On the Determination of Vertical Profiles of Ionospheric Velocity from Digital Ionosonde Measurements

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ABSTRACT

The so-called ionosonde drift technique of determining ionospheric velocities from angle of arrival and Doppler shift measurements is now well established. In the standard digital ionosonde technique, commonly called the drift mode, the velocity of the F region is usually determined without detail of its height variation. In this paper, we report the measurement of the height variation of the velocity profile through the E and F regions at Casey, Antarctica. In the standard analysis, velocities are interpreted as if they arose from mirror reflectors in free space. According to Dyson (1975), this gives valid results when the ionosphere moves with a constant bulk velocity. However, the velocity may vary through the ionosphere and the purpose of this paper is to discuss the affect of such variations on the derivation of the drift velocity. A simplified inversion routine is developed enabling average drift velocity profiles to be corrected for the velocity variation with height. The procedure has been applied to an average daytime velocity height profile obtained at Casey during a four day campaign in March 1996. The drift velocity component perpendicular to the magnetic field direction was found to increase rapidly through the bottom of the E region from a value of 170 m/s at 95 km to a peak value of over 800 m/s at 110 km. It then dropped rapidly to around 700 m/s at 115 km and remained in the range 600-700 m/s up into the F region. The corrected values were about 10% larger in the lower E region but the difference is not important because of the very rapid change in velocity with height. In the F region the correction was 3% or less. At 110 km where a narrow, intense velocity peak occurred, the correction was 20%, dropping to 7.5% near 150 km. Even in the region of largest correction, the change in the shape of the velocity profile was modest. The results support the interpretation of drift velocities as reflection point velocities (at least within ~5-10%) except in regions of extreme velocity change and certainly support the routine interpretation of high-latitude measurements of the F-region velocity as a bulk convection velocity.

1. Introduction

The advent of digital ionosondes has brought two new major developments to ionospheric sounding. The first is automatic scaling of echo traces to derive ionospheric parameters and true height profiles of electron density. The second is the combination of angle of arrival and Doppler shift measurements to routinely determine ionospheric motions.

The determination of true height profiles involves inversion of the equation

$$h' = \int_o^{h_R} \mu' \, dh \qquad (1)$$

where h' is the virtual height,

μ' is the group refractive index,

h_R is the height of reflection.

Sophisticated inversion methods have been developed to account for various difficulties that arise in, for example, determining a starting height and accounting for a valley between the E and F regions (e.g. Titheridge, 1985; Gamache et al., 1992).

The Doppler shift, Δf, of a radio signal transmitted at frequency f, is given by Bennett (1968) as

$$\Delta f = -\tfrac{f}{c}\tfrac{dP}{dt} = -\tfrac{f}{c}\left(\int_a^b \tfrac{\partial\mu}{\partial t}\cos\beta\, ds + [\mu\hat{\boldsymbol{p}}.\boldsymbol{v}]_a^b\right) \qquad (2)$$

where μ is the phase refractive index,

β is the angle between the wave normal and ray directions,

$\boldsymbol{v}$ is the velocity at the ray end points, a and b,

$\hat{\boldsymbol{p}}$ is a unit vector in the wave normal direction,

ds is an element of arc length,

c is the speed of light in free space.

If the Doppler shift is due to a reflector in free space ($\mu = 1$) returning a signal to its origin, then equation (2) reduces to

$$\Delta f = -\frac{f}{c}\frac{dP}{dt} = -\frac{2f}{c}\boldsymbol{v_R}.\boldsymbol{\hat{p}} = -\frac{2f}{c}(\boldsymbol{\hat{v}_R}.\boldsymbol{\hat{p}})v_R \qquad (3)$$

where $\boldsymbol{v}_R$ is the velocity of the reflector and $\boldsymbol{\hat{v}}_R$ is the corresponding unit vector. $\boldsymbol{\hat{p}}$ is the unit vector in the ray direction. The factor of 2 comes about because the ray path is from the transmitter to the reflector and back again. This result incorporates Pfister's result for a reflector in free space moving horizontally (Pfister, 1971).

Now $\boldsymbol{v_R}.\boldsymbol{\hat{p}}$ implies the component of velocity along the angle of arrival direction. Hence this component of the reflector's velocity can be determined from angle of arrival and Doppler shift measurements. If at least three echoes at different angles of arrival are obtained from reflectors moving with the same velocity, then the full velocity vector of the reflectors can be determined.

Dyson (1975) showed that equation (3) is not restricted to just the case of a reflector in free space but applies to ionospheric echoes returned to a transmitter site when the ionosphere moves with a single bulk velocity. This point was further developed by Bennett and Dyson (1993) who showed that the result may be regarded as a generalisation of Pfister's result for a moving reflecting surface in free space (Pfister, 1971). In practice then, digital ionosonde measurements are used to determine the ionospheric motion by applying equation (3) to concurrent measurements of Doppler shift and angle of arrival of many near-vertical oblique echoes (e.g. Scali et al., 1995). The technique is now commonly referred to as the 'drift mode' and the velocity so obtained, the 'drift velocity'. This convention is adopted here and we specifically use the term 'drift velocity' for velocities derived using equation (3). That is, if the ionosphere moves with a single bulk velocity then the measured drift velocity, $v_D = v_R$. Of course it should be remembered that the motion of the ionosphere is affected by a number of processes, such as convection driven by electric fields, passing TIDs, and coupling of the neutral wind. They will all affect the drift velocity though in certain situations one may dominate.

Digital ionosondes have the capability of observing the variation of ionospheric velocity with height by determining the drift velocity as the transmitting frequency is swept in a similar way to that used to obtain a swept-frequency ionogram. However, obtaining a good quality velocity determination using the drift technique requires transmission on a single frequency for at least several seconds. Consequently, constraints on the use of the radio spectrum, and the amount of data processing involved, mean that usually only a single velocity is obtained in routine drift determinations of ionospheric velocity.

In spite of these constraints, it has been possible to run some special campaigns at Casey Station, Antarctica, to obtain the drift velocity as a function of height through the bottomside ionosphere (Parkinson et al., 1997). A feature of the results is that the velocity varies rapidly with height through the E region. Thus the assumption of a single, uniform ionospheric velocity, a requirement for strict validity of equation (3), is violated. The significance for the interpretation of the frequency profiles is examined here.

2. Observations

The results presented were obtained with a Lowell Digital Portable Sounder-4 (DPS-4) operated at the Australian Antarctic Station at Casey (66.3^0 S, 110.5^0 E, -80.8^0 CGM latitude). Whilst operation of other digital sounders may differ in some respects from the DPS-4, the general principles of relevance here are the same.

The DPS-4 (Haines and Reinsich, 1993) uses an array of four receiving antennas and when operated in the drift mode a time series of the complex amplitude is obtained at each antenna and for each frequency of operation. Each time series is converted to a Doppler frequency spectrum enabling signals with the same Doppler shift to be identified at each antenna. The relative phases of these signals then gives the angle of arrival. Hence equation (3) can be applied to each Doppler signal to determine the ionospheric drift velocity. In practice the ionosphere is not always a smooth reflector and multiple echoes are observed simultaneously but with different Doppler shifts and the ionospheric drift velocity is determined by the least-squares application of equation (3). Details of this approach have been given by Scali et al. (1995) who have implemented the technique as part of the standard analysis software of the DPS-4.

At a high-latitude station such as Casey, the ionosphere is often very irregular and many echoes are observed. This improves the accuracy of the drift velocities. Furthermore, the F-region motion at high latitudes is dominated by convection, simplifying the interpretation of the drift velocities. Comparisons with other techniques (Scali et al., 1995; Grant et al., 1995; Smith et al., 1998) have shown that the drift-mode technique is reliable at high latitudes.

During January - March 1996 several special experimental campaigns were conducted using the Casey DPS-4 to compare drift velocities in the E and F regions and to obtain vertical profiles of the drift velocity. The detailed results of those campaigns are discussed elsewhere (Parkinson et al., 1997). Of relevance here is the observation that the drift velocity varied with height, particularly through the E region, and the consequence of this on the interpretation of drift velocities is discussed in detail.

As convection dominates at Casey it is convenient to consider the drift velocity component perpendicular to the magnetic field lines and this component will be referred to here as the convection velocity. Since the dip angle at Casey is 82^0, the convection velocity is not significantly different from the horizontal velocity component. Figure 1 shows an average daytime velocity profile for the convection velocity derived by applying equation (3) to measurements obtained within 3 hours of magnetic noon on days 71-74. The corresponding average true height profile is also shown. Further details on the analysis methods used to obtain these profiles were given by Parkinson et al. (1997).

Note that in Figure 1 the velocity increases rapidly by several hundred m/s between 95 and 110 km. The sharp enhancement of velocity near the E layer peak is an artifact caused by averaging over the non-stationary random data samples. The small number of echoes detected from the E layer peak occurred during intervals when the convection velocity was unusually large. Within the F region the velocity remains reasonably steady up to the height of the F2 peak, with a value in the range 650-700 m/s. Dyson (1975) showed that the drift velocity derived using equation (3) will underestimate the velocity at the reflection height if the velocity in the ionosphere increases with height. That is, the drift velocity will be less than the true velocity at the reflection height. In the simple, illustrative example in Dyson (1975), in which the vertical velocity varied linearly with height from a value of zero at the base of the ionosphere, the drift velocity was half the value of the true velocity at the reflection point. Hence we can anticipate that the drift velocities between 95 and 110 km will be underestimates of the velocities at those heights. If it were real, the sharp peak in velocity at 110 km would also affect the determination of velocities above that height. However, well into the F region there is little variation in velocity with height so the drift velocities should be accurate there. This is examined quantitatively in the next section.

3. Analysis

The aim is to determine the effect of the height variation of velocity on the derivation of velocity height profiles using equation (3). In principle an inversion procedure based on individual measurements could be developed using equations (1) and (2) to determine both the electron density and velocity profiles. However, since echoes are received over a range of angles of arrival, three-dimensional ray tracing would be needed to provide a completely general solution to the problem. Nevertheless it is profitable to proceed in a slightly less general way.

First consider the inversion of equation (1) to obtain electron density profiles. The methods in common use assume that the ionosphere is horizontally stratified. This is rarely strictly true but the consequential errors in determining the layer structure of the ionosphere are considered to be small, particularly when compared to the likely errors associated with determining the ionospheric base height and E-F valley structure. Inversion in the presence of complicated ionospheric structures has been attempted; for example, Dyson and Benson (1978) determined the electron density variation along ionospheric bubbles by inverting topside ionogram echo traces arising from field-aligned propagation. In that instance they assumed that the electron density contours were perpendicular to the field line within the central part of the bubble itself.

The application of equation (2) to determine ionospheric velocity vectors depends in fact, on off-vertical reflections occurring. The reason is that the horizontal component of velocity will not contribute to the Doppler shift of a ray propagating at vertical incidence in a horizontally stratified ionosphere, but it will contribute to the Doppler shift of off-vertical rays. Hence the inversion of equation (2) is inherently more difficult because off-vertical rays must be considered.

3.1 Reflection from the $\mu = 0$ contour

To simplify the problem, we assume that for each echo the tilt of the refractive index contours along the ray path is not significantly different to that at the reflection point. If we also ignore the effect of the Earth's magnetic field on the refractive index ($\alpha = 0$), then the ray paths will not deviate significantly from straight lines tilted to the vertical. Since the ionosonde is stationary on the surface of the Earth where $\mu = 1$ and, since under the conditions assumed reflection takes place where $\mu = 0$, equation (2) becomes

$$\Delta f = -\tfrac{f}{c}\tfrac{dP}{dt} = -\tfrac{2f}{c}\int_S \tfrac{\partial\mu}{\partial t} ds \ . \qquad (4)$$

Suppose the change in μ is due entirely to the motion of the ionosphere, then we may write $\partial\mu/\partial t = v_x(\partial\mu/\partial x) + v_y(\partial\mu/\partial y) + v_z(\partial\mu/\partial z)$ so that, noting that in order to be reflected, μ decreases overall as s increases, equation (4) becomes

$$\Delta f = -\tfrac{2f}{c}(\boldsymbol{\hat{v}}\boldsymbol{.}\boldsymbol{\hat{p}}) \int_0^1 v\, d\mu \qquad (5)$$

where $\hat{\boldsymbol{p}}$ is a unit vector in the ray direction.

Hence in this special case the application of the drift technique will yield a drift velocity $v_D = \int_0^1 v\, d\mu$ rather than $v_D = v_R$ as is the case for motion with a single bulk velocity.

We can now use equation (5) to determine the velocity at the reflection height provided the ionospheric electron density profile is known (i.e. the spatial variation of μ under the assumptions made). Following the procedure generally used in the inversion of equation (1) to obtain the electron density profile, we regard the ionosphere as divided into a number of slabs. In this case the slabs are defined by the plasma frequencies at the top and bottom of the slab, and within the slab the true velocity is assumed to vary linearly with the refractive index. Hence the velocity variation in the *n*th slab is given by

$$v_n = v_{bn} + k_n(\mu - \mu_{bn}) \qquad (6)$$

where $k_n = \frac{v_{tn}-v_{bn}}{\mu_{tn}-\mu_{bn}}$ is a constant for the n^{th} height interval,

v_{bn} and v_{tn} are the velocities at the bottom and top of the n^{th} slab respectively,

μ_{bn} and μ_{tn} are the refractive indices at the bottom and top of the n^{th} slab respectively.

Hence

$$v_D = \int_0^1 v\, d\mu = \sum_{n=1}^{N} \int_{\mu_{tn}}^{\mu_{bn}} v_n\, d\mu \text{ , since } \mu_{tn} < \mu_{bn} \qquad (7)$$

where N is the number of slabs from the base of the ionosphere to the reflection point.

Evaluating the integral in equation (7) with the aid of equation (6) leads to

$$v_D = \tfrac{1}{2}\sum_{n=1}^{N}[(v_{bn} + v_{tn})(\mu_{bn} - \mu_{tn})] \qquad (8)$$

Suppose the drift velocity is measured at a series of *o*-ray frequencies, f_1, f_2, ... f_N..... f_M, to give a series of drift velocities, $v_{D1},\ v_{D2}, ...v_{DN}.....v_{DM}$. Let the series of frequencies divide the ionosphere into slabs bounded by the same set of plasma frequencies and let the true velocities at the reflection heights of these frequencies be $v_{R1},\ v_{R2}, ...v_{RN}.....v_{RM}$. The frequency f_1 is reflected at the top of the first slab and from equation (8) we have $\mu_{b1} = 1$ and $\mu_{t1} = 0$, so

$$v_{R1} = 2v_{D1} - v_B \qquad (9)$$

where $v_B = v_{b1}$ is the velocity at the base of the ionosphere.

For the frequency f_2 equation (8) becomes

$$v_{D2} = \tfrac{1}{2}[(v_B + v_{R1})(1 - \mu_{b2}) + (v_{R1} + v_{R2})(\mu_{b2})], \text{ since } \mu_{t1} = \mu_{b2} \qquad (10)$$

giving $$v_{R2} = \frac{2v_{D2} - (v_{R1} + v_B)(1 - \mu_{b2})}{\mu_{b2}} - v_{R1} \qquad (11)$$

Similarly for the N^{th} frequency,

$$v_{RN} = \frac{2v_{DN} - \sum_{n=1}^{N-1}[(v_{R(n-1)} + v_{Rn})(\mu_{bn} - \mu_{tn})]}{\mu_{bN}} - v_{R(N-1)}. \qquad (12)$$

Hence the method can proceed step by step using the drift velocity measurements to determine the height profile of the velocity. However, if the slabs represent small steps in μ, the denominator term, μ_{bN}, becomes small and the process becomes sensitive to errors. As a consequence, in application to the velocity profile measurements reported here, this method proved unstable so an alternative procedure was adopted, which used the measured values of v_D as the starting profile for an iterative process.

As a general starting point, suppose $v_E(\mu)$, an estimate of the velocity profile is known, then the true velocity profile may be written as

$$v_R(\mu) = v_E(\mu) + \varepsilon(\mu), \quad \text{where } \varepsilon(\mu) \text{ is the error.} \tag{13}$$

It follows from equation (7) that

$$v_D = \int_0^1 (v_E + \varepsilon)\, d\mu = v_{DE} + \int_0^1 \varepsilon\, d\mu \tag{14}$$

where v_{DE} is the drift velocity calculated using equation (7) applied to $v_E(\mu)$.

Now at each radio frequency we want to determine the velocity at the reflection point and hence it is convenient to write $\Delta\varepsilon(\mu) = \varepsilon(\mu) - \varepsilon_R$ so that

$$v_D = v_{DE} + \varepsilon_R + \int_0^1 \Delta\varepsilon\, d\mu \tag{15}$$

Then to a first approximation, $\varepsilon_R = v_D - v_{DE}$ with the error given by the integral term in the above equation. Now there is no *a priori* guarantee that this error term will be small, but it will obviously be small in regions where the velocity does not change rapidly near the reflection height. Figure 1 shows that this occurs over most of the F region. The error term will also be small even if the velocity changes rapidly provided the change in μ over the corresponding height range is small. Hence the error term will be small for frequencies reflected in the F region, despite the rapid change in velocity in the lower E region.

So, v_D is the set of drift measurements, v_{DE} can be calculated, hence ε_R can be estimated for each v_D using equation (15), and equation (13) can then be used to determine each v_R. If necessary the process can be iterated using the newly estimated velocity profile. Since $v_D = v_R$ in the absence of velocity shears, we can take the measured v_D profile as the initial profile.

This procedure has been applied to the average convection velocity profile shown in Figure 1. The results shown are for a single application of the procedure as a second iteration changed the velocities by only a few percent or less. The corresponding average true-height profile, also shown in Figure 1, has been used to specify radio frequencies and to convert the $v(h)$ profile in Figure 1 to $v(\mu)$ profiles. The velocity at the bottom of the ionosphere was taken to be that measured at the lowest height. The corrected velocity values are shown by open squares in Figure 1. It is apparent that while the corrected velocities in the lower E region are higher (typically 10%) than those measured, the velocity is changing so rapidly with height that the change in the velocity profile is small. The major difference occurs near 110 km where there is a pronounced, narrow peak in the velocity profile. As pointed out earlier, this peak is an artifact of the data. Nevertheless, it is still interesting to examine the effect such a feature has on the determination of velocities. We note that the value of the peak velocity is 20% greater than the corresponding drift velocity and the presence of this peak affects the measurements at heights immediately above, and up to approximately 150 km. Once this altitude is reached, the correction to the drift velocity is less than 7.5%, and is no more than a few percent in the F region.

Overall then, the analysis shows that the derivation of ionospheric drift velocities using equation (3) gives reasonably accurate values in the F region. Even in the lower E region where the velocity changes rapidly with height, drift velocities can be considered accurate since even if they are in error by 10-15% at the actual reflection height, they give the velocity at a height within a kilometre or so. The data examined showed a narrow velocity peak near 110 km altitude which caused the drift velocities to be as much as 20% below the velocity at the corresponding reflection points. This velocity peak had a significant influence on the drift velocities up to about 150 km altitude causing the magnitude of the velocities at the reflection points to be underestimated. However, the velocity profile shape was not affected significantly.

3.2 Reflection from below the $\mu = 0$ level.

The above analysis assumed that echoes arose from reflections at the $\mu = 0$ level. Of course echoes may arise below this level so we now consider this situation. Suppose an echo occurs from an irregularity where the background refractive index is μ_I. Then using equation (2), equation (5) is replaced by

$$\Delta f = -\tfrac{f}{c}\tfrac{dP}{dt} = -\tfrac{2f}{c}(\hat{\boldsymbol{v}}.\hat{\boldsymbol{p}})\left(\int_{\mu_I}^{1} v\,d\mu + \mu_I v_I\right) \quad . \tag{16}$$

Hence we may write

$$v_D = \int_0^1 v_T\,d\mu - \int_0^{\mu_I} v_T\,d\mu + \mu_I v_I \tag{17}$$

where $v_T(\mu)$ is the true velocity profile and v_I is the true velocity at the echoing point.

Now by the mean value theorem we may write equation (17) as

$$\begin{aligned} v_D &= \int_0^1 v_T\, d\mu - \bar{v}_T \int_0^{\mu_I} d\mu + \mu_I v_I \\ &= \int_0^1 v_T\, d\mu - (\bar{v}_T - v_I)\mu_I \end{aligned} \qquad (18)$$

where $\bar{v}_T$ has a value between v_I and v_R, the value of v_T at the $\mu = 0$ level.

For convenience we represent the velocity profile determined assuming reflection at the $\mu = 0$ level by $v_R(\mu)$. Then since $v_D(\mu)$ represents the measurements,

$$v_D = \int_0^1 v_T\, d\mu - (\bar{v}_T - v_I)\mu_I = \int_0^1 v_R\, d\mu \qquad (19)$$

Now if echoes arise from below the $\mu = 0$ level but in a region where the velocity is not changing between the $\mu = \mu_I$ and $\mu = 0$ levels then $\bar{v}_T = v_I$. Hence $\int_0^1 v_T\, d\mu = \int_0^1 v_R\, d\mu$ and the application of equation (5) gives the correct answer. However, if the velocity increases (decreases) between the $\mu = \mu_I$ and $\mu = 0$ levels then $\bar{v}_T > v_I$ ($\bar{v}_T < v_I$) so that $\int_0^1 v_T\, d\mu > \int_0^1 v_R\, d\mu$ ($\int_0^1 v_T\, d\mu < \int_0^1 v_R\, d\mu$). These inequalities will be true if $v_T > v_R$ ($v_T < v_R$).

The application of the method developed using equation (5) assumes reflection at the $\mu = 0$ level so if echoes arise from below this level errors will occur if the velocity is changing with height. Assuming that the vertical profile of electron concentration is correct, then the velocity v_R will be ascribed to a particular height instead of v_T. Hence if the velocity increases (decreases) with height, the velocity at a particular height will be underestimated (overestimated).

With reference to Figure 1, the major region in which the velocity increases with height (and therefore decreases with $\mu = 0$) is the base of the E region. As already discussed, the velocity rises so rapidly in this region that the velocity profile is not greatly affected. Above the E region peak the velocity decreases with height so that the corrected values given in Figure 1 will be smaller than the true velocities if the echoes are from below the $\mu = 0$ level. Hence these corrected velocities represent lower limits but the correction term, $(\bar{v}_T - v_I)\mu_I$, is likely to be small since both components of this term will generally be small. Of course ionosonde drift measurements at high latitudes are dominated by reflections at or near the $\mu = 0$ level rather than by partial reflections or backscatter reflections.

As a final remark, in one respect there is a correspondence between drift velocity and virtual height in that each provides a measure of the integral effect of the ionosphere rather than an exact measurement of the property at the reflection point. However the results of this study show that, unlike virtual height, the drift velocity is a good estimate of the velocity at the reflection height in all but extreme situations. To emphasize this point consider how well the drift velocity profile reproduced the shape of the velocity profile derived by inversion. This is in stark contrast to virtual height which, when plotted as a function of frequency, usually exhibits extreme cusps which vastly exaggerate the real height variation of plasma frequency.

Conclusions

The accuracy of ionosonde drift-velocity measurements has been examined for the situation in which the ionospheric velocity varies with height. This has been done by developing a simple inversion technique and applying it to an average drift velocity profile obtained at Casey, Antarctica. The results show that the ionosonde drift velocity technique provides reasonable results in the lower E region and F region. A narrow velocity peak near 110 km caused the drift velocity technique to underestimate the velocity at this level by as much as 20%. However the discrepancy dropped quickly at higher heights, falling below 7.5% at 150 km.

The results support the use, at each measurement epoch, of a single estimate of the F region convection drift at a high-latitude station such as Casey.

As with other measurements of ionospheric parameters, drift velocity profile measurements on a more rapid time scale will show much more variability than the average profile shown here. The results of this study suggest that such results could be validly interpreted provided it is recognized that such profiles may represent a smoothing of the true velocity profile in regions of rapid variation of velocity with height. While the inversion procedure developed here is simplified and appropriate for the average profile presented, it does provide a reasonable first estimate of the true velocity profile. A more rigorous approach will probably be required for “instantaneous” velocity profile measurements as it will probably be necessary to consider the specific angles of arrival of echoes more explicitly.

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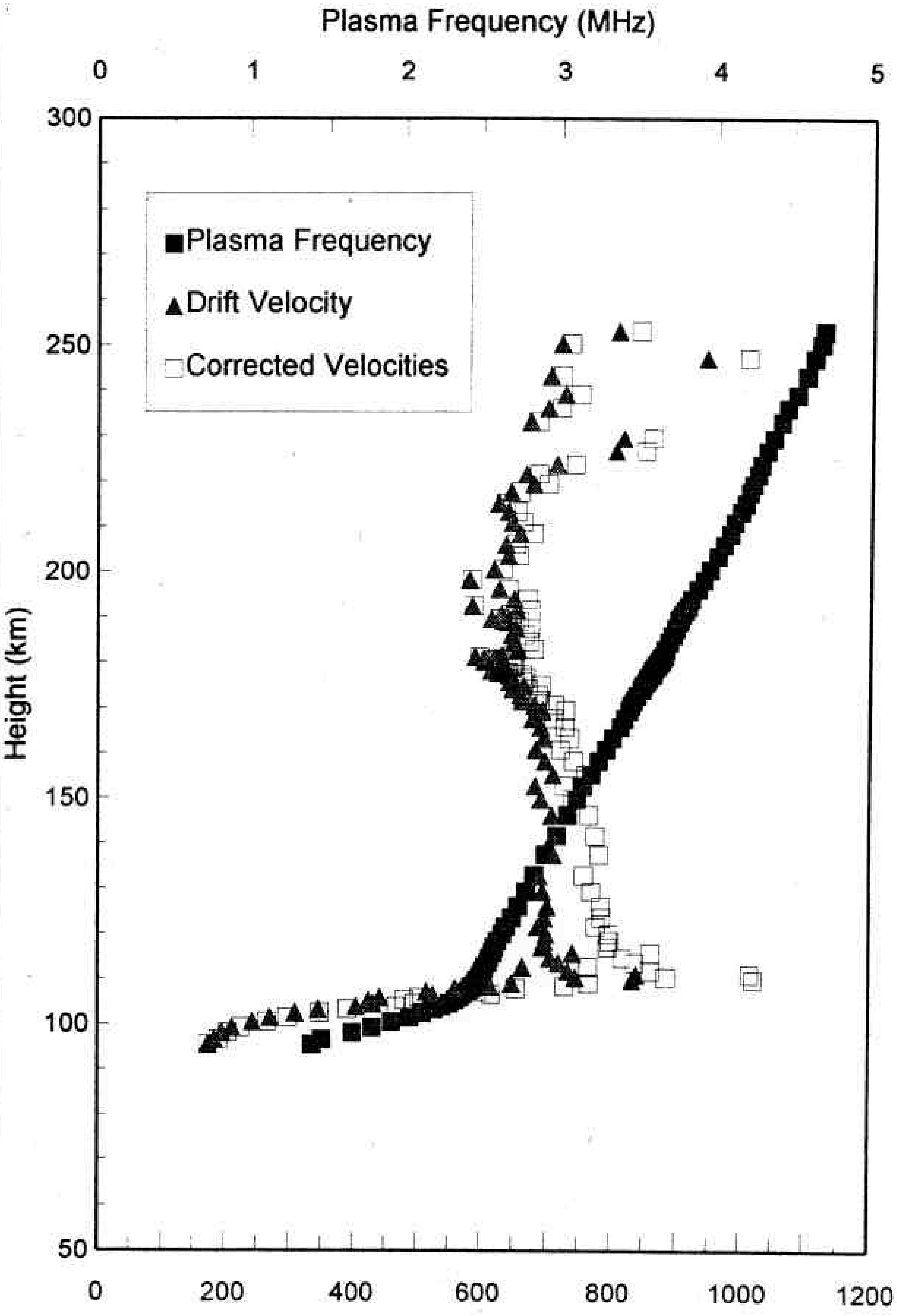
Figure Caption:

Figure 1. Shown are: (i) the average height profile of convection velocity measured at Casey (triangles). The profile was obtained using measurements made within 3 hours of magnetic noon during March 11-14, 1996; (ii) the corresponding average plasma frequency profile is also shown (filled squares); and (iii) the velocities derived for the reflection points of the transmitted frequencies (open squares).


Plasma Frequency (MHz)
0
1
2
3
4
5
300
250
200
150
100
50
Height (km)
■Plasma Frequency
▲Drift Velocity
□Corrected Velocities
0
200
400
600
800
1000
1200
Velocity (m/s)