GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 14, PAGES 2167-2170, JULY 15, 1999

Low-latitude quasiperiodic echoes observed with the Piura VHF radar in the E region

Jorge L. Chau[1] and Ronald F. Woodman

Radio Observatorio de Jicamarca, Instituto Geofísico del Perú, Lima, Perú

Abstract. We present the first quasiperiodic (QP) echoes from 3-m E region field-aligned irregularities observed in the Southamerican sector, just outside the magnetic equator (7.5°N geomagnetic). These QP echoes occur only at night and between 105 and 120 km. In general, Piura QP echoes present periods close to the Brunt-Väisälä period (5 to 10 min), striations with positive slopes and altitude rates of 20-25 m s^{-1} (upward/northward), striations spacings of 3 to 10 km, and downward/southward Doppler velocities. These results are compared to midlatitude QP echoes from 3- and 6-m irregularities observed between 13.3°N and 46.7°N geomagnetic. We found that the general characteristics that are common to our observations and other QP observations are the nighttime occurrence and the periods close to the Brunt-Väisälä period. On the other hand, the discrepancies with some of the QP echoes observed at midlatitudes are found in the slope and spacing of the striations, the mean phase velocities, and the mean altitude location of the E layer containing the striations.

Introduction

Quasiperiodic (QP) echoes from E region field-aligned irregularities (FAI) were first reported by *Yamamoto et al.* [1991] using the middle and upper atmosphere (MU) radar in Japan (25.0°N$_m$, hereinafter we use N$_m$ for North geomagnetic). The QP echoes, as observed by the MU radar, are localized in a slant range, from a kilometer to more than 50 km in extend, and often appear as thin striations with negative slopes (altitude rates towards the radar, i.e., downward/southward) and with periods comparable to the Brunt-Väisälä period (~5 min) [*Yamamoto et al.*, 1991, 1994; *Ogawa et al.*, 1995]. They are highly correlated with the presence of sporadic E (*Es*) layers and occur primarily at night and during local summer [*Yamamoto et al.*, 1992]. These QP striations are centered around 110 km.

The sloping and periodic characteristics resemble those of atmospheric gravity waves. The QP echoes have been explained in terms of atmospheric gravity waves (AGW) modulating *Es* layers in such a way to make them nonlocally unstable to gradient drift processes [*Woodman et al.*, 1991; *Tsunoda et al.*, 1994].

[1]Also at Laboratorio de Física, Universidad de Piura, Piura, Perú

Paper number 1999GL900488.
0094-8276/99/1999GL900488$05.00

QP echoes have been also observed at other midlatitude sites: Chung-Li in Taiwan [*Chu and Wang*, 1997; *Pan and Tsunoda*, 1998], Tanegashima in Japan [*Tsunoda et al.*, 1998], Clemson University in South Carolina [*Hysell and Burcham*, 1999], and Standford in California [*Tsunoda et al.*, 1999]. The characteristics of most of these observations will be presented and compared to our results later in the text.

E region observations over Piura (5.2°S, 80.6°W, 7.5°N$_m$) have been made since 1991. *Woodman et al.* [1999] have presented the results of observations made between 1991 and 1996. During this period no clear indication of QP echoes, as observed by the MU radar, were observed. In this letter, we report the first QP echoes from E region FAI over Piura. This time, we made the measurements with a higher time resolution (40 s) and a wider spectral window (-300 to 300 m s^{-1}) than those used during the first years (180 s time resolution and -150 to 150 m s^{-1} spectral window). E region echoes are obtained by pointing the antenna beam 14° off-vertical to the north. Additional observational parameters and details on the Piura system can be found in *Woodman et al.* [1999]. Here we concentrate on the characteristics of QP echoes observed on October 21, October 31 and November 1, 1998. These characteristics will be compared to those found at midlatitudes.

Data Presentation

Figure 1 shows contour plots of signal-to-noise ratios (SNR) and spectral moments (Doppler velocity and spectral width) of QP E region echoes observed on October 21, 1998 between 0100 and 0500 LT. The altitude resolution is ~500 m. The scale on the right indicates the altitude of the echoes, obtained by multiplying the range by the sine of the elevation angle. The exact elevation angle is defined by the beam width of the antenna and more importantly by the narrow aspect sensitivity of the scattering mechanism. Doppler velocities (positive towards the radar) and spectral widths are shown only when their corresponding SNR are greater than 0 dB. Grayscales are shown at the right of each panel.

Examining Figure 1a, we can observe QP striations with periods of 5 to 10 min and altitude extensions of 3 to 8 km. The striations are confined to the 105-120 km region and present mainly a positive slope (i.e., upward/northward) with an altitude rate of 20 to 25 m s^{-1} (i.e., range rates of 20.6 to 25.8 m s^{-1}). A negative slope (i.e., downward/southward), which is rarely seen over Piura, can be observed between 0100 and 0130 LT with an altitude rate of ~-25 m s^{-1}. Moreover, by following the SNR peaks, we can observe a modulation of the altitude of the E region layer containing the striations, i.e., decreasing (5 km from 115 km) between 0100 and 0140 LT, increasing (2 km) between 0140

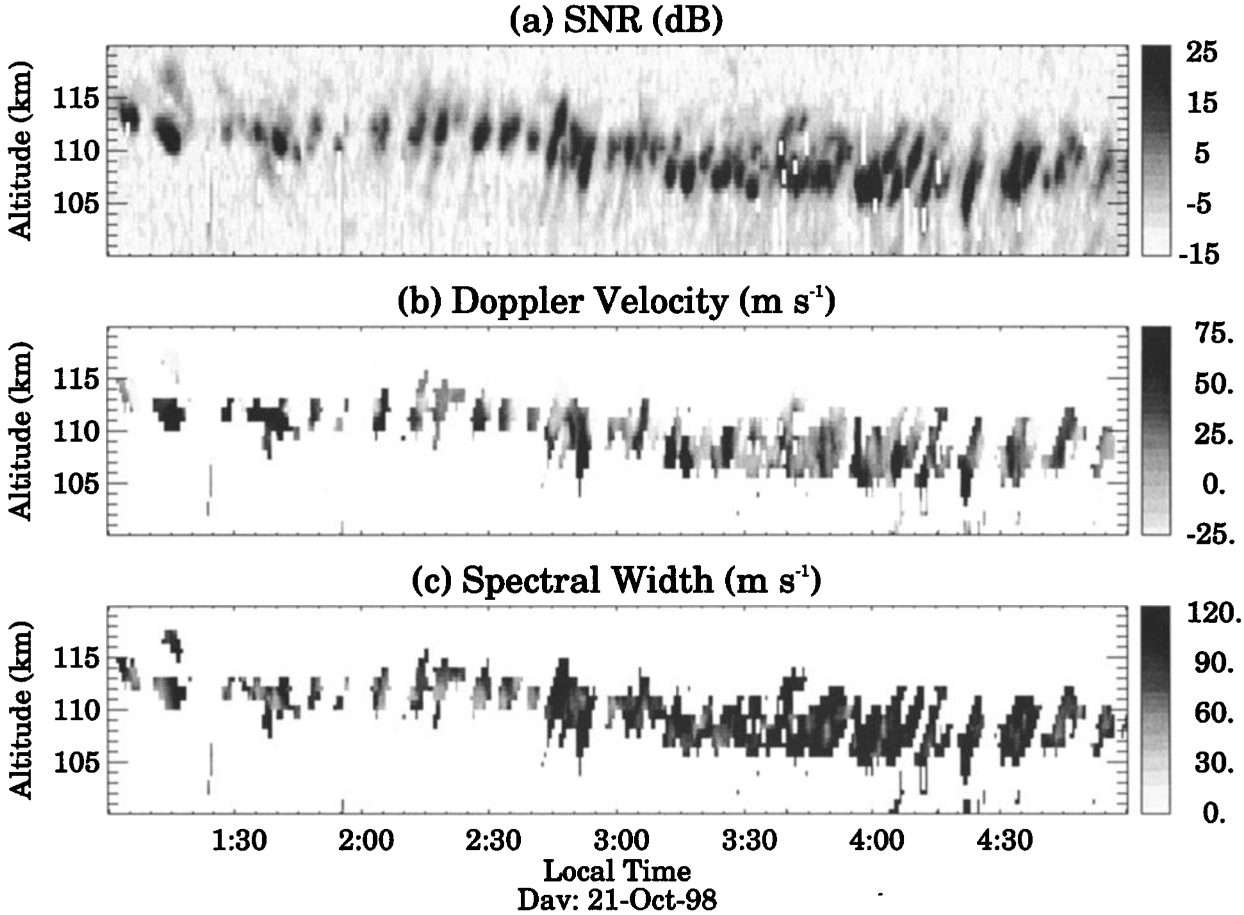

Figure 1. Altitude-time plots of a) SNR, b) Doppler velocity, and c) Spectral width, from 0100 to 0500 LT on October 21, 1998. Grayscales are shown at the right of each panel. Doppler velocities and spectral widths are shown only when SNR is greater than 0 dB.

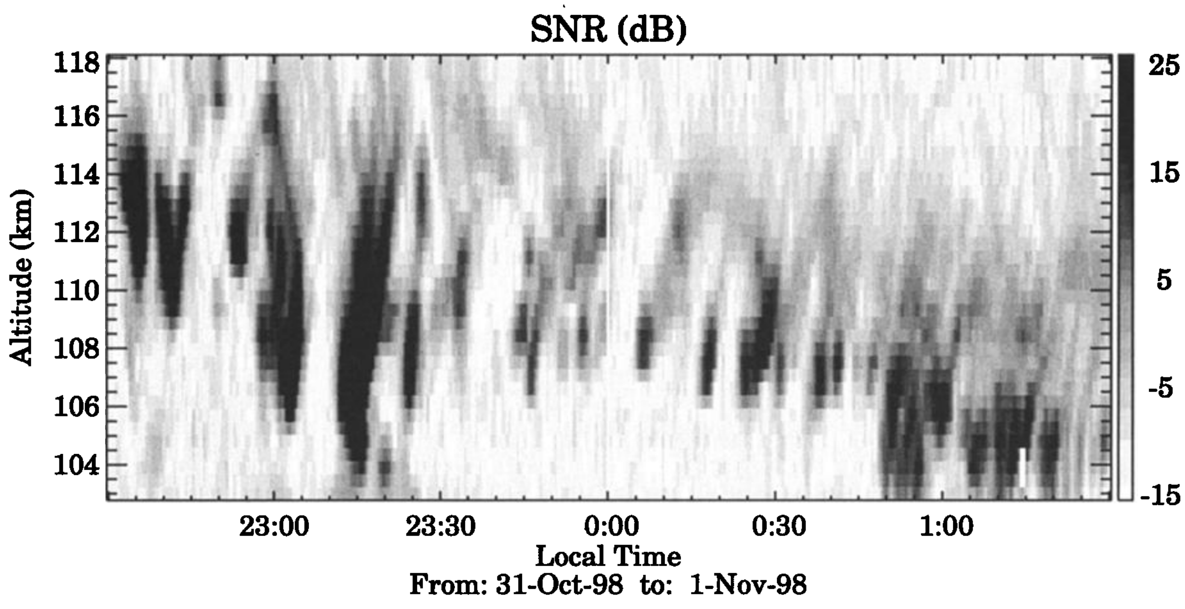

Figure 2. Altitude-time plots of SNR between 2230 LT on October, 31 and 0130 LT on November 1, 1998.

and 0220 LT, decreasing (6 km) between 0220 and 0400 LT, and increasing (2 km) between 0400 and 0500 LT.

From Figure 1b, the mean Doppler velocity is positive (downward/southward), and of the order of 20-25 m s^{-1}. The velocities vary between -50 and 100 m s^{-1}. The highest velocities are observed between 0100 and 0200 LT. In Figure 1c, spectral widths vary between 30 and 100 m s^{-1}, with a mean value of ~60 m s^{-1}. In general the spectral widths between 0100 and 0240 LT are smaller (30-60 m s^{-1}) than those observed between 0240 and 0500 LT (50-100 m s^{-1}).

In Figure 2 we show the SNR contour plot of another example of QP echoes observed between 2230 LT of October 31 and 0130 LT of November 1, 1998 (Note the change of scales). In this example the period is ~10 min and the altitude extension varies between 3 and 10 km. Following the peaks of maximum SNR the striations are confined to a layer that is approaching the radar with an altitude rate of 3 km $hour^{-1}$. Again we observe, most of the time, striations with positive slopes and an altitude rate of ~21 m s^{-1}. Two striations with negative slopes are observed between 2230 and 2240 LT with an altitude rate of -25 m s^{-1}. The values of Doppler velocities and spectral widths for these echoes are similar to those presented in Figure 1, namely, a mean positive Doppler velocity (i.e., downward/southward) of ~20 m s^{-1}, and a mean spectral width of ~60 m s^{-1}.

It is important to point out that these QP echoes are confined to the same altitudes of the upper *E* region echoes reported by *Woodman et al.* [1999] with a 15-day data set taken in 1996. Although QP echoes were not clearly observed during the first years of observations, the "patchy" characteristic of the 1996 upper *E* region echoes, could well have been due to the presence of QP echoes. We are almost certain that at that time, we were not able to see QP echoes because of the insufficient time resolution employed (180 s compared to 40 s). The higher resolution allowed us to clearly identify the striations. Moreover, the spectral characteristics of the upper *E* region echoes and our QP echoes are very similar. The main differences are: 1) higher mean Doppler velocity and 2) smaller mean spectral width in the QP echoes, respect to the 1996 upper *E* region values. Nonetheless, these discrepancies are certainly due to differences in the time and spatial (due to the wave-like behavior of the irregularities) averaging.

In addition, we have incoherently-integrated four times the 40-s spectral data in order to have a comparable time resolution to the 1996 data set. We found that indeed QP echoes resemble the 1996 upper *E* region echoes. Taking advantage of this similarity, we infer that QP echoes occur, mainly, between 22 and 06 LT (at least 50% of the time), particularly during the months of October and November [see, *Woodman et al.*, 1999, Figure 2].

Comparison to Midlatitude QP Echoes

We start this section by summarizing the main characteristics of the low- latitude (just outside the magnetic equator) QP echoes as observed by the Piura radar.

1. Their periods are between 5 and 10 min.

2. They are confined to the 105-120 km region and the striation spacings are short (between 3 and 10 km).

3. They present, mainly, striations with positive slopes (i.e., upward/northward) and altitude rates of the order of 20 to 25 m s^{-1}. Striations with negative slopes present altitude rates of ~-25 m s^{-1}.

4. Their mean Doppler velocity is positive (i.e., downward/southward), opposite to their apparent bulk velocity.

5. They appear, mainly, between 22 and 06 LT. This result is inferred from the similarities of our QP echoes and the upper *E* region echoes reported by *Woodman et al.* [1999] with a more extensive time coverage.

Now we proceed to compare these QP characteristics to midlatitude results obtained at four different northern latitudes, with the following radars: 1) the Middle and Upper Atmosphere (MU) VHF radar in Shigaraki Japan (34.9°N, 136.1°E, 25°N_m) [*Yamamoto et al.*, 1994, 1991; *Ogawa et al.*, 1995], 2) the HF frequency-agile radar (FAR) in Tanegashima Japan (30.4°N, 131°E, ~20°N_m) [*Tsunoda et al.*, 1998], 3) the Chung-Li VHF radar in Taiwan (24.5°N, 121.1°E, 13.3°N_m) [*Chu and Wang*, 1997; *Pan and Tsunoda*, 1998], and 4) the Clemson University HF radar in USA (34.7°N, 82.8°W, 46.7°N_m) [*Hysell and Burcham*, 1999].

A general characteristic to all the QP observations is the similar range of periods observed, i.e., 5 to 10 min. Recently, *Hysell and Burcham* [1999] have reported the observations of smaller-scale striations with periods of the order of 1 min. So far, we have not been able to observe these short-period striations, however our time resolution was not high enough (40 s).

The QP echoes reported by the MU and Clemson radar, and the FAR, appear at a broad altitude span (95-125 km for the MU radar, and 90-140 km for the HF radars) and with a large striation spacing (>15 km), while those reported in the equatorial anomalous crest zone (i.e., by the Chung-Li radar) are confined to the 100-110 km region and with a striation spacing of 3-5 km. The Piura QP echoes are centered around 110 km, and coincides with the centers of QP echoes observed by the MU and the two HF radars. On the other hand, the Chung-Li QP echoes are centered at a lower height (between 100 and 105 km).

The majority of QP echoes reported at midlatitudes present negative slopes with altitude rates of the order of -40 to -100 m s^{-1} [*Yamamoto et al.*, 1991, 1994; *Ogawa et al.*, 1995; *Hysell and Burcham*, 1999]. Sometimes positive slopes have been observed with the MU radar and the FAR [*Ogawa et al.*, 1995; *Tsunoda et al.*, 1998], but their characteristics are not well defined. On the other hand, QP echoes with positive slopes (PQP) are commonly observed with the Chung-Li radar with altitude rates of ~20 m s^{-1}. In addition, QP echoes with vertical orientation (VQP) have also been observed with the Chung-Li radar [*Pan and Tsunoda*, 1998]. With our current data set we have observed only sporadic occurrence of VQP (results not shown here) and they are not as persistent as those observed with the Chung-Li radar.

Overall, the mean Doppler velocities reported by the MU and Clemson radars are away from the radar, i.e., upward/northward. Therefore, at this location phase propagation is upward/northward while altitude rates are downward/southward [*Yamamoto et al.*, 1991; *Hysell and Burcham*, 1999]. Over Chung-Li, phase propagation and altitude rates are upward/northward. On the other hand, our general results are downward/southward phase propagations and upward/northward altitude rates. Although all the aforementioned radars are located North of the geomagnetic equator, it is important to note that the Piura radar is located South of the geographic equator, whereas the other radars are located North of the geographic equator. Therefore, there is a preference for going away from the equator (geographic) mean Doppler velocities in all the sites.

Another general characteristic of QP echoes is that they occur at night. QP echoes observed with the MU and Clemson radar, and the FAR, occur preferentially from right after sunset until midnight [*Ogawa et al.*, 1995; *Hysell and Burcham*, 1999; *Tsunoda et al.*, 1998]. Observations made with the Chung-Li radar find that PQP are found mostly before local midnight while PQP are detected after midnight [*Pan and Tsunoda*, 1998].

Finally, QP echoes with negative slopes and large striation spacings have been explained by the model presented by *Woodman et al.* [1991]. Woodman et al.'s model suggested the gradient-drift instability as the basic mechanism but triggered by the modulation of *Es* by propagating short-period gravity waves. The recent observations of PQP and VQP echoes with short striation spacings at latitudes below 20°N_m suggest the need to modify the existing theories. However, the idea that AGW could modulate *Es* in a way that could favor the occurrence of the instabilities at specific fronts of these waves, is still feasible to explain the low-latitude observations.

Concluding remarks

In this letter, we have presented the first observations of QP echoes at a very low-latitude site (7.5°N_m), just outside the magnetic equator. The general characteristics that are common to our observations and other QP observations are that the Piura QP echoes occur only at nights, and they have periods close to the Brunt-Väisälä period (between 5 and 10 min). On the other hand, the major discrepancies with other QP echoes are found in the slope and spacing of the striations, the mean Doppler velocities, and the mean altitude location of the *E* layer containing the striations. The echoes over Piura present, overall, striations with positive slope and spacings of 3-10 km, downward/upward mean Doppler velocities, and they are centered around 110 km.

We have limited this work to report the QP echoes due to 3-m irregularities at 7.5°N_m and to compare them to echoes due to 3- and 6-m irregularities observed between 13.3°N_m and 46.7°N_m. In order to understand this latitudinal phenomena more thoroughly, one needs to obtain more information about the background ionosphere and the neutral wind. For example, using a digisonde and a meteor radar. Furthermore, similar *E* region radar observations should be made at Southern latitudes. This project is very feasible given that only small and inexpensive systems can do the job.

More radar measurements are being performed at Piura in order to understand the seasonal dependence of *E* region echoes at this latitude. We are also planning to run an experiment with a higher time resolution to see if very short-period (periods < 1 min) QP striations are observed over Piura. Finally, we are studying the feasibility of incorporating interferometry to our measurements, to increase the capabilities of the Piura system, e.g., measurements of east-west drifts and three-dimensional spatial distribution of the echoing regions.

Acknowledgments. The Piura wind profiler is operated by Laboratorio de Física of Universidad de Piura, Perú with support from NOAA and from NSF under agreements ATM-9214657 and ATM-9614613. Additional support have been received from the Instituto Panamericano de Geografía e Historia via project GEOF3.4.5.16. We thank L. Flores and L. Torres (Laboratorio de Física, Universidad de Piura) for helping in the experimental setup and data acquisition. We also thank Arthur Richmond and an anonymous reviewer for their suggestions on the original manuscript. One of us, J.L.C., was supported by NSF under agreement ATM-9813910.

References

Chu, Y. H., and C. Y. Wang, Interferometry observations of 3-dimensional spatial structure of sporadic *E* irregularities using Chung-Li VHF radar, *Radio Sci.*, *32*, 817–832, 1997.

Hysell, D. L., and J. D. Burcham, HF radar observations of quasiperiodic *E* layer echoes over North America, *J. Geophys. Res.*, *104*, 4361–4371, 1999.

Ogawa, T., M. Yamamoto, and S. Fukao, Middle and upper atmosphere radar observations of turbulence and movement of midlatitude sporadic *E* irregularities, *J. Geophys. Res.*, *100*, 12,173–12,188, 1995.

Pan, C. J., and R. T. Tsunoda, Quasi-periodic echoes observed with the Chung-Li VHF radar during the SEEK campaign, *Geophys. Res. Lett.*, *25*, 1809–1812, 1998.

Tsunoda, R. T., S. Fukao, and M. Yamamoto, On the origin of quasi-periodic radar backscatter from midlatitude sporadic E, *Radio Sci.*, *29*, 349–365, 1994.

Tsunoda, R. T., S. Fukao, M. Yamamoto, and T. Hamasaki, First 24.5-MHz radar measurements of quasi-periodic backscatter from field-aligned irregularities in midlatitude sporadic *E*, *Geophys. Res. Lett.*, *25*, 1765–1768, 1998.

Tsunoda, R. T., J. J. Buoncore, A. Saito, T. Kishimoto, S. Fukao, and M. Yamamoto, First observations of quasiperiodic radar echoes from Standford, California, *Geophys. Res. Lett.*, *26*, 995–998, 1999.

Woodman, R. F., M. Yamamoto, and S. Fukao, Gravity wave modulation of gradient drift instabilities in midlatitude sporadic *E* irregularities, *Geophys. Res. Lett.*, *18*, 1197–1200, 1991.

Woodman, R. F., J. L. Chau, F. Aquino, R. R. Rodriguez, and L. Flores, Low-latitude field-aligned irregularities observed in the *E* region with the Piura VHF radar: First results, *Radio Sci.*, *in press*, 1999.

Yamamoto, M., S. Fukao, R. F. Woodman, T. Ogawa, T. Tsuda, and S. Kato, Midlatitude *E* region field-aligned irregularities observed with the MU radar, *J. Geophys. Res.*, *96*, 15,943–15,949, 1991.

Yamamoto, M., S. Fukao, T. Ogawa, and T. Tsuda, A morphological study on mid-latitude *E*-region field-aligned irregularities observed with the MU radar, *J. Atmos. Sol. Terr. Phys.*, *54*, 769–777, 1992.

Yamamoto, M., N. Komoda, S. Fukao, R. T. Tsunoda, T. Ogawa, and T. Tsuda, Spatial structure of the *E* region field-aligned irregularities revealed by the MU radar, *Radio Sci.*, *29*, 337–347, 1994.

J. L. Chau and R. F. Woodman, Radio Observatorio de Jicamarca, Apartado 13-0207, Lima, Perú (e-mail: chau@jro.igp.gob.pe; ron@geo.igp.gob.pe)

(Received March 15, 1999; revised May 1, 1999;
accepted May 21, 1999.)