Auroral and low latitude VLF hiss

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The morphological features of VLF hiss observed at the auroral and low latitude stations are summarized and generation mechanisms are discussed. The suggestion that these waves are generated by Cerenkov mechanism is re-examined by computing incoherent Cerenkov radiated power from the soft and energetic electrons present in the inner magnetosphere, which falls short of the measured power spectral density. To explain the difference between the measured and computed spectral density it is suggested that the generation mechanism of VLF hiss is a two-step process. In the first step, waves are generated by incoherent Cerenkov process from the soft electrons present in the magnetosphere and as a second step, these small amplitude waves are amplified during interaction with energetic electrons having anisotropic velocity distribution function. It is shown that the low latitude hiss consists of midlatitude hiss and equatorial hiss. Alternative generation mechanism for the equatorial hiss in terms of lightning discharges has also been discussed.

1 Introduction

Very low frequency (VLF) hiss emissions present in the ionosphere and magnetosphere have constant power spectral density over the observed frequency band similar to white thermal noise, producing a hissing sound. Three principal zones of intense VLF hiss have been observed: (i) the first is located at invariant latitudes above 70°, (ii) the second near 50° and (iii) the third below 30°. Low latitude hiss occurring below 30° latitude is also known as equatorial hiss, which are less intense than those observed at middle and high latitudes. Jorgensen showed that amplitude of VLF hiss decreased with decreasing latitude (10 dB per 1000 km) and explained it in terms of attenuation of propagating hiss in the earth-ionosphere wave-guide from the auroral zone to middle and low latitudes. Thus, the low and middle latitude hiss was considered to be a part of the auroral hiss. Hayakawa et al. made an extensive comparison of morphological characteristic features (diurnal variation, frequency spectra) of hiss observed at the auroral latitude station Syowa (geomagn. lat. 69°S, L=6.11) and midlatitude station Moshiri (geomagn. lat. 34.5°N, L=1.59) and showed significant differences between them. Midlatitude hiss spectral density exhibits a peak around 5 kHz with an upper limit of 8 kHz, whereas auroral hiss spectrum shows a broad bandwidth extending from a few hundred Hz to 500 kHz and even higher. Thus, the low and midlatitude hiss seems to be independent of the auroral hiss. The auroral hiss emissions are classified into two types, namely, continuous hiss and impulsive hiss. Continuous hiss does not reveal any large change in its spectral structure for several minutes and even for hours, whereas impulsive hiss spectra change is considerably even within a fraction of second. The comparative features of the auroral and low latitude hiss are shown in Table 1, wherein the observed spectral details, seasonal and diurnal variation of occurrence rate and their association with precipitated electrons have been summarized. It is shown that the auroral hiss are associated with the electrons of 1 keV energy and equatorial hiss are associated with soft electrons of 10 eV. Kleimenova et al. have shown that the upper boundary of the low latitude hiss observation zone is associated with the main ionospheric trough (decrease of F-region ionization). Auroral hiss and mid latitude/plasmaspheric hiss observed both at ground stations and onboard satellites have been reviewed and their generation mechanism has been discussed.

The early observations of low latitude VLF hiss come from Japanese workers. Khosa et al. have
Table 1—Comparison of auroral and low latitude hiss

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<thead>
<tr>
<th>Auroral hiss</th>
<th>Low latitude hiss</th>
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<tr>
<td>(i) Predominantly it is observed around midnight (2000-0400 hrs MLT). Satellite observations show additional maximum around 1400 hrs LT.</td>
<td>(i) The quiet time hiss has a pronounced peak at 0500 hrs MLT and coincides with peak in occurrence rate of low latitude whistlers.</td>
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<tr>
<td>(ii) Auroral hiss tends to appear predominantly in winter season.</td>
<td>(ii) The quiet time hiss appears predominantly in winter, whereas storm time hiss shows less seasonal dependence.</td>
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<td>(iii) Duration of the auroral hiss is predominantly less than one hour.</td>
<td>(iii) Duration is predominantly 1-2 hours. Long lasting nature (5 hours) have also been observed.</td>
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<td>(iv) The intensity spectrum shows a maximum around 10 kHz and extends from 1 kHz to 100 kHz. The bandwidth and peak position vary with geomagnetic activity.</td>
<td>(iv) Relatively narrow band spectrum with the centre frequency lying between 4 and 5 kHz. Upper frequency limit extends up to 8 kHz. The satellite results show the presence of two peaks around 6 kHz and below 1 kHz.</td>
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<td>(v) The hiss intensity observed at the ground lies in between $10^{-19}$ and $10^{-14}$ Wm$^{-2}$ Hz$^{-1}$, whereas on board satellite it is $10^{-12}$ Wm$^{-2}$ Hz$^{-1}$.</td>
<td>(v) The hiss intensity at the ground lies in the range $10^{-17}$-$10^{-18}$ Wm$^{-2}$ Hz$^{-1}$, whereas at the satellite, it is $10^{-12}$ Wm$^{-2}$ Hz$^{-1}$.</td>
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<td>(vi) Hiss observations are closely associated with the precipitation of energetic electrons (~1 keV) in the auroral zone.</td>
<td>(vi) The observations of electron precipitation at low latitudes are not available. Instead, a correlation between low latitude hiss and intense fluxes of soft electrons (~10 eV) has been observed.</td>
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reported, for the first time, VLF hiss from Srinagar, India (geomagn. lat. 24° 10' N) in the frequency band 1-3 kHz and 5-7 kHz. Recently Singh et al. have reported VLF hiss observed at Varanasi in the frequency band 0.4-2.6 kHz and 4.6-6.1 kHz. Characteristics of low latitude VLF hiss have been studied using Injun-3 satellite data, OGO-6 satellite data and Aerial-3 satellite data. The Areal satellites (3 and 4) provided a lot of evidence to support the association of low latitude and equatorial VLF noises with lightning discharges. It has also been found that the maximum intensity of VLF hiss correlates with the regions of high thunderstorm activity, which is indicative of the embryonic effect of lightning in generating VLF hiss.

Early observations of VLF hiss were explained in terms of incoherent Cerenkov radiation from electrons present in the ionosphere and magnetosphere. The computed flux density was smaller than the observed flux density and hence other generation mechanisms such as coherent Cerenkov radiation, convective beam amplification of incoherent VLF radiation, Doppler shifted cyclotron resonance instability have been suggested. Solomon et al., based on experimental result, have argued that amplification of background noise to observed intensity is possible. Draganov et al. performed extensive ray tracing analyses of the life time of multiply-reflected whistlers and showed that whistler rays entering the magnetosphere at a distributed set of points generate a continuum of wave energy which may have hiss-like spectrum. The world-wide thunderstorm may inject enough wave energy into the ionosphere and magnetosphere to maintain the experimentally observed levels of hiss.

Based on limited observations, Knudsen and Heikilla have reported correlation of the location of equatorial hiss with the intense fluxes of soft electrons (10 eV). Later on, many workers compared the low latitude radio noises observed onboard Ariel satellite with the corresponding soft electron flux measurement by Heikilla, and they found a good correlation between the two. In view of the above reported correlation and to explain the VLF hiss observed at low latitude station Varanasi ($L=1.07$), we have evaluated Cerenkov radiated power by soft electrons as a function of electron energy and wave frequency for low ($L=1.07$) and midlatitude ($L=4.0$). It is shown that even if we decrease the energy of the radiating electrons, we are not in a position to account for the observed VLF wave power using only incoherent radiation mechanism.
2 Power radiated from electrons

The accelerated charged particles moving through the magnetoplasma radiate electromagnetic waves through various processes such as synchrotron, cyclotron, Cerenkov and Bremsstrahlung mechanisms. The details of the theory of radiation mechanism have been studied by a number of investigators\textsuperscript{36-39}. Assuming the medium to be cold, collisionless, dispersive and anisotropic in nature, and neglecting the wave magnetic field as compared to the ambient static magnetic field (because it is small), the radiated power from a charged particle moving along the geomagnetic lines of force having small pitch angles ($v_{l} \equiv 0$) is given by \textsuperscript{24,36}

$$dP/d\nu = (e^{2} \beta_{l} \omega \nu e_{0} c) \, T_{JJ} \left\{ 1/(B_{n}^{2} - 4C_{n}e_{l}) \right\}^{1/2} \ldots (1)$$

where,

$$T_{JJ} = \epsilon_{1}^{2} - \epsilon_{2}^{2} - \epsilon_{1} n^{2} + (n^{2} - \epsilon_{1} n^{2}) \cos \theta$$

$$B_{n} = n^{2} \cos^{2} \phi \left( \epsilon_{3} - \epsilon_{4} \right) + \epsilon_{2}^{2} - \epsilon_{1} \epsilon_{3}$$

and

$$C_{n} = n^{2} \cos^{2} \phi \left( \epsilon_{1}^{2} - \epsilon_{2}^{2} - \epsilon_{1} \epsilon_{3} \right) + \epsilon_{3} \left( \epsilon_{1}^{2} - \epsilon_{2}^{2} \right)$$

Using Eq. (1), the power radiated per unit frequency bandwidth from electrons of different energy is computed. Considering the radiating electrons to be distributed in energy, the total radiated power from electrons having energy between $E_{1}$ and $E_{2}$ per unit volume is written as

$$(dP/d\nu)_{total} = \int_{E_{1}}^{E_{2}} (dP/d\nu) f (E) \, dE \ldots (2)$$

where, $f (E) = \{1/V(E)\} \, dJ/dE$ is the energy spectrum of the radiating energetic electrons. Frank and Ackerson\textsuperscript{40} have shown that $dJ/dE \sim E^{-\delta}$, where $\delta$ varies between 1.5 and 2.5. In the present computation we have chosen $\delta = 2.17$ (Ref. 40). The lower limit of electron energy $E_{1}$ is taken as 5 eV and upper limit $E_{2} = 100$ keV. The contribution from the electrons of energy greater than 100 keV is negligibly small.

The computed Cerenkov powers as a function of electron energy, geomagnetic field and cold plasma density for $L = 1.07$ and $L = 4.0$ are shown in Fig. 1 [(a) and (b)]. The radiated power per electron increases with frequency, and after reaching a peak value at certain frequency (critical frequency) the radiated power suddenly falls to a very small value. The radiated power decreases as the energy of electron increases. The incoherent radiated power is integrated over the radiating electron energy by considering measured electron energy spectrum\textsuperscript{46}, which is approximated by specifying the equivalent number density of electron in energy intervals.

![Fig. 1 — Variation of radiated power per electron with frequency for $E=0.005$, 0.5, 1.0 and 10 keV at (a) $L=1.07$, and (b) $L=4.0$.](image)
centered on a finite number of energies. The computer programme is developed which calculates the number density of energetic electrons in each energy segment and multiplies it by the power radiated per particle per unit frequency and sums it over energy and pitch angle range to get the total power per unit volume. In Fig.2 is shown the computed spectral density which reaches the ground surface without amplification or attenuation. The peak spectral density for \( L = 1.07 \) and \( L = 4.0 \) are \( 5.53 \times 10^{-21} \) and \( 4.79 \times 10^{-24} \) \( \text{Wm}^{-3} \text{Hz}^{-1} \) at frequencies 700 kHz and 12 kHz, respectively. It is shown that the maximum power radiated from electrons in the equatorial region vary with frequency. At lower latitudes, higher frequencies are generated, although they will be heavily attenuated while propagating through the ionosphere. 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 are mostly below 10 kHz. The numerical computation of the attenuation of wave propagating through the ionosphere shows that the minimum attenuation is for the waves having frequencies close to 5 kHz, which is in close agreement with the VLF waves observed at low latitudes.

Assuming perfect guiding of the emitted wave and that all the electrons radiated in phase we can add all the produced power in the flux tube to obtain total received power at the surface of the earth. In computing this power we have considered that all the electrons lying in the flux tube between \( \pm 15^\circ \) and \( \pm 6^\circ \) from the equator for \( L=4.0 \) and \( L=1.07 \) radiate in phase. Thus, the total power to be received on the surface of the earth is shown in Fig.3. From Fig.3 it is seen that due to larger radiating flux tube area at higher \( L \)-value, the spectral density to be received at the earth surface is larger as compared to smaller \( L \)-values. In the present computation the maximum power density is \( \sim 7 \times 10^{-14} \) \( \text{Wm}^{-2} \text{Hz}^{-1} \) near 10 kHz wave frequency for \( L=4.0 \). At lower frequencies the radiated power is smaller. For example, at 2 kHz, the maximum power is \( \sim 5 \times 10^{-15} \) \( \text{Wm}^{-2} \text{Hz}^{-1} \). From lower \( L \)-value (\( L = 1.07 \)) the maximum radiated power is obtained to be \( 8 \times 10^{-13} \) \( \text{Wm}^{-2} \text{Hz}^{-1} \) corresponding to 700 kHz wave frequency. For 10 kHz wave frequency the radiated power comes out to be \( \sim 1.3 \times 10^{-14} \) \( \text{Wm}^{-2} \text{Hz}^{-1} \).

### 3 Results and discussion

The computed results show that the maximum

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**Fig. 2** — Variation of total radiated power per unit volume (spectral density) with frequency in the equatorial region of \( L = 1.07 \) and \( L = 4.0 \).

**Fig. 3** — Variation of total radiated power (spectral density) in a flux tube of unit cross-section with frequency in the equatorial region of \( L = 1.07 \) and \( L = 4.0 \).
power generated from the radiating electrons having energy spectrum $E^{-2.17}$ and distributed along the field lines decreases as $L$-value decreases for VLF wave frequency 1-10 kHz. Higher frequencies are generated at lower $L$-values with relatively more power. However, due to strong attenuation these waves are not observed at the ground surface. In the evaluation of total power, unrealistic assumptions such as all the electrons radiate in phase and zero attenuation of the radiated power, are made. If we relax these assumptions then the total power to be received at the earth surface will be drastically decreased. The computed power for high $L$-values and lower $L$-values are in close agreement with those reported by other workers for different $L$-values $^{14,21,22,25}$.

Recently, Singh et al. $^{14}$ have presented two types of ELF hiss recorded at Varanasi. In the absence of reported power we cannot compare the computed results. Even the reported events by Khosa et al. $^{13}$ observed at Srinagar did not have the intensity measurements. Hayakawa $^{18}$ had summarized the essential features of equatorial VLF hiss for $L < 1.2$. The observed power flux was of the order of $10^{-14}$ Wm$^{-2}$Hz$^{-1}$ for the wave frequencies 5-10 kHz. Considering the satellite altitude it is found that the equatorial VLF hiss was observed below the altitude of 350 km. Thus, if we neglect the attenuation of the emitted wave, the observed flux density can be explained. The reported peak intensities of the equatorial VLF hiss were ~ $10^{-12}$ Wm$^{-2}$ Hz$^{-1}$ which are, at least, two orders of magnitude higher than the computed power. To explain this difference in computed and observed power, Singh et al. $^{14}$ computed the amplification of the propagating whistler mode VLF hiss in the equatorial plane. The computed amplification factor for 5 kHz wave frequency is 1.3 for $L=1.07$ and 31.5 for $L=4.0$, which is less than the required value to explain the observed spectral power. If we assume that the wave bounces back and forth many times before being received on the earth surface, then the wave passes through the interaction region many times and each time it interacts with the ambient energetic electrons and gets amplified. If amplification factor remains the same, then to reach the recorded intensity, the wave requires approximately 100 bounce, which is in conformity with the assertion of Helliwell $^{41}$. During multiple bouncing the signals having different intensity may couple from one duct to another and produce structureless signals of constant intensity as is observed in the case of VLF hiss.

Singh et al. $^{14}$ have shown that the relative intensities of hiss events vary with frequency and time in the same event and also vary widely from event to event. The same is true with the observations reported by Khosa et al. $^{13}$. Singh et al. $^{14}$ have argued that they have recorded midlatitude hiss and low latitude hiss. Midlatitude hiss has reached the ground station Varanasi, following the earth-ionospheric wave-guide path after exiting from the midlatitude magnetospheric ducts. Midlatitude hiss has narrow band around 5 kHz which is a typical property of midlatitude storm-time hiss. Hayakawa $^{18}$ has suggested that the hiss events presented by Khosa et al. $^{13}$ could be plasmaspheric ELF hiss and storm-time midlatitude hiss. In the absence of direction finding measurements it is not possible to determine the $L$-value of these events. Hayakawa $^{18}$ has also stressed that discrete emissions of high latitude origin are often received at the lowest latitude station Kagoshima (geomagn. lat. $-20^\circ$) in Japan. Plasmaspheric ELF hiss events have also been reported by Hayakawa and Tanaka $^{42}$ and Hayakawa et al. $^{13}$ from the analysis of data recorded at Moshiri ($L=1.6$). The polarization measurements indicated that the hiss has penetrated through the ionosphere near the latitude of Moshiri, but they $^{42,43}$ have concluded that these emissions originated just inside the plasmapause with very oblique wave normal angles and hence they are just the plasmaspheric hiss.

The generation mechanisms of VLF hiss remain controversial despite extensive theoretical and experimental work, because both the Cerenkov radiation mechanism and the wave-particle interaction (instability) mechanism required wave propagation parallel to the geomagnetic field lines. Although, experimental data show that hiss often propagates at oblique angles and may originate in the source regions with relatively high wave-normal angles $^{44}$. Somwalkar and Inan $^{45}$ have shown that a hiss -like signal often follows lightning-generated whistlers. Draganov et al. $^{31}$, based on ray-tracing simulations and estimates of whistler wave damping, suggested that lightning-generated whistler wave energy can develop into plasmaspheric hiss via
multiple reflections, and thunderstorm activity on a global scale may be sufficient to support observed hiss levels. Recently, Savchenko and Vaisman have presented VLF hiss preceding the whistlers. Based on the data analysis and numerical simulations, they have shown that the VLF hiss bursts observed on the ground could have been formed by refraction and scattering of the VLF waves in the ionosphere on irregularities generated during the precipitation of energetic electrons induced by whistlers.

The VLF hiss observed at low latitude stations is classified into two types: one belonging to midlatitudes and the other belonging to the equatorial hiss. The generation mechanism of these emissions is not properly understood. It is not clear whether the equatorial hiss observed by Gurnett was generated in the equatorial region or in the topside ionosphere. Satellite observation supports the idea that most of the equatorial hiss events originated in lightning discharges. It is suggested that both ground and satellite observations should be carried out simultaneously to understand the morphological features and generation mechanism of VLF hiss at low latitudes.

4 Conclusion

In this paper an attempt has been made to explain the observed power fluxes of VLF hiss in terms of Cerenkov radiation from electrons having energy from 10 eV to 100 keV. The incoherently radiated power is short of two orders of magnitude, which can be compensated by the amplification of the wave during interaction with energetic electrons present in the magnetosphere. This two-step generation process could explain the observed level of power fluxes at low frequencies. It has also been argued that equatorial/midlatitude hiss having large wave normal angles may find their origin in lightning discharges.

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