Lower E-region MF radar spaced antenna measurements over magnetic equator

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Abstract

Medium frequency (MF) radar spaced antenna observations at heights close to the location of the equatorial electrojet over Tirunelveli (8.7°N, 77.8°E, geographic, 0.35°N magnetic dip) are used to examine the influence of the electrodynamical processes in the determination of neutral winds in the lower E-region. On many days, daytime wind and tidal characteristics change at heights above 94 km, when analysis is performed on day-to-day basis. Under these conditions, the spaced antenna measurements need not represent neutral winds at all. On the other hand, on a few other days, the ‘drifts’ at 98 km are opposite to those expected from the electrodynamical considerations leading us to believe that we might be measuring neutral winds around this time. Selected days during the year 1995 bring out this complex nature of the spaced antenna measurements carried out over the magnetic equator. Ground-based geomagnetic field data provide information on the electrodynamical state of the equatorial ionospheric E-region.

Keywords: MF radar drifts; EEJ electric field; Equatorial MLT region

1. Introduction

Since the work of Fraser and Kochanski (1970), the partial reflection ‘drifts’ (PRD) technique has been widely used in the past in the studies of middle atmosphere dynamics, in the mid- and high latitudes (Vincent and Stubbs, 1977; Fraser, 1984; Philips and Vincent, 1989; Manson et al., 1997; Malinga et al., 1998; Hocke and Igarashi, 1999; to state a few) and at low and equatorial latitudes (Vincent and Lesicar, 1991; Fritts and Isler, 1992; Rajaram and Gurubaran, 1998; Tsuda et al., 1999). Because of the collisional coupling of neutral gas and the ionized species, the drift measurements at heights below 100 km have been considered to represent the bulk motion of the neutral gas (Fraser, 1968, for example). Details of the technique and the method of analysis adopted in the determination of mesospheric winds are widely discussed in the literature (Hocking, 1983; Briggs, 1984, for extensive reviews).

The partial reflection of the radio wave can be explained in terms of scattering of the incident wave in a medium containing irregularities of refractive index but where the mean refractive index does not deviate greatly from unity. More precisely, Fresnel or partial refractions are caused by horizontally stratified and stable regions of refractive index irregularities which arise due to electron density fluctuations and cover at least one Fresnel zone (λz)1/2 in horizontal extent, and with a vertical extent no > λ/4 where λ is the wavelength of the probing radio wave and z is the height of the scatterer. It is believed that the thin anisotropic turbulence causes partial reflections for a vertically pointing beam that explains the observed aspect sensitivity, while the more isotropic turbulence contained within the layer is responsible for reflections from a off-zenith pointing beam (Hocking, 1989, for example). In spite of the limitations of the technique (Lesicar, 1993, for a review) the partial reflection radars operating in the medium frequencies are generally accepted to yield reliable measurements of...
horizontal winds in the mesosphere and lower thermosphere (60–100 km) region.

A potential problem for the radars operating near the geomagnetic equator has been indicated by Gurubaran and Rajaram (2000) (herein referred to as GR). Determination of neutral winds by the spaced antenna method at latitudes close to the geomagnetic equator is influenced by the presence of equatorial electrojet (EEJ), an enhanced east–west current system flowing in a narrow latitudinal belt of ±3° at an altitude of ~105 km. Early ionospheric soundings detected an anomalous scattering region at these heights. The corresponding ionospheric echoes were called ‘equatorial sporadic E’ (E$_{sq}$) echoes. It was Matsushita (1951) who first showed that the intensity of E$_{sq}$ is well correlated with the electrojet strength. Later theories took into account various plasma instabilities, which were shown to generate type I and type II irregularities in the presence of ambient electric field and the background plasma density gradient. These irregularities are responsible for much of the radar signals in the VHF range (Fejer and Kelley, 1980, for a review). In the medium frequencies (MF) the echoes associated with the plasma turbulence may easily overshadow the normal echoes arising from the neutral turbulence possibly generated by gravity wave breaking. This possibility was discussed in the paper by GR.

In the earlier work based on the data obtained by the MF radar operated at Tirunelveli (8.7°N, 77.8°E, geographic, 0.35°N magnetic dip), only a few days in one of the winter months of 1996 were selected as examples to demonstrate the effect of electrodynamical processes in the determination of mesospheric winds. We have considered a larger data base for the present work and include a discussion on how these processes influence the estimates of tidal parameters as well.

In addition to the horizontal velocities, one of the geometrical parameters, namely, the pattern decay time, which is derived from the full correlation analysis (Lesicar, 1993, for a complete description), is examined in the present work. The geometrical parameters can be used to characterize the general nature of the scattering medium. Ground geomagnetic data yield measures of the strength of the equatorial electrojet, which is proportional to the primary zonal electric field that drives the current system.

It is shown in the present work that on many occasions the horizontal velocities measured at the highest height (98 km) sampled by the radar reflect the electrodynamical control of the scattering/reflection processes responsible for the observed radar echoes.

2. Observations

The MF radar, operating at 1.98 MHz, has been yielding data on winds in the mesosphere and lower thermosphere in the altitude region (68–98 km) over Tirunelveli since the middle of 1992. Though the range resolution of the radar is ~ 4.5 km, the sampling region is probed at 2 km height interval. The full correlation analysis of Briggs (1984) is used to determine several dynamical and spaced antenna parameters. Valuable results on mean wind, tidal and planetary wave climatologies were reported earlier (Rajaram and Gurubaran, 1998; Gurubaran and Rajaram, 1999; Gurubaran et al., 2001).

Simultaneous measurements of the H-component of the geomagnetic field variations from the nearby location, Trivandrum (8.5°N, 77°E, geographic, 0.65°N magnetic dip), are utilized as complementary data while examining the nature and behaviour of the PR velocities measured by the MF radar. The ground magnetic field variations represent the height-integrated overhead ionospheric current density which is concentrated at ~105 km in the electrojet region (Forbes, 1981, for a review on the equatorial electrojet phenomenon). It is usual practice to determine the electrojet strength from geomagnetic data obtained from the two stations: one under the influence of the electrojet and the other away from the electrojet region. In the presentation below we have also used ground geomagnetic data obtained from the permanent magnetic observatory at Alibag (18.6°N, 72.9°E, geographic; 25.5°N magnetic dip). The difference in ΔH between these stations (Trivandrum and Alibag) will yield a measure of the EEJ strength (Kane, 1973).

In the present work we have not gone into the exercise of the determination of actual height of reflection, though the corresponding group delays may be relevant as the tail of the E-region is approached. We do not intend to apply the differences in the detected and the real heights to the presentation of data in this paper, as our sole aim is to show that the drifts at the highest height sampled by the radar are controlled by the plasma processes associated with the equatorial electrojet. Considering the problem of total reflection, it may be noted that the receivers are expected to go into saturation under these conditions. The rejection criteria, adopted in the full correlation analysis (Briggs, 1984), do not permit useful velocity estimates at these times when the signal saturation takes place. It may be possible to identify the height of total reflection from a profile of received signal strength (Turek et al., 1998, for example). In the standard operation of the MF radar at Tirunelveli, information regarding the received signal strength is not stored. It is the strength of the fluctuations in the signal that is stored for the analysis after removing the mean signal level. With the rejection criteria, the analysis does not lead to determination of velocities when the signal attains saturation amplitudes. It has been observed that the percentage of acceptance of 2-min data samples above 94 km during the day varies between 30 and 50, which is appreciable. This indicates that the total reflection is not severe enough at these heights to reduce the useful data yield considerably. Further, it is possible that the echoes associated with E$_{sq}$ irregularities overshadow those associated with the total reflection. On ionograms obtained at an equatorial station, it is often noticed that the trace corresponding to E-region total reflection levels is obscured by
the $E_{sq}$ echoes whenever present. A similar situation may arise with the MF radar signal when the signature of total reflection is sought after. A rigorous analysis is being pursued by the authors to identify conditions under which a totally reflecting layer can be detected.

3. Results

In Fig. 1 the hourly values of EEJ strength (top panel), derived from the difference between $\Delta H$ at Trivandrum and $\Delta H$ at Alibag, are compared with the hourly mean zonal velocity (bottom panel) measured by the MF radar at a height of 98 km for four selected days in December 1995. The error bars in the bottom panel represent the standard error of the mean velocity at 95% confidence level. All these days are geomagnetically quiet days as indicated by their Ap values. The reversal in the afternoon electrojet strength, referred to as a ‘counter electrojet’ (CEJ) (Mayaud, 1977, for a review) is well pronounced on 6–8 December, whereas this feature is not seen on 12 December. On these CEJ days, the EEJ strength reaches a maximum at $\sim$1000 IST (Indian standard time) and the minimum (a depression in $\Delta H$ below the nighttime level) occurs between 1400 and 1500 IST. On 12 December a contrasting behaviour is noticed for the EEJ strength. There was no afternoon reversal in the current and the maximum occurs at 1300 IST.

In response to the temporal variation of the electrojet strength the measured zonal velocity at the highest height ($\sim$98 km) sampled by the radar shows a minimum (most westward) between 0900 and 1000 IST on 6–8 December. The morning drift reversal (from eastward to westward) which commences at 0600 IST is well pronounced on 6 and 7 December. The drift velocity changes from 20 m/s (eastward) to 65 m/s (westward) on one of the days between 0600 and 0800 IST. Around this time ($\sim$0600 IST) the EEJ strength begins to develop as the production of ionization immediately after sunrise increases the electrical conductivity of the dynamo region. On 12 December, the temporal variation of the drift velocity is quite different. The reversal to westward motion had occurred 3 h later (at $\sim$0900 IST) and the largest westward speed of $\sim$90 m/s is observed in the afternoon hours. On this day there was no CEJ as evident in the top panel. On the rest of the days under consideration, the westward flow at 98 km tends to reverse in the afternoon hours where the geomagnetic field variation clearly reveals a depression below the nighttime level.

Fig. 1 illustrates the realistic behaviour of the lower E-region partial reflection drifts measured very close to the magnetic equator. As expected, the drifts at 98 km respond well to the changing electrodynamical condition of the equatorial E-region. This example reiterates the conclusion arrived at in the earlier work of GR.

The nature of the scatterers and their response to the dynamo electric field are now examined. Fig. 2 depicts the pattern decay time (expressed in seconds) for the above days in the altitude region 84–98 km. While estimating this parameter, the effects of large-scale motions are inherently removed in the analysis as the observer moves with the pattern, and therefore, the pattern decay time is expected to solely
represent the random changes of the scattering echoes (Lesicar, 1993). It may be noted in Fig. 2 that on all the four days under consideration, the pattern decay time decreases as higher altitudes are reached. Further, one can immediately notice the U-shaped structure during daytime above 90 km. This structure does not retain its shape from one day to the next. Rather, responding to the day-to-day variability of the electrojet strength (see Fig. 1), the U-shaped structure shrinks on one day (8 December) when the electrojet reverses early (around noon) but extends for a longer duration (on 12 December) when there is no reversal in the electrojet. Further, the occurrence of the shortest pattern decay time (< 1 s) coincides with the time of electrojet maximum.

A remarkable feature illustrated in Fig. 2 is that the temporal variation of the pattern decay time at altitudes above 94 km is in tune with the $\Delta H$ variation. Further, the day-to-day variability of the primary electric field that drives the electrojet is clearly reflected in the evolution of the pattern decay time, which varies from one day to the next. Since it is presumed in the analysis that the pattern decay time represents the random changes within the layer that is probed, it is strongly believed that the mechanism responsible for the reflection/scatter and resulting echoes is associated with the plasma instabilities driven by the electric field and background plasma density gradient in the equatorial E-region.

Though the general trend at 98 km is that the measured zonal drift follows the $\Delta H$ variation, on some days the behaviour is different, for example, on 1 and 2 June 1995. In Fig. 3 we depict the time-variation of $\Delta H$ at Trivandrum and the zonal velocity at 98 km on 21 May, 1 and 18 June and 21 December 1995. Out of these randomly selected days, 1 and 18 June are moderately disturbed, their Ap values being 25 and 14, respectively. The very large depression in $\Delta H$ ($\sim -80$ nT) at 1600 IST on 18 June is contributed by the ongoing geomagnetic storm. The zonal velocity variation on all four days except 1 June follows the trend noted above. On the magnetically disturbed day (18 June), the rapid decrease in $\Delta H$ indicating a weakening of the zonal electric field as expected during a magnetic storm, is reflected well in the zonal drift at 98 km that shows the reversal commencing at 1000 IST. Because the drifts change their direction as expected, the depression in the magnetic field is possibly due to the weakening of the electrojet current system. Magnetospheric ring current contributions do produce such changes in the magnetic field, especially during the main phase of a geomagnetic storm, but on this day the reversal of the observed PR drifts indicates a response to the changing electrodynamical condition in the lower E-region heights. Penetration of storm-time magnetospheric electric field into low-latitude ionosphere will cause this changing scenario (Somayajulu et al., 1987) that influences the PR drift measurements reported herein.

In contrast to the rest of the days the behaviour on 1 June appears to be distinctly different. The zonal velocity was eastward during daytime (0800–1600 IST) when on other days it was westward. A similar variation is noticed for 2 June (not presented here). It may be noted that the electrojet strength on this day has the usual noontime maximum ($\Delta H_{\text{max}} \sim 60$ nT). In other words, the electrodynamical conditions on this day may be considered to be normal. We may be measuring neutral winds around this time since the direction of the measured zonal velocity is opposite to the direction of the expected electric field-driven motions. This inference is strengthened by more examples presented below.

Fig. 4 (bottom panel) depicts the behaviour of zonal velocities measured at 98 km on a few other days, 16 April, 18 May, 31 July, 5 August and 26 September, all in 1995. For comparison, we have plotted the variation of the $H$ component of the geomagnetic field at Trivandrum in the top panel. The electrojet was fully developed on all these days as can be seen from the $\Delta H$ curves. Contrary to the behaviour of the zonal motions observed on other days (refer to Figs. 1 and 3), the measured ‘drifts’ do not seem to respond to the equatorial electric field. Instead of measuring westward drifts on these days when the electrojet was fully developed, the MF radar measured eastward velocities. The lifetime of the irregularities as represented by the FCA parameter, pattern decay time, was more than a second and varied in the range 1–3 s on these days (not presented here). This is more than the < 1 s value that was observed for certain other days when the electric field controls the motions of the MF radar scatterers (refer to Fig. 2).
The contrasting examples (Figs. 1 and 4) presented herein illustrate the complex nature of the probing region close to electrojet heights. Though at times we expect to measure the drifts driven by the equatorial electric field, the actual measurements reveal otherwise and they perhaps represent neutral winds at these heights. The tidal phases (to be discussed next) on these days reveal descending trend beginning at 98 km with vertical wavelengths in the range 25–30 km, indicating that the ‘drifts’ indeed represent neutral air motions. The factors contributing to the complexities of the probing region that pose difficulties in interpreting the spaced antenna measurements need to be examined in detail.

We now examine the effect of the electrojet on the estimates of tidal parameters obtained from the MF radar data. In Fig. 5 a histogram for the local time distribution of the phase of the diurnal tide in the zonal direction is presented. Hourly values of radar drifts between 84 and 98 km are subjected to harmonic analysis and the estimated tidal phases for all days in 1995 are grouped in different time intervals: 0000–0200, 0200–0400, 0400–0600, 0600–0800 and so on. It may be noted that it is not possible to retrieve tidal information for all days of the year. There are local time intervals for which the data are rejected and on these days the tidal amplitudes and phases are not estimated. This is the reason why the counts do not add to 365 at any of the heights plotted in Fig. 5. For comparison, the diurnal phase of the EEJ strength is plotted at the top. As expected, the frequency of occurrence is largest for days during which the time of maximum EEJ strength occurs around noon hours.

A remarkable feature noticed in the histogram is that there is a tendency for the tidal phases to be distributed around local midnight at 98 km whereas at lower heights (84–88 km) the phases are mostly distributed around noon. The former feature demonstrates the influence of the EEJ on the tidal phases at 98 km. If it is presumed that the measured zonal drifts are due to the same electric field that drives the equatorial electrojet, one can expect the phase of the diurnal tide variation to be in the late night/early morning hours since the drifts attain maximum westward (negative) velocities around noon. We have noted in examples presented in Figs. 1 and 4 that the largest westward motion occurs around the same time as the ΔH maximum. This clearly shows that the radar measured drifts at 98 km are primarily driven by the E-region dynamo electric field. This influence reflects in the estimated tidal parameters as well.

In Fig. 6 the altitude profiles of the tidal amplitudes (left) and phases (right) for the selected days (6, 7, 8 and 12
December in the top and 21 May, 1, 2 and 18 June and 21 December in the bottom panels, all during 1995) are presented. On the top of each of the phase profiles, we have indicated the phase of the EEJ strength for that particular day. On 12 December, unusually large diurnal tide amplitude (~48 m/s) at 98 km is observed. Referring to Fig. 1, we notice that the \( \Delta H \) variation on this day is primarily diurnal with no signatures of afternoon reversal. This variation in EEJ strength will correspond to westward electron drifts (eastward current) with large diurnal amplitude. The large diurnal amplitude (~48 m/s) observed in the zonal velocity at 98 km close to electrojet heights is an overestimate for tidal winds at such heights and is possibly contributed by the strong diurnal variation of the driving zonal electric field.

Examining the phases, we notice that only on 1 and 2 June the phase structure clearly shows descending trend with vertical wavelengths in the range 25–30 km in accordance with the prediction for the (1, 1) diurnal tidal mode based on classical tidal theory. We mentioned earlier that on these days the drifts are different and we might be measuring the component of the neutral wind vector. On days when the drifts are driven by the electric field, we expect little phase variation with height. Tidal estimates for 18 June and 7 and 8 December do show this behaviour and they are possibly due to the influence of the electrojet.

Comparing the phases of the tidal velocities at 98 km with those of the EEJ strength, one can notice that the difference is <2 h on 7, 12 and 21 December, 21 May and 18 June.

Fig. 6. Altitude profiles of the amplitude (left) and phase (right) of the diurnal tide in the zonal component for the days considered in Figs. 1 and 4.
This figure is arrived after advancing the tidal phase by half the period, because, as mentioned earlier, the large westward (negative) maximum occurs at times when the electrojet strength is maximum and the tidal analysis yields phase for eastward (positive) maximum. Nearly identical phases in both the parameters indicate once again the electrodynamical control of the tidal estimates at 98 km.

4. Discussion and conclusion

It has been nearly three decades since the partial reflection drift technique (this name no more appears in the current literature) was first shown to yield reliable estimates of mesospheric winds. Beginning with Hines et al. (1993), there were numerous studies in the recent past that compared the spaced antenna wind measurements with measurements using other techniques (Burrag et al., 1996; Manson et al., 1996; Turek et al., 1998, to state a few). In spite of the limitations which are expected for any radar technique, much of the useful information on mean winds, tides, planetary-scale waves and gravity waves in the mesosphere and lower thermosphere region has come from the MF radar spaced antenna wind measurements.

For radar systems operating in the equatorial region (where the inclination of the geomagnetic field is close to zero), complexities in interpreting the drift measurements at heights close to 100 km arise because of the electrodynamical processes playing a dominant role in the generation and movement of electron density irregularities. The geomagnetic field configuration at the magnetic equator permits intense vertical polarization fields to be developed, which drive the electrojet. The intense east–west current system that flows in a narrow layer centred at ~105 km is the seat of a variety of plasma instabilities (Kelley, 1989, for a review). The plasma within the electrojet often becomes turbulent and causes the type I and type II echoes received by VHF radar. The nature and characteristics of these echoes distinctly differ from each other.

MF radars which operate in the spaced antenna mode require sharp gradients in refractive index (vertical extent should be no more than 1/4 of the radar wavelength). The structure of the scatterers responsible for the received echoes and their generation mechanisms at heights close to where the electrojet current flows are currently not known. Because the probing region is located in the vicinity of the electrojet, the echoes are possibly associated with a plasma instability mechanism generating the requisite gradients in the refractive index. It was noted by a number of workers in the past that the echo generating region encompasses the heights beginning at 93 km (Fejer and Kelley, 1980) and above and therefore, it is anticipated that the plasma instability processes extend down to altitudes of the MF radar probing region and produce noticeable signatures in the detected echoes. In this context it is useful to note that HF spaced receiver experiments were carried out from the Indian equatorial station, Thumba in the mid- to late sixties, and the drift measurements were shown to be associated with the electrojet (Chandra and Rastogi, 1973). The conventional ionosonde operated from the same location yielded ionograms that were used to associate the results from the spaced receiver experiment with the $E_{\text{sq}}$ phenomenon. In particular, Chandra and Rastogi (1973) observed fast fading, westward drift and highly elongated ground diffraction pattern when $E_{\text{sq}}$ was present. During periods when there was no $E_{\text{sq}}$, the fadings were found to be very slow, the drift direction was reversed to the east, and the ground diffraction pattern became almost isotropic. They concluded that the characteristics of the fading and those of the ground diffraction pattern during periods when $E_{\text{sq}}$ disappeared are similar to the characteristics observed at mid-latitudes.

In the present work, the response of the radio wave scatterers to the changing electrodynamical conditions is well brought out in Fig. 2 which contours the pattern decay time for the four selected days in December 1995. On 6–8 December, the zonal velocities turned eastward in the afternoon hours. The lifetime of the irregularities expressed as pattern decay time lengthens at these hours as noticed in Fig. 2. Lifetimes as long as 4 s were observed in the afternoon hours on 6 and 8 December at the highest height sampled by the radar. On 12 December, when the drifts did not reverse, the daytime pattern decay time remained < 2 s. These features are in agreement with the results obtained by Chandra and Rastogi (1973). As pointed out by these authors, the electric field reversal in the afternoon hours does not favour the gradient drift instability mechanism to generate the irregularities leading to the disappearance of $E_{\text{sq}}$ on an ionogram. The plasma is less turbulent under these conditions and the fading is expected to be slower and is much more like that observed for non-electrojet conditions as noted by Chandra and Rastogi (1973).

In the present work we have illustrated with many examples the electrodynamical influence over the estimates of hourly mean wind and tidal characteristics at heights close to 100 km. The signatures of the day-to-day variabilities of the zonal electric field, the reversal in the afternoon current system (referred to as counter electrojet) and the effects of the daytime penetration of high-latitude magnetospheric electric fields into the equatorial ionosphere are all noticeably seen in the MF radar measurements made at Tirunelveli.

Though the MF radar spaced antenna measurements at heights above 94 km indicate the increasing importance of equatorial plasma processes in their interpretation, the electrodynamical signatures in the ‘drift’ measurements are nearly absent on certain days (refer to Fig. 4). It is yet to be determined what ‘switches off’ the electrodynamical control of the MF radar scatterers and their motions below 100 km. These unexplored aspects of the scattering/reflection processes warrant an extensive investigation.

Briggs (1977) summarized the results of spaced receiver experiments carried out at electrojet latitudes in the past and emphasized the need for caution in interpreting the
spaced-receiver drifts in terms of neutral air motions. Using the PRD technique, it might be possible to obtain reliable wind measurements at heights below the electrojet and at latitudes away from the electrojet, where the electrodynamics is expected to play a minor role in governing the spaced antenna drifts. Future MF radar spaced antenna wind measurements made at low latitudes, close to the magnetic equator, will have to consider the problem posed herein and examine the possible linkage of the scattering/reflection processes with the $E_{sq}$ phenomenon while interpreting the measurements in terms of neutral winds. It will be interesting to compare MF radar measurements from two latitude sites: one in the electrojet axis and the other outside the electrojet belt. We intend to carry out this exercise in the near future with simultaneous data now available from the other Indian MF radar located at Kolhapur ($16.8^\circ$N, 74.2$^\circ$E).

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