On the Simultaneous Observations of Daytime Whistlers and ELF/ VLF Emissions at Low Latitudes: A Review

S. A. Sheikh, K. K. Singh, Farooq Ahmad, and Lalmani

***Abstract*—This paper reports an unexpected simultaneous observation of whistlers and different types of ELF/VLF emissions during daytime at a low latitude Indian ground station Jammu (geomag. lat., 22° 26′ N; *L*=1.17), which are (a) pulses of atmospheric bursts, (b) discrete chorus riser ELF emissions triggered from the bottom of the atmospherics, (c) whistlers, (d) whistler-triggered discrete chorus riser VLF emissions triggered from the lower end of the whistler, (e) long enduring ELF/VLF hiss emissions, (f) band limited pulsing ELF/VLF hiss emissions, (g) hook and inverted hook ELF emissions, (h) oscillating tone discrete chorus riser ELF emissions. The simultaneous observations of this type during daytime has not been found in any of the Indian stations and is the first such observation to be reported in this paper. The observed characteristics of these simultaneously recorded whistlers and ELF/VLF emissions are described and interpreted. The data presented here indicate that there is a strong possibility that lightning is an important source of different types of ELF/VLF emissions at least in the embryonic sense.**

***Index Terms*—Whistlers, ELF/VLF emissions, hiss, chorus, pulsing hiss, hook, inverted hook.**

I. Introduction

Whistlers and emissions in the extremely low frequency (ELF) and very low frequency (VLF) are considered to be invaluable tools in probing the plasma of the ionosphere and magnetosphere. In particular whistler mode waves and their interactions with energetic particles has been a subject of interest since the discovery of the radiation belts. The wave particle interactions occurring in the magnetosphere generate a variety of emissions in the ELF/VLF range. ELF/VLF emissions from the Earth's magnetosphere in the range of few hertz to 30 kHz, both continuous or unstructured and discrete or structured in nature are very fascinating, challenging and interesting natural phenomena [1]. Although the ELF/VLF emissions of different types are often observed at different times at low latitude ground stations in Japan and India [2]-[5], but almost there is no evidence of their simultaneous occurrence during daytime.

We here report the first simultaneous observation of whistlers and different types of ELF/VLF emissions during daytime at a low latitude Indian ground station Jammu which includes (a) pulses of atmospheric bursts, (b) discrete chorus riser ELF emissions triggered from the bottom of the atmospherics, (c) whistlers, (d) whistler-triggered discrete chorus riser VLF emissions triggered from the lower end of the whistler, (e) long enduring ELF/VLF hiss emissions, (f) band limited quasi-periodic pulsing ELF/VLF hiss emissions, (g) hook and inverted hook ELF emissions, (h) oscillating tone discrete chorus riser ELF emissions. An attempt has been made to explain the generation and propagation mechanisms of these simultaneously observed whistlers and emissions during disturbed periods at low latitudes. The present work is in fact intended to contribute greatly the wave-particle interaction process taking place during magnetically disturbed periods at low latitudes.

Manuscript received April 3, 2012; revised August 28, 2012.

S. A. Sheikh and Farooq Ahmad are with the Department of Physics, University of Kashmir, Srinagar- 190006, Kashmir, India (e-mail: shabir_222@rediffmail.com).

K. K. Singh is with the Department of Physics, Banaras Hindu University, Varanasi 221005, India.

Lalmani is with the Department of Physics, National Institute of Technology, Srinagar-190006, Kashmir, India

II. Experimental Results

Under All India Coordinated Program of Ionosphere Thermosphere Studies (AICPITS) program we have conducted initial observation of whistlers and VLF/ELF emissions at our ground based station Jammu and obtained an unique and very interesting result of the simultaneous occurrence of whistlers and different types of VLF/ELF emissions during daytime. Such type of daytime observations has never been reported from any of the low latitude ground stations so far and is the first result to be reported here. A preliminary description of whistlers and different types of VLF/ELF emissions recorded simultaneously during daytime at Jammu in the magnetically disturbed periods on 06 January 1999 alongwith their possible interpretations are given.Some typical and interesting examples of these simultaneously recorded ELF/VLF data at Jammu are shown in Fig. 1-7. The date and time of the observation of each whistler and VLF/ELF emission are mentioned on the top of each figure. These were observed simultaneously only on a single day in winter local day times on 06 January 1999 during magnetically disturbed period with the sum of K_p indices as 18 ($\sum K_p$ = 18+). This activity started around 1400 hrs IST (Indian Standard Time) and continued for about two hours.

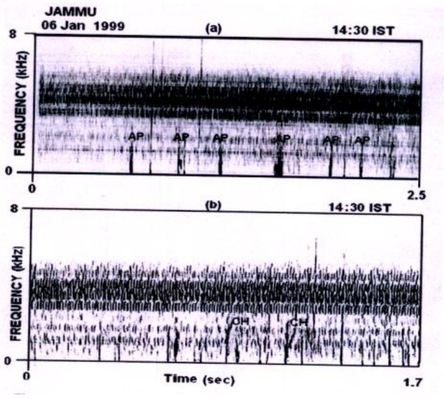

Fig. 1. Temporal variation of frequency spectra of pulses of atmospheric bursts and discrete chorus riser ELF emissions observed simultaneously during daytime at Jammu (AP: Atmospheric Pulses; CH: Chorus).

Fig. 1 shows dynamic spectrograms of pulses of atmospheric bursts and triggered rising tone discrete chorus emissions in the ELF range (≤ 3 kHz) recorded at 1430 hrs IST on 06 January 1999. The spectrum analysis of the events shown in Fig.1a clearly shows that the VLF/ELF activity on this day was started with the pulses of atmospheric bursts in the ELF range with a regular time intervals of ~ 0.30 sec immediately after the commencement of the events, whereas Fig.1b shows a dynamic spectrum of two sets of sharp discrete chorus riser emissions in the ELF range in the frequency range ~ 0.60 to 3.0 kHz with a time separation of ~ 0.30 sec between them. It is interesting to see that these emissions are triggered from the lower end of the lightning generated atmospherics above ~ 500 Hz. A band of noise (continuous hiss type structure) in the frequency range ~ 2.8 to 6.3 kHz is seen in this figure, it may have occurred due to some local noise present at the time of observation.

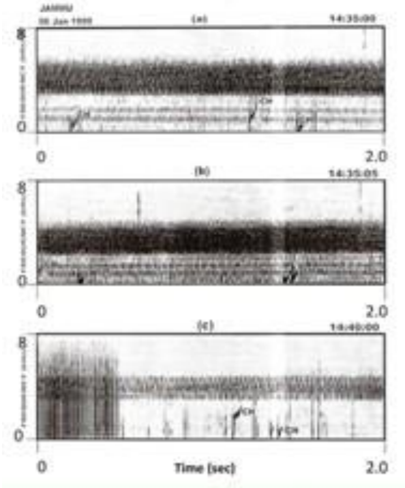

Fig. 2. Temporal variation of frequency spectra of discrete chorus riser ELF emissions observed simultaneously during daytime at Jammu (CH: Chorus).

Fig. 2 shows the dynamic spectrograms of many events of rising tone discrete chorus emission (marked as CH) in the ELF range (≤ 3 kHz) recorded at ~ 1436 hrs IST. It is very interesting to see that these emissions are diffused having very appealing nice structure and triggered from the lower end of the lightning generated atmospherics above ~ 500 Hz. A band of noise is continued to be persisted in these spectrograms also.

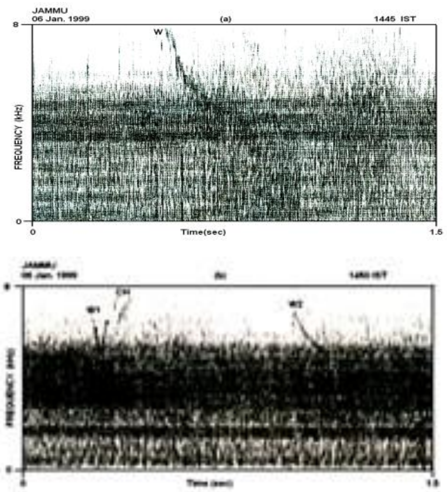

Fig. 3. Temporal variation of frequency spectra of whistler and whistler-triggered discrete chorus riser emissions observed simultaneously during daytime at Jammu (W: Whistler; WT: Whistler-triggered).

Fig. 3a depicts one of the typical example of a temporal variation of frequency spectra of a diffused whistler observed simultaneously at 1445 hrs IST. In this event the whistler marked W has a dispersion of ~ 55 $sec^{1/2}$ and the path of propagation has L = 4.35 where as Fig.3b shows another interesting typical examples of a temporal variation of frequency spectra of VLF waves observed simultaneously at 1450 hrs IST. Firstly it contains a whistler-triggered chorus riser emission event. In this event the whistler marked W1 has a dispersion of ~ 28 $sec^{1/2}$ and a chorus emission (marked CH) is triggered from the lower end of the whistler W1. The corresponding path of propagation of whistler W1 is L = 3.4. Immediately after 0.8 second another whistler W2 appears with a dispersion of ~ 52 $sec^{1/2}$ and the path of propagation has L = 4.25. Just below the spectra of whistler-triggered VLF chorus riser emission and whistler, the same noise band structure is continued to be persisted in this figure also.

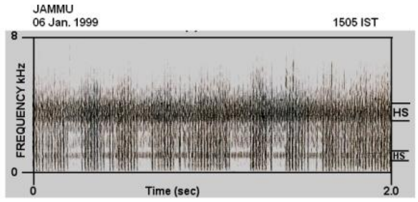

Fig. 4. Temporal variation of frequency spectra of ELF/VLF hiss emissions observed simultaneously during daytime at Jammu (HS: Hiss).

Fig. 4 contains clear bands of both VLF and ELF hiss emissions with the presence of large number of atmospherics. The band of VLF hiss occurs in the frequency range ~ 3.8 to 6.0 kHz where as ELF hiss in frequency range ~ 1.1 – 1.8 kHz observed simultaneously at 1505 hrs IST respectively. Bands containing large number of sferics is seen to occur at regular time of intervals. The time separation between the bands of sferics is ~ 0.1 sec.

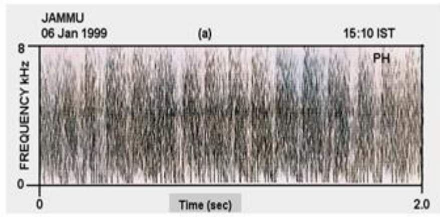

Fig. 5. Temporal variation of Quasi-priodic pulsing hiss emissions observed simultaneously during daytime at Jammu (PH: Pulsing hiss)

Fig. 5 illustrates typical examples of frequency spectra of quasi-periodic pulsing hiss emissions recorded simultaneously at 1510 hrs IST. This figure contains pulsing hiss in both frequency range of VLF and ELF starting from ~ 300 Hz upto ~ 8 kHz frequencies.

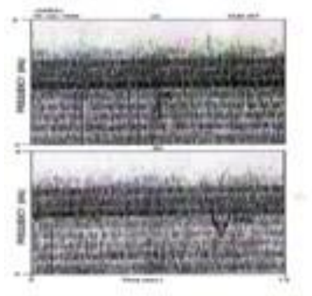

Fig. 6. Temporal variation of frequency spectra of hook and inverted ELF hook emissions observed simultaneously during at Jammu (HK: Hook; IHK: Inverted Hook)

Fig. 6 is one of the very interesting typical examples of a temporal variation of frequency spectra of hook (Fig. 7a) and inverted hook (Fig. 7b) emissions in ELF/VLF range recorded simultaneously alongwith other types of emissions on 06 January 1999 at 1530 hrs IST. In this figure a normal sharp hook emission first appear in the frequency range between ~ 1.5 and 2.6 kHz and immediately after ~1.5 seconds a trace of diffused inverted hook emissions appear one over in the frequency range ~ 2.4 to 3.4 kHz. In this figure also dominant noise band structure persists on the spectrogram in the same frequency range as in Fig. 2- 4.

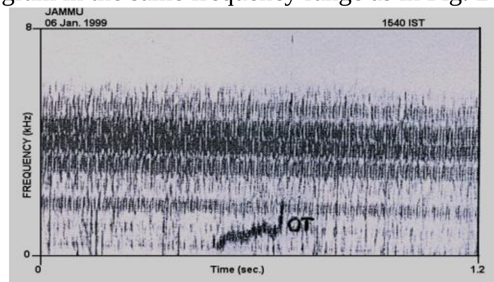

Fig. 7. Temporal variation of frequency spectra of oscillating tone discrete chorus riser emissions observed simultaneously during daytime at Jammu (OT: Oscillators tone)

In Fig.7 we show a typical example of frequency spectrum of a diffused oscillating tone discrete chorus riser emission recorded simultaneously at 1540 hrs IST on 06 January 1999.This event is recorded after ten minutes of the occurrence of hook emissions shown in Fig.7 and appear in the ELF range between ~ 0.5 and 1.3 kHz. Noise band structure is also seen to be present in this spectrum.

It is known that the regions of high thunderstorm activity are correlated with the maximum intensity of hiss, which is an indicative of the embryonic effect of lightning in generating hiss [6]-[8]. The reported event of daytime whistlers and emissions are observed during high thunderstorm activity. The effect of thunderstorm activity is evident in the present observation. The analysed spectrograms of this event contains lot many bursts of intense atmospherics due to thunderstorms. Our spectrum analysis also shows that ELF discrete chorus riser emissions are clearly seen to be triggered from the foot of the lightning generated atmospherics almost at the start of the ELF/VLF activity (Fig. 1b and Fig. 4). These results clearly indicate that there is a strong possibility that lightning is an important source of different types of ELF/VLF emissions observed simultaneously during day time at Jammu on 06 January 1998. Therefore it appears that wave energy introduced in the magnetosphere by atmospheric lightning discharge may play an important role not only in the loss of particles through wave-induced precipitation but also in the embryonic generation of different types of ELF/VLF emissions at low latitudes.

III. Generation Mechanism

Several mechanisms have been proposed from time to time to explain the generation mechanism of ELF/VLF waves[6]. Experimental observations show strong evidence that these emissions are generated near the magnetic equator by trapped energetic electrons. Out of various mechanisms proposed from time to time, the non linear cyclotron resonant interaction between whistler mode waves and energetic electrons could explain most of the characteristics of different types of ELF emissions recorded simultaneously on our ground station Jammu during daytime. In resonance interaction the kinetic energy of electrons increases as frequency decreases. In our proposed mechanism for the generation of these emissions, a simple model has been advanced by Singh et al [7]. According to this model constant frequency oscillations are generated from the interaction region if situated on the equator, whereas interaction region situated on the down stream (upstream) sides of the magnetic equator generates oscillations with rising (falling) frequency. The cyclotron resonance condition which is basis for this mechanism is expressed as

$$\omega - \omega_H \beta = k v_{II} \qquad (1)$$

where ω and k are the angular wave frequency and wave vector of the whistler waves, $k = |k|$, ω_H is the electron gyrofrequency, v_{II} is the field aligned component of the electron velocity, $\beta = (1 - v^2 / c^2)^{-1/2}$ is the relativistic correction factor, v, is the velocity of interacting particle and c is the velocity of light in free space. In an inhomogeneous magnetic field, ω_H, k and v_{II} are functions of the coordinate z along the magnetic field B_o. The electrons with different v_{II} interact with the same wave (ω, k) at different points along the geomagnetic field lines.

In order to explain the frequency spectrum of the ELF/VLF emissions observed at Jammu we have applied the non-linear cyclotron resonance mechanism as discussed in detail by Singh et al [7]. Under the second order cyclotron resonance condition df/dt values of the dynamic spectrum of ELF/VLF emissions can be written as

$$\frac{df}{dt} = \frac{1}{2\pi}\left(\frac{\omega}{2\omega + \omega_H}\right)\left[\left(3v_R - \frac{kv_\perp^2}{\omega_H}\right)\frac{\partial \omega_H}{\partial_Z} - 2\Omega_{tr}^2 s\right] \qquad (2)$$

where f is the wave frequency, v_R is the resonance energy of the electrons, $v_\perp$ the perpendicular velocity of the electron, z is the coordinate along the geomagnetic filed line. $\Omega_{tr} = (kv_\perp e B_\omega / m)^{1/2}$ (the oscillation frequency of the trapped electrons) where e the charge of electron m the mass of electron, Bω the wave-magnetic field and S is the inhomogeniety in the magnetic field.

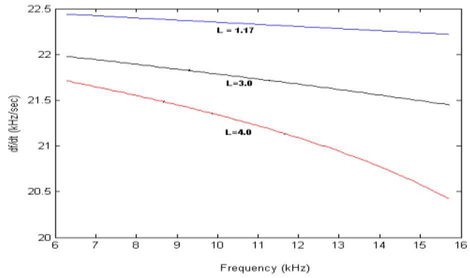

Fig. 8. Variation of df/dt as a function of frequency for a=15, Q=0 and s=0.2, 0.5 and 0.8 for L=1.17, L=3 and L=4 respectively.

We have computed df/dt as a function of wave frequency, pitch angle and L-value. The results are given in Fig.8.

The most important among the events recorded simultaneously on 06 January 1999 at Jammu is pulsing hiss. In order to interpret dynamic spectrum of pulsing hiss recorded simultaneously for the first time during daytime at our low latitude ground station Jammu, Knott and Bahnsen [8] suggested that the pulsed hiss type of emission is a plasmasheet associated phenomenon and depends critically on the level of anisotropy of energetic electrons (> 20 keV).

Whistler mode waves propagating along geomagnetic field lines and interacting with counter streaming energetic electrons would scatter electrons in to the loss cone. This may drive highly localized field-aligned currents leading to generation of Alfven waves that may cause growth of whistler wave and set up pulsing hiss along the field line. Considering the parameters appearing in the wave growth as time dependent functions, separating the variables and differentiating the basic equation for the wave growth coefficient γ can be written as [8]

$$\gamma = \left(\frac{1 + b\cos\omega_0 t}{1 + b}\right)^{\left(\frac{1+2A}{A} - \frac{3m\Omega_0^2}{kT_{II}K_\omega^2}\right)}$$

$$.\exp\left[\frac{2m\Omega_0^2 b}{kT_{II}K_\omega^2}(\cos\omega_0 t - 1)\right] \quad (3)$$

where b is the normalized amplitude of propagating micropulsation / whistler wave, $A= (T_\perp - T_\parallel)/ T_\parallel$ is an anisotropic facture , $T_\perp$ and $T_\parallel$ are the characteristic temperatures of the electron's motion perpendicular and parallel to the local geomagnetic field respectively, $\boldsymbol{\omega_0}$ is micropulsation frequency

K_ω is the wave vector of the interacting wave, m is the mass of electron k is Boltzmann constant, Ω_0 is the oscillation frequency of the trapped electrons.

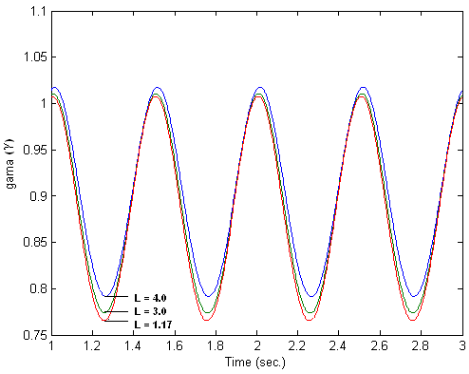

Fig. 9. Variation of growth rate with time for different L-values (L=1.17, L=3.0 and L=4.0).

This shows that hiss amplitude has fundamental frequency component of micropulsations. The second harmonics does not appear. We have evaluated Equation (3) for the parameters relevant to L = 1.17, 3.0 and 4.0 which is shown in Fig.9 In the computation b = 0.05, $\omega = 2\pi f_o$, f_o =1.9987 Hz, A = 1.5, $T_\parallel = 4.6615 \times 10^7$ °K has been used, ω_H (local electron gyrofrequency) and ω are chosen corresponding to the equatorial value for L = 1.17, 3.0, and 4.0 and wave frequency is taken as 8 kHz. Growth rate in oscillating and amplitude of oscillation decreases as L-value increases for L = 4.0 the oscillation lies between 0.78 and 1.26.

IV. Results and Discussions

We now discuss the implications of our simultaneous observations from several different perspectives. Detailed spectrum analysis of whistlers and different types of VLF/ELF emission events observed simultaneously on 06 January 1999 at Jammu were made in order to find out the possibility of their occurrence. The possibility that the occurrence of these events was just a coincidence does not seem to be likely because we have observed many similar events subsequently which occurred one after the other.

From the dispersion analysis of the simultaneously observed whistlers, it is found that they have dispersions in the range ~ 28 to 55 $sec^{1/2}$ and correspondingly L- values were found in the range of ~ 3.4 to 4.35 derived from the Dowden-Allcock method [9]. Subsequently the L-value of VLF/ELF source computed with the help of the upper boundary frequency (UBF) method as developed by Smirnova [10] was found to be L ~ 4.0 for f_{UB} = 8.0 kHz. Our spectrum analysis of whistlers and VLF/ELF emissions simultaneously observed clearly shows that whistlers and VLF/ELF emissions have propagated in ducted mode along the same field line of higher L-values and after existing from the duct they penetrated the ionosphere and are trapped in the Earth-ionosphere wave-guide. The wave normal (lying in the range of ~ 0.2-2.3°) at the entrance into the wave-guide is such that they propagated towards the equator and are recorded at Jammu. It is now well established that whistlers at low latitudes are observed during daytime through ducted mode of propagation in the presence of the equatorial anomaly. We have made computations of df/dt for L = 1.17, 3.0 and 4.0. The observed df/dt values agrees well with the computed results for L = 1.17, 3.0 and 4.0. According to the simplified model given by Singh et al [7], oscillating tones are triggered when interaction region oscillates near the equatorial zone along the field line. This explains the whistler-triggered emissions shown in Fig. 3b. The riser event (Fig. 1 and Fig. 2) is generated when interaction region lies in the southern hemisphere.

In the present case of quasi-periodic pulsing hiss observed simultaneously at Jammu during daytime on 06 January 1999, the pulsing hiss time period is about 0.5 sec which corresponds to continuous pulsation PC 1. PC 1 forms a standing wave pattern along the geomagnetic field line and thus produces oscillation in the trapped electrons bouncing back and forth along the field lines. Thus the wave-particle interaction is also modified. Considering hiss emission intensity to be result of amplification of waves, we except corresponding pulsation in the hiss-emission intensity.

An alternate source of VLF/ELF hiss (Fig. 5) could be lightning discharge. Parrot [11] has shown that the regions of high thunderstorm activity are correlated with the maximum intensity of hiss, which is an indicative of the embryonic effect of lightning in generating hiss [12]. VLF hiss generated by embryonic process could also be modulated through wave-particle interaction in the presence of micropulsations. Ward [13] based on comparative study of pulsing hiss and pulsating aurora showed that hiss pulses and auroral pulses have similar periods whereas the micropulsations had periods which were considerably longer for the cases analyzed. These discussions show that while working out the generation mechanism of pulsing hiss, one should take into the account the generation mechanism of pulsing aurora and micropulsation, which find their origin in the ionosphere.

Davidson and Chiu [14] have discussed a non-linear mechanism for auroral pulsation, which may provide some indication on the possible origin of pulsing hiss. We have made a detailed analysis of the ELF/VLF data observed at Jammu along with other Indian stations during the year 1997 to 1999. From this review it is found that the simultaneous observations of this type during daytime reported in this paper have not been found in any of the stations and is the first such observation reported in this paper.

V. Conclusion

The most important among the various types of whistlers and VLF/ELF emissions recorded for the first time is the simultaneous observations of these events during daytime at low latitudes. The data presented in this paper indicate that there is a strong possibility that lightening is an important source of VLF/ELF emissions.

Acknowledgements

S. A. Sheikh, acknowledges support from Head of department of Physics, University of Kashmir India and K.K. Singh form the DST India for Fast Track Project and Physics Department, Ashoka Institute of Technology and Management, Varanasi, India.

References

[1] R. A. Helliwell, *Whistlers and related ionospheric phenomena.* Stanford University Press, Polo Alto Calif, 1965, pp. 1-6.

[2] M. Hayakawa, Y. Tanaka, and J. Ohtsu, "On the morphologies of low latitude and auroral VLF hiss," *J. Atmos. Terr. Phys.,* vol. 37, pp. 517-529, 1975.

[3] P. N. Khosa, Lalmani, R. R. Rausaria, and M. M. Ahmad "Whistlers and VLF hiss recorded at Srinagar," *Ind. J. Radio Space Phys.,* vol. 10, pp. 209-210, 1981.

[4] D. K. Singh, A. K. Singh, R. P. Patel, R. P. Singh, and A. K. Singh, "Two types of ELF hiss observed at Varanasi," *Ann. Geophysicae*, vol. 17, pp. 1260-1267, 1999.

[5] Ashutosh, K. Singh, K. K. Singh, A. K. Singh, and Lalmani, "Simultaneous observations of whistlers and emissions, during a geomagnetically quiet period at low latitude," *Astrophys. Space Sci.,* vol. Do1 10.10071, pp. 10509-010-0465-0, 2010.

[6] R. P. Singh, R. P. Patel, K. Singh, and A. K. Singh, "Observations of pulsing hiss at low latitudes," *J. Atmos. Solar. Terr. Phys.,* vol. 67, pp. 1497-1503, 2005.

[7] R. P. Singh, R. P. Patel, and D. K. Singh, "Triggered emissions observed at Varanasi," *J. Planetary. Space Sci*., vol. 51, pp. 495-503, 2003.

[8] K. Knott and A. Bahusen, "Observations in North Europe," *Report on 5th workshop on I.M.S,* New York, 1981.

[9] R. L. Dowden and G. M. Allcock, "Determination of nose frequency of non-nose whistlers," *J. Atmos. Terr. Phys*., vol. 33, pp. 1125-1129, 1971.

[10] N. A. Smirnova, "Fine structure of the ground observed VLF chorus as an indicator of the wave particle interaction process in the magnetosphere," *Planet, Space Sci*. vol. 32, pp. 425-438, 1984.

[11] M. Parrot, "Word map of ELF/VLF emissions as observed by a orbiting satellite," *Ann. Geophysicae*, vol. 8, pp. 135-146, 1990.

[12] V. S. Sonwalkar and U. S. Inan, "Lightning as an Embryonic source of VLF hiss," *J. Geophys. Res*., vol. 94, pp. 6986-6994, 1989.

[13] I. A. Ward, "Pulsing hiss and associated phenomena: a morphological study," *J. Atmos. Terr., Phys.*, vol. 45, pp. 289-301, 1983.

[14] G. T. Davidson and Y. T. Chiu, "An unusual nonlinear system in the magnetosphere A possible driver for auroral pulsations," *J. Geophys. Res.*, vol. 96, pp. 19353-19362, 1991