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Correlation of Wind and Electric Field in the Nocturnal *F*-Region

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Introduction

The incoherent scatter radar of the Arecibo Observatory operates at a frequency of 430 MHz and a peak transmitter power of 2 MW. Combined with an antenna that is 300 m in diameter, the radar is sufficiently sensitive to measure the drift velocity of *F*-region ions parallel to the radar beam to an accuracy of 2 m. s $^{-1}$ after an integration time of only 10 min. The radar beam can be pointed in any direction within 22° of the zenith. If it is assumed that ionospheric drift velocities do not vary with position over horizontal distances of about 200 km and vary with time in a linear fashion it is possible to combine line-of-sight velocity measurements made in various directions to derive three orthogonal components of the ion drift velocity vector (Behnke, Harper, 1973). Figure 1 illustrates this procedure in two dimensions.

A particularly useful coordinate system to use for the drift velocity is one which specifies the components parallel to the geomagnetic field, perpendicular to the magnetic field and horizontal, and perpendicular to the field in the magnetic meridian plane. At *F*-region heights, where the ion-neutral collision freduency is much smaller than the cyclotron frequency, ion motion perpendicular to the magnetic field can be produced only by an electrostatic field. The parallel component of the motion is caused by the combined influence of the neutral wind (only the component parallel to the magnetic field is effective) and ambipolar diffusion.

This paper is concerned with the relationship between the parallel component, designated $v_{\parallel}$, and the perpendicular component in the vertical plane containing the magnetic meridian, designated $v_{\perp}$. These two components to-

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gether influence the continuity equation for F-region ionization and the height of the F-layer. The horizontal component of the ion drift velocity does not affect the electron density profile unless horizontal gradients in the ionosphere are large.

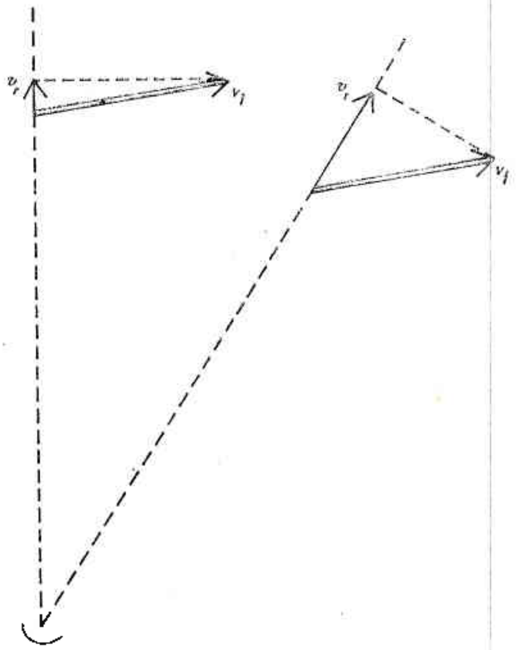

Fig. 1. Provided it does not vary horizontally, the ion velocity vector, v_i, can be derived from measurements of the line-of-sight velocity, v_r, made with the radar beam pointing first in one direction and then in another

The very surprising result revealed by Arecibo measurements in the nocturnal ionosphere is that there is a strong negative correlation between $v_{\parallel}$ and $v_{\perp}$ (Behnke, Harper, 1973). A representative example of this negative correlation is shown in Fig. 2. The figure reveals marked fluctuations in both velocity components on a time scale of an hour or two, with the fluctuations of the two components being approximately equal in amplitude and opposite sign. Since both components are defined as being positive upward and since the magnetic dip angle at Arecibo is 50°, it appears that the vertical component of $v_{\parallel}$ tends to cancel the vertical component of $v_{\perp}$, while the two horizontal components add. Evidently there is some feedback mechanism in the F-region that constrains ionization to move horizontally rather than vertically, even when the magnetic field is neither horizontal nor vertical.

The nature of this feedback mechanism has not yet been convincingly etablished. This paper reviews various mechanisms that have been suggested, reaches some tentative conclusions, and recommends directions for further research.

Theoretical considerations

Three mechanisms have been suggested to explain the negative correlation between $v_{\parallel}$ and $v_{\perp}$. They are ion drag (Dougherty, 1961; Rishbeth et al., 1965; Behnke, Harper, 1973; Thomas, Williams, 1975), *F*-re-

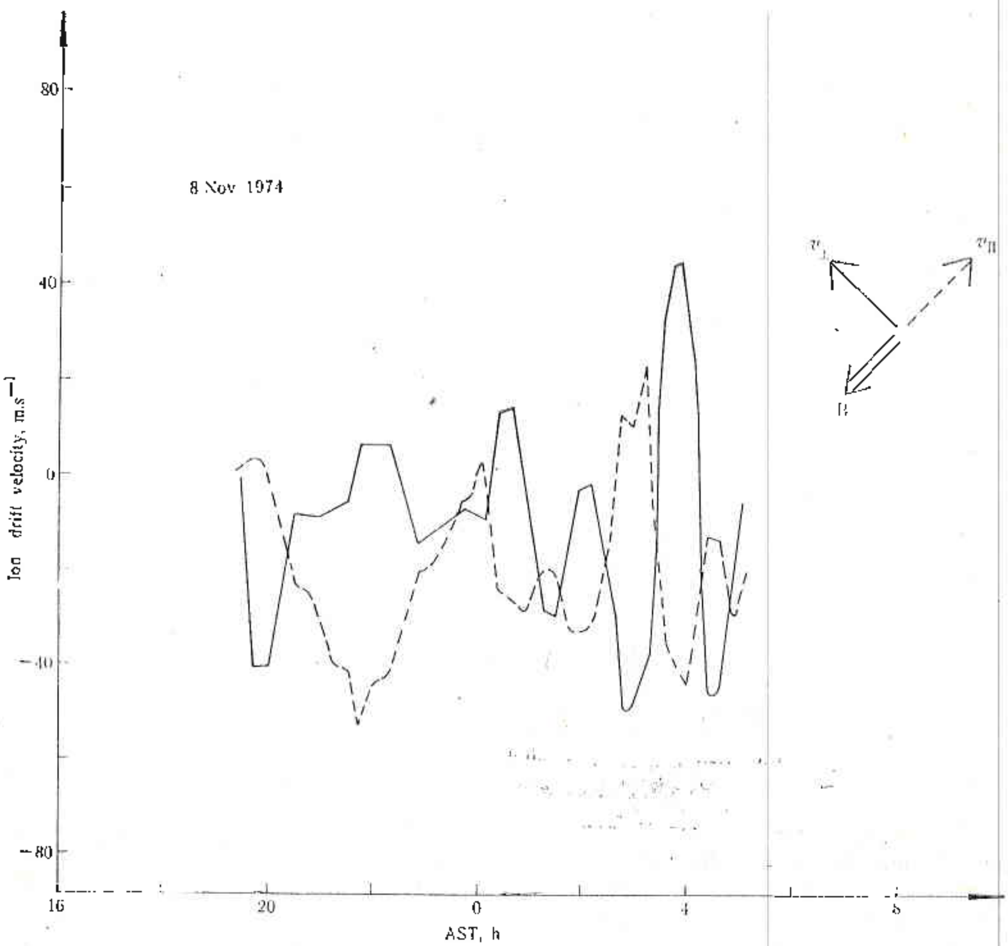

Fig. 2. Measurements of the ion drift velocity vector in the nocturnal *F*-region over Arecibo reveal a marked negative correlation between the components parallel and perpendicular to the geomagnetic field

gion polarization field (Rishbeth, 1971a, b; Behnke, Hagfors, 1974; Heelis et al., 1974), and diffusion (Rishbeth, 1967; Stubble, Chandra, 1970). This section describes these three mechanisms and compares, in qualitative fashion, their predictions concerning ionospheric behavior.

The ion drag mechanism is illustrated in Fig. 3. It is assumed here that the eastward electric field increases, causing an immediate increase in $v_{\perp}$. The friction of the ions drifting through the neutral gas affects the motion of the neutrals so that, after some time, the neutral wind U acquires an additional northward component. This northward component of the wind blows ionization down the magnetic field, causing a negative perturbation in $v_{\parallel}$. Equilibrium is achieved when there is no relative motion of ions and neutrals, the situation illustrated in Fig. 3.

There is no doubt that the ion drag mechanism can, in principle, cause a negative correlation of $v_{\parallel}$ and $v_{\perp}$. The problem, at least for the nocturnal

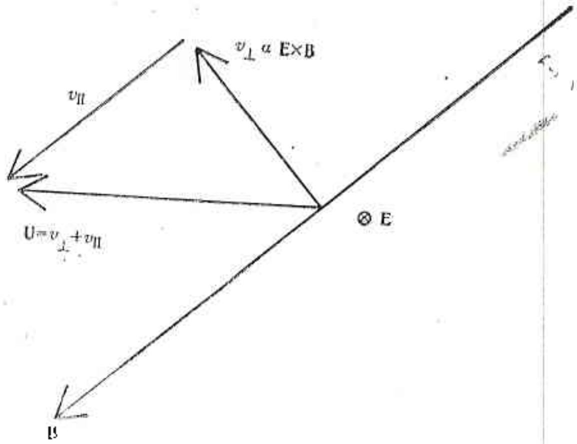

Fig. 3. The ion drag mechanism. See text for explanation

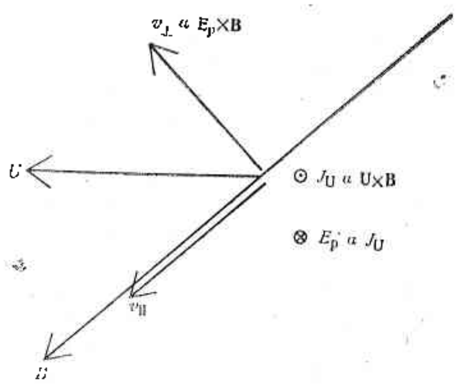

Fig. 4. The polarization field mechanism. See text for explanation

ionosphere, is associated with the time it takes for ion drag to modify the neutral wind. Roughly speaking, the neutral wind can change significantly only after all of the neutral atoms have collided at least once with an ion (Rishbeth, Garriott, 1969). The characteristic time for the ion drag mechanism is therefore the inverse of the neutral-ion collision frequency. For nocturnal ion densities less than 3×10^5 cm^{-3} this time exceeds 1.5 hours. Evidently the ion drag mechanism cannot explain the negative correlation of $v_{\parallel}$ and $v_{\perp}$ on a time scale of an hour or two that is shown in Fig. 2.

The polarization field mechanism is illustrated in Fig. 4. It is assumed here that the northward component of the neutral wind changes, causing a downward increase in $v_{\parallel}$ and, at the same time, an increase in the westward flow of Pedersen current in the *F*-region If the flow of this electric current is inhibited by horizontal variations in the ionospheric conductivity or wind, charge will accumulate, and an eastward polarization electrostatic field will develop to restrict the flow of F-region Pedersen current. The polarization field, in turn, will cause an upward increase

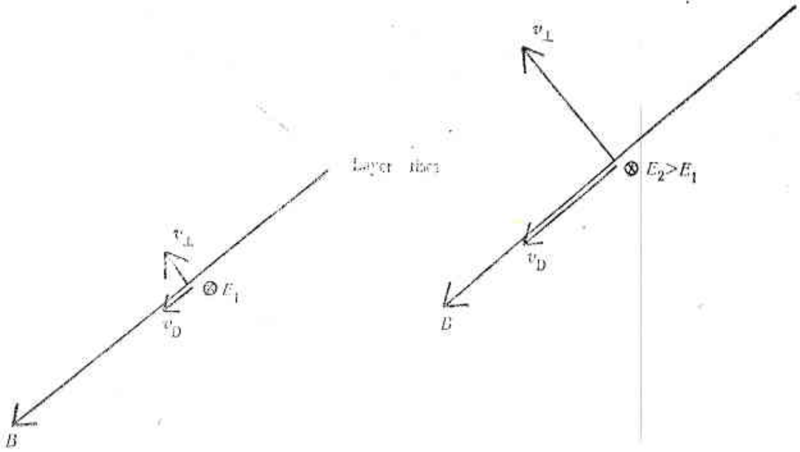

Fig. 5. The diffusion mechanism. See text for explanation

in $v_\perp$, as shown in Fig. 4. In equilibrium there is no relative motion of ions and neutrals and no current flow. The response of the ion velocity components to a change in neutral wind is instantaneous, but the polarization field mechanism works only if the flow of F-region current is inhibited by horizontal variations.

The diffusion mechanism is illustrated in Fig. 5. Here it is supposed that an increase in the eastward electric field causes an upward increase in $v_\perp$. The vertical component of $v_\perp$ causes the F-layer to rise from the position shown on the left of the figure to that shown on the right. Because the diffusion coefficient increases exponentially with increasing altitude, the downward diffusion velocity, v_D, increases as the layer rises. The increasing diffusion velocity appears in the data as a downward increase of $v_\parallel$ which accompanies the upward increase of $v_\perp$. The characteristic time associated with this mechanism is the time for the height F-layer to respond to changes in externally imposed vertical drift velocity. Theoretical considerations indicate that this time is less than about 15 min.

Comparison of the Theories

The three mechanisms therefore differ in several respects. The ion drag and diffusion mechanisms both assert that the basic cause of fluctuations in $v_\parallel$ and $v_\perp$ is fluctuations in the externally imposed electric field. According to the ion drag mechanism, the neutral wind contribution to $v_\parallel$ changes in response to the field induced change in $v_\perp$; according to the diffusion mechanism it is the diffusion component of $v_\parallel$ that responds to the change in $v_\perp$. The polarization field mechanism differs from both ion drag and diffusion by attributing the fluctuations not to externally-imposed electric field change but to externally-imposed change in the neutral wind. We do not, at present, know why either the wind or the field should fluctuate on a time scale of hours during the night, but identification of which of these mechanisms is responsible for the negative correlation of $v_{\parallel}$ and $v_{\perp}$ would tell us which fluctuation requires explanation.

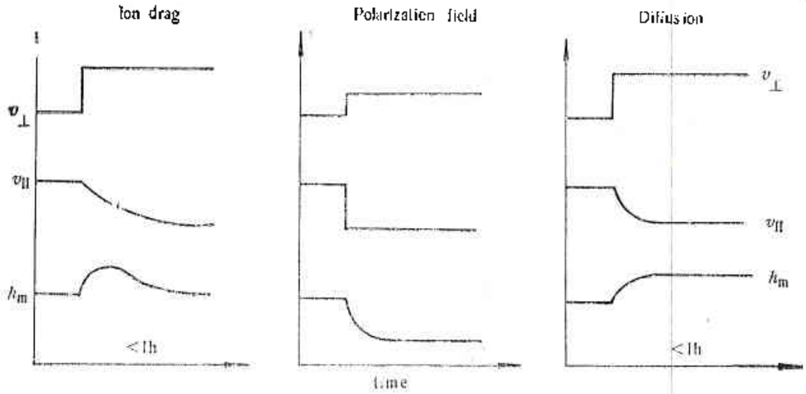

Fig. 6. Predictions of the three mechanisms concerning the correlation between change in F-layer height and change in the velocity components

The three mechanisms differ also in their predictions concerning the time lag between fluctuations in one velocity component and fluctuations in the other. The time resolution of the data is not good enough to permit a choice between the instantaneous response of the polarization field mechanism and the 15-min. response of the diffusion mechanism, but it is good enough to rule out the 1 to 2 hour response of the ion drag mechanism (see Fig. 2).

Finally, the three mechanisms differ in their predictions concerning the response of F-layer height to changes in ion drift velocities. These responses are compared in Fig. 6. According to the ion drag mechanism, a sudden increase in upward $v_{\perp}$ causes a rapid rise in F-layer height. Gradually ion drag increases the northward neutral wind and $v_{\parallel}$ ncreases downward. Increasing negative $v_{\parallel}$ drives the F-layer down again until, after several hours, the vertical components of $v_{\parallel}$ and $v_{\perp}$ are equal in magnitude but opposite in sign and the F-layer has returned to its original height.

According to the polarization field mechanism, a sudden downward increase in $v_{\parallel}$ is accompanied by a sudden upward increase in $v_{\perp}$. The mechanism is not perfect however; some current must flow, to return either through the E-region, the conjugate point ionosphere, or in a horizontal circuit through the F-region. Therefore the upward increase in $v_{\perp}$ is not as large as the downward increase in $v_{\parallel}$. As a result, the F-layer moves downward in response to a net downward component of the combination of $v_{\parallel}$ and $v_{\perp}$.

According to the diffusion mechanism, a sudden upward increase in $v_{\perp}$ causes the F-layer to rise. As it rises the downward diffusion velocity increases until a new balance is achieved, with $v_{\perp}$ upward, a smaller $v_{\parallel}$ downward, and the F-layer at a greater height than before. The important distinction between the polarization and diffusion mechanisms, therefore, is that the former predicts a positive correlation between F-layer height and $v_{\parallel}$ while the latter predicts a positive correlation between F-layer height and $v_{\perp}$.

We therefore compare, in Fig. 7, the measured F-layer height and the measured velocity components for the night illustrated in Fig. 2. The correlation between F-layer height and $v_{\perp}$ during the latter half of the night is striking. Unfortunately, there appears to be an equally strong correlation bet-

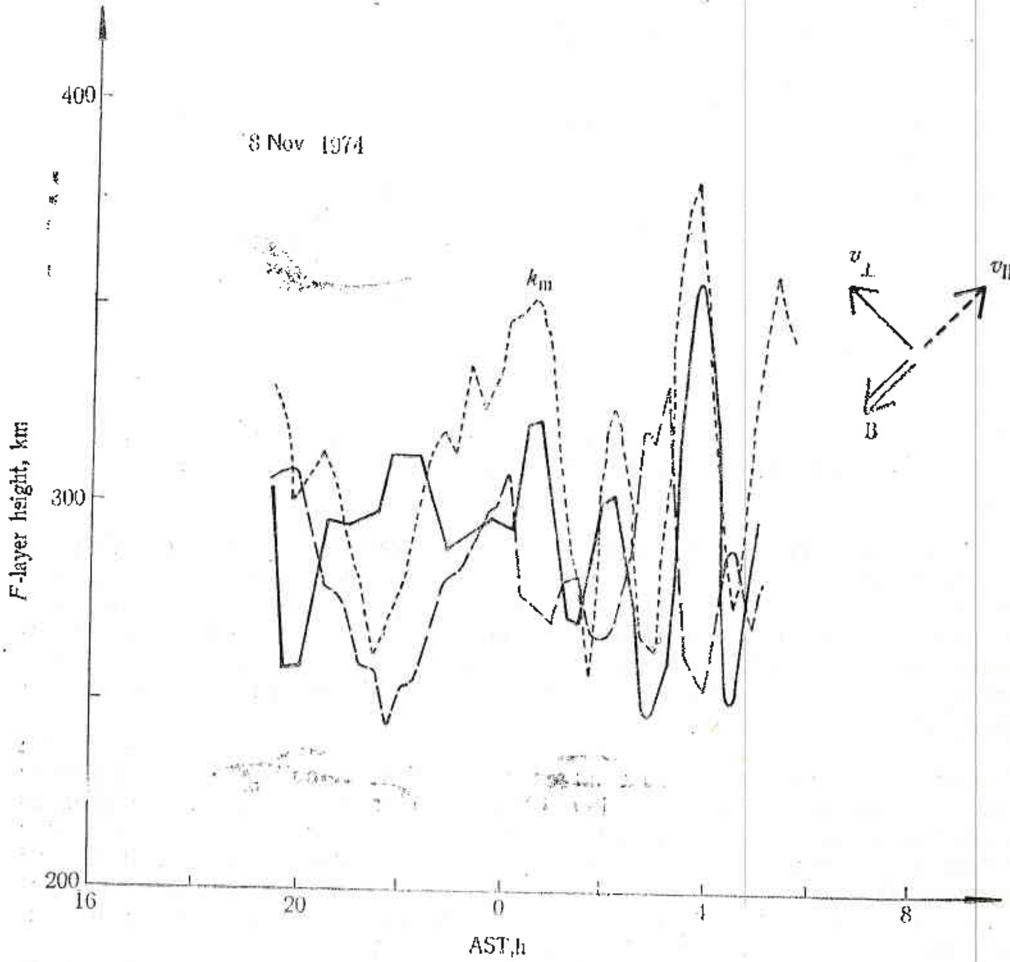

Fig. 7. Measured F-layer height (dotted line) compared with measured velocity components

ween height and $v_{\parallel}$ during the first half of the night. Examination of other nights of Arecibo data leads to the same result. The negative correlation of $v_{\parallel}$ and $v_{\perp}$ is nearly always well-developed, but the height of the F-layer correlates sometimes with one velocity component and sometimes with the other. Possibly both the polarization field and the diffusion mechanisms are contributing, with a relative importance that varies during the night for unkown reasons.

Suggestions for Further Research

It might be possible to distinguish between the polarization and diffusion mechanisms by comparing F-layer height changes at the two ends of a geomagnetic field line. Figure 8 indicates what the two mechanisms predict.

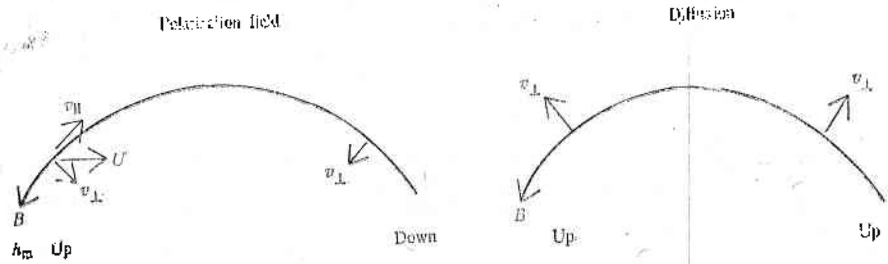

Fig. 8. Changes in F-layer height at the ends of a geomagnetic field line according to the polarization field and diffusion mechanisms

According to the polarization field mechanism, an equatorward wind at one end of the field line causes the F-layer to rise while developing a polarization field that causes a downward $v_\perp$. The polarization field, but not the wind perturbation, is transmitted to the conjugate point by the large field-aligned electrical conductivity of the topside ionosphere and protonosphere. Thus the F-layer rises in one hemisphere while falling in the other. The diffusion mechanism, on the other hand, predicts that the F-layer will rise at both ends of the field line under the action of the externally imposed electrostatic field. Changes in neutral wind are not involved in this mechanism. A study by Petelski (1972, 1973) indicates that F-layer height changes at conjugate points are generally correlated positively, but the correlation has not been investigated for stations at geomagnetic latitudes as low as that of Arecibo (30°N).

The considerations described in this paper have been entirely qualitative. Quantitative theoretical analysis of the various possible explanations for the negative correlation of $v_\parallel$ and $v_\perp$ combined with a careful comparison of theoretical predictions with data can be expected to clarify the situation. Scientists of any nation wishing to use the observing facilities of the Arecibo Observatory or existing Arecibo data to study this or any other problem in ionospheric physics (or in radio or radar astronomy) are invited to contact the Director of Observatory Operations, Arecibo Observatory, P. O. Box 995, Arecibo, Puerto Rico 00612, U.S.A.

Conclusion

For reasons that are not known either the wind or the electric field (or both) in the nocturnal F-region fluctuates in direction on a time scale of an hour or two. The resultant fluctuations in the externaly imposed ion drift velocity would have a very large effect on the structure of the nocturnal ionosphere were it not for the existence of an imperfectly understood negative feedback mechanism that causes a negative correlation between ion drift velocity components parallel and perpendicular to the geomagnetic field. This paper has called attention to the phenomenon and has offered several possible explanations, but sufficient work has not yet been done to provide a clear understanding of the mechanism.

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Корреляция между ветром и электрическим полем в естественной *F*-области

Дж. С. Дж. Уокер

(Резюме)

Измеренная скорость ионов в *E*- и *F*-областях показывает отрицательную корреляцию между параллельной компонентой электрического поля, которая представляет собой комбинированный эффект диффузии и меридионального ветра и перпендикулярной компонентой, которая вызвана зональным электрическим полем. Представлены объяснения этой корреляции. Одно из них связано с ионным увлечением, которое вызывает отклик ветра в *F*-области на изменение ионной скорости. Другой механизм предполагает, что ветер в *F*-области является причиной возникновения поляризационного электрического поля, которое вызывает дрейф. Дискутированы возможные следствия от действия отдельных механизмов.