AN EXPERIMENTAL EVIDENCE OF NON-DUCTED PROPAGATION DURING DAYTIME FROM THE ESD WHISTLER OBSERVATIONS AT LOW LATITUDE GROUND STATION JAMMU

LALMANI[1], MADHU KAUL BABU[1], RAJOU KUMAR[1], RAJESH SINGH[2] and
KRISHNA KUMAR SINGH[3]
[1]*Department of Physics, Regional Engineering College Srinagar, Camp Jammu, Canal, Road Jammu – 180001, India;* [2]*Atmospheric Research Lab., Physics Department; and* [3]*Applied Physics Department, Institute of Technology, Banaras Hindu University, Varanasi-221005, India*

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Abstract. The propagation mechanism of low latitude daytime whistlers is investigated on the basis of ground measurements made continuously during daytime in North India at Jammu (geomag. lat. 22°26′ N; L = 1.17). On February 14, 1998 extremely small dispersion (ESD) whistlers with dispersion varying from 5–10 sec$^{1/2}$ in surprisingly large numbers were recorded at Jammu during daytime in the late afternoon. The results of a study of the characteristics of ESD whistlers are presented and the discussion indicates that ESD whistlers recorded are the VLF waves radiated from the return stroke of the lightning discharge launched at the ionosphere with different initial wave normal angles, propagated upwards under either quasi-longitudinal conditions or pro-longitudinal whistler mode, turned around at different heights due to quasi-transverse propagation and received at Jammu with the dispersion of the order of 5–10 sec$^{1/2}$. The validity of this suggestion has been tested by performing actual ray-tracing computations in the presence of equatorial anomaly model.

Keywords: Dispersion, magnetosphere, whistlers

1. Introduction

The investigation of whistler waves were pioneering and heuristic in Space Physics. It is well known that lightning discharges are accompanied by the generation of electromagnetic waves in a wide frequency range (Pathak et al., 1982; Prasad and Singh, 1982). The broadband very low frequency (VLF, 0.3–30 kHz) radiation from the lightning propagates in the Earth – Ionosphere cavity as impulsive signals (spherics) and in the dispersive plasma regions of the ionosphere and magnetosphere it propagates as tones of descending or rising frequency (whistlers) (Helliwell, 1965). The study of whistlers and related ionospheric radio noise phenomenon first began in 1989. Since the pioneering work of Storey (1953), who was the first to give a correct interpretation of whistler spectra in terms of magneto-ionic theory, the observation of whistlers has been continued over a wide range of high to low latitudes (Hayakawa and Tanaka, 1978). Originally whistlers were looked upon essentially as middle and high latitude phenomena but the pioneering work of Indian and Japanese scientists during the last two decades have not only detected

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whistler traces at much lower latitudes but have also established many of their new morphological features. A wide variety of whistlers recorded during day and night times at low latitude ground stations are markedly different from those recorded at middle and high latitudes (Somayajulu et al., 1972; Hayakawa and Tanaka, 1978; Hayakawa and Ohta, 1992; Singh, 1993, 1997; Ohta et al., 1997; Lalmani et al., 2000).

It is now reasonably well established that whistler waves propagate in the ionosphere and magnetosphere in two different modes, mainly ducted and nonducted. The ducted propagation is characterised by their confinement to the field-aligned columns of enhanced or depleted ionisation (Smith, 1960, 1961; Helliwell, 1965) whereas the nonducted propagation is characterised by simple propagation controlled by electron density and magnetic field gradients (Cerisier, 1971, 1972, 1973; Hayakawa and Tanaka, 1978).

Although whistlers have been extensively observed at low latitude ground stations (see Hayakawa and Ohta, 1992 for a review), relatively few cases have been reported of satellite observations (Bullough et al., 1975; Hayakawa et al., 1992). One of the principal conclusions of ground-based whistler studies at low latitude station is that while some of the whistlers observed on the ground propagated in ducts, a nonducted propagation path is needed to explain the properties of a large number of low latitude whistlers. This is primarily due to (1) the relatively high curvature of the low latitude field lines which requires unreasonably large enhancements ($\sim$100%) in density to effectively guide the waves along the field lines, and (2) the requirement of favourable ionospheric tilt at the duct entrance and exit (see for a detailed discussion, the introduction of Tanaka and Cairo, 1980).

Low latitude whistlers are characterized by a sharp occurrence peak in the daytime and a broad small maximum in the post-midnight period (Hayakawa and Tanaka, 1978). Daytime whistlers are found to appear during the very restricted hours in the late afternoon. Their rate of occurrence is extremely high, mainly in the form of multifiash whistlers, and hence the dispersion remains nearly constant. On the other hand, nighttime whistlers are observed over a wide time interval but generally peak in the early morning, and their dispersion is widely distributed (Hayakawa and Tanaka, 1978). The daytime and nighttime whistlers are quite different from each other in respect of their different propagation mechanisms. In particular, much evidence has accumulated to indicate ducted propagation for the daytime whistlers at low latitudes. It is also suggested that the daytime whistlers are associated with the equatorial anomaly of the ionosphere (Hayakawa et al., 1990). Indirect evidence of ducted propagation of daytime whistlers has been obtained by means of the simultaneous observations of a multistation network (Hayakawa and Ohtsu, 1973; Kohtaki et al., 1974). Iwai et al. (1974, 1976) have obtained in situ evidence of ducted propagation for daytime whistlers from their measurement of wave normal directions aboard a rocket. Hayakawa and Tanaka (1978) have made a comprehensive review of the propagation of low latitude whistlers, where they have clearly shown the ducted propagation for the daytime whistlers on the basis of not only observational but also theoretical studies.

In order to obtain further understanding of the propagation mechanism of low latitude daytime whistlers and to supplement the earlier findings, we have carried out whistler measurement at our newly installed ground-based station Jammu (geomag. lat., 22°26′ N; $L = 1.17$) in the year 1997. Using standard whistler recording system at our field station Jammu, we have observed extremely small dispersion (ESD) whistlers during daytime in significant numbers. However, to our knowledge such daytime ESD whistlers have never been reported from any of the low latitude ground station so far. From the dispersion analysis of the daytime whistlers recorded at Jammu, it is found that all the whistlers have extremely small dispersion in the range of 5–10 $s^{1/2}$. Such ESD whistlers can only be explained with the help of nonducted propagation. Thus the observation of ESD whistlers at Jammu provides an indirect and strong evidence of nonducted propagation of daytime whistlers at low latitudes, completely in contrast to the earlier findings of ducted propagation of low latitude daytime whistlers.

It is the purpose of this paper to present results of ESD whistlers recorded at our field station Jammu and to discuss critically the origin of ESD whistlers and propagation mechanisms of daytime whistlers in support of nonducted propagation at low latitudes. An attempt has been made to explain, by the ray tracing technique, the ESD whistlers observed at our low latitude ground station Jammu. Ray tracing studies were carried out specifically to explain the lower and upper cut-off frequencies of the observed ESD whistlers, and hence their dynamic spectrum.

2. Data Selection and Analysis

The recording of whistlers at our low latitude ground station Jammu was started in the month of December, 1996 on routine basis. At low latitudes, the whistler occurrence rate is low and sporadic. But once it occurs, its occurrence rate becomes comparable to that of mid-latitudes (Hayakawa et al., 1988). Similar behaviour has also been observed at our low latitude Indian station Jammu. For the present study we have chosen some whistler events recorded during daytime at our ground station Jammu on February 14, 1998 as a large number of whistlers were observed on this day. On February 14, 1998, the spurt in activity started around 1230 IST (Indian Standard Time) and lasting for about 5 hours, ending finally at 1730 IST. During this period about 100 whistlers were observed. The period of observation was magnetically quiet with total K_p index = 11 (average $K_p \sim 1$).

For spectral analysis we use the normal procedure of analysis by means of Sonographic Equipment. Detailed spectrum analysis have been done for the daytime whistlers on February 14, 1998, in order to study the propagation characteristics of these whistlers. From the detailed analysis it is found that the measured values of all the recorded whistlers on this day have extremely small dispersions lying in the range of 5–10 $\sec^{1/2}$. A sample record of the ESD whistlers observed on February 14, 1998 is shown in Figure 1 out of a huge collection of similar events recorded on this day. Figure 1a shows a single trace of a short whistler (W_1) of dispersion $\sim$10 $\sec^{1/2}$ with distinct causative atmospherics. Figure 1b depicts two multifiash whistlers (W_2 and W_3) having same dispersions of 10 $\sec^{1/2}$. A single short whistler (W_4) of dispersion 5 $\sec^{1/2}$ is shown in Figure 1c. Figure 2 illustrates the temporal evolution of the occurrence rate of whistlers at our low-latitude station Jammu during daytime on February 14, 1998. As seen from the figure, the occurrence rate peaks at around 1300 IST to 1350 IST. This is in good agreement with the earlier results reported by other workers at low latitudes (Hayakawa and Tanaka, 1978; Hayakawa et al., 1990). Figure 3 depicts occurrence histogram of dispersion values for whistlers recorded on February 14, 1998 at Jammu. This figure shows the maximum number of occurrence of ESD whistlers with dispersions around 7 $\sec^{1/2}$ in contrast to the dispersion values reported earlier from the low latitude ground stations (Hayakawa and Tanaka, 1978).

3. Results and Discussion

The measured dispersion values of all the recorded whistlers on February 14, 1998 during daytime are found to be extremely small lying in the range of 5–10 $s^{1/2}$. The observation of such daytime ESD whistlers provide an indirect and strong evidence in support of nonducted propagation of daytime whistlers at low latitudes. The daytime ESD whistlers recorded at Jammu are found to obey the Eckersley law (dispersion being constant with frequency), thereby indicating that the whistlers had a quasi-longitudinal whistler mode of propagation with a right handed circular polarisation. The normal dispersion values of whistlers observed at Jammu should be about 22 $s^{1/2}$ based on the minimum critical frequency of the F2-layer and the electron number density at the equatorial height of the geomagnetic line of force corresponding to Jammu, and from the regression line given by Hayakawa and Tanaka (1978) and also based on the Allcock's formula (Allcock, 1960). The observation of such ESD whistlers provides us an indirect and strong evidence in support of nonducted propagation of daytime whistlers at low latitudes. Table I shows the details of ESD whistlers recorded during daytime on February 14, 1998 at Jammu.

Hayakawa and Tanaka (1978) have shown ducted propagation of daytime whistlers based on the simultaneous observations of a multistation network and measurement of wave normal directions aboard a rocket. The propagation characteristics of the ESD whistlers recorded at Jammu on February 14, 1998 during daytime are not clear. Here, we discuss the propagation characteristics of these daytime ESD whistlers thoroughly. It is well known that whistlers are propagated in the ionosphere and magnetosphere in two different modes of propagation, namely, ducted and nonducted modes. While the majority of whistlers recorded on

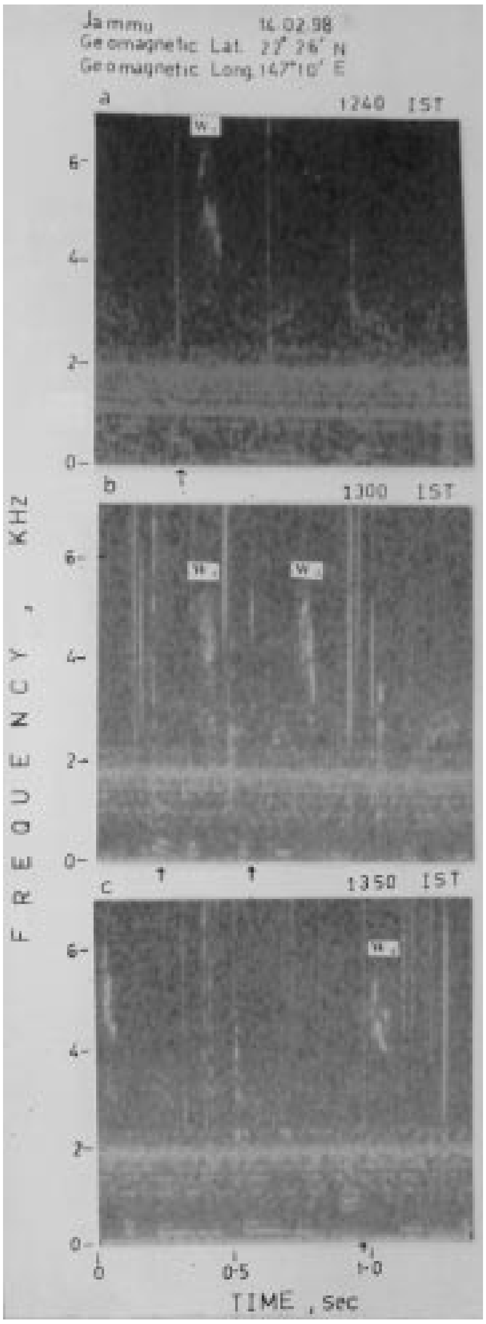

Figure 1. Sonographs of daytime whistlers recorded at Jammu on February 14, 1998.

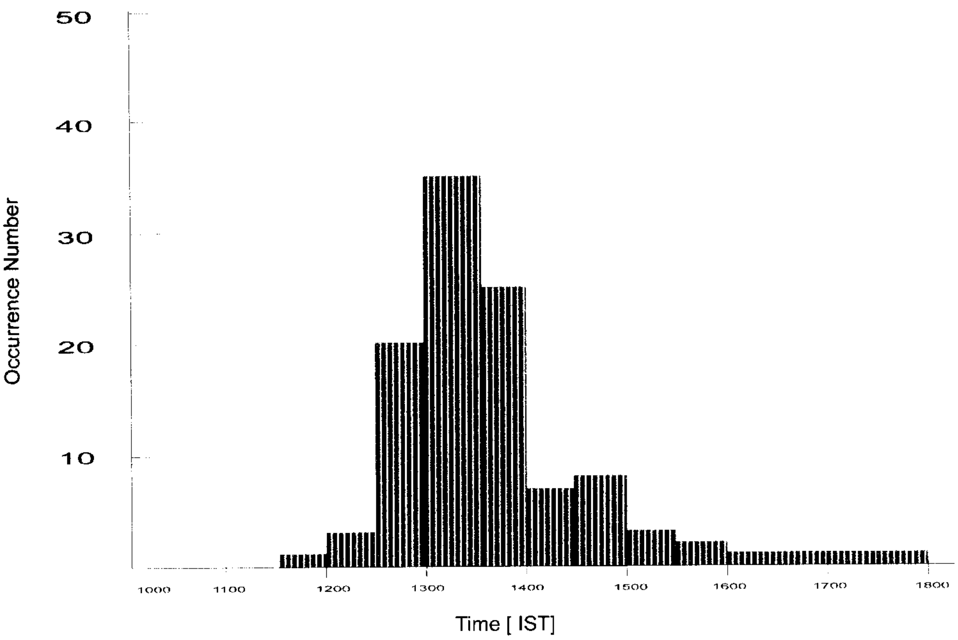

Figure 2. Temporal evolution of the occurrence rate of ESD whistlers at low latitude ground station Jammu observed on February 14, 1998.

TABLE I

Details of extremely small dispersion daytime whistlers observed at low latitude ground station Jammu (*L* = 1.17) on February 14, 1998

Time	Dispersion	Lower cut off	Upper cut off
1240	10	4.42	6.42
1300	10.3}multiflash	3.92	5.42
	10 }whistlers	3.21	5.35
1350	5	3.86	5.14

the ground are interpreted in terms of ducted mode, the nonducted whistlers are not transmitted to the ground on account of large wave normal angles associated with them and hence they are recorded mostly in the satellites. The prolongitudinal mode is a special case of nonducted propagation in which the travel time and associated wave normal directions are characteristics of ducted modes of propagation, and in this mode of propagation, whistlers can be observed on the ground also (Scarabucci, 1969; Singh, 1976, 1997)

In order to arrive at the best plausible propagation mechanism for daytime ESD whistlers recorded at Jammu, two different interpretations have been proposed.

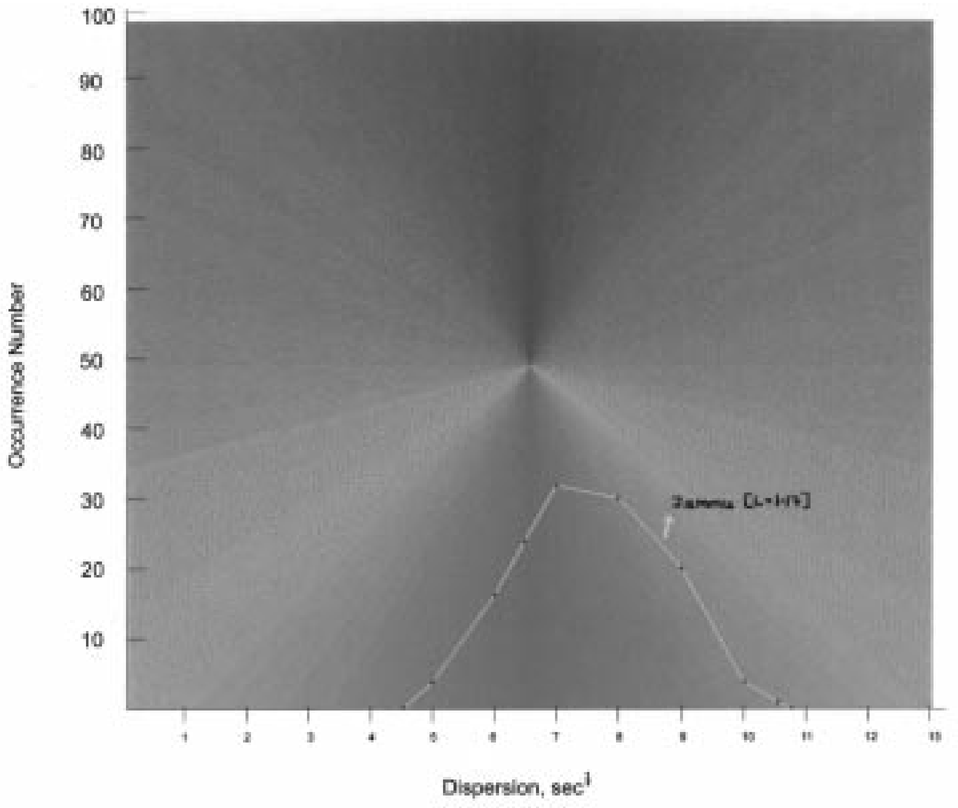

Figure 3. Occurrence histogram of dispersion values for daytime ESD whistlers recorded at Jammu on February 14, 1998.

The first is the field – aligned ducted propagation suggested by Tsuruda et al. (1964) who speculated a hybrid propagation in which they assumed that the source region is around the magnetic equator and the field-aligned mechanism is present at latitudes as low as 10°. However, Tsuruda et al. (1964) have not observed any traces of hybrid whistlers. This problem was re-examined by Okuzawa and Horita (1974) and concluded that the field-aligned propagation model does not apply to ESD whistlers. The second and very promising mechanism was originally given by Ohtsu (1963), who has suggested that a small dispersion of 5 $s^{1/2}$ could be due to oblique propagation effect such that the angle between the wave normal and the geomagnetic field directions happens to be relatively large at low latitudes. Similar mechanism have also been proposed by Dikshit et al. (1971) and Singh et al. (1972), who have carried out ray tracing of nonducted whistlers in the realistic ionosphere model to explain the small dispersion whistlers observed simultaneously at two stations of Gulmarg and Nainital.

The Ariel 3 satellite study on the association of daytime whistlers with the equatorial anomaly was made by Bullough et al. (1969), who indicated the great enhancement of the spheric wave field intensity in the region of the anomaly. Even if the equatorial anomaly has a drastic influence on the daytime whistlers, how the whistlers are trapped by the anomaly is not yet clear-cut. But there have been no simultaneous measurements of the anomaly and daytime whistlers so far. Recently, Singh (1980) has studied the effect of equatorial anomaly on whistler mode propagation at low latitudes. He has shown from ray-tracing studies that the computed initial and final latitudes of the raypaths in the background electron density model with no anomaly are much different from each other. The final wave normal angle was found to be +11° which indicated that the waves corresponding to raypath can not penetrate the lower ionosphere to be observed on the ground. Further in the presence of equatorial anomaly the final wave normal angles of the raypaths were much higher than that obtained in the case of no anomaly. The final wave normal angles of the raypaths were found to vertically downward closer to ±180°, a condition to the waves to be observed on the ground. Recently, Sonwalkar and Inan (1995) have also shown from their ray-tracing analysis that the presence of equatorial density anomaly, commonly observed in the upper ionosphere during evening hours, leads to the focussing of the wave energy from lightning near the geomagnetic equator at low latitudes. The effect of anomaly is to introduce horizontal density gradients in the ionosphere, which bend the rays equatorward much more rapidly with distance along the ray path than would be the case in the absence of the anomaly.

Early, ray-tracing studies by Hasegawa et al. (1978) have indicated that the enhancement factor for the ducts to be able to trap whistlers at lower latitudes is a few hundred percent, with an additional serious requirement of smaller duct width similar to the work of Singh and Tantry (1973) and Hayakawa and Iwai (1975). So owing to the unrealistically high enhancement factor required, duct propagation at low latitudes seems to be less unlikely than nonducted propagation. Further, Cerisier (1973, 1974) and Smith and Angerami (1968) have also found that nonducted propagation occurs on lower L-shells. Recently, Ohta et al. (1997) have studied the propagation characteristics of very low latitude whistlers by means of three-dimensional ray-tracing computations for realistic ionosphere/magnetosphere models. They have shown that high occurrence rate of echo-train whistlers, observed by Ondoh et al. (1979) and Hayakawa et al. (1990) are attributed to the nonducted propagation. They have concluded that it is possible to find closely spaced set of paths to reproduce the one-hop and three-hop whistlers in the north and to have the dispersion ratio of 1 : 3 by nonducted propagation.

The present results are in agreement with the conclusion of Hasegawa et al. (1978) drawn on the basis of their ray-tracing study on the trapping conditions that the ducted propagation of low latitude daytime whistlers appears to be improbable. The daytime ESD whistlers observed at our ground station Jammu are thus consistent with the suggestion of nonducted propagation at low latitudes given by different investigators (Smith and Angerami, 1968; Singh and Tantry, 1973; Hayakawa and Iwai, 1975; Cerisier, 1973, 1974; Hayakawa et al. 1978) in complete contrast to the well established earlier findings of ducted propagation of daytime whistlers in the presence of equatorial anomaly (Hayakawa and Tanaka, 1978).

In the light of above discussion, we have then made an attempt to determine the propagation characteristics of the daytime ESD whistlers observed at Jammu during a quiet day on February 14, 1998 with the help of ray-tracing technique in the presence of equatorial anomaly. It is shown that the propagation and dispersion characteristics of the daytime ESD whistlers observed at Jammu are most satisfactorily explained if the raytracing computations are carried out on the assumption that the VLF waves radiated from the return strokes of a lightning discharge penetrated the ionosphere and at different entry points, propagated to the opposite hemisphere in the whistler mode and are received on the ground of geomagnetic latitude corresponding to Jammu.

For the computations of raypaths of the daytime ESD whistlers observed at Jammu, we employed equatorial anomaly model similar to that of Singh (1976). Singh (1976) has suggested that the low latitude VLF waves are propagated to the ground station in the pro-longitudinal mode under the influence of negative horizontal density gradient of the equatorial anomaly existing in the low latitude ionosphere around the equator. Now in order to simulate the model of the equatorial electron density distribution in our calculations, we introduce an expression (1) of Singh (1976) for the horizontal density variations (see for details Equation (1) of Singh, 1976). The background electron density model is a diffusive equilibrium model and is similar to that adopted by Chauhan and Singh (1992), Singh and Singh (1997) and Singh (1997) which was represented at the height of 400 kms by an electron density of 1.5×10^5 el.per cc, $O^+ = 95\%$, He = 4.75%, H = 0.25%, and temperature of 1000 °K. Since the computations are done down to 120 km (base of the F-region ionosphere), the ionosphere-exosphere model similar to that of Singh (1976) is also employed.

Using ray-tracing equations and computer programme for two dimensional raytracing of Taylor and Shawan (1974), we calculated raypaths of ESD whistler waves of frequencies from 1 to 8 kHz. Raypath computations for the waves of the frequencies 1 kHz to 8 kHz starting from 25° N to 7° N initial latitudes with about 15° N and 2° initial wave normal angles are found suitable for this purpose. The ray paths arrive at 120 km in the opposite hemisphere at final latitude lying around 22° N with almost the same dispersion as that of the observed daytime ESD whistlers as shown in Figure 4. The waves of the frequencies 1, 2, 3 and 8 kHz which started from 25° N latitude with about 10° initial wave normal angles deviate away from the arriving latitude of the other whistler waves thus explaining the lower and upper cut-off frequencies of the ESD whistlers shown in Figure 1a. Similarly the waves of the frequencies 1, 2, 3, 7 and 8 kHz which started from 7° N latitude with 2° initial wave normal angle deviate away from the arriving latitude of the other whistler waves, thus explaining the lower and upper cut-off frequencies of the ESD whistlers shown in Figure 1c. Using ray tracing technique, the calculated dispersions for the whistlers arriving at the latitude of Jammu is about 5–10 $s^{1/2}$. It

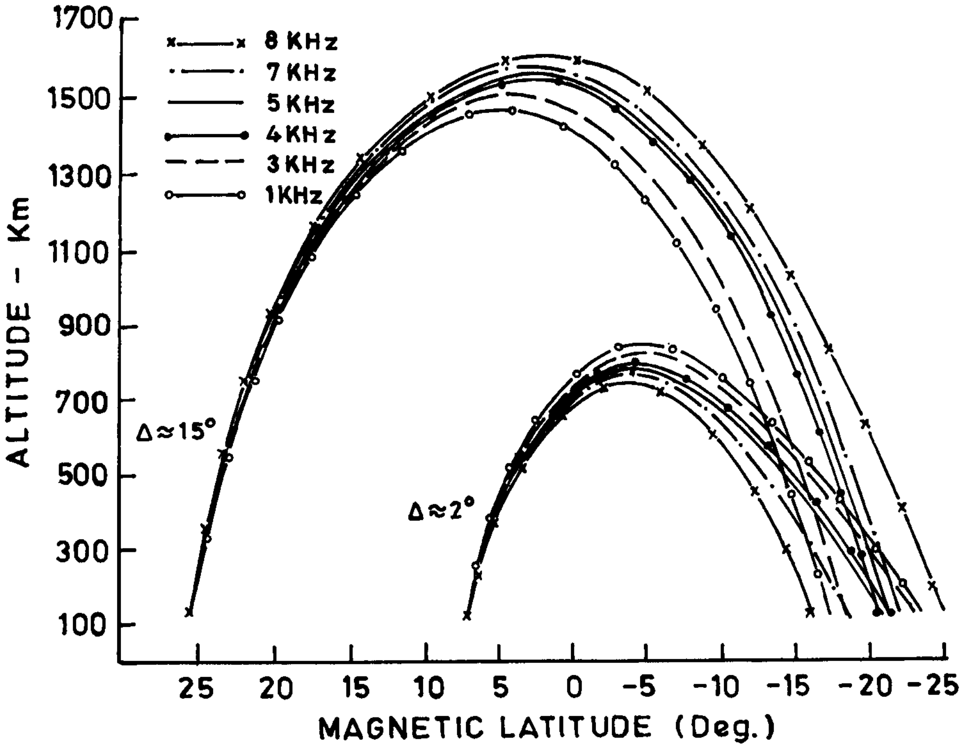

Figure 4. Ray paths for different frequencies computed at 120 km for one-hop whistlers recorded at Jammu on February 14, 1998.

is evident from Figure 4 that daytime ESD whistlers observed during quiet periods on February 14, 1998 attributed to the nonducted propagation in complete contrast to the well established earlier findings of ducted propagation of daytime whistlers in the presence of equatorial anomaly (Hayakawa and Tanaka, 1978).

An extensive study is highly required for the complete understanding of propagation mechanisms of daytime low latitude whistlers. Perhaps a large amount of experimental data on daytime ESD whistlers at low latitudes is required to come to a definite conclusion regarding their propagation mechanisms. However, inspite of above limitation the present exercise is still worthwhile.

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