric electric fields at tropical latitudes, JGR, 102, 11521-11532 (1997). <http://dx.doi.org/10.1029/96JA03839>
- Ogawa T, Takahashi O, Otsuka Y, Nozaki K, Yamamoto M, et al., Simultaneous middle and upper atmosphere radar and ionospheric sounder observations of mid-latitude *E*-region irregularities and sporadic *E* layer, JGR, 107, SIA 3-1-SIA3-13 (2002). <http://dx.doi.org/10.1029/2001JA900176>
- Ogawa T, Yamamoto M, Fukao S, Middle and upper atmosphere radar observations of turbulence and movement of mid-latitude sporadic *E* irregularities, JGR, 100, 12173-12188 (1995). <http://dx.doi.org/10.1029/95JA00261>
- Otsuka Y, Onoma F, Shiokawa K, Ogawa T, Yamamoto M, et al., Simultaneous observations of nighttime medium-scale traveling ionospheric disturbances and *E*-region field-aligned irregularities at mid latitude, JGR, 112, A06317 (2007). <http://dx.doi.org/10.1029/2005JA011548>
- Otsuka Y, Shiokawa K, Ogawa T, Yokoyama T, Yamamoto M, Spatial relationship of nighttime medium-scale traveling ionospheric disturbances and *F*-region field-aligned irregularities observed with two spaced all-sky airglow imagers and the middle and upper atmosphere radar, JGR, 114, A05302 (2009). <http://dx.doi.org/10.1029/2008JA013902>
- Pan CJ, Liu CH, Rottger J, Su SY, A three dimensional study of *E*-region irregularity patches in the equatorial anomaly region using the Chung-Li VHF radar, GRL, 21, 1763-1766 (1994). <http://dx.doi.org/10.1029/94GL01195>
- Pan CJ, Tsunoda RT, Quasi-periodic echoes observed with the Chung-Li VHF radar during the SEEK campaign, GRL, 25, 1809-1812 (1998). <http://dx.doi.org/10.1029/98GL00302>
- Patra AK, Sripathi S, Kumar VS, Rao PB, Evidence of kilometer-scale waves in the lower *E* region from high resolution VHF radar observations over Gadanki, GRL, 29, 137-1-137-4 (2002). <http://dx.doi.org/10.1029/2001GL013340>
- Perkins FW, Spread F and ionospheric currents, JGR, 78, 218-226 (1973). <http://dx.doi.org/10.1029/JA078i001p00218>
- Ragharavao R, Patra AK, Sripathi S, Equatorial *E*-region irregularities: A review of recent observations, JASTP, 64, 1435-1443 (2002). [http://dx.doi.org/10.1016/S1364-6826\(02\)00107-4](http://dx.doi.org/10.1016/S1364-6826(02)00107-4)
- Saito A, Iyemori T, Blomberg LG, Yamamoto M, Takeda M, Conjugate observations of the mid-latitude electric field fluctuations with the MU radar and the Freja satellite, JASTP, 60, 129-140 (1998). [http://dx.doi.org/10.1016/S1364-6826\(97\)00094-1](http://dx.doi.org/10.1016/S1364-6826(97)00094-1)
- Saito A, Nishimura M, Yamamoto M, Fukao S, Tsugawa T, et

- al., Observations of traveling ionospheric disturbances and 3-m scale irregularities in the nighttime *F*-region ionosphere with the MU radar and a GPS network, *EPS*, 54, 31-44 (2002).
- Saito S, Yamamoto M, Fukao S, Marumoto M, Tsunoda RT, Radar observations of field-aligned plasma irregularities in the SEEK-2 campaign, *Ann. Geophys.*, 23, 2307-2318 (2005). <http://dx.doi.org/10.5194/angeo-23-2307-2005>
- Saito S, Yamamoto M, Hashiguchi H, Imaging observations of nighttime mid-latitude *F*-region field-aligned irregularities by an MU radar ultra-multi-channel system, *Ann. Geophys.*, 26, 2345-2352 (2008). <http://dx.doi.org/10.5194/angeo-26-2345-2008>
- Schlegel K, Coherent backscatter from ionospheric *E*-region plasma irregularities, *JATP*, 58, 933-941 (1996). [http://dx.doi.org/10.1016/0021-9169\(95\)00124-7](http://dx.doi.org/10.1016/0021-9169(95)00124-7)
- Swartz WE, Kelley MC, Makela JJ, Collins SC, Kudeki E, et al., Coherent and incoherent scatter radar observations during intense mid-latitude spread *F*, *GRL*, 27, 2829-2832 (2000). <http://dx.doi.org/10.1029/2000GL000021>
- Tanaka T, Venkateswaran SV, Characteristics of field-aligned *E*-region irregularities over Iioka (36°N), Japan, I, *JATP*, 44, 381-393 (1982). [http://dx.doi.org/10.1016/0021-9169\(82\)90045-9](http://dx.doi.org/10.1016/0021-9169(82)90045-9)
- Tsunoda RT, Fukao S, Yamamoto M, On the origin of quasi-periodic radar backscatter from mid-latitude sporadic *E*, *Radio Sci.*, 29, 349-365 (1994). <http://dx.doi.org/10.1029/93RS01511>
- Tsunoda RT, Fukao S, Yamamoto M, Hamasaki T, First 24.5-MHz radar measurements of quasi-periodic backscatter from field-aligned irregularities in mid-latitude sporadic *E*, *GRL*, 25, 1765-1768 (1998). <http://dx.doi.org/10.1029/98GL01086>
- Woodman RF, Yamamoto M, Fukao S, Gravity wave modulation of gradient drift instabilities in mid-latitude sporadic *E* irregularities, *GRL*, 18, 1197-1200 (1991). <http://dx.doi.org/10.1029/91GL01159>
- Yamamoto M, Fukao S, Ogawa T, Tsuda T, Kato S, A morphological study on mid-latitude *E*-region field-aligned irregularities observed with the MU radar, *JATP*, 54, 769-777 (1992). [http://dx.doi.org/10.1016/0021-9169\(92\)90115-2](http://dx.doi.org/10.1016/0021-9169(92)90115-2)
- Yamamoto M, Fukao S, Tsunoda RT, Pfaff RF, Hayakawa H, SEEK-2 (Sporadic-*E* Experiment over Kyushu 2)-Project Outline, and Signature, *Ann. Geophys.*, 23, 2295-2305 (2005). <http://dx.doi.org/10.5194/angeo-23-2295-2005>
- Yamamoto M, Fukao S, Woodman RF, Ogawa T, Tsuda T, et al., Mid-latitude *E*-region field-aligned irregularities observed with the MU radar, *JGR*, 96, 15943-15949 (1991). <http://dx.doi.org/10.1029/91JA01321>
- Yamamoto M, Itsuya T, Kishimoto T, Tsunoda RT, Pfaff RF, et al., Comparison of *E*-region electric fields observed with a sounding rocket and a Doppler radar in the SEEK campaign, *GRL*, 25, 1773-1776 (1998). <http://dx.doi.org/10.1029/98GL01055>
- Yamamoto M, Komoda N, Fukao S, Tsunoda RT, Ogawa T, et al., Spatial structure of the *E*-region field-aligned irregularities revealed by the MU radar, *Radio Sci.*, 29, 337-347 (1994). <http://dx.doi.org/10.1029/93RS01846>