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Azimuth-Time-Intensity striations of quasiperiodic radar echoes from the midlatitude E region ionosphere

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Abstract. The Valensole high frequency (HF) radar in the south of France is an ionospheric Doppler sounder which can perform *E* region coherent backscatter measurements over an azimuthal sector of 86°, from 26° E to 58° W, with ~ 2° angular resolution. This large azimuthal coverage is taken advantage of in order to study quasiperiodic (QP) echoes in the zonal direction using azimuth-time-intensity (ATI) analysis. ATI plots show sequential sloping striations of scatter reminiscent of those detected routinely in the range-time-intensity (RTI) plots of midlatitude radars which view the medium at a fixed azimuth about the meridian. It was found that ATI striation periods range from a few minutes to less than 30 min, whereas the striation slopes are systematically negative (motions westward) prior to local midnight, and turn positive (motions eastward) in the post-midnight hours. The zonal rates, dx/dt, computed from the striation slopes take values between ~ 30 and 160 m/s. These are due to real motions of unstable plasma structures, most likely sporadic *E* patches that drift along with the neutral wind, that have zonal scale lengths of several tens of kilometers. The present observations imply that the mechanism responsible for QP echoes is independent of azimuth and can basically operate effectively in any direction in the horizontal plane.

Introduction

In recent years there have been many studies of coherent radar backscatter from the midlatitude *E* region ionosphere, a phenomenon that occurs in close connection with sporadic *E* (E_s) layers (e.g., see [*Riggin et al.*, 1986];[*Haldoupis and Schlegel*, 1993];[*Tsunoda et al.*, 1994];[*Hysell and Burcham*, 2000], and references therein). An important property revealed in all radar experiments is the occurrence of pronounced periodicities in echo intensity. The most spectacular periodicities, which came to be known as quasiperiodic (QP) echoes, are best manifested in range-time-intensity (RTI) plots as sequential sloping striations of backscatter with periods from a few minutes to ~ 20 min and range rates, dR/dt, from ~ 20 to 100 m/s. These signatures were first identified by [*Yamamoto et al.*, 1991] with the Middle and Upper atmosphere (MU) radar near Kyoto and have since attracted considerable attention.

Since the first QP observations there have been several experiments in both the Asian and American longitudinal sectors which have reported more RTI observational details of QP echoes (e.g., see recent paper by [*Hysell and Burcham*, 2000] for a summary of results and references), and new ideas and mechanisms have been put forward for the explanation of these echoes as well. These include a conceptual model by [*Woodman et al.*, 1991], based on strong E_s altitude distortions forced by short period atmospheric gravity waves, and a mechanism proposed by [*Larsen*, 2000], which relies on large vertical wind shears and the action of the Kelvin-Helmholtz instability.

All QP observations and relevant findings published to date refer to fixed azimuth studies, mostly along the magnetic meridian. In this paper we report the first azimuthal, or zonal, observations of QP echoes made in the European sector with an oblique HF sounder operating near the town of Valensole in the south of France. In this work the Valensole radar's unique advantage of performing scans over a large azimuthal sector of ~ 85° is utilized in order to investigate backscatter periodicities in azimuth-time-intensity (ATI) plots. The present results are complementary to those obtained from many RTI observations, and thus are useful in providing an integrated picture for the QP echoes in the radar observing plane.

Experiment

During the last few years the Valensole radar (43.8°N; 6.1°E geographic; 37.1°N; 82.2°E geomagnetic) has been utilized in a number of sporadic *E* experiments (SPOREX) for studying coherent echoes from decameter wavelength irregularities. The radar employs several synchronized receivers and beam forming techniques to cover a large azimuthal sector with good angular resolution. It uses a wide-beam antenna for northward transmission (3-db beam width at 15 MHz was ~ 60°) and a narrow beam 560 m-long linear array of 48 vertical antenna elements for phased-array reception. At the receiver, a steering unit switches the array beam in steps of 12° over seven adjacent sectors each divided into 6 sub-sectors using digital beam-forming. As such, a full azimuthal scan consists of 42 elementary beams between 26° E and 58° W, each having a 3-db beam width of 2° at 15 MHz. For example, in this setup the radar covers a zonal distance of ~ 320 km at the 200 km range.

In SPOREX, the received signal was gated every 18 km to give 15 range-gates between 100 and 370 km. This satisfied the 0° aspect sensitivity condition for *E* region altitudes between 90 and 130 km over a large ionospheric area centered near 37° invariant magnetic latitude, $L = 1.7$, and magnetic dip of ~ 60°. Another novel aspect was the simultaneous radar operation in two or more, pulse-to-pulse interlaced, frequencies. The radar computer also used an array processor for real time fast Fourier transform Doppler

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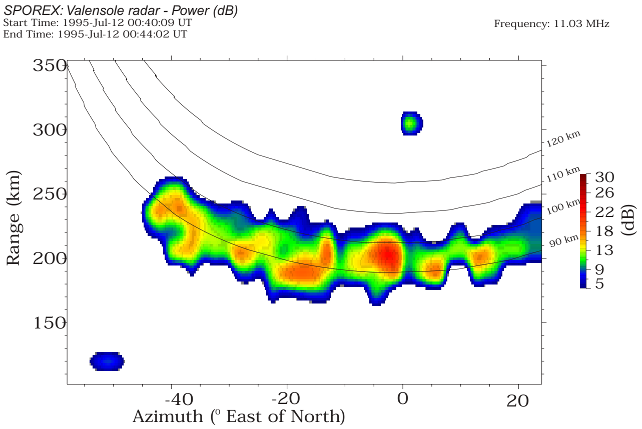

Figure 1. Range and azimuth coverage of the Valensole radar.

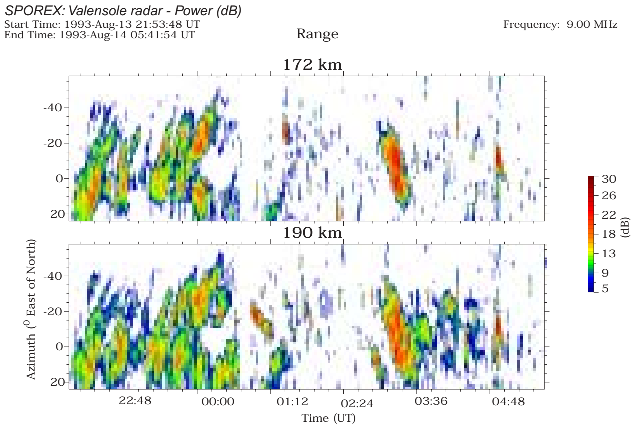

Figure 3. Overnight ATI striation activity showing a clear slope reversal.

spectrum computations. For more details on the radar and its capabilities, see [*Six et al.*, 1996].

Azimuthal Backscatter Observations

In this paper data from SPOREX experiments run during summer periods in 1993 and 1995 are used. In SPOREX-93 the operation allowed for two frequencies (9.0 and either 12.4 or 14.8 MHz) to be pulse-to-pulse interlaced and a single west to east azimuthal scan was completed in 80 s (for more on SPOREX-93 and the first results see [*Bourdillon et al.*, 1995]). In SPOREX-95 there were four pulse-to-pulse interlaced frequencies (9.23, 11.03, 12.71 and 16.09 MHz), but the same azimuthal scan now needed 240 s to complete (for more on SPOREX-95 see [*Hussey et al.*, 1999]). The present analysis was based on seven active nights of scatter when the radar operated continuously from 1800 to 0600 UT (UT = LT − 25 min).

The *E* region radar field-of-view is seen in Figure 1, which shows a range-azimuth-intensity (RAI) "snapshot" observed at 11.03 MHz. Note that in this, and the following figures, the plotted data are smoothed by using cubic convolution interpolation. Shown also across the radar field-of-view in Figure 1 are line of sight, zero magnetic aspect angle contours calculated for altitudes of 90, 100, 110 and 120 km using the International Geomagnetic Reference Field (IGRF). In the azimuthal plane the radar detects a spatial sequence of echoing regions with a characteristic zonal scale length of ∼ 40 km. This belt of aspect sensitive scatter stretches out in the zonal direction and along the magnetic aspect angle contours for ∼ 250 km. As shown by [*Hussey et al.*, 1999], the scatter prefers to appear at near ranges because of refraction effects inside E_s layers centered above 100 km. This means that the low scatter altitudes implied from the straight-line propagation aspect angle geometry are, most likely, incorrect.

The radar is capable of monitoring the motions of the scattering regions in the observing plane. The latter, however, can be done best in azimuth because in range there are restrictions imposed by the relatively poor range resolution (18 km) and the aspect sensitivity condition. The azimuthal motions of the echoing regions is a striking feature in the Valensole radar observations, manifested regularly in time sequential RAI plots. Next, in order to quantify better the zonal motions, we present only results of ATI analysis. This was done in analogy with past RTI studies at fixed azimuths.

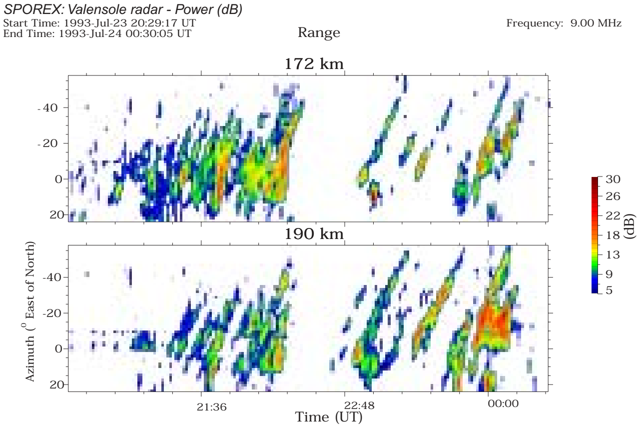

Figure 2. Typical pre-midnight ATI striations.

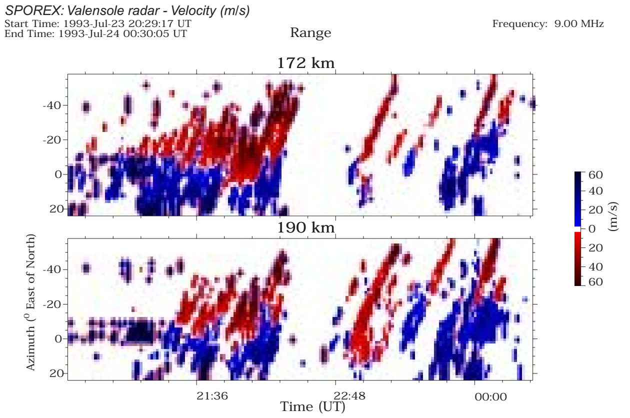

Figure 4. ATV plot showing a systematic Doppler reversal with azimuth.

Azimuth-Time-Intensity Striations

The observations show that most backscatter does occur prior to local midnight. Figure 2 illustrates a typical ATI signature of QP echoes observed in the pre-midnight sector. Shown are plots for two consecutive radar ranges, 172 and 190 km, where 9 MHz echoes are usually located because of considerable ray bending due to refraction. In general, QP echoes recur in groups during time intervals from 1 to 3 hours. Figure 2 shows two groups of striations, one prior to 2210 and one after ~ 2250 UT, having characteristic periods of about 7 and 15 min, respectively. The striations last from a few minutes to perhaps more than about 20 min and all exhibit positive slopes as a result of a prevailing westward motion. In this example, the measured slopes, or zonal rates dx/dt, range from about 120 to 150 m/s and represent some of the highest zonal velocities measured in the data.

In four out of the seven available nights of scatter, there was also some echo activity present in the early morning hours after ~ 0200 LT characterized again by striated scatter and QP echoes. In this post-midnight scatter, however, the striation slopes were now negative in sharp contrast with the positive slopes seen in the pre-midnight ATI plots. This suggests a reversal in the inferred zonal motion of the unstable plasma regions, from westward in the evening to eastward in the morning. This overnight reversal is illustrated in Figure 3, which presents ATI plots at two consecutive radar ranges (172 and 190 km) for the night of August 13–14, 1993. Basically, there are two groups of striated QP echoes: a long lasting one prior to ~ 0030 UT and a weaker one later in the morning after a quiet period of about two hours. For this event, the zonal velocities dx/dt were between +65 and +80 m/s in the evening and near −120 m/s in the morning. Since the situation depicted in Figure 3 was seen, to a lesser or greater extent, in all the available nights, we conclude that this is a common characteristic of the data.

Overall, the measured striation periods range from a few minutes to ~ 20 to 30 min, whereas the zonal rates dx/dt are between 30 and 160 m/s. In individual striations, the intensity is at times structured and organized in a wavelike fashion with zonal scale lengths from about 10 to 80 kilometers. At other times, however, the striation relates to a single large region of unstable plasma having a zonal extent well in excess of 100 km. Also, ATI striations can exhibit significant differences between adjacent radar ranges and at times there is a multiplicity of simultaneous striations seen at a given range. Finally, the observed spectra were mostly low Doppler velocity spectra that could classify as type 2.

Observed Zonal Motions

The ATI analysis revealed that unstable plasma regions undergo a zonal motion, which is westward prior to local midnight and eastward after ~ 0200 LT. A question that arises is the following: is this zonal motion an apparent or real motion?

An apparent motion could result from, say, the propagation of a large-scale wave-like disturbance, e.g., a gravity wave or a large scale plasma wave, which can somehow act upon the ionized medium as a seeding source of short-scale plasma destabilization. As such, for an observer on the ground, the echoing plasma regions are expected to undergo an apparent motion; that is, the motion of the propagating source. For example, this situation could apply to the mechanism of [*Woodman et al.*, 1991] wherein a propagating gravity wave causes altitude distortions of a sporadic E layer, which may become susceptible to strong gradient drift plasma destabilization if $\mathbf{E} \cdot (\nabla N_e)_\perp > 0$; e.g., if the ambient electric field and electron density gradient perpendicular to the magnetic field point in the same direction. In this case, the Doppler shift of the radio wave scattered from short-scale irregularities will not be affected by the phase velocity of the seeding source, e.g., that of a gravity wave. On the other hand, if the instability regions do really drift zonally, for instance with the neutral wind, then their motion will affect the mean Doppler shift which must undergo an azimuthal sine-law dependence.

The measured zonal motions are indeed due to bulk motions of large scale plasma structures, possibly unstable E_s ionization patches moving with the neutral wind. This was verified by analysing the Doppler spectra at a fixed radar range for all azimuths as a function of time. In this way, the mean Doppler velocity was found to change gradually from positive (motions towards) in the east to negative (motions away) in the west during the lifetime of a positive-slope striation seen in the pre-midnight sector. This is illustrated in Figure 4, which shows an azimuth-time-velocity (ATV) plot that corresponds to the event in Figure 2. On the other hand, and for all the events available, the Doppler polarity changes with azimuth at a given radar range were reversed in the post-midnight sector when ATI striations with negative slopes signified the presence of an eastward motion. The azimuth changes in Doppler velocity were between about −50 and +50 m/s, and agreed well with the components of the zonal rates dx/dt projected along the observing azimuthal directions. Finally, it is important to stress that comparisons of the measured zonal motions with zonal winds predicted by the Horizontal Wind Model HWM93, see [*Hedin et al.*, 1996], show a fairly good agreement for altitudes above 105 to 110 km. Unfortunately, because of space limitations the HWM93 results cannot be shown in this letter.

Concluding Comments

The Valensole radar observations revealed for the first time the occurrence of midlatitude QP striated scatter in ATI plots, which resemble the RTI striations seen by several radars. The present findings suggest that radar striations in midlatitude E region backscatter are simply signatures produced by the motion of unstable plasma structures, possibly patches or clouds of E_s ionization, which drift in the horizontal plane with the neutral wind.

The basic unresolved problem relates to the source of the observed strong periodicity, e.g., the physical mechanism which forces these structures to form in sequence. The present evidence alone cannot exclude either of the two mechanisms proposed so far for the generation of QP echoes; namely, the "gravity wave E_s modulation" and the "Kelvin-Helmholtz instability" mechanisms. This is because both mechanisms are capable of acting on a uniform E_s layer to distort it in altitude and therefore create large-scale plasma inhomogeneities, which then may move with the neutral wind. For both mechanisms, the QP echoes simply result because part, or the whole, of these large plasma inhomogeneities may become unstable to the gradient drift instability (and to subsequent nonlinear cascade of wave energy to shorter wavelengths), depending on the combined action of the driving instability electric fields (ambient and polarization) and electron density gradients (vertical and lateral). In addition, one cannot exclude the possibility that strong neutral winds may also play a role in plasma destabilization (e.g., see [*Kagan and Kelley*, 1998]).

Although there is no direct evidence in favor of either one of the proposed two mechanisms for QP echoes, the observation that the drifting plasma structures are seen in every direction in the horizontal plane, which means there are no azimuthal constraint impositions, is perhaps more in agreement with the Kelvin-Helmholtz instability process proposed by [*Larsen*, 2000], than the gravity wave E_s altitude distortion mechanism of [*Woodman et al.*, 1991] which requires a strict matching condition for the wave propagation direction in the azimuthal plane. In addition, the observation of rather large zonal motions which imply the presence of strong neutral wind conditions at backscatter altitudes, is in general compatible with the large vertical wind shears that are known to exist in the same range of E region altitudes and which are required for the Kelvin-Helmholtz process to become active there. On the other hand, the evidence here cannot be exclusive of the possibility that the process of E_s distortion and breaking by gravity wave action may also apply to produce periodic E_s clouds and thus QP echoes, perhaps under much less stringent conditions than those required by the [*Woodman et al.*, 1991] model.

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References

Bourdillon, A., C. Haldoupis, and J. Delloue, High-frequency Doppler radar observations of magnetic aspect sensitive irregularities in the midlatitude E region ionosphere, *J. Geophys. Res., 100*, 21,503, 1995.

Haldoupis, C., and K. Schlegel, A 50 MHz radio Doppler experiment for midlatitude E region coherent backscatter studies: System description and first results, *Radio Sci., 28*, 959, 1993.

Hedin, A. E., et al., Empirical wind model for the upper, middle, and lower atmosphere, *J. Atmos. Terr. Phys., 58*, 1421, 1996.

Hussey, G. C., C. Haldoupis, A. Bourdillon, and D. Andre, Spatial occurrence of decameter midlatitude E region backscatter, *J. Geophys. Res., 104*, 10,071, 1999.

Hysell, D. L. and J. D. Burcham, The 30-MHz radar interferometer studies of midlatitude E region irregularities, *J. Geophys. Res., 105*, 12,797, 2000.

Kagan, L. M., and M. C. Kelley, A wind-driven gradient drift mechanism for midlatitude E region ionospheric irregularities, *Geophys. Res. Lett., 25*, 4141, 1998.

Larsen, M. F., A shear instability seeding mechanism for quasiperiodic radar echoes, *J. Geophys. Res., 105*, 24,931, 2000.

Riggin, D., W. E. Swartz, J. Providakes, and D. T. Farley, Radar studies of long wavelength waves associated with midlatitude sporadic E layers, *J. Geophys. Res., 91*, 8011, 1986.

Six, M., J. Parent, A. Bourdillon, and J. Delloue, A new multibeam receiving equipment for the Valensole skywave HF radar: Description and applications, *IEEE Trans. Geosci. Remote Sens., 34*, 708, 1996.

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

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, 1991.

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, 1991.

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