Observation of coherent echoes with narrow spectra near 150 km altitude during daytime away from the dip equator

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Received 19 April 2004; revised 27 August 2004; accepted 9 September 2004; published XX Month 2004

[1] We present the rare observation of backscatter echoes perpendicular to the geomagnetic field from the 150 km altitude vicinity over a region situated away from the dip equator, namely, at Gadanki (13.5\(^\circ\)N, 79.2\(^\circ\)E, 6.4\(^\circ\) dip latitude). A layer of weak echoes, having Signal-to-Noise Ratio (SNR) of the order of -12 to -3 dB, was seen drifting downward from 157 km at 0930 LT to about 148 km at 1028 LT on July 12, 1997. The Doppler velocity as well as Doppler Width was in the range 10–20 m s\(^{-1}\). While there was no quasi-periodicity as such in terms of echo occurrence, the echo properties were in other respects very similar to 150 km echoes seen in equatorial regions. This included the descending phase with time during the morning hours. These constitute the first observations of daytime 150 km echoes away from the dip-equator and only add to the mystery regarding the origin of these structures.


1. Introduction

[2] The observation of magnetic field-aligned radar echoes from the upper E-region during the daytime has been a regular phenomenon at the dip-equator. Initial reports on echoes from the height region between 140 km and 180 km came from the Jicamarca radar [Balsley, 1964; Royvirk, 1982; Royvirk and Miller, 1981]. The echoes were described as weak non-thermal echoes and were simply labeled “150-km echoes”.

However, since these observations were conducted with a relatively coarse range resolution of 2.4 km, many details of the irregularity structures inside the 150-km echo band could not be revealed. Interest in these echoes was therefore renewed after Kudeki and Fawcett [1993] reported on some unique features associated with them when they operated Jicamarca at a range resolution of 375 m. Not only did they observe a “necklace” pattern in the temporal evolution of the echo intensity as a function of height but they also suggested that the Doppler shift of the echoes could be used to determine the drift of the plasma. This Doppler shift hypothesis was later shown to be true by Woodman and Villamayor [1995]. The necklace pattern itself came from the motion of the structures, as they moved systematically in altitude, from 170 km in the morning, down to 140 km around noon, and back up to 170 km in the afternoon. The quasi-periodic variation in echo intensity with respect to time constituted the “pearl” in the “necklace”.

The 150-km echoes have now been reported from almost all HF and VHF radars operating in the vicinity of the dip-equator, that is: the Pohnpei radar in the Pacific [Kudeki et al., 1998], the HF radar at Sao-Luis in Brazil [de Paula and Hysell, 2004], and the HF radar on the Ivory Coast in Africa [Blanc et al., 1996] (although in this latter case the genuine 150-km echoes were seen at a 180 km range because of the very low frequency that was being used [Farges et al., 1999]). These echoes, however, have never been reported from any of the mid or low latitude VHF/HF radar locations. The lack of occurrence in low or mid-latitude stations has given rise to the notion that the 150 km echoes may have been an exclusive “dip-equator” phenomenon. Indeed Kudeki et al. [1998] reported that “a large low latitude VHF radar system at Tirupati, India, the Indian MST radar, has been used to search 150-km irregularities with no apparent success”. In view of the keen interest of the radar community in the 150-km echoes, we therefore wish to report in this paper on the detection, for the first time, of coherent echoes observed near 150 km altitude during daytime by the Indian MST radar at Gadanki.

2. Experimental Setup

[4] The Gadanki radar is a highly sensitive, pulse-coded, coherent VHF radar operating at 53 MHz. The antenna system has a physical dimension of 130 m × 130 m and has a peak power aperture product of 3 × 10\(^{10}\) Wm\(^2\). The phased array consists of 32 × 32 three-element Yagi antennas and emits radiation at a peak power of 2.5 MW. The radar can transmit both coded and uncoded pulses with 90 inter pulse period in the range of 1 ms to 16 ms. The uncoded pulses can vary in pulse width from 1 to 32 \(\mu\)s in 2\(^{n}\) multiples of 2. The coded pulses are either 16 or 32 baud biphase complementary pairs with baud length of 1 \(\mu\)s. The transmitter can operate up to a maximum duty cycle of 95.25%. The antenna generates a radiation pattern with a main beam unidirectional. The received beamwidth with a 1 dB drop is 43\(^\circ\). The two-way range resolution is 2.4 km. The antenna is biphase complementary pairs with baud length of 1 \(\mu\)s. The transmitted signal is a linear frequency modulation (LFM) pulse of 32 baud biphase complementary pairs with baud length of 1 \(\mu\)s. The transmitted signal is a linear frequency modulation (LFM) pulse of 32 baud biphase complementary pairs with baud length of 1 \(\mu\)s.
lobe 3° wide, a gain of 36 dB, and a side-lobe of −20 dB.

More details on the radar system may be found in work by Rao et al. [1995].

The orientation of the narrow antenna beam of the Gadanki radar at 13° zenith angle due North satisfies the perpendicularity condition at E-region heights. We used this beam on June 24–25, 1996; July 08–12, 1997; August 21–22, 1997 and August 16–23 2001 between 0830 and 1800 LT to study the field-perpendicular echoes from the upper E region. Experiments were conducted using a 8 µs un-coded pulse with an inter-pulse period of 2000 ms. This yielded a range resolution of 1.2 km. The range coverage was between 85 and 180 km. The data were sampled with 128 fast Fourier transform (FFT) points using 4 coherent and 8 incoherent integrations. The experiments, in this way, were conducted with an unambiguous range coverage of 300 km, a Nyquist window of ±180 m/s and a velocity resolution of 2.6 m/s. The statistical uncertainties associated with the estimation of Doppler velocity were comparable to the velocity resolution: for radar echoes with our SNR, which was of the order of −12 to −3 dB (as shown below), the uncertainty in the Doppler shift and Doppler width had to be of the order of 5 to 10% [Ferrat and Crochet, 1994; Choudhary, 1998].

[6] We present here a rare event for which field-aligned echoes from the upper E region were observed on July 12, 1997, between 0930 and 1028 LT.

3. Results

[7] The spectral characteristics of field-aligned echoes received from the height region between 90 and 140 km at Gadanki show that lower E-region echoes are of a “type-II” nature, namely, they have Doppler velocities of the order of 20–60 ms⁻¹ with comparatively large Doppler widths of the order of 20–120 ms⁻¹ [Choudhary et al., 1996]. By contrast, the Doppler width of echoes received from the 150-km range is narrow while also less powerful than their lower E-region counterparts. In Figure 1 we present an example of the spectrum of echoes received between 145 and 165 km range. The signal-to-noise ratio associated with these echoes is low compared to normal E-region echoes, being in the range of −12 to −3 dB.

[8] In Figure 2 we present the altitude profile of signal-to-noise ratio (SNR) obtained at 09:54:39 LT, 10:01:23 LT, 10:11:29 LT and 10:21:16 LT. Clearly, echoes with SNR as low as −12 dB are above the average noise level, which is of the order of −15 dB. We conclude from this that radar echoes in excess of −12 dB can be assumed to be genuine field-perpendicular echoes from the ionosphere.

[9] One should also note the descendence of weak echoes with respect to time in Figure 2. While at 09:54:39 LT echoes appear between 156 and 158 km, they move down to 150–152 km by 10:21:16 LT. To better show this temporal evolution, we present in Figure 3 the height-time intensity contour plot of backscattered power received from all range. The signal-to-noise ratio associated with the upper E region echoes observed on July 12, 1997. Each cell covers roughly 1.2 km in height. See color version of this figure in the HTML.
heights between 144 km and 177 km for the interval 0925 LT to 1028 LT (note that echoes from the 150 km height range were observed only during the period shown, despite the fact that the radar was operating throughout the day). The signal intensity has been plotted in Figure 3, using nine shades of pixel coding between −12 and −3 dB.

[10] From Figure 3, it can be seen that the echoes were located near 158 km at 0930 LT before drifting down to about 145 km by 1028 LT. The echo layer, 2–3 km thick, therefore descended approximately 10 km in one hour. This gives a ‘radar rate’ associated with the echoes of the order of 3 ms$^{-1}$. This is much larger than the estimate from the lower E-region, which is of the order of 0.5 ms$^{-1}$.

[11] For a study of the other spectral characteristics of the upper E region echoes seen at Gadanki, we also produced in Figure 4 a scatter plot of the line-of-sight Doppler velocity and Doppler width versus altitude. Figure 4 shows that the line-of-sight Doppler velocity and the Doppler width are both of the order of 10–20 ms$^{-1}$ in magnitude. This makes the echoes received from the 150-km height region inherently different from their lower counterparts with their broader spectra and larger Doppler shifts [Choudhary et al., 1996].

4. Discussion and Conclusions

[12] The echoes discussed in the previous section have properties that are distinct from lower E region echoes. This alone rules out the fact that they could have been coming from the E region trough side-lobes. In addition, if side-lobes had been involved, one would have to explain why their effects would not be seen more often. Another possibility for an artifact would be range aliased echoes coming from 300 km above the nominal 150 km region. However, once again, the spectral properties, including the Doppler shift, are quite different from the F region, not to mention the fact that the periodicity of the diurnal tide prevailing at those heights. Finally, Figure 3 is suggestive of a modulation in echo occurrence. A close look at the data suggests that the periodicity of this modulation decreases with height and time, being of the order of 12–15 min near 152 km and going down to 5–7 min by 146 km.

[13] Upper E region echoes are routinely observed at the dip-equator and are simply labeled as “150-km echoes”. Their properties have many similarities to the Gadanki echoes, which is another reason to believe they are not an artifact. Like 150-km echoes at the dip-equator, the Gadanki echoes descended in altitude during the morning hours. The fact that the echoes observed at Gadanki were less powerful than the lower E region echoes is also a feature which is common to the dip-equator. Lastly, the range of Doppler Velocity and Doppler width observed at Gadanki is similar to what we see at dip-equator.

[14] There are, nevertheless, some differences between Gadanki upper E region echoes and similar echoes observed at the dip equator. In particular, at Gadanki, the upper E region echoes were observed only during a limited time period of about one hour between 0930 and 1028 LT on July 12, 1997 in spite of the fact that the radar operated on several other days but could not observe the echoes again. It may be worth noting that the echoes on July 12, 1997 disappeared in spite of the fact that the sky noise was becoming weaker, thereby indicating that the triggering mechanism had itself disappeared by 10:28 LT (the sky noise peaks when the center of the galaxy is overhead. In Gadanki’s case this was at 0703 LT).

[15] In what is probably a related feature, backscatters from 150-km at Jicamarca are also far more powerful than at Gadanki. This conclusion is based on the following considerations: Jicamarca measures its SNR in the range of 20–25 dB, while Gadanki recorded its echoes in the range of −12 to −3 dB, that is, up to 12 dB above noise level. However, we must also compare the detectability of the Gadanki radar to that of the Jicamarca radar. The experiment at Gadanki was performed at 0.4% duty cycle of the peak power (2.5 MW) of radar. The effective antenna area of Gadanki is 1.69 × 10$^4$ m$^2$. Given the fact that the experiments were conducted with a 1200 m range resolution and 20 sec time resolution, the system sensitivity at Gadanki could be improved either by using an enhanced radar duty cycle and/or by increasing the temporal resolution in the future efforts to observe these echoes. However, for the present set of observations, considering the 10 dB system sensitivity factor, we find that upper E region echoes from Jicamarca are at least 20 dB stronger than at Gadanki. This in turn suggests that the m-size irregularities over 150 km at Gadanki are far more weakly-driven than their Jicamarca counterpart.

[16] While the spectral and morphological similarities between the Gadanki echoes and dip-equator observations lead us to believe that they probably share the same generation mechanism, the rarity of the Gadanki observations and their relatively weak power also lead us to conclude that whatever the generation mechanism, it operates much less efficiently at the Gadanki latitude than at the dip equator. One mechanism that first comes to mind when dealing with 150 km echoes is the interchange (gradient-drift) mechanism. It could be argued that during the daytime, the electron density gradient points up starting around 150 km altitude. In addition, the plasma drift generated by the ambient electric field is upward. This favors the growth of an F-region type of a gradient-drift instability, albeit primarily for large structures and with a horizontal wave-vector. Nevertheless, as in seen in countless examples...
in the ionosphere [Kelly, 1989], these primary structures could, through cascading and turbulence, in turn generate the smaller scale structures responsible for the backscattering of field-perpendicular echoes along the vertical. While this description explains why the 150 km region is favored (upward density gradients) and goes well with the observation of an upward drift equal to the ambient plasma drift, one major problem with the mechanism is that, as correctly pointed out by Kudeki and Fawcett [1993], the primary gradient-drift waves themselves are actually heavily damped by chemical recombination. Thus, we should not, on this basis, expect the growth of structures of any size through the classical gradient-drift mechanism under the conditions thought to exist near the dip equator at 150 km.

[17] The above considerations led Kudeki and Fawcett [1993] to invoke Atmospheric Gravity Waves (AGW) as the trigger mechanism. They got this notion from the observation at Jicamarca of the quasi-periodicity of the fluctuations in the echo intensity, which was deemed responsible for rendering a pearl shape in range-time intensity plots. In particular, the 10–15 minute quasi-periodicity was rather comparable to what could be expected from shorter period AGW’s. According to Kudeki and Fawcett [1993], AGW’s would produce horizontal density fluctuations in the plasma by inducing divergences (along the geomagnetic field lines if nothing else). The waves would also introduce vertical electric fields (that is, zonal plasma motion) through the action of their zonal wind fields. With this, small scale perturbations elongated along the east-west direction (vertical wave-vectors) could grow with the aid of the gradient drift/interchange mechanism provided the zonal drift was large enough, namely, of the order of 100 m/s according to Kudeki and Fawcett [1993]. One difficulty with the idea however is that the AGW zonal electric field would be shorted out by field aligned currents along the magnetic field (as evidenced by the clear connection between irregularity drift and the electric field of the region of density minimum between the E and F regions. [18] Another possibility brought up by Tsunoda [1994] is the mapping of a vertical electric fields from the lower E-region up to the 150 km height range along the magnetic field line. This mechanism has the advantage of not having the vertical electric fields short-circuited by the E region, since it is the E region itself that generates them. As geomagnetic field lines at 150 km over the dip-equator connect to the E-region at low latitudes, the magnetic field line integrated polarization process might be able to provide large enough fluctuations in the electric field to counter the damping recombination rate. A horizontal modulation in the density would still be needed for this mechanism to operate, raising once again the possibility of at least a partial role being played by AGW’s. Going back to the generating fields: Tsunoda and Ecklund [2004] have argued that the field line over 150 km at Pohnpei, which is at the dip-equator, maps to 105 km at 5.7° dip latitude, just where intense blanketing sporadic E (E_{sh}) are common. In their morphological study, Tsunoda and Ecklund [2004] further showed that the frequency of occurrence of 150-km echoes at Pohnpei matched the frequency of occurrence of intense E_{sh} at the geomagnetic connecting region. The E, layer instability proposed by Cosgrove and Tsunoda [2002] was brought forth to generate the vertical polarization electric field that could be mapped along the magnetic field line to provide sufficient electric field to sustain a gradient-drift instability process at 150 km altitude. One difficulty here, however, is that the theory has been advanced for nighttime situations and 150 km echoes are a daytime phenomenon. This aside, we note that the electric field predicted by the [Cosgrove and Tsunoda, 2002] theory should be 19 degrees east of vertical (R. Cosgrove, private communication, 2004), basically in the right direction for the excitation of structures with a near vertical wave-vector. No matter what, a key question to resolve before accepting either the AGW or the Cosgrove mechanisms is why the preferred altitude for excitation would be near 150 km, that is, right around the region of density minimum between the E and F regions.

[19] At this point therefore, with the theoretical avenues that have so far been proposed, one still has to either invoke the presence of electric fields and/or winds that have yet to be widely accepted or documented and to describe why 150 km would be a favored altitude, or one has to somehow find a way around the chemical recombination issue. In the latter case, it may be that there could be enough metallic ions being lifted up by the equatorial fountain effect to slow down the chemical effects enough to see weak irregularities (J. MacDougall, private communication, 2004). A larger amount of metallic ions than expected would reduce (but not nullify) the need for reasonably strong localized electric fields by slowing down the chemical recombination rate.

[20] What then of the unusual circumstances that created 150-km echoes at Gadanki? The rarity of our observations could perhaps have something to do with unusual Es conditions taking place in the E-region, 5 to 7 degrees north of Gadanki. Alternatively there might have been an unusual amount of metallic ions and/or AGW activity at 150-km height region over Gadanki on the day the echoes were observed. Possibly, the observations might have even required a combination of these factors.

[21] Acknowledgments. The National MST radar facility (NMRF) is operated as an autonomous facility under DOS with partial support from CSIR. The work of RKC and JPSS has been supported by Canadian National Science and Research Engineering Council. KKM is thankful to CSIR, India, for an Emeritus Scientist award.

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