Comparison between the ionospheric plasma drift and the motion of artificially induced irregularities as observed by HF backscatter radars

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ABSTRACT. Theories of striation generation by powerful HF waves state that the irregularities should convect with the plasma, without propagating through the medium. This prediction has been checked by observing, with the two SAFARI radars, the backscatter from striations generated in the *F*-region by the HEATING facility at Tromsø. The magnitude and direction of the Doppler velocity of the fluctuations is derived from the line-of-sight velocities measured by the two HF radar stations. The comparison between the electric field, derived from SAFARI, and the *E*-region current deduced from magnetometer data show that the magnitudes are well correlated. The directions of the velocity and this current are, however, not exactly antiparallel. Another comparison between the SAFARI *F*-region Doppler velocity and the *E*-region drift measured by STARE shows, on the average, a good agreement between the estimates. The experimental evidence therefore agrees with the theoretical suggestion that the irregularity motion should be the $\mathbf{E} \times \mathbf{B}$ drift.

Key words : ionosphere, backscatter, heating.

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INTRODUCTION

The Doppler shift of radar echoes from naturally produced field-aligned density fluctuations is commonly used to derive plasma drift velocities and electric fields in the high-latitude ionosphere (e.g. Greenwald, 1983). In the *E*-region, these irregularities are mainly generated by the two-stream instability and occur only when the drift velocity exceeds a threshold near the ion-acoustic velocity. Several studies have shown that the relationship between the Doppler velocity, measured by the radars, and the drift velocity is quite complex (St-Maurice and Schlegel, 1983; Nielsen and Schlegel, 1983). However, it is now well determined (Nielsen and Schlegel, 1985), though still not theoretically understood. Small-scale irregularities have also been studied in the high-latitude *F*-region with HF coherent radars (Hanuise *et al.*, 1981; Baker *et al.*, 1983). A recent comparison with incoherent scatter data has proved experimentally that their Doppler motion is, as predicted theoretically, characteristic of the *F*-region plasma drift (Villain *et al.*, 1985).

Backscatter from field-aligned irregularities, artificially induced in the *F*-region by means of a powerful radio transmitter radiating into the ionosphere, has also been observed for a decade (Gordon *et al.*, 1971; Thome and Blood, 1974). The signal is exclusively detected when the heating facility operates in *O*-mode polarization (Stubbe *et al.*, 1982). The absence of fluctuations associated with *X*-mode heating can be explained by the fact that an *X*-mode wave does not reach the altitude where the heating frequency equals the upper hybrid frequency and where the striations are generated (Das and Fejer, 1979). The Doppler

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spectra of the backscattered signal are narrow and usually exhibit a small Doppler shift (Hedberg *et al.*, 1983), which might be related to the ionospheric plasma drift, in agreement with the predictions of the various theories.

During one of the periods of operation of the heating transmitter at Tromsø, HF backscatter from striations produced in the *F*-layer was simultaneously observed from two stations located in Sweden and Finland. It was, therefore, possible to measure two components of the Doppler velocity of these irregularities and to derive the horizontal velocity vector. These observations have been used to study the motion of the heater induced irregularities and to verify the theoretical suggestion it is equal to the **E** × **B** drift. We review first the existing theories of striations generated by powerful HF waves. We show that these theories predict a purely growing instability, meaning that the striations should not propagate through the plasma. We present thereafter the experimental comparison between the Doppler velocity of the striations and the plasma drift measured by other methods, and we determine if the experimental facts contradict or agree with the theoretical conjecture.

THEORIES OF STRIATIONS

The excitation of *F*-region striations in HF heating experiments, giving rise to HF, VHF and UHF backscatter and to anomalous absorption of *O*-mode HF waves, has attracted wide theoretical attention. Theories to explain the generation of striations have been developed by Perkins (1974), Grach *et al.* (1977), Vaskov and Gurevich (1977), Das and Fejer (1979), and Inhester *et al.* (1981). The link between the occurrence of striations and of anomalous absorption has been established by Graham and Fejer (1976).

In the striation theories referenced above, the common understanding is that the generation mechanism is based upon nonlinear interaction between two HF waves, giving rise to differential heating and subsequent enhancement of the striations by pressure gradient forces. It is mainly the assumption about the nature and origin of these HF waves which discriminates the theories. The HF waves in question are (*a*) the electromagnetic heating wave; (*b*) Langmuir waves excited by the parametric decay instability; (*c*) Langmuir waves generated by linear mode conversion of the heating wave at the density gradient of the striations; (*d*) secondary Langmuir waves generated by scattering of the primary Langmuir waves (*b*) at the striations; (*e*) secondary Langmuir waves generated by scattering of the primary Langmuir waves (*c*) at the striations. The interaction mechanisms considered are (*b*) + (*d*) (Perkins, 1974), (*a*) + (*c*) (Grach *et al.*, 1977; Das and Fejer, 1979) and (*c*) + (*e*) (Inhester *et al.*, 1981). Trapping of Langmuir waves (*c*) within the depleted portion of a striation, which may be described as (*c*) + (*c*)′, is invoked by Vaskov and Gurevich (1977).

Two features are common in all of these theories. One is that only an *O*-mode heating wave can cause the striations. The other is that the striations excited are purely growing. This implies that the striations do not move with respect to the ambient medium. A diagnostic radio wave will therefore conserve its frequency, unless the medium as a whole is moving. The Doppler shift is thus expected to be a measure of the bulk motion.

EXPERIMENTAL CONDITIONS

The observations reported here were performed in October 1982 with the HEATING facility at Ramfjordmoen near Tromsø, Norway (Stubbe *et al.*, 1982) and the SAFARI (Scandinavian And French Auroral Radar Investigations) HF coherent radars installed at Lycksele, Sweden, and Oulu, Finland. The geometry of the experiment is shown in figure 1. During our campaign, the heating transmitter was generating an effective radiated power (ERP) of up to 280 MW. It was operated on 5.423 MHz with a transmission scheme illustrated in figure 2. The operation started at each full and half hour with successive 2 min *O*-, *X*-, and *O*-mode heating at full power. This was followed by a power variation during 10 min consisting of forty 5 % steps of increasing and decreasing power, each of them lasting 15 s, and finally by a 5 min full-power transmission.

The SAFARI radars can operate between 3 and 30 MHz, depending on the antenna system used for transmission. In Lycksele, an array consisting of 8 three-element Yagi antennas at the top of 18 m towers, spaced 12.5 m apart, was used. The antenna beamwidth was 10 degrees at 14 MHz, with the beam directed northwards in the direction of Tromsø. The array in Oulu was similar but consisted of only 4 antennas, spaced 15 m apart. The beamwidth was in this case nearly 20° with the center of the beam pointed towards Tromsø. The data were recorded on analog magnetic tapes and processed further to obtain the Doppler spectra at any range within the backscatter region. Both places are located approximately at 600 km from the heater, and the angle between the two radar lines of sight is 35°. Other radar parameters were a pulse length of 100 μs, giving a resolution of 15 km along the beam, and a pulse repetition frequency of 100 Hz. Most of the observations were performed on 14.2 MHz, and, therefore, the systems were sensitive to irregularities with wavelength of 10-m according to the Bragg condition. Some observations used a higher radar frequency but usually no echoes were detected on that frequency under the ionospheric conditions encountered during this campaign.

It is now generally accepted that the striations induced by HF heating are generated at the altitude where the heating frequency equals the upper hybrid frequency (e.g. Stubbe *et al.*, 1982). This altitude changes obviously with the electron density and the pump frequency. Large scale striations are found to grow upward and downward from the height of generation (Hedberg *et al.*, 1983). The density profiles derived from ionosonde data obtained at the same site as the heater show that the fluctuations detected by the HF radars remained in the range from 230 to 270 km during the whole period of HF radar observations. Measuring the range to the radar target, we find that the returns should be observed at elevation angles between 20 and 25°, and that some amount of refraction is needed for the wave to achieve perpendicularity to the magnetic field at these altitudes. A simple ray-tracing calculation, using the same density profiles, explained why backscatter was usually not observed on 21 MHz. A wave with this frequency is normally not sufficiently bent to experience perpendicularity to the magnetic field at any point of its path in the *F*-region.

The Doppler velocity, deduced from the HF radar observations, should have been directly compared with the plasma drift velocity measured by the EISCAT incoherent scatter radar. Unfortunately, this facility was unable to operate during the campaign. However, we were fortunate to have available other sets of data, which also provide an estimate of the ionospheric drift or electric field. Firstly, the electric field, deduced from the radar observations, has been compared to the *E*-region current, derived from the magnetograms recorded at Tromsø and Kiruna. Secondly, since we actually wanted to know the drift rather than the currents, we have thus compared the SAFARI Doppler velocity with the drift velocity measured by the STARE radars in the *E*-region.

MAGNETIC OBSERVATIONS

The magnetograms recorded at both Tromsø and Kiruna were available for the whole observation period. The digitised magnetograms from Kiruna have been systematically used to derive an equivalent current at electrojet heights. Their validity to represent the state of the ionosphere at the location of the heater has been checked by comparing them with the analog magnetogram recordings from Tromsø. These have not been directly used in our study because of their more laborious processing. The computation is performed by applying Ampere's law to the simple model of an uniform sheet current located at an altitude of 100 km. It is also assumed that Hall currents give the dominant contribution to the magnetic effects seen on the ground and the observed variations were not appreciably influenced by the magnetic field due to induced currents (Küppers *et al.*, 1979). Several problems are associated with this method. Firstly, the magnetograms require a simplifying model to yield the ionospheric currents. Secondly, the measurements are performed at a distant location from the volume probed by the radars and, finally, the currents are not uniquely related to the electric field which is the parameter of interest.

An example of the comparison between the equivalent current and the radar data is presented in figure 3. Such a comparison is possible when the heater transmits *O*-mode, as no irregularities are generated during *X*-mode heating. When data are absent during periods of *O*-mode heating, the SAFARI radars were not operating. To derive the electric field from the Doppler velocity, we assume that the electron drift measured in the *F*-region is a pure **E** × **B** drift, and that the coupling to the *E*-region through the magnetic field lines is perfect. The comparison demonstrates that the radars detect low (high) electric fields when the magnetograms show weak (strong) currents, as could be expected. Moreover, the variations in the magnitude of the two parameters are well correlated while the agreement is not so good between their direction. As a consequence of our hypotheses, the electric field and the current should be perpendicular to each other, but the current is deviated slightly northwards from east when the electric field is due north, or the **E** × **B** drift is due west, as from 12 : 40 to 13 : 00 UT in figure 3. When the electric field is low, as around 12 : 20 UT, the discrepancy is worse. In this case, the values found for the direction of the electric field exhibit a great variability due to the limited resolution in the measurement of the radial velocity from each radar station (8 m/s). A slight variation in either one of the two components has under these circumstances a great influence on the direction of the resulting velocity vector while it does not so strongly influence on the computed magnitude of the drift.

In agreement with previous results (Hedberg *et al.*, 1983), we find that most of the spectra which were observed during the October 1982 measurement campaign exhibit small Doppler shifts. We have, nevertheless, measured higher drifts on a few occasions which, for example, is demonstrated in figure 3, when the electric field reaches the value of 20 mV/m, corres-

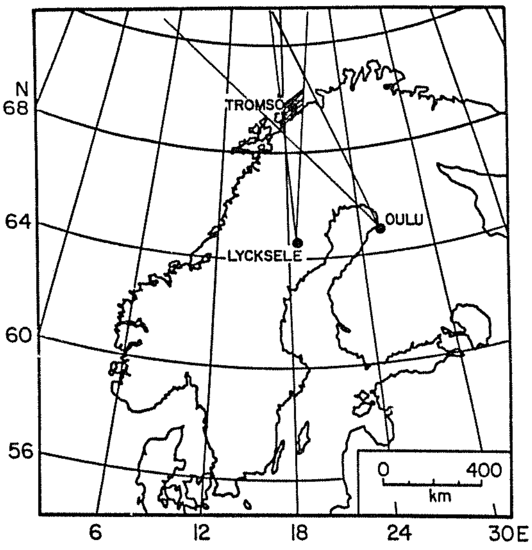

Figure 1
Map of Scandinavia showing the location of the HEATING *facility near Tromsø and the geometry of the* SAFARI *observations from Lycksele and Oulu.*

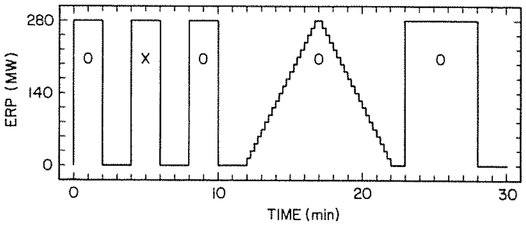

Figure 2
Heating transmission scheme, repeated every full and half hour. The power variation from minute 12 *to* 22 *consists of forty* 5 % *steps, each lasting for* 15 s.

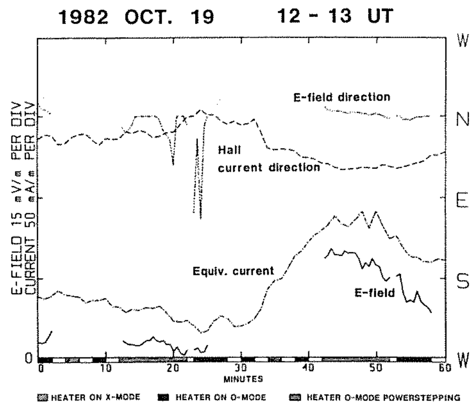

Figure 3
Comparison of the electric field, derived from the SAFARI *data, with the equivalent current, derived from the Kiruna magnetograms for October* 19, 1982. *The magnitude variations are well correlated, while the directions are not exactly perpendicular to each other, as they should be in an assumed Hall current case.*

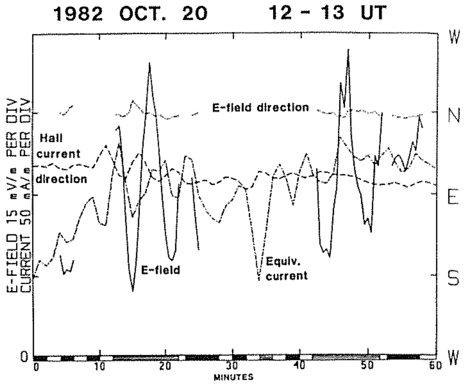

Figure 4
Same as figure 3 *for October* 20, 1982. *Note the large amplitude pulsation seen in the* SAFARI *data.*

ponding to a drift velocity of 400 m/s. Another noticeable exception concerns the data obtained on October 20, 1982 shown in figure 4. The periodic oscillations, which are clearly defined in the radar data, have an amplitude of 45 mV/m for the derived electric field, corresponding to a drift velocity of 900 m/s, and a period of 5 min which is in the period range of *Pc* 5 pulsations observed at the latitude of Tromsø (Samson and Rostoker, 1972). The maximum magnitude of the electric field is up to 60 mV/m, or a Doppler velocity up to 1200 m/s. The electric field data are again well correlated with the superimposed magnetic data in figure 4. Variations with shorter time scales are seen on the magnetograms. Their absence in the radar data is probably due to the poorer temporal resolution (30 s) of the latter. The electric field measured by the radars is again northward on this day, or the Hall plasma drift is westward. The *E*-region current is again slightly displaced from east towards north, but the deviation from perpendicularity between the electric field and the equivalent Hall current remains less than 10°. It is interesting to note that no detectable irregularities are present in the *F*-region when the heater is either transmitting in *X*-mode or not operating, in spite of the fact that, as can be inferred from the magnetic recording, the velocity continues to exhibit large amplitudes and strong variations. Natural density fluctuations which are often excited in the high-latitude *F*-region were obviously not generated at the time of our observations.

OTHER RADAR OBSERVATIONS

The Doppler velocity measured in the *F*-region by the HF radars has also been compared with the estimates of the drift velocity derived by the STARE system using backscatter from naturally created irregularities in the *E*-region. Nielsen and Schlegel (1983, 1985) have shown that the Doppler velocities measured by STARE are limited in magnitude to near the ion-acoustic velocity. This means that the fluid and kinetic theories are inadequate to account for the relationship between Doppler and electron drift velocities, and that a new approach, the ion-acoustic approach, should be used to interpret the Doppler data. Then, the STARE estimates of the drift velocity are in good agreement with EISCAT incoherent scatter measurements (Nielsen and Schlegel, 1985).

The comparison between STARE and SAFARI data has been performed for October 20, 1982 and is plotted in figure 5. The STARE Doppler velocities have been interpreted in the ion-acoustic approach to yield estimates of the electron drift velocity in the *E*-region. The data are averaged over 18.5° to 20.0° E in longitude and 69.6° to 70.0° N in latitude to obtain a spatial resolution similar to SAFARI. The temporal resolution is 30 s for SAFARI and 40 s for STARE. The two estimates of the drift direction agree fairly well, within less than 15 degrees. Both indicate a westward drift, or northward electric field. The STARE data nevertheless exhibit variations with an amplitude larger than observed in the SAFARI data. The estimates of the drift magnitude also exhibit a similar behaviour, even if a few discrepancies can be noted. For example, the fluctuations observed from 12 : 13 to 12 : 25 UT have the same measured period by the two radar systems (5 min), but the maximum value of the drift is higher for the STARE data (by 10 %). Similarly, the minimum occurring near 12 : 21 UT is much more pronounced in the SAFARI data, while the maximum seen at 12 : 47 UT with SAFARI is not present in the STARE data.

Having compared data from the HF radars with the equivalent current in figure 4 and with the STARE drift velocities in figure 5, we have found it interesting to compare the latter two measurements which are both associated to *E*-region phenomena. We have therefore plotted, in figure 6, the horizontal component of the Tromsø magnetogram, digitised in steps of 1 min, and a predicted magnetogram calculated from the STARE data. The derivation is performed by integrating the current from 68.3° to 71.1° N in latitude, and from 16.0° to 23.0° E in longitude assuming homogeneous conductivity. As can be seen, the agreement is very good between the two curves. Furthermore, both Kiruna and Tromsø magnetograms are nearly identical. This similarity is a further proof of the validity of the hypotheses made for the derivation of the equivalent current from the magnetograms.

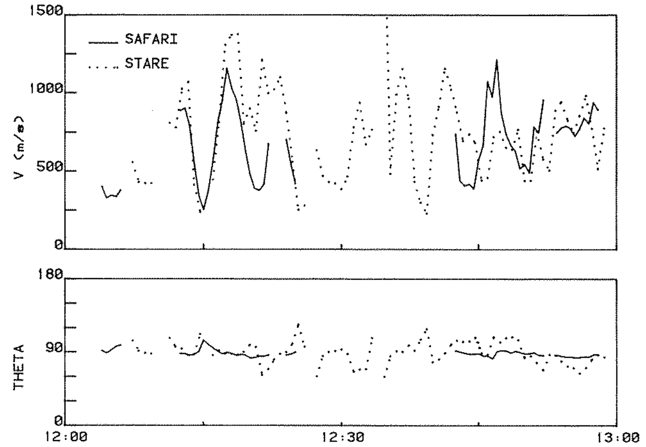

Figure 5
Comparison of the SAFARI *and* STARE *estimates of the drift velocity for October* 20, 1982. *On the average, the magnitudes and the directions are within* 10 % *and* 3 % *of each other, respectively.*

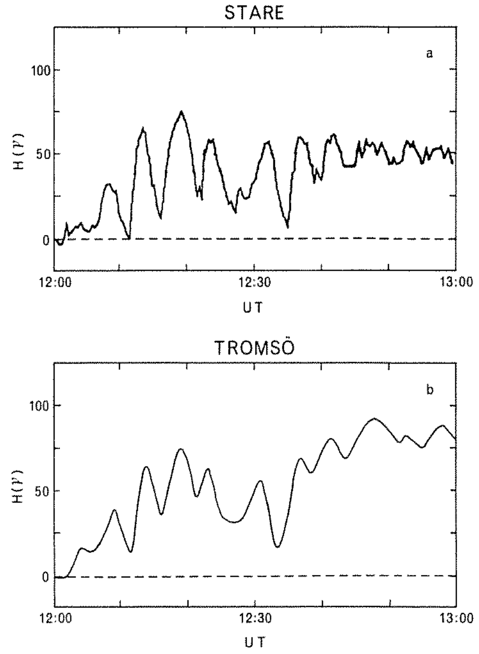

Figure 6
Variations of the horizontal component of the magnetic field as predicted from STARE *data (a), compared to the digitised* H *trace of the Tromsø magnetogram (b).*

DISCUSSION

The previous comparisons show that the Doppler velocity of artificially induced irregularities is in basic agreement with the plasma drift deduced from both STARE and magnetometer data. Before concluding on the propagation or convection of the striations, we will, nevertheless, study possible reasons for the discrepancies which exist between the SAFARI data on one side and the equivalent current and the STARE velocity data on the other.

The fundamental difference between the various observing methods lies in the altitude where the observations are performed. The HF data are obtained from striations mainly located in the *F*-region, around 250 km, while both STARE and magnetic data are due to phenomena occurring in the *E*-region, around 110 km. It is well known, from the equation of motion of charged particles in the ionosphere, that the *F*-region plasma drift is exclusively controlled by the electric field and is orthogonal to it. If the Doppler velocity is equal to the plasma drift velocity, it will, therefore, also be related to the electric field. In the region below 160 km, several additional terms must be considered in the equation of motion, such as terms due to a Pedersen current parallel to the electric field, and the effect of a neutral wind.

The major discrepancy between the equivalent current and the HF Doppler data is found in the direction of the motion. Excepting the periods of very low velocities, when the radar measurements of the direction are doubtful, the electric field, derived from the radar data, and the current are not perpendicular to each other, as they should be with the hypothesis of a Hall current. The presence of a Pedersen current, rotating the total current towards the direction of the electric field, could explain this observation. However, the magnetic effects of such currents are cancelled by the effects of field-aligned currents (e.g. Fukushima, 1976) if the conductivity is uniform. It is therefore more likely that the difference is due to a neutral wind, the effect of which has been neglected in the analysis of the magnetic data. The velocity vector would then be rotated, in a plane perpendicular to *B*, by an angle which depends on the direction of the neutral motion and on the ratio of Hall to Pedersen conductivities at any given altitude. Finally, we should mention that the magnetic observations are also responding to possible temporal changes of the electron density profile.

A similar reasoning applies to the comparison between SAFARI and STARE data. Both facilities measure the Doppler velocity of the density fluctuations, and their estimates of the drifts are therefore not prone to the uncertainties related to the height integration and temporal variations of the electron density or the conductivity, which are encountered in the derivation of the equivalent current. In the *E*-region, STARE observes the irregularity drift which is perpendicular to the electric field. The agreement between the magnitude and the direction, within less than 15°, of the drift as measured by SAFARI is therefore an indication that the irregularities convect with the plasma.

One of the most obvious explanations to the discrepancies between the drift magnitudes measured by STARE and SAFARI is that the two radars do not always detect irregularities at the same geographical location, or more exactly, that the *E*- and *F*-region observations are not performed along the same magnetic field lines. The artificially induced irregularities are generated inside the modified volume, which is located overhead Ramfjordmoen (69.6° N) and has an horizontal extent of the order of 70 km (Hedberg *et al.*, 1983). If we take into account the effect of the magnetic field, this region is in fact slightly displaced towards north. An exact knowledge of the location of the perpendicularity between the HF radio wave and the magnetic field would be necessary to improve the precision in locating the observations. This would require a very precise ray tracing calculation, using real electron density data, which were not available during our campaign. The location of the STARE observations is known more precisely, as the path of the 140 MHz radio wave is only negligibly modified by the ionosphere. The data that have been used in our study have been spatially averaged in a box of 50×50 km^2 at an altitude of 110 km at the latitude of 69.8° N. Due to the inclination of the magnetic field, the corresponding field lines are traversing the *F*-region about 30 km to the south, i.e. inside the modified region. There is, therefore, no large geographical difference between the *E*-region measurements performed with STARE and the *F*-region data collected with SAFARI. Nevertheless, we cannot rule out that the region giving the strongest backscatter for one radar is not exactly colocated with the region giving the strongest return for the other radar.

Another explanation to the discrepancies seen in figure 5 is related to the calibration of the STARE data with the ion-acoustic approach to derive the plasma drift. The validity of the treatment has been proved experimentally for large data bases (Nielsen and Schlegel, 1985), but some uncertainty appears when the method is applied to individual data points.

The data that are available for our comparison are not sufficient for a more quantitative analysis on the discrepancies between the various experimental data sets. As a matter of fact, the differences are minor when compared with the basic agreement between the results of the three methods. We, therefore, conclude that the experimental evidence does not contradict the theoretical conjecture that the artificially induced irregularities convect with the plasma without propagating through the medium. Thus, the Doppler motion of artificially induced irregularities in the *F*-region do depict the drift of the bulk plasma due to the ionospheric electric field.

CONCLUSION

In this paper we have presented the first comparisons between the plasma drift and the Doppler motion of *F*-region irregularities, artificially induced by ionospheric heating. The agreement between the various experimental data sets shows that the striations convect with the bulk plasma in the *F*-region and do not propagate through the ionosphere. Furthermore, the striations can be used as a tracer of the plasma motion and, consequently, of the ionospheric electric field. Such measurements are possible at velocities ranging from a few m/s to at least 1200 m/s and do not require the presence of natural irregularities in the *F*-region.

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