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On the electric field control of the MF radar scatterers in the lower E region over the magnetic equator

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[1] Medium frequency (MF) spaced antenna radar observations from Tirunelveli (8.7°N, 77.8°E, geographic; 1.4°N magnetic dip) are used to examine the characteristics of lower E-region echoes and their possible association with the electrodynamical processes that drive the equatorial electrojet (EEJ). For the period (January 2006) under study, intense echoes were observed at 90 km and above at times of strong EEJ, indicating a possible electric field control of the radar scatterers. Under strong EEJ conditions, smaller pattern lifetimes, larger pattern scale sizes and axial ratios and strong pattern alignment along the geomagnetic field are routinely observed during this period. During the afternoon counter electrojet conditions, the electric field control of radar scatterers appears to weaken and the echo intensities are diminished. The work presented here calls for a detailed investigation that should address fundamental issues like the nature of the scatterers responsible for the MF radar echoes and their underlying generation mechanisms.

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1. Introduction

[2] Radio-wave probing of the mesosphere-lower thermosphere (MLT) region using medium frequency (MF) radars has been carried out by several groups during the last few decades. Because of the close collisional coupling between the neutral and ionized species, the spaced antenna drift measurements at these heights (80–100 km) have been considered to represent the bulk motion of the neutral gas. Details of the spaced antenna technique and the method of analysis adopted in the determination of mesospheric winds are widely discussed in the literature (see *Hocking* [1983] and *Briggs* [1984] for extensive reviews).

[3] The MF radar echoes arising from equatorial and auroral ionospheric heights are expected to be influenced by the electrodynamical processes that are known to penetrate to heights as low as 90 km. This issue was investigated for the equatorial region by *Gurubaran and Rajaram* [2000] and *Ramkumar et al.* [2002]. For radar systems operating in the vicinity of the magnetic equator, complexities in interpreting the drift measurements arise because of the presence of the equatorial electrojet (EEJ) that plays a dominant role in the generation and movement of electron density irregularities in the lower E region [*Kelley*, 1989].

[4] The EEJ is an enhanced east-west current system flowing in a narrow latitudinal belt of ±3° at an altitude of $\sim$105 km. The current itself is a seat of a variety of plasma instabilities resulting in an anomalous scattering region that can be detected by ionospheric sounders in the form of equatorial sporadic E (E_{sq}) echoes [*Rastogi*, 1973]. Theoretical studies showed that plasma instability processes unique to the equatorial region generate type I and type II irregularities in the presence of zonal and vertical electric fields and background plasma density gradients. Type I irregularities are excited by the two-stream instability and the type II irregularities arise due to the gradient drift instability. Many of the echoes detected by VHF radars are caused by these irregularities (see *Fejer and Kelley* [1980] for a review). At medium frequencies, at heights close to 100 km, the scattering due to plasma turbulence could cause intense echoes whose characteristics are distinctly different from those arising from neutral turbulence [*Ramkumar et al.*, 2002].

[5] The MF radar operating at Tirunelveli (8.7°N, 77.8°E, geographic; 1.4°N magnetic dip) offers an excellent opportunity to investigate the role of the equatorial electrodynamical processes governing the formation of ionospheric irregularities responsible for the echoes observed at MF frequencies. Earlier work making use of the MF radar data from this site revealed that the partial reflection drifts at 98 km were influenced by the combined effects of mesospheric winds and EEJ [*Gurubaran and Rajaram*, 2000]. Subsequent work examined the ground diffraction pattern on several days under different electrodynamical conditions including the presence of the afternoon counter electrojet (CEJ) [*Ramkumar et al.*, 2002]. When analysis was performed on a day-to-day basis, the daytime wind and tidal characteristics were found to exhibit complex behavior. During one set of conditions, the dynamical parameters revealed close connection to EEJ, whereas during certain other conditions, the drifts at 98 km were different from those of EEJ origin.

[6] The present effort extends the earlier work of *Ramkumar et al.* [2002] by examining the signal-to-noise ratio (SNR) of the observed echo from heights at and above 90 km and the parameters associated with the ground diffraction pattern on a selected few days during which different EEJ conditions prevailed. The peculiarities in the observed echo characteristics are discussed in the context of known physics underlying the formation of equatorial ionospheric irregularities.

2. Observations

[7] The MF 1.98 MHz radar operating at Tirunelveli has been yielding data on winds in the MLT region at heights

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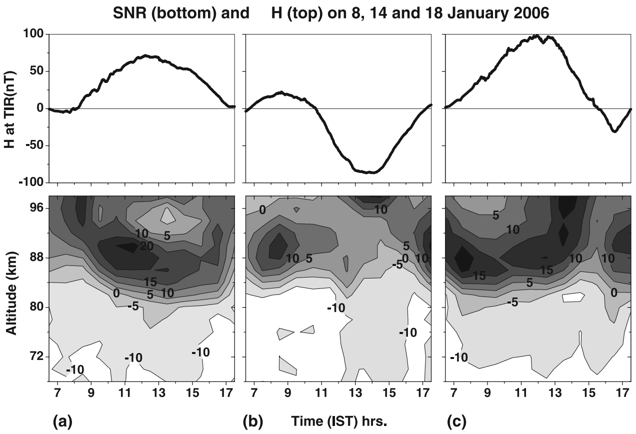

Figure 1. (top) ΔH determined from the ground magnetometer data and (bottom) daytime SNR in the height range 68–98 km on (a) January 8, 2006, (b) January 14, 2006, and (c) January 18, 2006.

between 68 and 98 km since the middle of 1992. The MF radar system is identical to the one placed at Christmas Island (see *Vincent and Lesicar* [1991] for details about this instrument). The full correlation analysis of *Briggs* [1984] is used to determine several dynamical and spaced antenna parameters. Every estimate obtained from this analysis at a time resolution of around 2 minutes is based on a 256- sample set, wherein each sample is a result of coherent integration of a predetermined number of pulses. For the radar operating at 50 Hz pulse repetition frequency (PRF), the analysis is performed with 32 coherent integrations during daytime, yielding a time resolution of 0.64 s for each of the 256 samples and around 2.8 min for every wind estimate. During nighttime, the number of coherent integrations is halved and at the same PRF, wind estimates are obtained at 1.4 min time interval. Several observational results pertaining to mean wind, planetary wave and tidal characteristics and their variabilities based on the MF radar data from Tirunelveli have been reported in the literature [*Gurubaran et al.*, 2005].

[8] Simultaneous measurements of the horizontal (H) component of the geomagnetic field variations obtained at 1-min time intervals from the co-located digital fluxgate magnetometer are made use of in the present work. The N-S field variation (ΔH) recorded on the ground represents the height-integrated current density, which over the magnetic equator corresponds to the intense east-west current of EEJ origin.

[9] For the present work a few geomagnetically quiet days during January 2006 were identified during which the EEJ conditions appeared different from one day to the other. The spaced antenna and the geometrical parameters representing the shape and orientation of ground elliptical diffraction pattern that were examined on these days are the SNR, the pattern lifetime, the pattern scale size, axial ratio and major axis direction.

3. Results

[10] Figure 1 (top) depicts ΔH and Figure 1 (bottom) SNR for receiver 1 (RX1) for heights between 68 and 98 km that were recorded on January 8, 2006 (Figure 1a), January 14, 2006 (Figure 1b), and January 18, 2006 (Figure 1c). All the three days happened to be magnetically quiet. Only daytime (corresponding to 0630–1730 Indian Standard Time (IST)) (IST is 5.5 hours ahead of UT and 0.31 hour ahead of local solar time) values of the relevant parameters are shown in Figure 1. Those data points of SNR having values of 50 dB were identified as due to signal saturation and were rejected and not considered for analysis. The near 2-minute samples were grouped in 1-hour blocks and the hourly averages are plotted in Figure 1. The electrojet had the usual development and decay on January 8 (Figure 1a), with ΔH registering a peak value of ~70 nT at 1230 IST. The SNR shows a remarkable dependence on altitude with negligible signal strength below 80 km and noticeable signal levels above 86 km. On this day, the temporal variation in SNR reveals large values (>20 dB) at times between 0900 and 1330 IST at 90 km close to the time of maximum of ΔH noticed in the ground magnetometer data. The signal level dropped to low values (less than 5 dB) in the afternoon hours (centered at around 1430 IST) in the height range 92–98 km.

[11] On January 14 (Figure 1b), the electrodynamical conditions were strikingly different from those on January 8. The normal electrojet current did not evolve fully but was observed to reverse in the pre-noon hours, a situation akin to CEJ condition. The depression in ΔH was characterized by a minimum at around 1400 IST. The MF radar echo at 90 km shows a similar temporal variation on this day. A maximum (~15 dB) in SNR was observed at 0800 IST at around 90 km. The signal level remained low between 0 and 5 dB throughout the afternoon hours when the CEJ was in progress. On January 18 (Figure 1c), the SNR at 90 km had larger values in the morning hours (0700–0800 IST) and around noon and early afternoon hours. The larger SNR region appears to move to higher altitudes (above 90 km) in the afternoon hours on this day. As noted in the H-variation, the electrojet was strong on January 18, with noontime values of ~100 nT.

[12] The strong dependence of the behavior of the MF radar echoes on the EEJ/CEJ condition is remarkably brought out in these three examples. The echo characteristics on several other magnetically quiet days during January 2006 were analyzed (results not shown here) and this dependence remained unchanged.

[13] The geometrical and the antenna parameters estimated using the full correlation analysis are next examined for the selected days of January 2006. While estimating the geometrical parameters associated with the ground diffraction pattern, the effects of large-scale motions are inherently removed in the analysis as the observer moves with the pattern, and therefore, they solely represent the random changes occurring within the scattering medium [*Lesicar*, 1993].

[14] Figure 2 shows the temporal behavior of the geometrical parameters, namely, the pattern lifetime, the pattern scale size, the major axis-to-minor axis ratio (axial ratio) and the direction of the major axis, plotted from the bottom, on the three selected days. Considering that the signal strength on the average is strongest at 90 km during these days, data sets for this height were used in this analysis. Individual near 2-min estimates are used in this

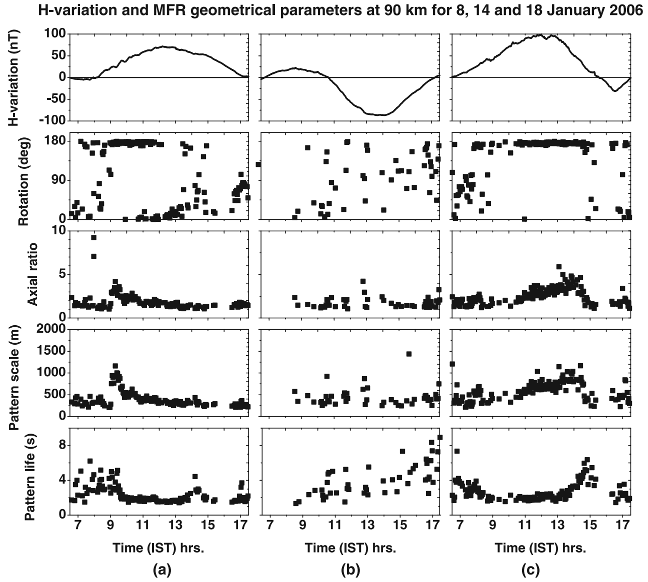

Figure 2. (from top) ΔH and radar geometrical parameters for pattern elongation (in degrees), axial ratio, pattern scale and pattern lifetime on (a) January 8, 2006, (b) January 14, 2006, and (c) January 18, 2006.

exercise in order to closely monitor their temporal variation in response to the changing background electrodynamical conditions. The ground geomagnetic ΔH values for these days are plotted in Figure 2 (top).

[15] On January 8 (Figure 2a) and January 18 (Figure 2c), when the electrojet was fully developed, strong radar echoes persisting throughout the day, enabled a large number of useful observations to be obtained. All the parameters reveal a consistent behavior between 0930 and 1330 IST on these days when the electrojet was strong. Beginning with pattern lifetime, we notice short ($\sim$2 s) lifetimes of irregularities during these times. Because the decay times increase in the afternoon hours (around 1400 IST) when the electrojet weakens, we may ascribe the MF radar scatterers with shorter lifetimes responsible for intense echoes observed just before and around noon hours to the irregularities driven by an ambient electric field through a plasma instability mechanism.

[16] The above inference is strengthened when the behavior of the other geometrical parameters is examined. The pattern scale sizes, computed using the full correlation analysis, are observed to be in the range 600–800 m around noon hours on January 18, at least 200 m greater than that observed during morning hours. A remarkable observational feature is the direction of the elongated pattern at these hours. This parameter yields information regarding the orientation of the major axis of the geometrical pattern. Angles are marked with reference to the geomagnetic north. Directions close to 180° observed between 1000 and 1430 IST on both January 8 and January 18, occurring around the time when the electrojet was fully developed, clearly indicate the presence of field-aligned irregularities that might be responsible for the observed echoes. The axial ratio on January 18 lies in the range 2–4 at times when the electrojet was most intense, which is larger than the values (in the range 1–2) observed during the other hours of the day.

[17] Beginning at 1330 IST on January 18, the electric field control of the radar scatterers appears to start diminishing in the afternoon hours as is evident in the slow variation noticed in the pattern lifetime, pattern scale size and pattern axial ratio. The lifetime of the irregularities lengthened and the pattern scale and the axial ratio both shortened indicating the weakening of the electric field drive. Further, the SNR started decreasing at 1400 IST to reach a minimum ($\sim$5 dB) at 1530 IST as can be seen in Figure 1. Later, at 1700 IST the SNR recovered to its daytime value of 20 dB. A weak afternoon counter electrojet signature is indeed noticed in the magnetometer record on this day. The afternoon features observed in the radar parameters on January 18 were not so prominent on January 8. The H-variation on January 8 does not reveal an afternoon reversal.

[18] Turning to January 14 (Figure 2b), when a large early afternoon CEJ event occurred, we notice distinctly different behavior for each of the estimated geometrical parameters of the ground diffraction pattern. As noted in Figure 1b, the SNR at 90 km on this day, after showing a peak at 0830 IST, started decreasing and led to small echo intensities between 1300 and 1500 IST nearly coinciding with the minimum of ΔH. The analysis further revealed that almost 65% of the data points were rejected due to low SNR during the period 1200–1500 IST. This resulted in a fewer useful data points during these hours as can be noticed in Figure 2b.

[19] Reflecting the weak electric field driving the EEJ on January 14, the results reveal longer (3–5 s) pattern lifetimes, smaller (300–500 m) pattern scale sizes and smaller (1–3) axial ratios. There was no preference for the pattern to be oriented in the magnetic N-S direction as was the case on January 8 and January 18. These features clearly bring out the varying role of the electric field drive in generating the scatterers responsible for the radar echoes under different electrodynamical conditions. This inference is, however, subject to the constraint that fewer observational data points resulted due to poor SNR on January 14, 2006.

[20] Earlier reports using the Tirunelveli MF radar data indicated significant electric field influence on the drifts measured at 98 km [*Gurubaran and Rajaram*, 2000; *Ramkumar et al.*, 2002]. In the present work because strong echoes were observed at 90 km, the nature of the radar scatterers and their link to electrojet has been examined for this height. Whether the electric field driving the EEJ has any say on the drift motions at 90 km on days chosen for the present analysis is next addressed.

[21] Figure 3 presents the zonal and meridional drifts at 90 km during daytime for January 8, 14 and 18. Referring to the zonal drifts plotted in Figure 3 (bottom), the temporal variations were nearly similar on January 14 and 18, whereas the variation on January 8 was distinctly different. It may be recalled that a large CEJ event occurred in the early afternoon (minimum observed at 1300 IST) on January 14 whereas January 18 was marked by a weak afternoon CEJ (minimum observed at 1630 IST). Though large differences in electrodynamical conditions were noticed on these two days, the drifts measured by the MF

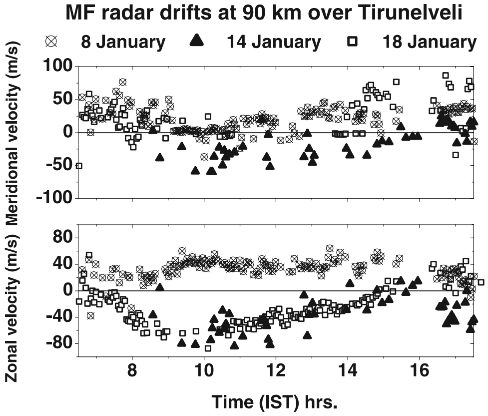

Figure 3. (top) Meridional and (bottom) zonal drifts at 90 km for January 8, January 14 and January 18, 2006. Positive (negative) zonal drift corresponds to eastward (westward) motions and positive (negative) meridional drift corresponds to poleward (equatorward) motions.

radar at 90 km do not reveal any significant difference. Further, though the evolution of EEJ was similar on January 8 and January 18 till noon hours, the drift motions were opposite (mean westward motion prevailed on January 18 whereas the time-mean flow was eastward on January 8). The drifts retrieved for the meridional direction (Figure 3, top) have similar large-scale variation during daytime on all the three days in spite of different EEJ behavior, particularly between January 8 and January 14. These examples suggest that the drifts at 90 km need not have been driven by the electric field and perhaps they represent the neutral wind.

4. Discussion

[22] MF radars have been traditionally used to obtain useful wind measurements in the mesosphere-lower thermosphere region. For those radars operating at or close to the magnetic equator, the wind determination is influenced by a possible role of large electric fields associated with EEJ driving the drifts measured at and above 90 km. Several instances have been shown in the earlier work wherein the bulk motions of the ionospheric irregularities at 98 km causing the radar echoes could be related to ΔH [*Ramkumar et al.*, 2002], which is a measure of the overhead current strength. There were also times when the drifts were in directions opposite to that expected for the electrojet flowing eastward during daytime. In the latter scenario, it was suggested that the drifts might be indicative of neutral winds blowing then at that height.

[23] The EEJ is often considered a seat of a variety of plasma instabilities that are driven by the ambient zonal and vertical electric fields and background density gradient of various scale sizes. Much of our understanding of the physics underlying these instabilities has come from VHF/HF radar observations from Jicamarca [e.g., *Farley*, 1985] and from India [*Reddy et al.*, 1987] and Africa [*Crochet et al.*, 1979]. Later observations from Pohnpei [*Tsunoda and Ecklund*, 1999] and from Brazil [*Abdu et al.*, 2002] have brought out the complexities in the generation of the irregularities in the EEJ region.

[24] *Chandra and Rastogi* [1973] carried out HF spaced receiver experiments from the Indian equatorial station, Thumba, in the mid- to late sixties. A close link between the measured drifts and the EEJ was established then. With the co-located ionosonde, it was demonstrated that fast fading, westward drift and highly elongated ground diffraction pattern resulted when E_{sq} was present. On the other hand, during periods when there was no E_{sq}, slow fading, eastward drift motions and near-isotropic ground diffraction pattern were noticed.

[25] The presence of intense MF radar echoes at heights as low as 90 km during strong EEJ conditions is a new observational feature reported in this work. Unlike the earlier work by *Gurubaran and Rajaram* [2000] and *Ramkumar et al.* [2002] wherein hourly averages were used and only drifts and pattern decay times were examined, the present work has made use of the near 2-minute samples and the whole sets of the antenna and geometrical parameters retrieved from the full correlation analysis were examined.

[26] With vertically transmitting antennas having wide beamwidth, the MF radar is expected to detect scatterers of large scale sizes that could be associated with the type II irregularities. It is well known that the daytime eastward electric field responsible for the EEJ drives intense type II plasma density irregularities when the vertical polarization field it produces is in the same direction as the background vertical plasma density gradient [*Kelley*, 1989]. Because the majority of intense MF radar echoes are observed when the overhead current strength is maximum, it is anticipated that favorable conditions for the generation of plasma density irregularities responsible for the radar echoes occur when the primary electric field that drives the EEJ is strong. Further, intense echoes are observed to arise from those irregularities which are largely magnetic field-aligned. During CEJ conditions, the intensity of the echoes from 90 km and above seems to diminish, reflecting the weakening of the relevant plasma instability mechanism as expected because of the weakening of the eastward electric field. Randomly oriented patterns and longer pattern lifetimes estimated during CEJ events provide support to this view. The ionograms retrieved from the digital ionosonde operating at Trivandrum, a nearby equatorial site, do not reveal the presence of blanketing type of echoes during the afternoon hours on January 14, though the E_s layer disappeared at around 1500 IST and reappeared later during the evening hours (T. Pant, private communication, 2006).

[27] With regard to the drift velocity estimates, the detected bulk motions of the scatterers at 90 km do not appear to be driven by the electric field, though other parameters (pattern orientation, for example) reveal strong link to the changing electrodynamical conditions associated with EEJ. One noticeable feature is the eastward drift observed during most of the day on January 8, 2006. One would not expect type II irregularities arising from the cross-field or gradient drift instability for eastward electron drifts. Because the EEJ was fully developed on this day, it is not known whether the large-scale motions detected by the radar do represent the electron drift. *Tsunoda and Ecklund* [1999] observed a counter-streaming region below 95 km in their VHF radar observations from Pohnpei. They ascribe

the westward current to a downward directed electric field associated with positive charge accumulation near the base of the eastward electrojet. Further, addressing three important issues pertinent to their low altitude observations, they emphasize a gradient drift instability mechanism acting on a large-scale plasma density structure driven possibly by neutral turbulence in order to explain the type II echoes in the counter-streaming region.

[28] Useful physical insights into the processes that cause the observed MF radar drifts could be obtained when a comparison is made with VHF radar observations for heights below 100 km, the useful probing region for the MF radar. Due to the non-availability of VHF radar data from Trivandrum for the period under study, this exercise could not be pursued herein. A digital ionosonde was installed recently at Tirunelveli and efforts are being made by the authors to deploy a VHF radar at this site. Complementary data from colocated digital magnetometer, ionosonde and VHF radar would be extremely valuable to interpret the MF radar drift observations. It would also help to assess the differences in the echo characteristics as observed by the two radar techniques because each of them views a different echoing region and the scatterers causing the observed echoes are characteristically different.

5. Conclusion

[29] Making use of radar observations on a few selected days during January 2006, the present investigation provides further evidence for the electric field influence on the MF radar scatterers in the lower E region over the magnetic equator. A significant observed feature not reported earlier is the alignment of the radar scatterers at altitudes as low as 90 km along the geomagnetic field when the EEJ is strong. Under reverse electrojet conditions, the echo intensities decrease and the orientation of the geometrical pattern produced by the scatterers is randomized. The exact nature of the electric field acting upon the local plasma to generate irregularities responsible for the MF radar scattering at heights as low as 90 km is largely unknown. A detailed investigation is required to address this fundamental issue.

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