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Two types of ELF hiss observed at Varanasi, India

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Abstract. The morphology of ELF hiss events observed at low-latitude ground station Varanasi (L = 1.07, geomagnetic latitude 14°55′N) are reported, which consist of two types: (1) events which propagated in ducted mode along the geomagnetic field line corresponding to observing station Varanasi and (2) events which propagated in ducted mode along higher L-values (L = 4–6), after reaching the lower edge of ionosphere excite the Earth-ionosphere wave guide and propagate towards equator to be received at Varanasi. To understand the generation mechanism of ELF hiss, incoherent Cerenkov radiated power from the low latitude and middle latitude plasmasphere are evaluated. Considering this estimated power as an input for wave amplification through wave–particle interaction, the growth rate and amplification factor is evaluated which is too small to explain the observed wave intensity. It is suggested that some non-linear mechanism is responsible for the generation of ELF hiss.

Key words. Ionosphere (equatorial ionosphere; ionosphere–magnetosphere interactions; wave–particle interactions).

1 Introduction

Extremely low frequency (ELF) hiss is a well-known form of electromagnetic emissions that arises in the plasmasphere and has constant spectral density in the limited frequency band (Ellis, 1957, 1960; Helliwell, 1965; Kimura, 1967; Sazhin and Hayakawa, 1992). Although its origin is poorly understood, it is believed that they play an important role in the precipitation of electrons from the radiation belt (Kennel and Petschek,

1966; Chang and Inan, 1983). Global distribution of ELF hiss is characterized by three principal zones of intense activity of which the first is located at invariant latitudes above 70°, the second near 50° and the third below ±30° (Bullough et al., 1975). Low-latitude hiss events occurring below ±30°, also known as equatorial hiss, are less intense than those observed at middle and high latitudes. Jorgensen (1966) showed that the amplitude of VLF hiss decreased with decreasing latitude (10 dB per 1000 kms) and explained it in terms of attenuation of hiss while propagating in the Earth-ionosphere wave guide from the auroral zone to middle and low latitudes. Thus, the low and middle latitude hiss were thought to be a part of auroral hiss (Jorgensen, 1966; Rao et al., 1972).

Several mechanisms have been proposed from time to time to explain the generation of ELF/VLF waves (Kimura, 1967; Sonwalker and Inan, 1989; Sazhin and Hayakawa, 1992; Dragnov et al., 1993). Following the suggestions of Ellis (1957), incoherent Cerenkov radiated power from energetic electrons of the magnetosphere was computed and it was shown that the computed power was less than the observed power (Jorgensen, 1968; Lim and Laaspere, 1972; James, 1973; Taylor and Shawhan, 1974). To explain the discrepancy between observed and computed incoherent radiated power, Maggs (1976) suggested convective beam amplification of the radiation as it propagated through the inhomogeneous ionosphere. Gallet and Helliwell (1959) and Dowden (1962) suggested travelling wave tube mechanism for the generation of VLF hiss. Swift and Kan (1975) studied beam amplification of electrostatic whistlers and argued that the beam amplification mechanism will produce VLF hiss from regions of low ionospheric plasma density at frequencies near the electron plasma frequency. The generation of hiss during resonance cyclotron instability between whistler mode wave and counter streaming energetic electrons is also envoked (Thorne et al., 1979; Ondoh et al., 1983; Church and Thorne, 1983; Helliwell et al., 1986; Sazhin, 1987; Sonwalker and Inan, 1988; Dragnov et al., 1993). In

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all the theoretical treatments it was assumed that the waves are amplified around the magnetic equator while propagating back and forth along the geomagnetic field lines till their intensity reaches the observed intensity. Solomon *et al.* (1988) suggested that the amplification of background noise to observed hiss intensity is also possible.

During routine observations of VLF waves, different types of ELF/VLF emissions are observed at Varanasi. Here observations of ELF hiss are reported and an attempt is made to discuss its generation mechanism. The experimental observations are discussed in Sect. 2. The probable generation mechanism is explained in Sect. 3. Brief discussions of the results are also presented. Finally Sect. 4 summarizes the results reported.

2 Experimental observation

The experimental set up for recording VLF waves at Varanasi ground station consists of T-type antenna, pre/main amplifier, magnetic tape/cassette recorder. The recorded data are analyzed by the Advance VLF Data Analysis System (AVDAS) which uses a digital processing technique and is capable of real spectrum display. The ELF hiss events were recorded during routine observations between 1991 and April 1998. The ELF

hiss events shown in Fig. 1a were recorded on 26/27 March, 1992, between 2352 h IST and 0040 h IST. The upper cut off frequency of these events are 2.6 kHz, 2.5 kHz, 2.4 kHz respectively and corresponding lower cut off frequencies are 400 Hz, 650 Hz, 650 Hz respectively. The VLF hiss phenomena shown in Fig. 1b were recorded on April 22, 1995, between 0100 and 0245 h IST. The upper cut off frequency of these events are 5.6 kHz, 5.7 kHz, 6.1 kHz respectively and lower cut off frequency are 4.3 kHz, 4.45 kHz, 4.6 kHz respectively. The relative intensities of ELF hiss vary widely from event to event and also vary with frequency and time (position) in the same event. To show the variation of intensity at different position we have tabulated the relative intensities of three hiss events in Table 1, which clearly shows the variation with time. In Fig. 2, the occurrence rate for different months during 1991–98 is shown. The occurrence rate for January to April is plotted since the occurrence rate in the other months is very small and regular observations were not carried out. Figure 2 clearly shows that large number of events were observed during January, February and March of 1997 and 1998. The largest number of events was observed during January and February 1997. The number of events recorded between 1991–1995 even during these months is quite small. Based on the distribution of observed data we find that the maximum
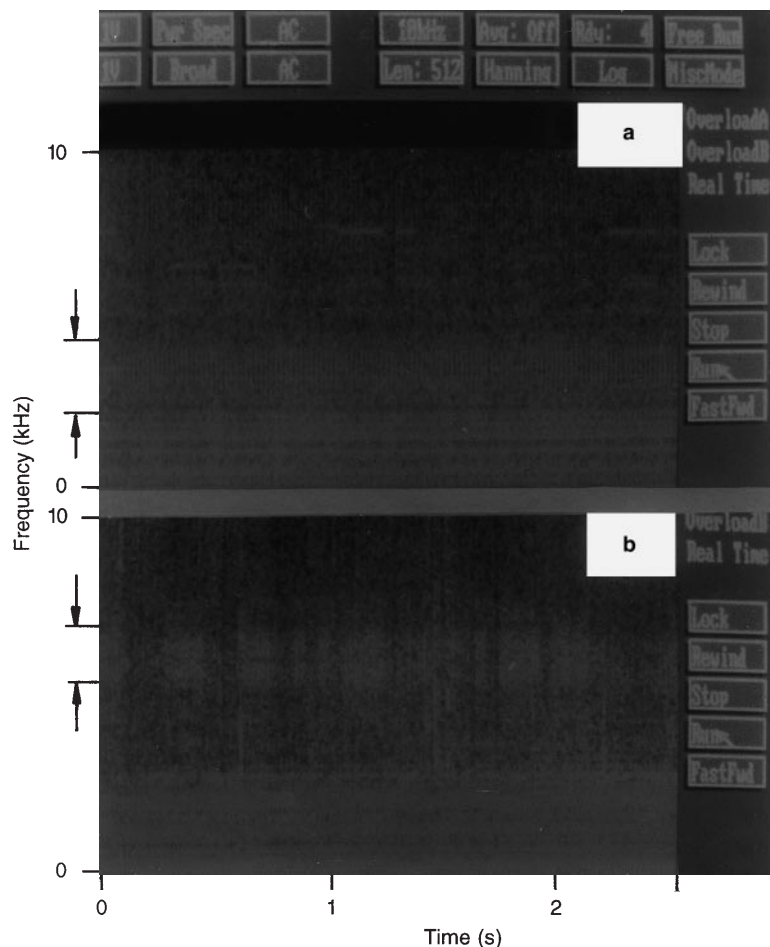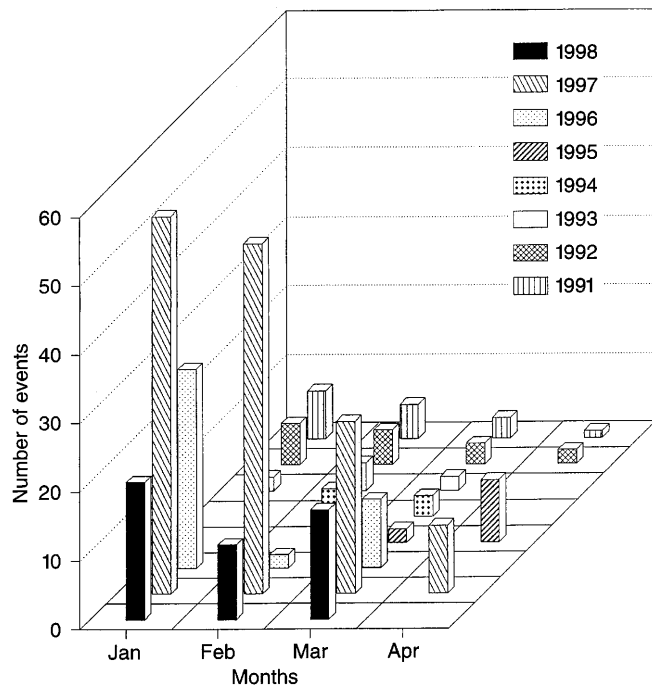

Fig. 1. a Spectrogram of ELF hiss recorded at Varanasi (date: 26:03:1992; time: 23 57 h);
b spectrogram of VLF hiss recorded at Varanasi (date: 22:04:1995; time: 01 00 h)

Table 1. Relative intensity of hiss

Date and time	Frequency	Relative time (S)	Relative intensity (dB)
26 March 1992, 2357 IST	2.0 kHz frequency band of hiss (0.6–2.7) kHz	0.516	65
		0.950	62
		1.110	60
		1.40	61
		1.50	62
		2.20	60
		2.315	59
22 April 1995, 0158 IST	5.0 kHz frequency band of hiss (4.3–5.4) kHz	0.02	64
		0.195	56
		0.43	59
		0.52	61
		0.735	60
		0.96	58
		1.56	55
		1.67	56
3 January 1997, 0226 IST	3.0 kHz frequency band of hiss (2.40–3.30) kHz	0.105	47
		0.230	55
		0.585	54
		0.875	55
		1.145	45
		1.415	57
		1.645	52
		2.020	46

Fig. 2. Monthly occurrence rate of ELF/VLF hiss during 1991–1998

number of events was observed during 1997. Further, the activity is maximum during January, February and March when the thunder storm activity is maximum in the conjugate hemisphere.

These are the characteristic features of ELF hiss events observed at Varanasi:

1. The dynamic spectra of ELF hiss varied from continuous to banded in nature (Fig. 1a, b).
2. The ELF hiss events have been observed in two frequency ranges (a) 400 Hz and 3 kHz, (b) 4 kHz and 6.5 kHz.
3. The hiss with a frequency cut off ~1.7 kHz (in some cases) coincides with the cutoff frequency of the first order mode of the Earth-ionosphere wave guide suggesting that the relevant hiss has propagated through the Earth-ionosphere wave guide before being received at the Earth's surface.
4. The hiss with a lower frequency cut off below the wave guide cut off frequency (in most cases) indicates that the waves have not propagated through Earth-ionosphere wave guide. Such waves may have penetrated the ionosphere close to the observing stations.
5. At low latitudes they are not regularly observed. They are observed during intense geomagnetic activity periods.
6. Relative intensities of ELF hiss vary widely from event to event and also vary with frequency and time in the same events (Table 1).

These observed features clearly support the view that some of the hiss events have propagated through the Earth-ionosphere wave guide and others may not have followed the wave guide path. The hiss events, generated in the equatorial region of higher L-values reach the lower edge of the ionosphere and excite the Earth-ionosphere wave guide, propagate towards equator and are received at low latitude ground stations (Rao et al., 1972). The wave normal angle of these waves in the equatorial region would be very small (almost zero).

The VLF waves after exciting from the duct, propagate through the ionosphere along the geomagnetic field line towards the Earth's surface. The waves will be attenuated but we do not consider attenuation because, even in the absence of attenuation, we cannot explain the expected maximum wave intensity which could be experimentally observed. Tsuruda et al. (1982) have measured the spatial attenuation of Siple signals and natural chorus emanating from ducts near the Siple conjugate point and showed a relatively rapid decrease of intensity from the foot of the duct (~7 dB/100 km) for both Siple signals and chorus. This shows that the attenuation is quite significant for waves propagating through the ionosphere with large wave normal angles.

The ELF hiss generated and amplified to observable amplitudes in the equatorial region of higher L-values may also propagate in a nonducted mode and reach the equatorial zone of lower L-value after magnetospheric reflection. They may also propagate in ducted mode along a lower L-value which can be received at low latitudes (Rycroft, 1972; Chang and Inan, 1983). The wave-normal angle of these waves in the generation region may be quite large. VLF hiss reaching low latitudes by this method will not exhibit a lower frequency cut off caused by Earth-ionosphere wave

guide mode propagation. Thus, in the absence of direction finding measurements the study of dynamic spectra only cannot help us to determine the source of ELF hiss events observed at Varanasi.

These discussions show that we have two sets of observations, namely those which were generated in the equatorial region of the L-value corresponding to recording station (Varanasi) and others which were generated in the equatorial region of higher L-values. The source of waves generated at higher L-value is obtained using the UBF method (Smirnova, 1984). Assuming the dipolar geomagnetic field, the L-value of hiss source is given by Smirnova's (1984) equation:

$$L = (440/f_{UB})^{1/3} \ , \tag{1}$$

where f_{UB} is the upper boundary frequency in kHz of the hiss observed at any Earth station. The observed f_{UB} for one typical ELF hiss event shown in Fig. 1b is 5.6 kHz. Thus the source location of the ELF hiss observed at Varanasi is calculated to be L = 4.16. Kishen (1986) has analyzed a number of VLF emissions observed at Gulmarg (L = 1.2) during the night time and has shown that the generation region is found to be L $\sim$ 4. Thus, based on the computation of source region and discussions of the observed spectrum, we suggest that at higher L-values ELF hiss events with small as well as large wave normal angles are generated. Hayakawa *et al.* (1985) analyzing ELF hiss observed at Moshiri (L = 1.6) concluded that some hiss emissions are associated with a large wave normal angle, and others are generated with a small wave normal angle. In order to explain the observed hiss events, a suitable generation mechanism should be invoked which can explain generation of waves with finite amplitude and varying wave normal angles. In order to explain the wide coverage of ELF hiss at ionospheric height Ondoh *et al.* (1983), on the basis of ray tracing studies, suggested that the waves must be generated at large wave normal angles in the equatorial region near L = 4. Their computations also support the idea that the wave normal direction of ELF waves, arriving at the ionospheric height at low latitudes, are directed mainly downward and lie within the transmission cone so as to be received at the low-latitude ground stations.

3 Probable generation mechanism

We have observed two types of hiss events, namely hiss generated at mid and high latitudes and those generated at low latitudes. Following the suggestions of Ellis (1957) incoherent radiation from energetic electrons was computed and it was found that there was discrepancy between computed and observed power for mid and high latitudes (Jorgensen, 1968; Mosier and Gurnett, 1972; Lim and Laaspere, 1972; James, 1973; Taylor and Shawhan, 1974). In the absence of the theoretically computed Cerenkov radiated power at low latitudes, we present computational results applicable for low and mid latitudes. The total power radiated per unit volume

in incoherent Cerenkov mode is computed from the expression

$$\left(\frac{dp}{df}\right)_{\text{total}} = \int\limits_{E_1}^{E_2} \frac{dp}{df} f(E) \, dE \tag{2}$$

where $f(E) = \frac{1}{V(E)} \frac{dJ}{dE}$, $\frac{dJ}{dE} \propto E^{-\delta}$, here $V(E)$ is the velocity of electron corresponding to electron energy E and δ is the power of electron energy spectrum. In the numerical computation the value of δ is taken as 2.17 (Frank and Ackerson, 1971). dp/df is power radiated from an electron moving along geomagnetic field lines and a detailed expression is given by Jorgensen (1968) and Lalmani *et al.* (1970). The lower limit of electron energy is $E_1 = 5$ eV and the upper limit is $E_2 = 100$ keV. The radiated power from electrons of energy greater than E_2 at low frequency (1–100 kHz) and low latitudes is insignificant and hence in the numerical computation we have restricted $E_2 = 100$ keV. Equation (2) is numerically integrated to obtain total power per unit volume per unit frequency. For numerical integration the measured energy spectra (Frank and Ackerson, 1971) is approximated by specifying the equivalent number density of electron in each intervals centered on a finite number of energies. The number density of energetic electrons in each energy segment is multiplied by the power emitted by the electrons of corresponding energy in the unit frequency range and the product is summed. The power emitted by an electron of given energy as a function of frequency is evaluated from the formula used by Lalmani *et al.* (1970).

The total computed power as a function of frequency for various L values depicted in Fig. 3a shows that the power radiated and the frequency range of maximum power radiation both decrease with the increase of L-value. This decrease is caused by the decrease in radiating electron number density, plasma frequency and gyrofrequency. It is found that the computed power for L = 1.07 is maximum near f = 700 kHz. However, at lower frequencies (1–10 kHz) the computed power lies between 10^{-23} W/m^3 Hz and 10^{-22} W/m^3 Hz for L = 2, 1.2 and 1.07. For L = 4, the radiated power lies between 6×10^{-25} and 6×10^{-24} W/m^3 Hz. Thus, it is observed that the radiated power at a low frequency (1–10 kHz) from high L-value decreases as the L-value increases.

Assuming perfect guiding of the emitted wave and that all the electrons radiate in phase we can add all the produced power in the flux tube to obtain the total received power at the surface of the Earth. In computing this power we have considered that all electrons lying in the flux tube between $\pm 15°$ from the equator for L = 4 radiate in phase. For L = 2, the length of the radiating electron flux tube is considered to be $\pm 10°$. For L = 1.2 and 1.07, the same is assumed to be $\pm 8°$ and $\pm 6°$ respectively. Thus, the total power to be received on the Earth's surface is given in Fig. 3b. Here it can be seen that due to larger radiating flux tube area at higher L-value, the spectral density to be received at the Earth's
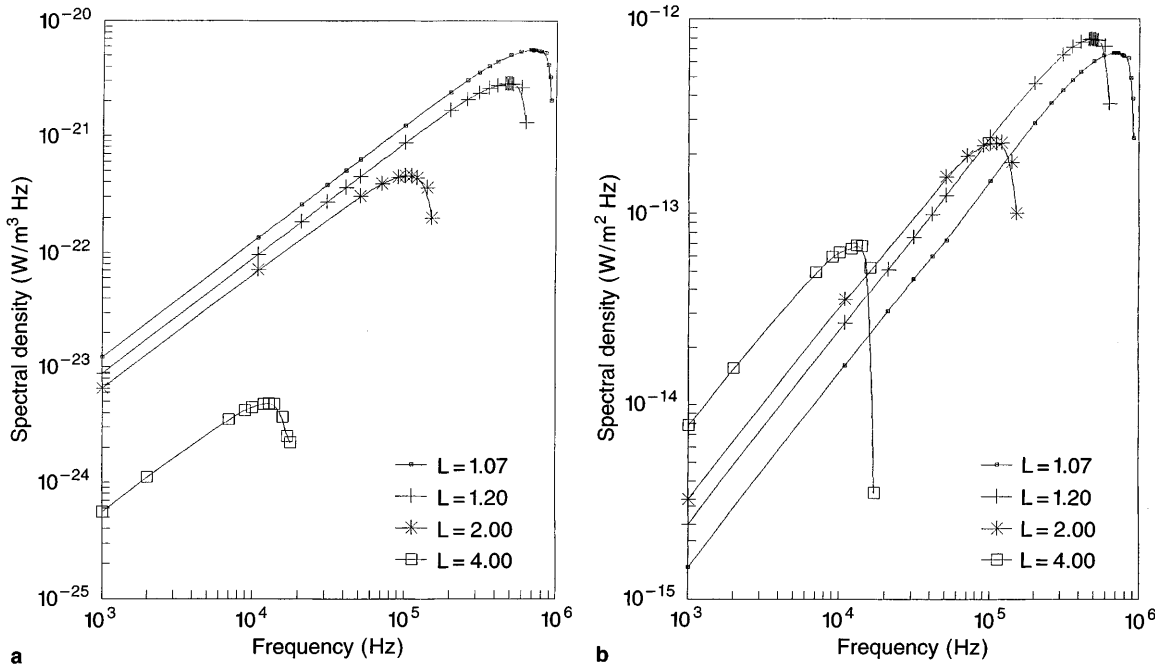
Fig. 3. a Variation of total radiated power per unit volume (spectral density) with frequency in the equatorial region of L = 1.07, 1.2, 2.0 and 4.0. **b** Variation of total radiated power (spectral density) in a flux tube of unit cross section with frequency at L = 1.07, 1.2, 2.0 and 4.0

surface is larger compared to small L-values. Of course, much higher frequencies may not be generated at higher L-values. But if they are generated then the expected power is larger at higher L-values. The maximum power density is $\sim 7 \times 10^{-14}$ W/m^2 Hz near 10 kHz wave frequency from L = 4. At lower frequencies the radiated power is smaller, for example at 2 kHz, the maximum power is $\sim 5 \times 10^{-15}$ W/m^2 Hz. From lower L-values (L = 1.07–1.2) the maximum radiated power is 8×10^{-13} W/m^2 Hz at 500 kHz. From the computation we find that the maximum power radiated from electrons in the equatorial region vary with frequency. At lower latitudes higher frequencies are generated. Although the higher frequencies while propagating through the ionosphere will be heavily attenuated. For example, at L = 1.07, 500 kHz frequency is generated with appreciable power but VLF waves in this frequency range have never been observed at any low-latitude ground stations. The VLF waves observed at ground stations lie mostly below 10 kHz. The numerical computation of the attenuation of waves propagating through the ionosphere shows that minimum attenuation is for the waves with frequencies close to 5 kHz, which is in close agreement with the VLF wave observations at low-latitude station Varanasi.

Thus, the computed power at low as well as at mid latitudes falls short of observed power. The discrepancy is more for low latitudes rather than high latitudes. This is because the radiation distance at mid latitude is much larger compared to that of low latitudes. It is known that the total power radiated incoherently by N particles is $P_T = NP$, where P is the power radiated by each particle. If the N particles radiate coherently, that is all with the same phase, then the total power would be

$P_T = N^2 P$ (Taylor and Shawhan, 1974). Thus, even a small number of electrons emitting coherently could substantially increase the power to the observed level.

To make up this deficiency in the experimental and theoretical power, it is suggested that the generated waves of small amplitudes interact with the energetic electrons while bouncing back and forth along geomagnetic field lines and are thus, amplified. The amplified wave finally may be received at the Earth's surface. The temporal growth rate for parallel propagating whistler mode wave is written as (Cornilleau-Wehrlin *et al.*, 1985)

$$\frac{r(E_R)}{\omega_{He}} = \frac{1.7 \times 10^{-6}}{f_P^2} (E_R)^{1/2} (1-x)^2 \{A(E_R) - A_c\}$$
$$\int_0^{\pi/2} J(\alpha, E) \tan\alpha \, d\alpha \qquad (3)$$

where $E_R = 253 \left\{ \frac{f_H}{f_P} \right\}^2 \left[\frac{(1-x)^3}{x} \right]$ (in keV) is the resonant energy of electrons, and r is the temporal growth rate. Plasma frequency f_P expressed in kHz, $x = f/f_H$, is the reduced wave frequency. The anisotropy A and critical anisotropy A_c required for wave growth is

$$A(E_R) = \frac{\int_0^{\pi/2} \tan^2\alpha \{\frac{\partial J}{\partial \alpha}\}_E d\alpha}{2 \int_0^{\pi/2} \tan\alpha \, J(\alpha, E) d\alpha} \qquad (4)$$

and

$$A_c = \frac{\omega}{(\omega_{He} - \omega)} \qquad (5)$$

where $J(\alpha, E)$ is the differential flux of energetic electrons of pitch angle α and energy E. The integration in Eqs. (3)

and (4) are to be performed keeping $E = E_R$. Equation (3) states that the wave amplification will take place only when $A(E_R) > A_c$. Kennel and Petschek (1966) showed that the instability occurs only when critical anisotropy $A_c > \frac{\omega}{(\omega_{He} - \omega)}$ which means that for whistler mode waves $A_c > 0$. In deriving this condition, the contribution of relativistic effect has been neglected which leads to a slight decrease in the frequency range of unstable waves (Sazhin, 1991). The observation of electrons with $A > 0$ in the equatorial magnetosphere (Frank, 1968; Bahnsen et al., 1985) supports the idea of wave amplification through wave particle interaction. Soloman *et al.* (1988) have calculated the value of anisotropy A from the flux data and they have shown that $A > A_c$ for the reduced wave frequency $x < 0.4$. The derived value of A lies between 0.2 and 1.5. In the present computation we have chosen some discrete values of A such as 0.5, 1.0, and 1.5.

Another parameter which is important in the evaluation of growth rates is the differential flux of the energetic electrons. In the absence of simultaneous measurements of the wave and energetic electrons, the term $\int_0^{\pi/2} J(\alpha, E) \tan\alpha\, d\alpha$ can be approximated by the omni directional flux of electrons with energy greater than the resonance energy E_R. For numerical evaluation the flux of energetic electrons at different values are taken from the measurement of Katz (1966) who reported the variation of electron flux as a function of energy for different L values. For some L values where measurements are not available, we have used extrapolated values (Singh *et al.*, 1994).

The growth rate for various frequencies (1–10 kHz) and different values of anisotropies ($A = 0.5, 1, 1.5$) are evaluated and shown in Fig. 4a, b for L = 1.07 and 4. It is seen that the growth rate increases with frequency as well as with anisotropy and decreases with increasing L-values. The amplitude of the wave increases exponentially with time and in the presence of large growth rate, the amplitude suddenly builds up which may lead to wave observation on the ground. The wave amplification factor is given by $A = \exp(2\int r\, ds/V_g)$ where ds is the path element, V_g is group velocity of the wave and integration is carried over the interaction length. We have calculated the amplification factor which works out as 1.29 for L = 1.07 and 31.50 for L = 4. The computed amplification factor is less than the required value to explain the observed spectral power. If we assume that the wave bounces back and forth along the geomagnetic field line before being received at the Earth's surface, then the wave passes through the interaction region many times and each time it interacts with the ambient energetic electrons and is amplified. Thus, if in each passage the amplification factor remains the same then the required experimental wave intensity can be achieved in 100 bounces of the wave across the equator for L = 1.07 whereas for L = 4 it is in the range of 50. Thus, the present computation shows that the linear wave amplification cannot explain the maximum observed intensity of the ELF hiss unless we assume large number of bounces. Huang *et al.* (1983) have claimed that the net growth rates are too small and that the
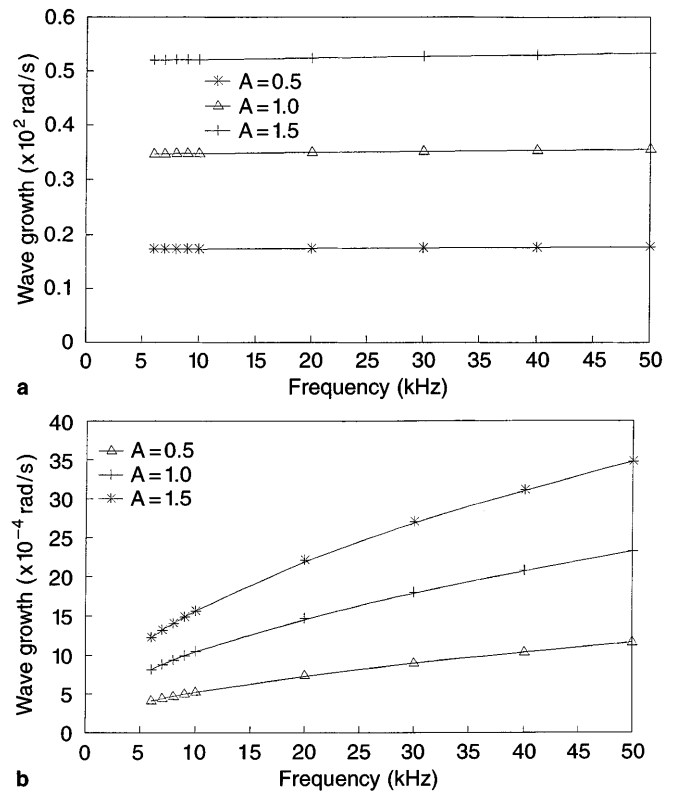

Fig. 4a, b. Variation of wave growth rate with frequency for different isotropies at **a** L = 1.07, **b** L = 4.0

cyclic waves do not provide a satisfactory explanation for hiss generation. Helliwell (1993) has stressed that ducted signals may echo repeatedly back and forth over one duct for hundreds of times. Further, Helliwell (1993) has argued that in the presence of multiple ducts signals can couple from the end of one duct to another and produce a complex distribution of components in multihop echoes, which can explain the presence of hiss in the ducts.

Further, Figs. 3a, b shows that the wave power generated in Cerenkov mode increases with frequency and also the growth rate increases with frequency. Hence, the resultant wave amplitude will increase with frequency. This shows that the proposed two-step process of ELF hiss generation produces a power spectrum identical to blue noise (increasing intensities with increasing frequency). The experimental observations show that the hiss intensity remains constant in the limited band of hiss emissions. This contradiction also supports the view point that some other alternative mechanism of hiss emissions may be developed. The alternative mechanism may include either a non-linear process of wave generation or interference of trapped whistler waves and other VLF waves bouncing back and forth along the field lines. The process involved should be able to produce a constant amplitude in the required frequency band.

To achieve the observed intensity required the bounce number is ~100 and therefore, during this period the magnetosphere should remain stable and support the

wave growth. Moreover, non-linear effects are also neglected which may come in to existence when the wave-amplitude becomes finite. In fact a quasi-linear theory of wave-particle interaction should be considered to explain the details of observed dynamic spectra. In computing the wave-amplification, the effect of an inhomogeneous magnetic field should also be considered. Hobara *et al.* (1998) have shown that in the presence of an inhomogeneous magnetic field, the amplification factor exhibits a quasi-periodic structure as a function of wave frequency or characteristic electron parallel velocity. Hobara *et al.* (1998) have also discussed the effect of dispersion in parallel velocity on the amplification factor. Recently Trakhtengerts *et al.* (1996) have shown that the step-like deformation of the distribution function at the boundary between resonant and non-resonant electrons leads to the strong amplification (2 orders of magnitude greater than that for a smooth distribution function) of the wavelets whose frequency corresponds to that for cyclotron resonance with electrons at the step. Thus, the non-linear effects may explain the observed maximum amplitudes of the reported ELF hiss.

4 Summary

ELF hiss recorded at Varanasi is categorized into two parts, namely the events which exhibit lower cut off frequencies equal to that of Earth-ionosphere wave guide mode propagation and those which do not exhibit such a frequency cut off. Based on their morphological behaviour we suggest two regions of the magnetosphere as the possible source region. One is the equatorial region of low-latitude inner plasmasphere and the other region is the equatorial region of mid latitude (L = 4) plasmasphere. Further, it is suggested that the generation mechanism should be able to generate waves at small as well as at large wave-normal angles. Computations corresponding to low latitudes as well as high latitudes clearly show that Cerenkov radiation mechanism and amplification mechanism through wave-particle interactions is unable to explain the observed amplitudes of the ELF/VLF hiss.

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