E-region irregularity observed by the Tanegashima Frequency Agile Radar during SEEK-2 campaign

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The present paper reports the nighttime field-aligned plasma irregularity (FAI) at 6.1 m in E-region during SEEK-2 (Sporadic E Experiment over Kyushu) campaign during July-August 2002 using Tanegashima (30.75°N, 131.03°E, geomagnetic 20.97°N, dip 43.2°N) Frequency Agile Radar (FAR) operated at 24.515 MHz. According to the characteristics of radar echo, the echoes are classified into four types: negative quasi-periodic (NQP) echo; positive quasi-periodic (PQP) echo; continuous echo; and undefined echo. A study shows that FAI appear generally at 80-110 km altitudes during 1800-0400 hrs LT, and FAI occur most frequently at 2200 hrs LT. Further, among the four different echo types, the occurrence probability of NQP is greater than other types.

Keywords: Ionospheric irregularities, Field aligned irregularities, Mid-latitude ionosphere, Quasi-periodic echoes

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1 Introduction

E-region field-aligned irregularities (FAI) have been intensively studied in the equatorial and auroral regions with radars and in situ measurements. Radar spectral studies in both regions have shown the existence of two types of echoes: type 1 (two-stream) and type 2 (gradient-drift). On the other hand, radar observations of FAI from mid-latitude E region⁵-⁷ have revealed that these irregularities are closely associated with sporadic E (Eₜ) layers and appear to be generated by the gradient drift instability mechanism. In addition, a unique category of echoes, i.e. quasi-periodic (QP) echoes have been reported by Yamamoto et al.⁵ during nighttime in Shigaraki (34.51°N, 136.06°E; dip 48.6°N), Japan using the powerful middle and upper atmosphere (MU) radar operating at 46.5 MHz. Yamamoto et al.⁵ observed the irregularities with a fine range resolution of 600 m and classified the 3.2 m scale size echoes scattered from FAI irregularities based on their different morphologies as: quasi-periodic (QP) type, which were found to appear during post-sunset period at around 100-125 km altitudes and intermittently in time with periods of 5 to 10 min; and continuous type observed during post-sunrise periods at 90-100 km altitudes. After the discovery of QP echoes with the MU radar, other mid-latitude locations including Tanegashima (Japan)⁶, Clemson (USA)⁷, and California (USA)⁸ have been added to the list, apart from a number of low-latitude locations: Chung-Li (Taiwan)⁴, Gadanki (India)⁹, and Piura (Peru)⁸.

Quasi-periodic (QP) echoes are field-aligned irregularity structures characterized by striations in the range-time-intensity (RTI) plots and quasi-periodic variation of echo intensity in time with 5–10 min. While the range rate (dr/dt) of QP echoes detected with MU radar is always negative meaning that QP structures are moving toward the radar, other category of QP echoes associated with positive range rates (structures moving away from the radar) have also been observed later at locations situated at lower magnetic dip angles (for example Tanegashima, Japan and Chung-Li, Taiwan). QP echoes characterized by negative and positive range rates are named as NQP and PQP echoes, respectively. The studies on QP echoes have received more attention among scientific community than continuous echoes possibly because of their wave like features. Several intensive observations have been made to unravel the source mechanisms of these interesting QP echoes (e.g. SEEK and SEEK-2).
rocket measurements with some ground-based sensors. The SEEK-2 campaign\textsuperscript{13} was carried out in summer 2002 as a follow up of SEEK campaign.

The present study reports on different characteristics of FAI including interesting QP (NQP, PQP), continuous and undefined type echoes observed by FAR during 12-day period (28 July - 09 August 2002) of SEEK-2 campaign.

2 Experimental details

The general description and objective of the SEEK-2 observation campaign are presented by Yamamoto \textit{et al.}\textsuperscript{13} During the SEEK-2 observation campaign, two ionospheric radars were installed on Tanegashima Island, located to the south of Uchinoura Space Center (USC) where two sounding rockets were launched into Es layers while intense FAI echoes were observed from the region of the rocket experiments. The two ionospheric radars were Lower Thermosphere Profiler Radar (LTPR), operating frequency 31.57 MHz, installed in the Tanegashima Space Center (TNSC), and Frequency Agile Radar (FAR), installed in the Tanegashima Meadow of Nishinoomote City (30.75°N, 131.03°E; dip 43.2°N) and was configured to operate at 24.515 MHz frequency. The FAR system had only one receiving channel and its main transmitting beam was pointed to 45° to the east from the geographic north. The FAR radar specifications are given in Table 1. The objective of FAR during SEEK-2 observation campaign was to determine large scale distribution of FAIs through LTPR observation as well as to monitor FAI occurrence as a back-up to the LTPR. The observation areas of both LTPR and FAR have been depicted in Fig. 1, wherein LTPR location can be identified as TNS (Tanegashima South site as it was installed in the south side of Tanegashima Island) and FAR location as TNN (Tanegashima North site) and USC represents Uchinoura Space Center.

3 Results

Apart from NQP, PQP, continuous, other category of echoes those did not show any particular shape known as undefined (UD) echoes are observed during the SEEK-2 campaign. FAR was operated during 1800-0600 hrs LT, i.e. 12 h continuously from 29 July to 09 August 2002. The detected echoes are classified into negative QP (NQP), positive QP (PQP), continuous, and UD according to their different morphologies when viewed from the range-time-intensity (RTI) contour map. Figures 2(a)–(d) show NQP, PQP, continuous and UD echoes, respectively along with Doppler velocities.

Figure 2(a) shows NQP type echoes observed on 30 July 2002 extended from around 127 km to as high as 220 km in range along with Doppler velocity (Range-time-velocity). Though the echoes started to appear after 2330 hrs LT and lasted up to 2420 hrs LT, sudden appearance/disappearance of the echoes within one hour viewed as different subgroups. The intensity and range extensions of these subgroups are different from each other, for instance, the echoes started to appear during 2330-2400 hrs LT were associated with high echo power and large range extension, while the echoes that appeared around 2410 hrs LT associated with less echo power and less range extensions. The Doppler velocities [shown in the bottom panel of Fig. 2(a)] are found to be mostly around -20 to +40 ms\textsuperscript{-1}. Positive (negative) Doppler velocities correspond to velocities away (towards)

\begin{table}[h]
\centering
\begin{tabular}{|l|c|}
\hline
Center Frequency & 24.515 MHz \\
Peak Power & 4 kW \\
Antennae & 4-element Yagi x8 \\
Pulse code & 13-bit Barker \\
Number of Receiver Channels & 1 \\
Beam width (−3dB, one way) & 6° \\
\hline
\end{tabular}
\caption{Specifications for the FAR}
\end{table}

Fig. 1 — Observation area of SEEK-2. Trajectories of the sounding rockets S-310-31 and S-310-32 are shown by the curves from USC (Uchinoura Space Center, ISAS/JAXA). Two portable radars (FAR & LTPR) were located at TNN (Tanegashima-north) and TNS (Tanegashima south) sites, and they observed E-region FAI echoes with azimuth angles of 30° and 45°, respectively.
from the radar. The velocities are found to be towards the radar till 2350 hrs LT and away from the radar around 2405 hrs LT. The Doppler velocities are characterized by a velocity shear. The QP echoes associated with gradual velocity shear have been reported in earlier studies\(^5,6\).

Figure 2(b) depicts PQP type echoes observed with the FAR on 02 August 2002. The PQP type echoes started to appear around 2135 hrs LT and persisted continuously, in contrast to the NQP echoes, until around 2240 hrs LT. Nonetheless, the echo power and range extensions seemed to decrease with time. Fukao \textit{et al.}\(^{12}\) reported that the range rate of QP echoes detected with the MU radar located at Shigaraki (34.51\(^°\)N, 136\(^°\)E) was always negative. Tsunoda \textit{et al.}\(^{8}\) by using the FAR, same as used in Tanegashima (30.8\(^°\)N, 131\(^°\)E), at Stanford, USA reported that the QP echoes always associated with negative range rates. However, Hysell & Burcham\(^{14}\) using the 30 MHz Clemson radar, Clemson (34.7\(^°\)N, 82.8\(^°\)W, dip 61.3\(^°\)N), South Carolina, USA reported the presence of PQP echoes after local midnight and NQP before local midnight. The Doppler velocities, shown in the bottom panel, are found to be in preferential directions with the sign of the range rate of echoes with velocities as high as 80 ms\(^{-1}\). Interestingly, the preferential direction condition continued as long as the backscatter echo persisted.

Figure 2(c) shows the continuous type echo extended from around 140 to 200 km range during 1815-2000 hrs LT. The Doppler velocities are found to be mostly confined from 0 to 40 ms\(^{-1}\). Figure 2(d) shows a complex type echo, which is categorized as undefined echo. The Doppler velocities (bottom panel of the figure) for these echoes are found to be in positive directions starting from 1941 to 2130 hrs LT.

To know the local time dependence of FAI, statistical results of FAR echoes obtained with a 12-day database during the SEEK-2 observation campaign have been studied. It may be noted that the different type of echoes have not been distinguished, instead the statistical details of all echoes detected by the FAR have been given and presented in Fig. 3. Figure 3 contour plot shows the percentage
occurrence of backscatter echoes detected with the FAR for 12 days (29 July – 09 August 2002) as a function of local time. The y-ordinate in the figure shows the corresponding apparent altitudes of E-region echoes calculated using the condition of perpendicularity of the radar k-vector and geomagnetic field in the radar main beam direction. It is clear that the FAI occurrence maximizes around 2200 hrs LT and the percentage occurrence is found to be minimum or nearly zero beyond 0400 hrs LT, although a minimum in occurrence is noticed between 0500 and 0530 hrs LT. It is also evident from this figure that most of the echoes are confined to the altitudes in the range 85-110 km. For total 144 h of observation during 29 July-09 August 2002, only 26% of the time echoes were observed, while 16% of time clear QP echoes were observed, in which NQP and PQP are observed 13 and 3% of time, respectively. The percentage occurrence of backscatter echoes in this present study is in agreement with the results reported with the MU radar. Figure 4 shows total time duration of NQP, PQP, continuous, and undefined type echoes observed with the FAR radar during a 12-day period during SEEK-2 campaign on a day-to-day basis during 1800 – 0600 hrs LT. In Fig. 4, the time duration of NQP, PQP and both (continuous and undefined) echoes is represented by green, red and blue colour horizontal lines, respectively.
4 Discussions

During the SEEK-2 campaign, the detected backscatter echoes are classified into four main types according to their characteristics, viz. negative quasi-periodic (NQP), positive quasi-periodic (PQP), continuous and undefined (UD). The non-QP echoes such as continuous and UD are detected 10% of the total echo observation time. The continuous echoes reported in this study differ in time of occurrence and altitude extensions in comparison with that of the continuous echoes reported using the MU radar. Later, continuous echoes have been reported throughout the night after the MU radar observations. By studying the QP backscatter echoes from FAI in mid-latitude sporadic E layer using the 24.5 MHz FAR located at Tanegashima, Tsunoda et al. reported that continuous echoes occurred 29% of the time and were found to occur at night with altitude extensions in the range 90-110 km. Thus, the results of present study are in good agreement with Tsunoda et al. observational study. The UD echoes, which were characterized with complex patterns in echo distribution, reported in this study have also been observed by other researchers. Saito et al. using a Lower Thermosphere Profile Radar (LTPR), operated at 31.57 MHz frequency, installed 40 km south of Tanegashima FAR, observed the complex pattern echoes and classified them as undefined (UD) type because of diffuseness in their echo distribution.

The results presented in this study reveal that the percentage occurrence of echoes found to be higher at 2200 hrs LT. Tsunoda et al. noticed the appearance of QP echoes that favor the local sunset timings. They concluded that the steep longitudinal gradient in conductivity produced by the solar terminator could lead to the development of polarization electric filed resulting in enhanced electric field that could act in driving the gradient-drift instability (GDI) more strongly than other times. The role of the solar terminator cannot be ruled out in the present findings as suggested by Tsunoda et al. There is another good reason to attribute the enhancement of echo timings with sporadic-E layer (ES) as the occurrence of ES.
layer maximizes two times during a 24-h day in summer over Japan\textsuperscript{19}.

Another noticeable finding from the present study is that the occurrence probability of NQP type echoes is relatively greater than that of other type echoes. It has been reported that when QP echoes were observed at midlatitude geographical locations, they usually appear as downward sloping striations (NQP type)\textsuperscript{8,12} implying that NQP type echoes seem to be more common at higher magnetic dip latitudes and a mixture of echo types is common at lower dip latitudes\textsuperscript{8}. An experimental evidence supporting the above conclusion has been reported by Pan & Tsunoda\textsuperscript{20} using the Chung-Li (24.9°N, 121.2°E, dip 38°N) VHF radar that in the total number of QP echoes, PQP occurred 84 times followed by NQP (48
echos), and vertical QP (VQP, i.e. those that appear to have extremely large range rates) (10 echos).

The present study shows the different characteristics of mid-latitude FAI at 6.1 m observed during the SEEK-2 campaign for a 12-day period. Haldoupis et al. found that the morphology of mid-latitude FAI agree with the well known morphology of strong sporadic E layers. However, at this point it is not possible to determine the exact morphology (seasonal and diurnal behavior) and source mechanisms of these echoes because of the limited radar observations and the lack of knowledge of other important parameters such as ambient density gradients, electric fields and neutral winds, etc.

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