Range rate variation studies of the low-altitude quasi-periodic radar echoes during SEEK-2 campaign

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The first experimental evidence on range rate reversal of low-altitude quasi-periodic (LQP) echoes from nighttime midlatitude sporadic E region with systematic characteristics in their occurrences for the echoes observed during SEEK-2 (Sporadic-E Experiment over Kyushu) campaign with 24.515 MHz frequency agile radar located at Tanegashima in southern Japan (30.75°N, 130.03°E, geomagnetic latitude 20.97°N, dip angle 43.2°N) is presented. Four reversal cases of LQP echoes are found during the observation period. The reversal times of these echoes from positive QP to negative QP are found between 2000 and 2400 hrs LT and negative QP to positive QP around 0200 hrs LT. Besides, Doppler velocities associated with these echoes show preferential directions meaning that they are consistent with the sign of range rate of QP echoes in most cases. As the backscatter echoes studied are confined to the collision dominated lower E region and semi-diurnal tide is most pronounced at latitude higher than 30°, large-period neutral winds such as tidal and planetary waves in addition to atmospheric gravity waves play a role in the generation and control of these backscatter echoes.

Keywords: Ionospheric irregularities, Mid-latitude ionosphere, Quasi-periodic echo; Low-altitude quasi-periodic echo; Positive quasi-periodic echo

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1 Introduction

Field-aligned irregularities (FAI) in the nighttime midlatitude E region have been observed with very high frequency (VHF) radars. Yamamoto et al. found two types of radar echoes: quasi-periodic (QP) echoes appearing intermittently at altitudes of sporadic E (Es) layer (above 100 km) with periods of 5-20 min; and continuous echoes appearing continuously at altitudes around 90-100 km. Another interesting aspect that has caught researchers’ attention is the plasma irregularity structures coming from the altitude below 100 km which have periods in the range of a few tens of seconds to 3 min. Due to their occurrence at lower altitudes, they are also referred to as low-altitude QP (LQP) echoes to differentiate them from the well-known QP echoes occurring at higher altitudes.

As the wave-like characteristics of QP echoes seem to have resemblance with that of atmospheric gravity waves (AGWs), theories soon surfaced in the literature to explain the generation mechanisms of QP echoes that rely on the gravity wave modulation of the sporadic E (Es) layers. The other possible source mechanisms of QP echoes such as Kelvin-Helmholtz (KH) structures associated with neutral wind shear, polarization electric field effects, and a Perkins-type instability have been proposed subsequently. The models proposed by Woodman et al. and Tsunoda et al. conjectured southward propagating atmospheric gravity waves as these waves are capable in modulating the existing sporadic E layers in altitude resulting in the generation of backscatter echoes. However, positive QP (PQP) echoes have been rarely observed with the MU radar and often observed with the 52 MHz radar at Chung-li, Taiwan.

On the other hand, large-period wavelike variations in Es layer parameters have been reported using the Arecibo incoherent scatter radar and conventional ionosonde radars. Very few studies, nevertheless, have been reported on large-period waves such as tidal and planetary wave effects on midlatitude ionospheric plasma processes. Only, Tsunoda et al. and Voiculescu et al. reported on the planetary waves and their possible role in the generation of coherent backscatter echoes scattered from unstable midlatitude E region ionosphere. But away from midlatitudes, over a low-latitude location Chung-li (24.9°N, 121.2°E, geomagnetic latitude 13.3°N, dip 35°), Pan & Tsunoda observed a systematic change...
in sign of the range rates associated with QP echoes for six consecutive nights using the 52 MHz VHF radar and they proposed the role of semidiurnal tides in the generation of these backscatter echoes and the reversal of range rates associated with QP echoes.

The present paper reports the first observational results on the systematic occurrence of reversal of range rates of low-altitude QP (LQP) echoes observed during the SEEK-2 campaign26 period by using 24.515 MHz frequency agile radar (FAR).

2 Experimental details

The information about SEEK-2 observation campaign is available in ref. 26. The FAR was installed in the Tanegashima Meadow of Nishinoomote City (131.03°E, 30.75°N, geomagnetic latitude 20.97°N). The main transmitting beam of FAR radar was pointed 45° to the east from the geographic north (azimuth direction) and 60° elevation angle of the radar beam above horizontal plane enabled observation of the field aligned irregularities at 100 km altitude. The FAR system had only one receiving channel. Due to the high magnetic aspect angle sensitivity of irregularities (<0.50), the volume observed by radar was small in north-south direction as compared to the east-west direction. The antenna array of the FAR consists of 4-element eight Yagis forming a linear configuration. This configuration provided beam width of 6°. FAR radar specifications are given in Table 1.

3 Observations

The FAR radar was operated from 29 July to 09 August 2002 from 1800 to 0600 hrs LT during SEEK-2 observation campaign. Echoes are observed 26% of the total observation time period of 144 h, while clear QP echoes are observed only 16% of time, in which the share of negative QP (NQP) and positive QP (PQP) are 13% and 3%, respectively. Among these, NQP echoes comprised the majority of echo types in consistent with the MU radar measurements1.

Out of twelve nights of observations, four reversal cases of LQP echoes are found and presented here. Figure 1 top panel shows the range-time-intensity (RTI) plot of backscatter echoes from 2330 to 0400 hrs LT along with Doppler velocities (bottom panel). The QP echoes, when present, are observed at around 190 km corresponding to altitudes around 92 km (right ordinate). The transition from positive-slope QP (PQP) to negative-slope QP (NQP), in this case, was around 0030 hrs LT and the periodicities of PQP and NQP echoes around 5 to 7 and 3 to 5 min, respectively. The range rates of PQP and NQP echoes are found between 30 and 35 & -20 and -35 ms⁻¹, respectively. It was found that Doppler velocities show preferential directions with the sign of range rate of echoes. For instance, Doppler velocities associated with PQP echoes are directed northward (upward) with higher velocities of about 40 ms⁻¹. On the other hand, the mean Doppler velocities associated with NQP echoes show southward (downward) directions with velocities around -25 to -35 ms⁻¹.

In Fig. 2 top left panel shows PQP type echoes from 2130 to 2249 hrs LT on 02 August 2002, top right panel shows the NQP type echoes from 0230 to 0315 hrs LT on 03 August 2002 along with Doppler velocity map (bottom panels). However, no echoes are observed between 2249 and 0230 hrs LT. In this case, PQP and NQP echoes are situated in the range 170-215 km and 165-205 km, respectively. Periodicities associated with PQP and NQP echoes are found to be ~5 to 8 and 3 to 5 min., respectively. The Doppler velocities for both echoes show a clear cut preferential direction in consistent with the observations during 31 July-01 August 2002 (Fig. 1). While the range rates of PQP and NQP echoes are between 10 and 20 & -20 and -30 ms⁻¹, respectively; the Doppler velocities are in the range 20-30 and (-30)-(-40) ms⁻¹.

In Fig. 3 shows QP echoes (top panel) from 1830 to 2230 hrs LT on 05 August 2002 along with corresponding Doppler velocities (bottom panel). The NQP type echoes are extended to higher altitudes, while PQP echoes confine to relatively lower range 170-192 km only. In this case, PQP echoes occurred from 1840 to 1930 hrs LT and NQP appeared from 2100 to 2230 hrs LT. The periodicities of PQP and NQP echoes in this case are around 3 to 4 and above 10 min, respectively. The preferential direction of Doppler velocities is also noticed in consistent with

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<th>Table 1 — Specifications for FAR</th>
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<tr>
<td><strong>Center Frequency</strong></td>
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<td><strong>Peak Power</strong></td>
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<td><strong>Pulse code</strong></td>
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Figs 1 and 2. The range rate values of these positive and negative slope echoes are 20-25 and (-15)--(-25) ms\(^{-1}\) and the Doppler velocities are in the range 30-40 and (-20)--(-30) ms\(^{-1}\).

Contrary to the LQP echoes reported in Figs 1-3, the LQP echoes (top panel of Fig. 4) occurred only during post midnight, 0106-0328 hrs LT on 07 August 2002 and the corresponding Doppler velocity map is shown in the bottom panel of figure. In this case, LQP echoes of interest occurred at altitudes 170-192 km (NQP echoes) and 167-181 km (PQP echoes). The quasi-periodicities and range rates are found to be 5-8 and 6-8 min and 15-20 and (-10)--(-15) ms\(^{-1}\), respectively for NQP and PQP echoes. The important finding of preferential Doppler velocities is observed in this night although the Doppler velocities associated with NQP echoes some times show positive velocities. Though the Doppler velocities of...
Fig. 3 — (a) Range-time-intensity (RTI) plot of PQP echoes from 1830 to 1930 hrs LT and NQP echoes from 2000 to 2230 hrs LT observed on 05 Aug 2002 along with, (b) corresponding Doppler velocity map

Fig. 4 — (a) Range-time-intensity (RTI) plot of PQP and NQP echoes from 0106 to 0328 hrs LT observed on 07 Aug 2002 along with, (b) corresponding Doppler velocity map
NQP echoes show positive values initially for half an hour, later negative values found are -20 and -30 ms$^{-1}$ and positive values for PQP echoes 10-20 ms$^{-1}$. In this case, transition from NQP to PQP has taken place at 0240 hrs LT.

The signal intensities of LQP echoes, shown in SNR, presented here are as high as 23 dB, quiet comparable to QP echoes that observed at higher altitudes (>100 km) and in contrast to the much weaker midlatitude lower E region backscatter echoes observed by the MU radar. Besides, the spectral widths associated with PQP echoes are found to be larger than those associated with NQP echoes (not shown here). The Doppler velocity of LQP echoes is in agreement with the sign of range rates of echoes although the magnitude of Doppler velocities are found to be higher than that associated with range rate striations consistent with observations reported from mid-latitude locations$^8$. The high resolution daytime LQP structures made using Gadanki VHF radar (79.2°E, 13.5°N, geomagnetic latitude 6.3°N) have often shown negative Doppler velocities. These velocities did not always agree with the range rates (slopes) of the LQP structures$^{27}$. The low-altitude echoes observed at as low as 85 km were reported by Patra et al.$^{28}$ using Equatorial Atmosphere Radar (EAR), located in West Sumatra, Indonesia (0.2°S, 100.32°E, geomagnetic latitude 10.36°S), did not show any systematic range rate and Doppler velocities. Based on the simultaneous observations of neutral winds (measured using a meteor radar), it was conjectured that FAI velocities essentially represent neutral winds as backscatter echoes emanated from the collision dominated lower E region. Further, it was proposed that the echoes observed below 90 km could not be explained by the existing theories and thus, need further investigation.

The first coordinated measurements of QP echoes, OI 557.7 nm airglow, and neutral winds by Ogawa et al.$^{29}$ were conducted over Shigaraki, Japan (34.9°N, 136.1°E, geomagnetic latitude 25°N) during the SEEK-2 campaign, in which QP echoes were observed as below as 90 km$^{29}$. Ogawa et al.$^{29}$ strongly argued that the slope change of QP echo striations, from positive to negative around 2045 hrs LT, was caused by a change in the neutral wind direction. Further, very high Doppler velocities of about 120 ms$^{-1}$ were observed at 90 km and it was postulated that the Doppler velocities were the representatives of neutral winds since the observations were confined to lower E region where high ion neutral collisions are common. More importantly, with simultaneous observations of field-aligned irregularities by using the FAR, operating at 24.515 MHz, and Lower Thermosphere Profiler Radar (LTPR), operating at 31.57 MHz, and neutral winds derived with meteor echoes from the LTPR, Saito et al.$^{30}$ found that positive (negative) range rates of echoes were due to a northward (southward) neutral wind. The LTPR operated in interferometry mode further revealed that the echoing regions, which were responsible for backscatter signals, were moving apparently across the radar beam including main and side lobes to provide quasi-periodic striations in the RTI plots. This experimental evidence strongly suggested that neutral wind plays role in the radar echo characteristics including Doppler velocity, range rates, etc. It may be worth mentioning that the FAR observed backscatter signals, the same system was utilized by Saito et al.$^{30}$, were analyzed to provide observational results presented in this paper.

4 Discussions

Using 24.515 MHz FAR located at Tanegashima during the SEEK-2 campaign$^{26}$ period 29 July-09 August 2002, it was observed that LQP radar echoes change the slope of their range rates from PQP to NQP during pre-midnight and from NQP to PQP in post-midnight during 12 h (1800 to 0600 hrs LT). Among 12 nights of observations, four cases with reversal of range rates of LQP echoes are found. The reversal time from PQP to NQP (for three cases observed on: 30 July-1 August; 02-03 August; and 05 August 2002, respectively) is noticed between 2000 and 2400 hrs LT, while the LQP echoes observed on 07 August 2002 is noticed at 0200 hrs LT from NQP to PQP. However, no echoes were observed during pre-midnight for 07 August 2002 reversal case. Overall, the transition from PQP to NQP occurred during pre-midnight and NQP to PQP occurred during post-midnight. Besides, the Doppler velocities of LQP echoes show preferential directions with the sign of range rate of echoes in most cases. As backscatter echoes were observed below 100 km altitude where collisions between ions and neutrals are relatively high and effect of semi-diurnal tide is most pronounced at
latitude higher than 30 deg\textsuperscript{31}, it is suggested that the background wind, such as semidiurnal tidal, and long period waves may play a role in generation and control of characteristics of these echoes (range rate reversal, periodicity, and Doppler velocity) in addition to AGWs.

It is obvious that plasma in the lower E-region is strongly affected by the neutral atmosphere due to the large ion-neutral collision frequency. Models have been proposed that plasma irregularities associated with sporadic E layers are driven by neutral wind\textsuperscript{32} and associated shears\textsuperscript{11}. Tsunoda et al.\textsuperscript{10} proposed that range rate was the trace velocity associated with the backscatter from the intersection of radar beam with a titled sporadic E layer. In their model, the slope was directly related to drift velocity of the titled FAI sheet. Pan et al.\textsuperscript{33} proposed that plasma patches generated by wind shear instability and that embedded in the background wind in turn cause quasi-periodic striations when they drift into radar volume either horizontally and/or vertically. These two models seem capable of explaining the range rate reversal associated with backscatter echoes as if irregularity is drifting with a background semidiurnal neutral wind. The presence of atmospheric gravity waves, however, is also essential as these are capable of modulating the existing sporadic E layer. Consequently, for a northward drifting of irregularity sheet along with northward propagating background neutral wind results in generation of PQP echoes that observed during pre-midnight in present observations. As the time advances, the background wind reversed to southward direction around midnight resulting in the northward drifting of irregularity sheet that causes PQP echoes. The same wind reversal phenomena again from southward to northward during post midnight could able to explain the range rate reversal of these echoes from NQP to PQP.

5 Conclusions

An experimental evidence of a systematic range rate reversal, i.e. from PQP to NQP and NQP to PQP has been reported during pre-midnight and post-midnight for LQP echoes by using the 24.515 MHz FAR located in Tanegashima, Japan during the SEEK-2 observation campaign. The Doppler velocities associated with these echoes show preferential directions with the sign of the range rates of LQP echoes in most cases. As the present observations confine to the collision dominated lower E region, it is likely that large-period background neutral winds such as tidal and planetary waves may play a role in the generation and control of these echoes. Although a neutral wind driven mechanism seems one of the possible mechanisms of these echoes, concurrent wind measurements along with background parameters (electric field and electron density) in E-region can provide exact solutions for source mechanisms of these echoes. As the present study was not supported by neutral wind and electric field data, it had to rely on published evidence in order to support the inference of a role for neutral winds.

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