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THE INFLUENCE OF NON-ISOTHERMAL ELECTRONS AND NEUTRAL WIND STRUCTURES ON THE DOPPLER PROPERTIES OF VERTICAL M-SIZE FIELD-ALIGNED IRREGULARITIES IN THE LOW LATITUDE E-REGION

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ABSTRACT. Meter size irregularities are routinely studied with radars in the equatorial and low latitude regions. In both instances echoes from the E-region (90 to 120 km altitude) are a common occurrence. The resulting echoes are labeled as so-called Type I or Type II according to their spectral signature. In this paper we show that the phase velocity of Type I echoes increases with decreasing altitude owing to thermal feedback effects taking place in the growth process. We also show that Type II echoes can be influenced by atmospheric neutral winds to the point of revealing the presence of Kelvin- Helmholtz billows, as shown by a recently studied example taken from the Gadanki radar in India.

Keywords: equatorial electrojet, plasma waves and instabilities, ionospheric irregularities, low latitude E-region, VHF radar spectra, quasi-periodic echoes, Kelvin-Helmholtz billows, turbulence.

RESUMO. Irregularidades com escala de metros são estudadas rotineiramente com radares nas regiões de baixas latitudes e equatoriais. Em ambos os estudos é comum a ocorrência de ecos da região E (90 a 120 km de altitude). Os ecos resultantes são denominados de Tipo I e Tipo II de acordo com sua assinatura espectral. Neste trabalho nós mostramos que a velocidade de fase dos ecos tipo I aumenta à medida que diminui a altitude devido a efeitos térmicos causados pela própria irregularidade durante seu processo de desenvolvimento. Nós também mostramos que os ecos do Tipo II podem ser influenciados pelos ventos neutros atmosféricos ao ponto de revelar a presença de ondas do tipo Kelvin-Helmholtz, conforme demonstrado em alguns exemplos de estudos recentes realizados com o radar Gadanki na Índia.

Palavras-chave: eletrojato equatorial, ondas de plasma e instabilidades, irregularidades ionosféricas, região E em baixas latitudes, espectros obtidos com radares em VHF, ecos quase-periódicos, ondas do tipo Kelvin-Helmholtz, turbulência.

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INTRODUCTION

Radar studies from all over the world are now showing that E-region turbulence is a ubiquitous phenomenon taking place at all latitudes. This has been a surprise at first because it had long been thought that the only places with the right combination of electric fields and density gradients were the equatorial electrojet region with its combination of strong currents and ambient density gradients and the auroral regions with their very strong ambient electric fields. However, following their initial discovery at mid latitudes, in association with sporadic E layers, (Tanaka & Venkateswaran, 1982; Ecklund et al., 1981; Riggin et al., 1986) it has become clear that E-region echoes have a rich morphology even at mid and low latitudes, as witnessed by so-called quasi-periodic (QP) echo patterns (Yamamoto et al., 1991; Choudhary & Mahajan, 1999; Chau & Woodman, 1999). In fact, while the association with sporadic E layers seems clear, it is interesting to note that some of the echoes at mid latitudes have Doppler shifts of the order of a few 100 m/s, which is clearly larger than any ambient electric field could provide (Haldoupis et al., 1997). The presence of sporadic E layers therefore is instrumental not just in providing gradients, but in also structuring the electric fields. A particularly clear and elegant illustration of how that can come about has been provided, for example, by Cosgrove & Tsunoda (2001).

There are two broad types of echoes being described when dealing with E-region radar backscatter echoes. So-called Type I echoes are relatively narrow and move with a Doppler shift comparable to the ion-acoustic speed of the medium. By contrast, Type II echoes have a relatively broad spectral width while their Doppler shift is much smaller. Over time, the consensus has evolved that Type I waves are linearly unstable waves that end up moving at the instability threshold speed, close to ion-acoustic speed of the medium, when they saturate. This, incidentally, must also imply that gradients could be instrumental in determining the observed speed by affecting threshold conditions (Farley & Fejer, 1975; St.-Maurice et al., 1994). Type II waves have likewise been associated with linearly stable waves excited by turbulence through a mode-coupling process (Keskinen et al., 1979; Sudan, 1983). As such they would have a Doppler shift consistent with the mean line-of-sight component of the electron drift, at least above 100 km altitude (more on this below).

In this paper we address the Doppler properties of echoes obtained while looking vertically or near-vertically with a low latitude HF or VHF radar. We discuss the echoes in light of the usual Type I and II morphology. We argue that as we go down to near 100 km in altitude, one should be careful to take account of the fact that the instability can no longer be considered isothermal. This means that the ion-acoustic speed, and therefore the Doppler shift of Type I echoes, increases with decreasing altitude in spite of the fact that the ambient temperature is actually going down. With regard to the Doppler shift of Type II echoes we argue that structures in the neutral wind can be very efficient at producing dynamos such that in the end the ions, electrons, and neutrals, all move together. This opens up the possibility that, under the right kinds of situations, radars can be used to monitor rather directly the neutral wind in the lower thermosphere.

VERTICAL TYPE I ECHOES AT LOW LATITUDES

When looking vertically with a radar, it is common in the equatorial electrojet region to observe Type II echoes. This is the normal situation, since the currents are moving in the east-west direction. This implies that the instabilities are excited primarily in the east-west direction (the magnetic field, $\mathbf{B}$, is horizontal and points north). Thus, when observing while looking up, a radar is normally not seeing linearly unstable (primary) waves, although turbulence ensures that secondary waves are produced through mode-coupling between primaries. Type II waves are therefore the norm.

Nevertheless, Type I waves are seen reasonably often when an equatorial radar is making vertical/close to vertical (in the east/west directions) observations. The mechanism behind the production of these "two-step" Type I waves was uncovered by Sudan et al. (1973). Basically, the electrojet first excites primary waves in the east-west direction on a scale of a few km. The primary wave now adds an east-west modulation to the primary vertical field. If the amplitude of the km size structure is sufficiently large, the east-west electric field becomes sufficiently large to, in turn, excite Farley-Buneman waves in the vertical direction. The process was first documented experimentally by Kudeki et al. (1982) who used interferometry to show that vertical Type I waves were moving alternately up and down in structures a few km in horizontal size.

Type I waves are moving at a speed that usually so closely approaches the ion-acoustic speed of the medium, no matter what the ambient electric field might be, that it has become an accepted empirical fact that the primary waves move at the threshold speeds when reaching their largest amplitude. A rough explanation for this state of affair is that a structure reaches its largest amplitude when the growth rate goes from positive to negative. Thus, the amplitude is largest when, somehow, nonlinear conditions match the threshold condition. More proper (less intuitive) theoretical explanations have been given in the literature on occasions. At high latitude, one explanation that has been advanced is that anomalous diffusion increases with the amplitude of a structure until it stops growing (Robinson, 1986). A problem with this mechanism, however, is that the diffusion is from the electron drifts and therefore at right angles to the direction needed for diffusion to affect the wave amplitude (St.-Maurice, 1990). Alternatively, a monotonic growth in the aspect angle has been shown by Drexler et al. (2002) to be inevitable at high latitudes and to certainly be able to affect slow growing modes by not only limiting their amplitude but also by eradicating them (through damping by large aspect angles). However, for fast growing m-size modes, the growth in aspect angles should normally be too slow to matter. Nevertheless, St.-Maurice & Hamza (2001) showed that the electric field inside field aligned individual structures actually rotates and decreases while the amplitude of the structure grows. This means that the growth also comes to a halt when the structure drifts at a speed close to the ion-acoustic speed. At that point, the monotonic increase in the aspect angle will make the amplitude decrease until that particular structure disappears. We note that Otani & Oppenheim (1998) also got important rotations inside structures in their 2-D numerical simulations. They attributed the rotation and resulting saturation to mode-coupling, which is consistent with the St.-Maurice & Hamza (2001) work, since both nonlinear mechanisms are described by the same operator. Neither Otani & Oppenheim (1998) nor St.-Maurice & Hamza (2001) were able to carry calculations that included the aspect angle evolution, however.

At low latitudes, the same principles behind the saturation of Type I modes may apply. However, the rotation of the electric field, in a plane perpendicular to the geomagnetic field, inside structures is most likely more important because the parallel aspect angle evolution should be very slow in regions for which the magnetic field is horizontal over several 100 km. Nevertheless, the electric field, even in two-step processes, is not expected to be so large as to show important rotations away from the primary direction of excitation. If so, the observation of vertical or near-vertical two-step Type I waves should provide an adequate description of the ion-acoustic (or threshold) speed of the medium in HF and VHF radar observations.

Figure 1 shows how the phase velocity of two-step Type I waves was changing with altitude during a strong equatorial electrojet episode observed by the Pohnpei radar on April 4, 2000 (St.-Maurice et al., 2003). The Pohnpei radar, operating at a frequency of 49.8 MHz, is located in the western pacific at 6.95° North, 158.19° East, 0.7°N magnetic dip. The experiment, described in St.-Maurice et al. (2003), was conducted at a range resolution of 1 km with antenna beam pointing in the vertical and two oblique directions (14.3° off-zenith angle) in magnetic east and west directions. In the figure, the points joined by a line are the averages and the bars indicate the standard deviations of the samples. While there was actual scattering in the observations, one cannot deny that the phase speed was increasing with decreasing altitude until it reached of the order of 420 m/s by 100 km altitude. While St.-Maurice et al. (2003) provided a detailed analysis of the data, it should be noted that similar observations had also been presented earlier by Swartz (1997).

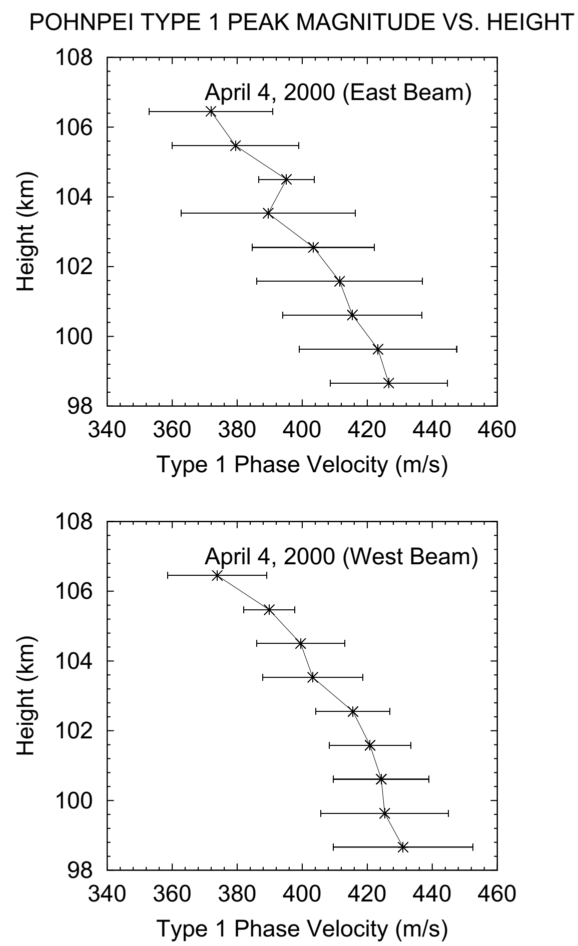

Figure 1 – Phase velocities of two-step Type I waves observed with two nearly vertical beams with the Pohnpei equatorial radar. Symbols “x” connected by the line are the averages obtained with the data samples. More details on the data can be found in St.-Maurice et al. (2003).

The reason for the observed increase in the threshold speed in spite of colder ion and electron temperatures is that the instability can no longer be considered isothermal at lower altitudes and small aspect angles. Instead of the usual dispersion relation we now have, because of corrections due to thermal fluctuations

(St.-Maurice & Kissack, 2000; St.-Maurice et al., 2003):

$$\omega - \frac{\mathbf{k}\cdot\mathbf{V}_{e0}}{1+\psi} - \frac{i\psi}{(1+\psi)\nu_i}\left\{\omega^2 - k_\perp^2\frac{T_{i0}}{m_i} - k_\perp^2\frac{T_{e0}}{m_i}\left[1+(1+g)\frac{t_{e1}}{n_1}\right]\right\} = 0 \qquad (1)$$

In this equation ω is the (complex) frequency, $\mathbf{k}$ is the wavenumber, $\mathbf{V}_{e0}$ is the electron drift, $\psi = \nu_e\nu_i/\Omega_e\Omega_i$, ν_j is the collision frequency of species j with the neutrals, Ω_j is the cyclotron of species j, T_{j0} is the background temperature of species j, m_i is the ion mass, $t_{e1} = \delta T/T_{e0}$ and $n_{e1} = \delta n/n_0$. This expression corresponds to the widely used isothermal results if the perturbed temperature perturbation, or t_{e1}, is negligible. However, this cannot always be assumed. For one thing when the electrons are compressed they get heated adiabatically. Therefore we should expect t_{e1} and n_1 to go up and down together, at least in principle. Then there is the matter of the cooling rates: for instance, ion temperature perturbations are less important in the lower E-region because cooling through elastic collisions is efficient. Not so for electrons, however: their cooling rate through elastic collisions with neutrals is so small that cooling is done through inelastic collisions instead. Therefore, the effect of electron adiabatic heating can be visible. In addition, the g term in the equation is positive and of order 1 (the best guess is 5/6). This term represents thermal diffusion and is mathematically equal to the logarithmic derivative of the elastic collision frequency. It describes the fact that because hot electrons collide more often than cold ones, there is an increase in particle diffusion from the hot to the cold regions, even when the electrons are magnetized. This phenomenon is described in detail by St.-Maurice & Kissack (2000). Solving for t_{e1} is straightforward but tedious. The expression is also not particularly easy to digest except in the case of zero aspect angles. In that case the growth rate, Γ, can be written as (St.-Maurice & Kissack, 2000; St.-Maurice et al., 2003):

$$\Gamma = \frac{\psi}{(1+\psi)\nu_i}\left\{1+\frac{\psi}{(1+\psi)\nu_i}k_\perp^2\frac{T_{e0}}{m_i}\xi\right\}^{-1} \times\left\{\omega_r^2 - k_\perp^2\frac{T_{i0}}{m_i} - k_\perp^2\frac{T_{e0}}{m_i}\left[1+\frac{(2/3)(1+g)^2(\omega_r-\mathbf{k}\cdot\mathbf{V}_{e0})^2}{\left[(2/3)\eta + k_\perp^2 D_e(5+2g)/3\right]^2+(\omega_r-\mathbf{k}\cdot\mathbf{V}_{e0})^2}\right]\right\} \qquad (2)$$

where ξ is a complicated mathematical expression (St.-Maurice & Kissack, 2000), D_e is the electron diffusion coefficient, and η is a cooling rate coefficient modified by thermal diffusion effects. This expression can be obtained by taking the imaginary part of (1) and using the solution for t_{e1}. In the denominator we have inelastic collisions (first term), and perpendicular heat diffusion through conduction (second term). Heat advection is described by the remaining terms. It should be apparent that, with any cooling and heat conduction at all, when the phase velocity matches the electron drift, t_{e1} = 0. This is no longer true, however, when the advection term is so large as to make cooling and conduction unimportant. When that happens, near 100 km and below, we obtain an adiabatic answer (5/3 T_{e0}), amplified by thermal diffusion. The electrons have, in that case, to be called "super-adiabatic".

It turns out that when the electrons are purely super-adiabatic, the threshold speed, obtained from setting the growth rate to zero, is 1.47 times the isothermal value. Except for the fact that this value is representative of the upper limit in the two-step Type-I observations and is therefore a bit higher than average observations, the computed super-adiabatic value remains much closer to the observations than the isothermal ion-acoustic speed. This includes not just the numerical value but also the clear increase in the observed phase velocity with decreasing altitude that can be seen in Figure 1: the lower altitudes are precisely the altitudes over which the cooling rates and heat conduction terms lose out to the heat advection term. Figure 2 illustrates this result with a calculation based on the conditions that prevail at Pohnpei, where the observations posted in Figure 1 were obtained. We note an excellent zeroth order agreement between theory and observations. This is in spite of the fact that we simply assumed zero aspect angles to do the computations. On the other hand, we have to also admit that the observed Doppler shifts are systematically smaller than indicated by the zero aspect angles computations.

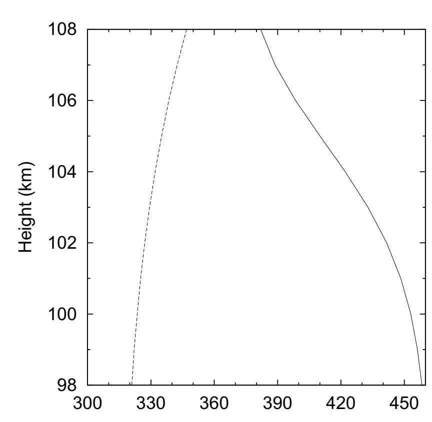

Figure 2 – Full line: phase velocity computed for the non-isothermal threshold speed. Broken line: isothermal ion-acoustic speed. Adapted from St.-Maurice et al. (2003).

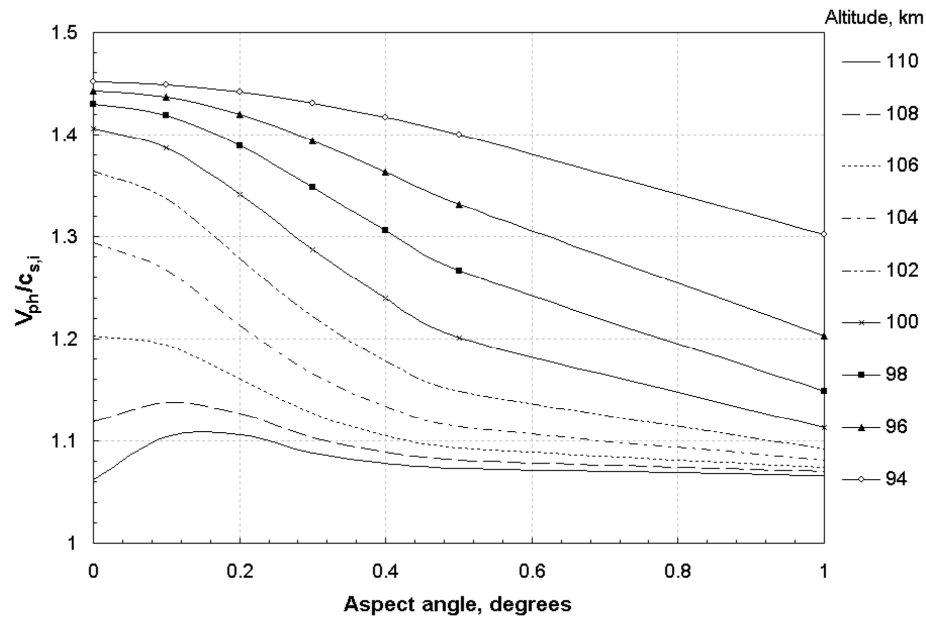

Figure 3 – Variations in the ratio of the threshold phase velocity to the isothermal ion-acoustic speed as a function of aspect angle and altitude. An aspect angle of 0.25 deg or less means substantially greater threshold speeds between 100 and 106 km altitude. The aspect angle is not so influential lower down. From Kagan & St.-Maurice (2004).

To address the role played by non-zero aspect angles, more comprehensive calculations were performed by Kagan & St.-Maurice (2004), in which nonzero aspect angles were included. The results were similar to, though somewhat different from earlier calculations by Dimant & Sudan (1995). As seen in Figure 3 nonzero aspect angles make the threshold speed smaller, as expected. The effect is stronger at intermediate altitudes, where a 0.25 deg aspect angle can make a measurable difference for the observed threshold speed.

This brings us to a final point, namely, the question of scatter in the data points. While all observations are well above the isothermal ion-acoustic speed value, a particularly interesting feature of the observations is that their upper envelope matches the zero aspect angle theory. This suggests that a source of scatter could actually be the aspect angle itself. If so, the next interesting question is: what is it that modulates said aspect angle? It should finally be mentioned that interferometry studies by Kudeki & Farley (1989) strongly indicated that the aspect angle of two-step Type I waves was 0.25 deg or less in their observations. This result is indeed consistent with our discussion.

VERTICAL TYPE II ECHOES AT LOW LATITUDES

At the equator, E-region Type II echoes are the product of turbulence in the equatorial electrojet itself. At mid and low latitudes there is no electrojet, but Type II echoes are frequently seen in association with sporadic E layers while radars look towards magnetic north (in the northern geomagnetic hemisphere). One interesting point about sporadic E layers below 110 km is that they require strong zonal wind shears for their formation. One can therefore wonder if the shears could be strong enough to themselves become unstable through what is commonly called the Kelvin-Helmholtz instability.

Two questions arise from the fact that Type II echoes are commonly observed with radars while looking towards the north in the northern hemisphere (south in the southern hemisphere), in a direction perpendicular to the magnetic field when sporadic E layers are present. The first question is: what is it that excites the primary waves that lead to the turbulence associated with Type II waves? The second question is: what is the cause of the organization in the observed structures?

There are two, not necessarily mutually exclusive, answers to the first question. The first answer is that there normally exists a northward field at mid-latitude (perpendicular to the magnetic field) which maps to a vertical field at the equator. This field has a large component along the vertical density gradients associated with the Es layer. It does not matter if the field is positive or negative in the sense that at least one side of the Es layer is unstable to the gradient drift mechanism. In addition, the unstable wave-

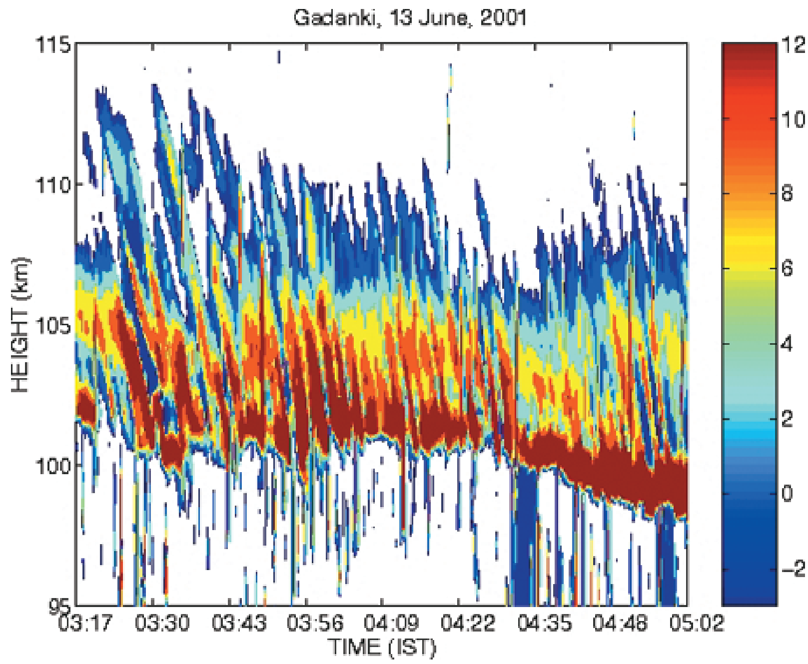

Figure 4 – Height-time-intensity plot of radar echoes showing a QP echo event observed by the Gadanki radar between 03:17 LT and 05:02 LT on June 13, 2001. Signal intensity has been plotted in eight shades of pixel coding between –3 and 12 dB.

vectors are in the zonal direction. An observer looking up and north will therefore only be able to see secondary Type II waves. A second mechanism was highlighted by Kagan & Kelley (1998), namely, the fact that the same wind field that is responsible for the creation of the Es layer is also able to destabilize both sides of the layer simultaneously through the $\mathbf{V}_n \times \mathbf{B}$ field. Thus, there is no problem with explaining the presence of Type II waves observed around Es layers. The next question has to do with the structures of the echoes, which often have a quasiperiodic (QP) appearance. At mid latitudes it is possible to argue that the changes in range associated with the echoes are actually not changes in altitude but rather correspond to a horizontal motion of the scatterer (Hysell et al., 2002). It is also possible to argue that structures leading to QP observations can be triggered by an instability of the Es layer itself (Tsunoda et al., 2004). However, QP echoes are also observed at very low latitudes, where the mid-latitude instability of the Es layer should not be taking place, and where an altitude structure also has to be acknowledged (a horizontal motion of the structures nevertheless remains perfectly consistent with the observations). Figure 4 shows the occurrence of a QP event detected by the Gadanki radar, which is located at 13.5°N, 79.2°E (geographic) and 6.4°N dip latitude.

The Gadanki radar, operating at a frequency of 53 MHz, is a highly sensitive, pulse-coded, coherent VHF radar. The antenna system has a peak power aperture product of 3×10^{10} Wm^2 and emits radiation at a peak power of 2.5 MW. It generates a radiation pattern with a main lobe 3° wide, a gain of 36 dB, and a side-lobe of –20 dB. The radar can transmit both coded and uncoded pulses with inter pulse period in the range of 1 ms to 16 ms. The uncoded pulses can vary in pulse width from 1 to 32 μs in multiples of 2. The coded pulses are either 16 or 32 baud biphase complementary pairs with baud length of 1 μs. More details on the radar system may be found in Rao et al. (1995). For the E-region experiments, the narrow antenna beam of the Gadanki radar is oriented at 13° zenith angle due North, and is positioned so as to satisfy the perpendicularity condition at E-region heights. The data presented here were obtained employing a 4-μs coded pulse with an inter-pulse period of 1000 μs. This yielded a range resolution of 600 m. The data were sampled at 128 fast Fourier transform (FFT) points with 8 coherent integrations and only one incoherent integration. This allowed us to study the irregularities with a fine temporal resolution of 3 sec.

High resolution Doppler shift measurements at Gadanki indicate that the individual striations themselves can have very interesting vortex-like structures. One example is displayed in Figure 5. Note that while the original vortex was clearly present in the data, the figure further enhances the vertical effect by subtracting the average from the data at each altitude.

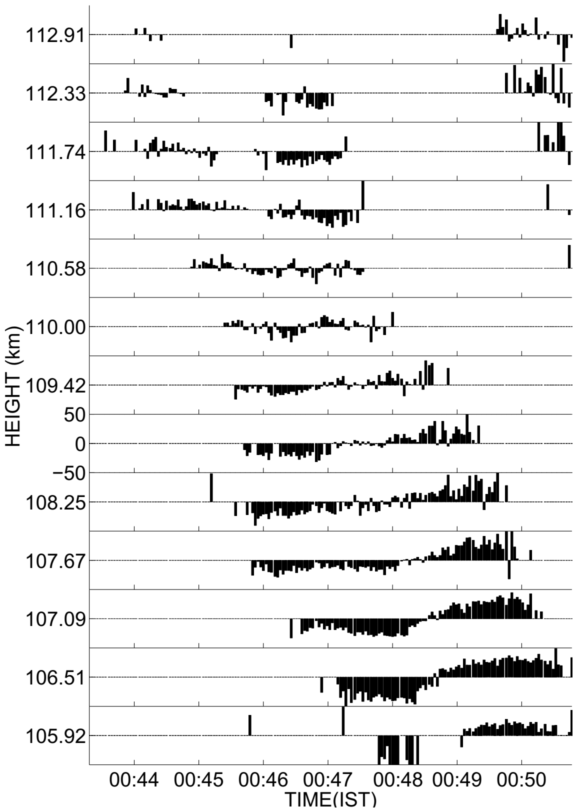

Figure 5 – Particularly clean example of a vortex-like structure seen in one QP striation with the Gadanki radar. The scale on the Y-axis between 108.25 and 109.42 km represents the line of sight Doppler velocity in ms^{-1}. From Choudhary et al. (2005).

The Gadanki Doppler observations are highly reminiscent of Kelvin-Helmholtz billows for the following reasons: 1) KH billows have oscillatory vertical wind fields that would look very similar to those seen in Figure 5; and 2) the layers are consistent with a reshuffling of the Es layers which periodically turns the layer into tilted columns that are extended in the north-south direction (Bernhardt, 2002). The latter would explain the QP look of the echoes, as the wind ferries the echoes across the radar field of view.

One loose end is left, namely, why should the radar actually see the vertical wind pattern with Type II waves? The cartoon shown in Figure 6 may help answering the question. While complications have to be addressed (Choudhary et al., 2005), the cartoon gives the basic answer, namely: with the $\mathbf{B}$ field lines basically horizontal, a vertical wind with some finite horizontal wavelength and finite vertical extent (such as is expected in KH billows) drags the ions along, but not the electrons. This introduces a vertical electric field, $\mathbf{E}_v$, pointing in a direction opposite to the vertical wind. In turn this sets up an electron $\mathbf{E}_v \times \mathbf{B}$ drift. The electrons pile up at the nodes of the vertical neutral wind. This in turn sets up a spatial oscillation in the zonal electric field. Once again, the electrons move in response to this zonal field. Their direction this time is the same as that of the neutral wind. If, in addition, we use the fact that the vertical extent of the vertical wind is limited in extent, then this drift has to be equal to the ion drift in order to achieve a self-consistent answer. The Type II phase speed is supposed to be given by (Fejer, 1996)

$$V_{ph} = \mathbf{k} \cdot \frac{\mathbf{u}_e + \psi \mathbf{u}_i}{1 + \psi} \qquad (3)$$

This is equal to $\mathbf{k} \cdot \mathbf{v}_n$ when $\mathbf{u}_{ev} = \mathbf{u}_{iv} = \mathbf{v}_{nv}$; $\mathbf{v}_{nv}$ being the perturbed vertical neutral wind velocity while $\mathbf{k}$ is also vertical (St.-Maurice & Choudhary, 2006). We essentially, therefore, are left with structures that move along with the neutrals for an observer looking up. Complications associated with mean winds and ambient electric fields must of course be added but the main result remains, namely, the vertical wind structure will be seen with the radar on top of whatever else might create ambient/average drifts.

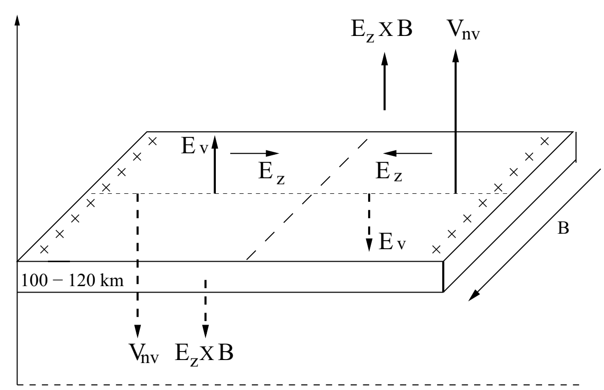

Figure 6 – Cartoon illustrating the basic reason why the vertical wind structure of a Kelvin-Helmholtz billow will be detected by an upward looking radar. From St.-Maurice & Choudhary (2006).

CONCLUSION

We have shown that a better understanding of the ionosphere and neutral atmosphere can be reached with modern high resolution studies of ionospheric irregularities. We have limited ourselves to vertical echoes obtained from the equatorial electrojet and from low latitude radars. We have shown that a proper understanding of the thermal feedback into the Farley-Buneman instability explains why the phase velocity increases with decreasing altitude in spite of smaller ion and electron temperatures. This knowledge can in turn be used to monitor the neutral temperature in the region, not to mention the potential for assessing the aspect angle and the electric field in the medium. Likewise, the monitoring of Type II waves at low latitudes can help understand thermospheric motion, such as Kelvin-Helmholtz billows. Our point is that diverging neutral wind structures may well create local electro-dynamical feedback of the kind we have seen with the Gadanki radar. Thus, it seems possible that atmospheric gravity waves might be studied by carefully monitoring the Doppler shift of Type II echoes wherever they may be.

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