GENERATION MECHANISM OF VLF HISS EMISSIONS OBSERVED AT INDIAN ANTARCTIC STATION, MAITRI (L = 4.5)

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Abstract - VLF Hiss is a well-known form of electromagnetic emission having constant spectral density in the limited frequency band with right hand polarization. During its propagation from the source, it interacts with energetic electrons in the magnetosphere. The characteristic features of VLF Hiss recorded at the Indian Antarctic Station, Maitri (geom. lat. = 70° 46′ S, long. = 11° 50′ E, L = 4.5) during February–March 2001 will be presented. Out of various generation mechanisms proposed from time to time, we find that these waves seem to be generated by low energy electrons through the Cerenkov Radiation Process and get amplified during interaction with relatively higher energy electrons. We have computed Cerenkov Radiation Power for L = 4.5 and L = 5 values. It is observed from the computation that the power radiated and the frequency range of maximum power radiated both decreases with the increase of L-value. The computed spectral density could not explain the observed spectra. To explain this deficiency in the observed and computed power, we have 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.

Keywords - VLF Hiss Emissions, Magnetospheric Lines, Incoherent Cerenkov Radiation, wave particle interaction, Plasmasphere.

I. INTRODUCTION

VLF emissions are a class of naturally occurring audio-frequency electromagnetic signal propagating in whistler mode and readily detectable at middle and high latitudes. Like whistlers, VLF emissions are also important because of their probing potentiality of ambient medium. VLF emissions, depending upon their spectral shapes can be broadly divided in to hiss, discrete, periodic, quasi-periodic and triggered emissions [1]. The required information to discuss the generation mechanism of these emissions are (a) mode of propagation from source to the observation point, (b) existence of the source of energy and (c) coupling mechanism which can convert a fraction of source energy to the electromagnetic energy in the form of VLF emissions. Amongst different kinds of emissions, hiss emissions are well known forms of electromagnetic emissions that arise in the magnetosphere and have constant spectral density in the limited frequency [2]. Earlier hiss was supposed to be high latitude phenomena but recent observations show that there are three principal zones of intense hiss activity: the first zone is located near invariant latitude of 70°, the second zone is near 50° invariant latitude and the third zone lies below ± 30°. Hiss events occurring in the third zone are called as low latitude or equatorial hiss and they are less intense than the mid/high latitude hiss. Hiss events observed in the first zone is also called as auroral hiss (4 kHz < f < 30 kHz). The reported hiss events recorded at Indian Antarctic Station Maitri belongs to this category.

In order to understand the generation mechanism, we note that the auroral hiss is associated with the electrons of 100 eV energy [3-4]. Attempts were made to explain the amplitude and frequency spectrum of VLF hiss in terms of incoherent Cerenkov Radiation but the computed amplitude was two to three order of magnitude smaller than the measured one and hence collective phenomena such as coherent radiation mechanism or instability mechanism was proposed [5-9, 4]. Using experimental data [10] argued that amplification of background noise could explain the observed intensity spectrum. Analyzing experimental measurements and numerical simulations. Savchenko and Vaisman[11] have suggested that VLF hiss bursts observed on the ground can be formed by refraction and scattering of the VLF waves in the ionosphere on irregularities generated during the precipitation of energetic electrons induced by whistler. Poynting flux measurement of VLF hiss onboard Injun-5 showed that, in most cases, the Poynting vector was directed downward to the Earth [12] this shows that the continuous hiss emissions observed in the ground seem to be generated above the Injun-5 orbit (apoage 2500 km) and propagate downward to the Earth without necessarily following the magnetic field lines [12].

Outsu et al. [13] showed that at low latitudes during quite time the pronounced peak in the occurrence rate of VLF hiss coincide with that of whistlers. Quiet time hiss appear predominantly in winter whereas storm time hiss shows less seasonal dependence [14]. Low latitude hiss usually have relatively narrow band spectrum with the center frequency lying between 4 and 5 kHz. However, upper frequency limit extends up to 8 kHz. The satellite results show two maxima, which are around 6 kHz and below 1 kHz. The hiss intensity at the ground station lies in the range $10^{17} - 10^{18} \text{ W m}^2 \text{ Hz}^{-1}$ whereas at the satellite (Injun-3), it is $10^{12} \text{ W m}^2 \text{ Hz}^{-1}$ [16]. Further, he has also shown correlation between low latitude hiss and intense fluxes of soft electrons (E ~ 10 eV). Kleimenov et al. [17] have shown that the upper boundary of low latitude hiss zone is associated with the main
ionospheric trough. Usually hiss occurs at large wave normal angles [18-19] causing it to have interactions with energetic electrons (E > 10 keV). Thus, these oblique wave-normal angles prevent the bulk of plasmaspheric hiss from resonant interaction with super thermal (~ 100 eV) electrons. Density gradients duct the VLF hiss making them field aligned, which resonantly interact with lower energy electrons. Thorne and Home [20] have demonstrated that Cerenkov resonance with super thermal electrons is the primary loss mechanism for magnetospherically reflected whistlers. Liemohn et al. [21] have shown that under the proper conditions guided plasmaspheric hiss scatter more efficiently electrons in superthermal range (50-500 eV) than Coulomb collisions.

Khosa et al. [22] reported VLF hiss from Srinagar (India) in the frequency band 1-3 kHz and 5-7 kHz. VLF hiss observed at Vurangani in two frequency range (0.4-2.6 kHz and 4.6-6.1 kHz) have been reported by [9,4], who have shown that the low latitude hiss consists of mid-latitude hiss and equatorial hiss. Generation mechanism of equatorial hiss in terms of lightning discharges has also been argued [4]. The Areal satellites 3 and 4 provided a lot of evidence to support the association of low latitude/equatorial hiss with lightning discharges [23]. Parrot [24] had shown that the maximum intensity of VLF hiss correlates with the region of high thunderstorm activity, which is indicative of the embryonic effect of lightning in generating VLF hiss. Recently Green et al. [25], after studying the longitudinal distribution of the hiss intensity and distribution of lightning discharge, also concluded that lightning as the dominant source for plasmaspheric hiss, which, through particle-wave interactions, maintains the slot region in the radiation belts. Meredith et al. [26] have studied that the intensity of plasmaspheric hiss has been observed to be higher near the magnetic equator during substorm conditions. They conclude that hiss must be generated by cyclotron resonant interaction with substorm ejected electrons.

In this paper we have reported the VLF hiss recorded at the Indian Antarctic Station Maitri during February – March, 2001. Section 2 describes the experimental observations of VLF hiss and their properties. Generation mechanism is briefly discussed in section 3. Numerical results are presented which show the variation of radiated power with frequency from different locations along L = 4.5 and 5. The computed power is small compared to the reported measured power at the ground stations and hence wave amplification by wave particle interaction is computed. Finally, main results of this study are briefly summarized in section 4.

II. EXPERIMENTAL OBSERVATIONS

VLF wave recording set up consisting of T-type (vertical) antenna 10 meter height and 40 meter horizontal length supported by two poles, transistorized amplifier and digital audio tape recorder is used to record VLF data at the Indian Antarctic Station Maitri. The location of the hut containing the recording setup is geom. lat. = 70° 46' S, Long. = 11° 50' E and the observations were carried out during January 10 to March 10, 2001. The data are stored on digital Audio Tapes. Tapes were replayed and some of the events were analyzed. During the analysis it was found that the noise was very high in some cases. The data with low noise level were selected for further analysis. Figure 1 shows VLF hiss at relatively higher frequencies (11 kHz < f < 13 kHz) observed on February 17, 2001 at 11.30:35 hrs GMT. From the figure it is noted that the noise level is very low. In addition to VLF hiss in figure 1 three horizontal lines at 6.2, 8.0 and 9.2 kHz are seen, which were present throughout the recording period and the intensity decreases as frequency increases. That is the line of 6.2 kHz is strongest and 9.2 kHz line has lower intensity. These are quite thick parallel lines showing fairly constant frequency on the spectrograms. Similar lines on the dynamic spectrum were reported by [27] from the ground based stations at Siple (Antarctica) and Roberval (Quebec) in the frequency range 2 – 5 kHz. These lines were termed as magnetospheric lines. Park and Helliwell[28] reported magnetospheric lines in the frequency range 1.5 – 8.5 kHz with a strong peak at 2.5 – 3.5 kHz. Recently Rodger et al. [29] analyzing ISIS2 satellite data have reported magnetospheric lines in the frequency range 1.8 – 2.3 kHz.

The hiss events presented in figure 1 continued for two hour (11 -13 hrs GMT) having almost the same intensity as inferred from the colour of the spectrogram. This shows a typical broad band continuous VLF hiss having the upper band frequency \( f_{UB} = 13 \) kHz and the lower band frequency \( f_{LB} = 11 \) kHz. The average \( Kp \) index on 17th February 2001 was \( \Sigma Kp = 5 \) and average \( Ap \) index is 2, which corresponds to a quite day. The source of wave generated at higher L-value is obtained using the upper band frequency (UBF)

\[
L = \left( \frac{440}{f_{UB}} \right)^{1/2}
\]

where \( f_{UB} \) is the upper boundary frequency in kHz of the VLF hiss observed at any Earth station. Thus, the source location of VLF hiss observed at Maitri, Antarctica is calculated to be \( L = 3.23 \).
III. GENERATION AND PROPAGATION MECHANISM

The observed VLF spectra depend on the generation and propagation mechanism from the source and observation point. Early observations of VLF hiss were explained using incoherent Cerenkov radiation from different models of the magnetosphere, the ionosphere and precipitating electron beams, [31–38, 9, 4, 39]. Incoherent Cerenkov radiation is considered because intensity of electromagnetic wave radiation from low energy electron is more as compared to that from cyclotron radiation mechanism, when wave frequency is well below the electron gyro-frequency [40–41]. It is important to note that in the existing theories of incoherent electron radiation, the electron trajectory is considered to be given a priori, which means that the influence of radiated wave on the electron trajectory is not considered. The radiated power from electrons increases as the electron energy decreases. Incoherent whistler mode radiation is most efficient for electrons having energies of the order of 10 – 100 eV [9].

The details of the theory of radiation mechanism have been studied by a number of workers [42–44, 40]. The results have been applied to study the generation of low frequency and very low frequency waves from the ionosphere. The derived expression is simplified by making certain assumptions about the medium such as cold, collision less, dispersive and anisotropic. The dielectric tensor is considered to be complex and Hermitian. We also consider that the wave magnetic field is very small as compared to the ambient static magnetic field present in the medium and hence it is neglected. The average radiated power by an energetic electron spiraling along geomagnetic field lines in the Cerenkov process is written as [40].

\[
\frac{dP}{df} = \frac{\epsilon_1^2 \omega^2 \beta_1 T_{11} (\epsilon_0) + \epsilon_1 n^2 \sin^2 \theta - \epsilon_2 n^2 \cos^2 \theta}{\epsilon_0 V_{\perp}} \left( \frac{1}{\beta_1^2 - 4 \epsilon_1 \epsilon_2} \right)^{1/2}
\]

where wave normal angle \( \theta \) is governed by the Cerenkov condition for wave emission, which is given by \( \cos \theta = 1/(\beta_1 n) \); where \( n \) is the refractive index of the wave, \( J_0 \) and \( J_1 \) are the Bessel function of zero order and first order. The computation of radiated power using equation 2 involves large computing time. For electrons moving along the geomagnetic lines of force having small pitch angles, we can assume \( V_{\perp} = 0 \) [40, 44, 45, 9] and equation 2 reduces to

\[
\frac{dP}{df} = \frac{2 \epsilon_1^2 \beta_1 \omega^3 T_{33} (\beta_1^2 - 4 \epsilon_1 \epsilon_2)^{1/2}}{2 \epsilon_0 C}
\]

Following the above equation, the radiated power per electron as a function of wave frequency and electron energy is shown in figure 2a for \( L = 4.5 \) in the equatorial \( (\phi = 0^\circ) \), figure 2b shows the power radiated from the region \( L = 4.5 \) and \( \phi = 30^\circ \) geomagnetic latitude. Comparing figure 2a and 2b, we note that the range of emitted wave frequency is increased when the radiation zone shift from the equatorial region to \( \phi = 30^\circ \) along \( L = 4.5 \) due to increased electron gyro-and plasma-frequency. The radiated power suddenly drops as wave frequency increases above 6 kHz [figure 2a], whereas the radiated power in the same frequency range is sufficiently large from the region \( L = 4.5 \), \( \phi = 30^\circ \). The radiated power from the region \( L = 4.5 \), \( \phi = 55^\circ \) is shown in figure 2c and figure 2d corresponds to \( L = 4.5 \), \( \phi = 55^\circ \). The radiated power and frequency range increases as geomagnetic latitude increases along the field line. The frequency corresponding to maximum power increases as the radiating electron move downward. For example along \( L = 4.5 \), the radiated frequency having maximum power is about 6 kHz for \( \phi = 0^\circ \), 20 kHz for \( \phi = 30^\circ \), 90 kHz for \( \phi = 45^\circ \) and 300 kHz for \( \phi = 55^\circ \). The radiated power corresponding to these frequencies from the electrons (energy = 10 eV) are \( 1.0 \times 10^{-31} \), \( 1.0 \times 10^{-30} \), \( 1.8 \times 10^{-29} \) and \( 2.2 \times 10^{-28} \) watt Hz\(^{-1} \) respectively. Similar results have been reported by [41, 45] and [4] for other L-values using the formulation of [40]. Comparing figure 2a and 2d, an interesting point emerges that the location of peak power shift towards lower frequencies for \( \phi = 0^\circ \) when energy of the radiating electron increases, whereas the same is not true for \( \phi = 55^\circ \). In this case, the peak power potion in frequency domain remains almost fixed. Further, the radiated power increases with latitude in the whole frequency range as is evident from the comparison of figure 2a-d.
Fig. 2 Radiated power as a function of wave frequency and electron energy for $L = 4.5$, (a) Geomagnetic latitude $\phi = 0^0$ (b) $\phi = 30^0$

The above discussion shows that the signal in the frequency range 1-6 kHz can be generated by incoherent Cerenkov mechanism in the equatorial range of $L = 4.5$. In fact in this frequency range VLF signal can be generated from any region along the field line $L = 4.5$. However, higher frequencies can only be generated from the non-equatorial zone. For example, waves in the frequency range 10-100 kHz can be generated from the auroral region ($40^0 < \phi < 55^0$). The power radiated per electron in this frequency range is $\sim 10^{-29} - 10^{-28}$ watt Hz$^{-1}$.

Fig. 3 Radiated power as a function of wave frequency and electron energy for $L = 5.0$, (a) Geomagnetic latitude $\phi = 0^0$ (b) $\phi = 30^0$

In addition to $L = 4.5$, we have also evaluated radiated power from electrons spiraling along $L = 5.0$. The results are shown in figure 3.

We find that except the reduction in frequency range and radiated power, other features remain the same. The responsible electron energy lies in the range of $5 - 300$ eV.
Higher energy electrons radiate very little power. Also, as the energy of radiating electron increases, the wave normal angle of the radiated wave increases, which may not reach the ground surface. From the correlation of 100-700 eV electron fluxes with VLF hiss intensity inside the auroral arc [46, 3] suggested that the source of VLF hiss energy could be electron fluxes of 100 eV. Gurnett and O'Brien [47] using Injune-5 satellite data showed the absence of intense fluxes of the energetic electrons in the auroral zone of intense VLF hiss activity which also suggest that VLF hiss could have been generated by low energy (E ∼ 1 keV) electrons and mechanism could be dependent on longitudinal resonance condition, because transverse resonance condition requires energetic electrons (in the keV range). However, energetic electrons may amplify the existing VLF hiss of low intensity through cyclotron resonance interaction. These computations have been carried out to explain the observed hiss at the Indian Antarctic Station, Maitri.

To explain the observed intensity of the VLF waves, the total radiated power from the whole electron population should be calculated. If we assume that the radiating electrons are distributed in energy then the total radiated power from electrons having energy between E₁ and E₂ per unit volume per unit frequency is written as

\[ \left( \frac{dP}{df} \right)_{\text{Total}} = \int_{E_1}^{E_2} \frac{dI}{dE} f(E) dE \]

where \( f(E) = \frac{1}{V(E)} \frac{dI}{dE} \) is the energy spectrum of the radiating electrons. Frank and Ackerson [48] using experimental data has shown that \( \frac{dI}{dE} \propto E^{-\delta} \), where \( \delta \) varies between 1.5 and 2.5. E₁ and E₂ are the lower and upper energy of the radiating electrons [49] and [3] have shown that the resonant velocity of the electrons responsible for the generation of the auroral hiss through Cerenkov process ∼ 330 eV. James [50] considered the instability of a beam of electrons with energies below 5 eV to explain saucer emission. In the present case E₁ = 5 eV and E₂ = 10 keV is considered. The radiated power from electrons of energy > 10 keV is very small. For some plasma parameters E₂ could be even less than 1 keV. Infact the maximum energy of the radiating electron is governed by the condition

\[ 1 + \frac{\omega^2}{\omega_{BH}^2} \geq \frac{c}{V_{||}} \]

which depends upon the plasma density and magnetic field of the medium.

Total power per unit volume per unit frequency is estimated by numerically integrating equation 4. For numerical integration, the measured energy spectrum is approximated by specifying the equivalent number density of electrons in each energy intervals centered on a finite number of energies. The number of density of electrons in each energy segment is multiplied by the radiated power from electrons of corresponding energy and the product is summed to obtain total power per unit volume and per unit frequency.

To explain the observation of VLF hiss at the Indian Station Maitri, we have to evaluated total radiated power from the whole volume of the generation region, which can be written as

\[ \text{Spectral Flux Density} = \int_{z_1}^{z_2} \left( \frac{dP}{df} \right)_{\text{Total}} dz \]

\[ = \int_{z_1}^{z_2} \int_{E_1}^{E_2} \left( \frac{dP}{df} \right) f(E) dE \ dz \]

where \( z_1 \) and \( z_2 \) define the boundary of the generation region along the field line. It is found that the maximum contribution comes from the lower altitudes (auroral zones) as compared to that from the equatorial zone for higher L-values. Singh et al. [4] have used this technique to evaluate the radiated power along different field lines, but they considered generation region to be mostly the equatorial zone. Using the measured flux density as a function of energy of auroral electrons, we have computed spectral flux density to be received on the ground surface. The flux density reported by [51] and [48] are superimposed to obtain flux density from 5 eV to 10 keV. Similar measurements have also been reported by other workers [52-55]. The electron fluxes reported by Frank [56] are only about one order of magnitude below the fluxes observed by Evans (1966) [51]. In the computation of total power we assume that the density of radiating electrons is the same everywhere in the radiating region. Further, it is also assumed that the pitch angle distribution is isotropic. The computed total power per unit volume per unit frequency is given in figure 4 for the frequency range 1-1000 kHz. The radiated power in the equatorial plane of L = 4.5 and in the frequency range 1-6 kHz is ∼ 10⁻²² watt m⁻³ Hz⁻¹, whereas for L = 4.5, \( \Phi = 55^\circ \), f = 1-400 kHz, the power radiated lies between 10⁻²¹ - 10⁻¹⁹ watt m⁻³ Hz⁻¹. Similarly, the radiated power from different part of L = 5.0 is slightly more than that of L = 4.5, but the radiated frequency range is reduced. The total power to be received on the Earth’s surface is obtained by summing the radiated power from different region of the magnetosphere along L = 4.5 and 5.0. In doing this, we assumed that all the electrons radiate in phase and the radiated waves propagate along the field lines. The radiated power from L-values is smaller and varies with frequency.

If generation region extends from 5000 km to 25000 km in the auroral zone (Gurnett et al., 1983) [57] along L = 4.5, then the radiated power to be received on the Earth’s surface would be ∼ 10⁻¹⁴ – 10⁻¹³ watt m⁻² Hz⁻¹ in the frequency range 1-10 kHz and 10⁻¹³ - 10⁻¹² watt m⁻² Hz⁻¹ in the frequency range 10-400 kHz.
If the radiation region extends further then the radiated power would be larger than the above reported value. From the figure it is seen that due to larger radiating flux tube area at higher L-value, the spectral density to be received at the Earth’s surface is larger as compared to smaller L-values. However, the received power on the Earth’s surface would be much less than the above reported value because the attenuation of the wave during propagating has not been considered. Also, it is improbable that all the electrons distributed along the field lines would radiate in phase and all radiated wave would propagate along the field lines. It is to be noted that in the reported event we have not measured the power flux spectral density of VLF hiss. The observed average power flux spectral density of auroral hiss at ground stations is $10^{-16}$ Wm$^{-2}$Hz$^{-1}$ [32] (Jorgensen, 1968), with a peak values up to $10^{-14}$ Wm$^{-2}$Hz$^{-1}$ or more [56, 3] (Makita, 1979; Sazhin et al., 1993). If attenuation of the waves from the source region to be receiving station is taken in to account then the generated spectral density should be larger than the above reported value. Gurnett and Frank (1972) [5] using Injune-5 data showed an association between VLF hiss in the auroral zone and high fluxes of low energy electrons and reported power fluxes as large as $10^{-11}$ – $10^{-12}$ Wm$^{-2}$Hz$^{-1}$ at 2.5 kHz. Jorgensen (1968) [32] using Mansfields (1967) [40] formulation evaluated VLF hiss spectrum for L = 8.5 corresponding to $70^0$ invariant latitude and assuming perfect guiding showed VLF wave power to be $\sim 10^{-14}$ Wm$^{-2}$Hz$^{-1}$. Thus, it is seen that the computed power is one to two orders of magnitude smaller than that required to explain the observed spectral density. It has been reported that the intense VLF hiss emissions in some cases are not associated with the intense electron fluxes. Therefore, it is necessary to consider either coherent mechanisms for the generation of VLF hiss emissions in the magnetosphere or some other non-linear mechanism.

Measurement of auroral electrons onboard satellites and rockets showed a peak around 1 keV in their velocity distribution with respect to $\parallel B_0$ [52, 48, 59, 55, 60] (Westerlund, 1969; Frank and Ackerson, 1971; Meng, 1976; Reasoner and Chappell, 1973; Bryant, 1983), which suggests that incoherently radiated waves can be further amplified due to Cerenkov instability [61] (Singh, 1972) when the wave phase velocity corresponds to the region where $V = \omega/k$, where $F_0$ is the electron distribution function. The measurements show the existence of the region where $\frac{\partial P}{\partial V} > 0$ for electrons with energies close to or below about 1 keV. Thus, hiss emissions will be amplified while propagating through such region. Maggs (1976) [62] had discussed different beam models and predicted that continuous hiss is amplified at much higher altitudes than impulsive hiss, which corresponds to the observational results [58] (Makita, 1979). Maggs (1976) [62] also predicted that the wave power flux becomes maximum both at frequency close to 10 kHz and at frequency close to plasma frequency ($\sim 10^{-11}$ Wm$^{-2}$Hz$^{-1}$). Later on, Maggs (1978) [63] considering wave refraction in the North-South direction due to vertical gradients in the ionospheric electron density showed that the value of dP/df close to plasma frequency decreases considerably. The VLF hiss generation in the auroral region may be closely related to the problem of whistler mode generation by an artificial electron beam [64-65] (Goerke et al., 1990; Neubert and Banks, 1992). In this case waves are amplified mainly due to coherently of electrons and their growth due to Cerenkov beam instability is generally small [66-67] (Harker and Banks, 1985; Farrell and Goertz, 1990)

IV. CONCLUSIONS

In this paper we have studied some features of VLF hiss emissions observed at the Indian Antarctic Station, Maitri. Based on the events and numerical computations described in this paper following points emerging:

I. VLF hiss are reported from the Indian Antarctic Station, Maitri. The basic physical process leading to the generation of this auroral hiss seems to be Cerenkov radiation from electrons.

II. The main energy source comes from electrons of energy lying in the range between 5 eV and 300 eV. These electrons populate the auroral region of the magnetosphere and may generate VLF hiss to be received on the Earth’s surface. By extending the energy range of the radiating electrons, it is shown that the total radiated power in the Cerenkov process has increased.

III. It is suggested that these emissions are initially generated by incoherent Cerenkov radiation process and then they are amplified through wave particle interactions. The amplification mechanism is also unable to explain the observed amplitudes of the VLF hiss and it is suggested that some linear mechanism may be responsible for the generation of VLF hiss.

IV. The waves from the source region propagate in ducted mode along the field line and penetrate the ionosphere to be received on the surface of the Earth.

V. Along with VLF hiss, we have also recorded magnetospheric lines at Maitri, whose generation mechanism is not known. Although attempts have been made to explain them in terms of harmonics of power lines.
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