Characteristics of ELF/VLF drifting emissions observed at low latitude station Varanasi during geomagnetic substorms

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Abstract. If the frequency within a set of periodic emissions changes significantly, the set is called drifting emissions. In this paper, characteristics of drifting ELF/VLF emissions are examined based on the ELF/VLF data recorded at low latitudes ground station Varanasi (geom. lat. 14° 55' N, long. 154° E, L=1.07) during the period Jan., 1990 to Dec., 1990. Total seven strong events of drifting ELF/VLF emissions have been observed on 28-29 April, 1990 at pre-midnight sector out of which 3 events were analyzed in detail. The observed ELF/VLF emissions exhibit a regular frequency drifts, increasing as well as decreasing drift. The ELF/VLF emissions observed are mainly periodic emissions of rising and falling tone chorus. These emissions were observed during a geomagnetic storm period, when minimum Dst-index was –98 nT and Kp-index ≥ 5. The repetition period, sweep rate and the frequency drift rate have been evaluated for all events. We have also computed the spectral power density, location of plasmapause, maximum intensity and maximum frequency attained. The generation mechanism of these drifting ELF/VLF emissions is explained in terms of a quasi-linear electron synchrotron instability model for wave excitation. The frequency drift in these emissions have been interpreted in terms of a combined effect of L-shell drift of energetic electrons and the change in convections electric field during the substorm developments. The computed maximum spectral power density of the wave varies between 1.8 × 10^{-21} to 4.08 × 10^{-22} Gauss^2/Hz. The computed frequency drift rates of these drifting emissions are found in good agreement with that of experimentally observed values.

1. Introduction
The class of natural radio phenomena from 200 Hz to 30 kHz observed either in association with whistlers or independently and having wide variety of dynamic spectra is known as VLF emissions (or VLF ionospheric noise) which may have origin in the ionosphere and magnetosphere [1-2]. The amplitude of emissions frequently fluctuates in a periodic or quasi-periodic manner, with periods ranging from less than a second to more than a minute [3]. The emissions spectra are characterized by a tendency for both the steady and the discrete forms to appear in well defined and sometimes relatively narrow frequency bands. These bands may remain relatively constant in frequency or they may show a systematic

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drift in frequency, either positive or negative [4-6]. Two or more interleaved sets with the same period are called multiphase periodic emissions [1]. In this type of emission the number of phases equals the number of sets. The frequencies of the sets may or may not be the same. If the frequency within the set changes significantly the set is called drifting and named as drifting VLF emissions [1, 4, 5]. It is well known that substorm activity is closely related to the activity of different types of VLF emissions observed at auroral, medium as well as low latitude [4-12]. The excitation of these emissions can be most easily associated with the injection of plasmasheet electrons into the inner magnetosphere and this makes it very convenient to study the corresponding wave particle interaction. These emissions provide a powerful tool for the study of the injection of electrons and the magnetospheric plasma structure, together with the dynamics of energetic electrons from the plasmasheet and the convection electric field during substorms [4, 5, 13]. Hayakawa et al. [5] have discovered frequency drift for pre-midnight VLF emissions and they have interpreted it in terms of a combined effect of L-shell drift of energetic electrons and the change in convection electric field during the substorm developments. At low latitude Indian stations it was reported that most of the VLF emissions were recorded when the magnetic activity was high [11, 12, 14].

Hayakawa et al. [4] investigated that the activity of mid-latitude VLF emissions has close association with geomagnetic substorms during the local dawn and pre-midnight time. Hayakawa et al. [4] interpreted these results using the quasilinear model for hiss-type mid-latitude emissions proposed by Sazhin [15]. The explanation of the observed frequency increase of the emissions was attempted in terms of energy dispersion of the drifting electrons. Sazhin and Vershinina [13] and Vershinina et al. [16] have given in more detail the explanation of decrease of frequency with time. The characteristics of pre-midnight substorm associated VLF emissions recorded at the same stations exhibited sharp frequency increase at the first stage of events followed by subsequent gradual decrease [5].

In this paper, we present observation and analysis of drifting VLF emissions recorded at our low latitude ground station Varanasi (geom. lat. = 14° 55' N, long. = 154° E, L = 1.07). Characteristics of all the different sets of observed drifting VLF emissions mentioning their upper and lower cut off frequencies, time duration of events, frequency drift rate, and sweep rate of each individual element are described in section 2. In section 3 we describe the generation mechanism of these emissions and the theoretical formulation using the model of Sazhin [15]. We have also computed the spectral power density, location of plasmapause, drift time of electrons, maximum intensity and maximum frequency attained. In section 4 we have presented discussion of results and summary of the paper.

2. Experimental Observation and Data Analysis
The experimental set up engaged at our low latitude ground station Varanasi (L = 1.07) to record the VLF signals consists of a T- type antenna, pre- and main- amplifiers having a bandwidth of 50 Hz -15 kHz and a magnetic tape recorder. T-type antenna with 25-meter vertical length, 6-meter horizontal length and 3.2 mm diameter (having impedance about 1 M \( \Omega \)) has been used to record vertical component of wave electric field. The antenna is rendered aperiodic with the help of a suitable RC network, to avoid any possible ringing effect [12]. The voltage induced in the antenna is amplified and recorded on magnetic tape recorder. The gain of the pre/main amplifier is varied manually from 0 to 40 dB, to avoid overloading of the amplifier at the time of intense VLF activity. The observations were taken continuously both during the day and nighttimes on a routine basis. The data were stored on magnetic tapes and then analyzed using newly installed analysis software named “Raven”. It is a software program for the acquisition, visualization measurement and analysis of sounds.

In order to study the storm / substorm generated emissions at low latitude, we analyzed the recorded data at Varanasi from Jan. 1990 to Dec. 1990. While analyzing the data we found some interesting VLF emissions on 28th–29th April 1990 at pre-midnight sector with the regular frequency drift in them. It is also remarkable that the period of received VLF drifting emissions coincided with the geomagnetic substorm period. We have shown the variation of interplanetary magnetic field (IMF), Dst and \( K_p \) indices.
with time in figure 1 consecutively in which the received VLF emission is also marked. It is noted that the drifting emissions were recorded during a strong geomagnetic storm period, which lasted from the 9th April to the 1st May 1990. The recorded drifting VLF emissions were observed on the 28th /29th April 1990 having the minimum Dst index –98 nT at 1000 UT which is shown in figure 1 (middle panel). The variation of Kp index is also shown in the figure 1(last panel), which shows the Kp index variation from 2- to 6-. From this figure we observed that our drifting emissions were recorded when the Kp index was 4+ with $\sum K_p = 27+$ on that day. The variation of interplanetary magnetic field (IMF) is also shown in figure 1 (upper panel), which clearly shows the southward direction of IMF values for most of the time during the substorm. Due to southward movement of IMF the energetic charged particles of the interplanetary origin enters in the plasmasheet of the Earth’s magnetosphere. These plasmasheet charged particles were injected into the inner magnetosphere, where they may have excited the drifting VLF emissions, which are recorded at our low latitude station Varanasi during the strong substorm period. Seven different sets of the drifting VLF emissions were recorded at around midnight of 28th – 29th April 1990 from 2332 (L.T.) - 0007 (L.T.). Out of total seven events we observed three long events with both increasing and decreasing drift rate which are shown in figure 2 (a), (b), (c).
From this figure it is clear that they are discrete periodic emissions (rising and falling tones) with a regular drift in frequency. The frequency is increasing as well as decreasing with local time in these events. The frequency drift rate for each set of events is evaluated by considering the mid frequency of the first and the last chorus element. Figure 2 (a) shows ten chorus elements with increasing frequency drift rate of 845.7 Hz/sec and eight elements with decreasing frequency drift rate of 374.81 Hz/sec. Here both rising and falling tones as well as some hook shaped elements were observed. Every individual element has different sweep rate \((df/dt)\), which varies from 8.5 kHz/sec to –4.3 kHz/sec. Figure 2 (b) shows various diffused chorus elements. The average repetition period of different elements is 0.53 sec with different sweep rates, which varies from 4.2 kHz/sec to 0.3 kHz/sec. The frequency drift rate initially increases with 496.1 Hz/sec and then decreases to 262.2 Hz/sec. Figure 2 (c) shows the two events of drifting VLF emissions with diffused strength. From this figure it is observed that there is a sharp fall in the frequency drift in the middle of the event. The average repetition period of the elements is 0.45 sec. The sweep rate \((df/dt)\) varies between 3.5 kHz/sec to 0.1 kHz/sec. From this figure we observed that the initially increasing frequency drift rate is 735.1 Hz/sec then it has a sharp decrease in frequency drift rate of 2457.1 Hz/sec. There is again a gradual rise of frequency drift rate, which is found to be 996.5 Hz/sec.
3. Generation Mechanism of Drifting VLF emissions

In this section, we attempt to explain the observed VLF drifting emissions using the theory proposed by Sazhin [15], which was earlier applied to explain the different types of drifting VLF emissions [4-6]. This model is based on the supposition that all the electrons penetrating into the magnetic field tube, where the waves are excited and partly drift across this tube and partly penetrates, under the influence of the wave field, into the ionosphere, so that the electron density in this tube remains constant [17]. The whistler mode wave propagating along geomagnetic field line interacts with the counter streaming electrons.

During the interaction, either wave can grow or decay depending upon the distribution function of interacting electrons. During the interaction, when wave grows, it is assumed that the wave excitation takes place and growth rate is maximum when during interaction, resonance condition is satisfied. For cyclotron resonance interaction, the growth rate can be written in the form [17]

\[
\alpha = \frac{\pi^2 \Omega v_D}{D} \left\{ \int_0^{\pi/2} \frac{\sin \alpha d\alpha}{\cos^4 \alpha} \int_0^{\pi/2} H(\alpha', v) \sin \alpha' d\alpha' \right\}
\]

(1)

here \( v_R \) is the electron resonant velocity (\( v_R = -\frac{\Omega}{k} \)), \( \Omega \) is electron gyrofrequency, \( k \) is whistler wave number, \( \alpha \) and \( \nu \) are the electron pitch angle and velocity, and \( D = \Omega \omega < B_f^2 > max / B_0^2 \), and \( < B_f^2 > max \) is the average spectral density of the squared waves magnetic field amplitude, \( f = \omega / 2\pi \), \( B_0 \) is the induction of the magnetospheric magnetic field, \( H \) is correspondingly the source and the loss function controlling the income and the loss of the electrons. Using diffusion equation and its solution we can obtain an explicit expression for \( < B_f^2 > max \) in the form [15]

\[
< B_f^2 > = \frac{\pi^2 m^2 c^4}{e^2 \omega^3 \ln (1 / R)} \int_{\nu_s}^{\nu_R} d\nu \frac{\Omega^6}{\Pi^2} \times \int_0^{\pi/2} \frac{\sin \alpha d\alpha}{\cos^4 \alpha} \int_0^{\pi/2} H(\alpha', v) \sin \alpha' d\alpha'
\]

(2)

Where \( e \) and \( m \) are correspondingly the electron’s charge and mass; \( \Omega \) and \( \Pi \) are supposed to depend on \( s \) and \( \Pi \) is the cold electron plasma frequency. The wave field expression as:

\[
< B_f^2 > = \frac{8\pi^{3/2} m R_E}{\ln (1 / R)c^2} \left( \frac{w^3 L \Pi_{eq}^2}{\Omega_{eq}^3} \right) \frac{dn}{dt} \Gamma(\beta_{eq} p, n)
\]

(3)

where, \( \Gamma(\beta_{eq}, p, n) = \beta_{eq}^{3/2} \int_0^{\pi/2} \frac{1 + 3 \sin^2 \frac{\lambda}{2}}{\cos^{35/4} \frac{\lambda}{2}} \Psi(\beta_s, p) d\lambda \)

(4)

Sazhin [15] has explained that \( < B_f^2 > \) has its maximum value when

\[
\omega = \omega_{max} \approx \frac{c^2}{W^2} \frac{\Omega_{eq}^3}{1.2 \Pi_{eq}^2}
\]

(5)

By using the numerical values of the parameters as \( m = 9.1 \times 10^{-28} \text{ gm}; c = 3 \times 10^{10} \text{ cm s}^{-1}; e = 4.8 \times 10^{-10} \text{ statcolumb}, R_E = 6.37 \times 10^6 \text{cm and R = 0.1} \) we can simplify equation (3) in the form [15]:

...
Where $n_{eq}$ is the cold electrons density in the equatorial plane, $W$ is electron energy expressed in electron volts. From equation (6), $< B^2_f >$ achieves its maximum $< B^2_f >_{\text{max}}$ when $\omega=\omega_{\text{max}}$ and $\Gamma=0.05$. Hence we obtain [15]

$$< B^2_f >_{\text{max}} = 5 \times 10^{-27} n_{eq} L^9 W^{3/2} \frac{dn_e}{dt}$$

(7)

From [15] it can be presented as

$$< B^2_f >_{\text{max}} = 5 \times 10^{-27} n_{eq} L^5 W^{1.5} \frac{dn_e}{dt}$$

(8)

Thus, the frequency $f_{\text{max}}$ can be written in more convenient form [5]

$$f_{\text{max}} (\text{kHz}) = \frac{1.6 \times 10^9}{L^9 n_{eq} (\text{cm}^{-3}) W_{\parallel} (\text{keV})}$$

(9)

The rate of change of $f_{\text{max}}$ (frequency drift rate) can be estimated from the formula [5]:

$$\frac{df_{\text{max}}}{dt} = f_{\text{max}} \left[ -9 \frac{dL}{L} \frac{1}{n_e} \frac{dn_e}{dt} - \frac{1}{W_{\parallel}} \frac{dW_{\parallel}}{dt} \right]$$

(10)

To estimate the value of $\frac{dW_{\parallel}}{dt}$ due to velocity dispersion of drifting electrons, we assume that the waves are registered at one station in two subsequent local times in the pre-midnight sector $t_a$ and $t_b$. The formula in equation (8) is used to compute the maximum spectral power density $< B^2_f >_{\text{max}}$ where $n_{eq}$ is the equatorial electron density (in cm$^-3$) at the $L$-shell where the waves are generated, and $dn_e/dt$ is the time derivative of the electron density considered as $3 \times 10^{-4}$ (cm$^{-3}$sec$^{-1}$) [15]. Our computed values of $< B^2_f >_{\text{max}}$ vary between $1.80 \times 10^{-21}$ to $4.08 \times 10^{-22}$ (Gauss$^2$/Hz).

The computations of the drift rate ($df_{\text{max}}/dt$) are extracted from equation (10) for different observed drifting VLF emissions. For figure 2 (a) we have computed the increasing drift rate after computing $W_{\parallel} = 1.51$ keV, $dn_e/dt = 3 \times 10^{-4}$ cm$^{-3}$ sec$^{-1}$ [15] $n_e = 2 \times 10^3$ cm$^{-3}$ [18], $\frac{1}{L} \frac{dL}{dt} = -1.33 \times 10^5$ sec$^{-1}$ and $\frac{dW_{\parallel}}{dt} = -0.975$ keV/sec, which is found as 3.4 kHz/sec. The decreasing drift rate for the observed drifting emissions (Figure 2a) is also computed which is found as 0.36 kHz/sec. The experimentally observed increasing drift rate for this event is 0.85 kHz/sec whereas decreasing drift rate is 0.37 kHz/sec. After comparing the observed and computed drift rates we found a good agreement for decreasing drift rate whereas the increasing drift rate differs. For figure 2 (c) the increasing drift rates is observed as 0.73 kHz/sec whereas the decreasing drift rate is 2.45 kHz/sec. The computed increasing drift rate for this event is 0.83 kHz/sec whereas the decreasing drift rate is 4.6 kHz/sec, which compares well with the observed drift rates. There was some discrepancy between our experimentally observed and theoretically computed value of drift rate. We can presumably explain this discrepancy by the fact that the equatorial
plasmapause is located at larger L-shell than measured onboard ISIS (i.e. the direct measurements of plasmapause location in the equatorial plane) as reported by Chappell et al. [18].

4. Discussions and Conclusions

It is well known that the substorm activity is closely related to the activity of different types of VLF emissions observed at high as well as low latitudes [4, 5, 9, 11, 14, 19]. The basic mechanism of the excitation of these emissions is associated with the injection of plasmasheet electrons into the inner magnetosphere during substorm. It has been recognized that the origin of VLF emissions is related to the development of whistler-mode instability in the equatorial magnetosphere [20]. This instability can be triggered by the penetration of plasmasheet electrons into the inner magnetosphere and quenched by their subsequent pitch angle diffusion by the wave field and their final precipitation into the loss cone. Several quantitative models of VLF emissions based on quasilinear models have been proposed [13, 15, 17]. To explain the observed VLF drifting emissions at low latitude station Varanasi, we have adopted the model of Sazhin [15], and used realistic magnetospheric parameters. Based on the present analysis we deduced the following fundamental features of low-latitude drifting VLF emissions:

(i) All the drifting VLF emissions are concentrated in the local time sector of pre-midnight (just around midnight).
(ii) The observed drifting VLF emissions are mainly of the structured type such as rising and falling tone chorus.
(iii) The drifting VLF emissions are observed during recovery phase of a strong geomagnetic storm period.
(iv) The region of the maximum computed intensity of drifting VLF emissions is likely to occur just around the plasmapause (L=3.6) and it propagates towards lower latitudes in the Earth-ionosphere waveguide.
(v) The observed VLF emissions exhibit a regular frequency drift (increasing as well as decreasing). The frequency drift rates are found to range from 0.08 kHz/sec to 2.45 kHz/sec.
(vi) The generation mechanism of these drifting VLF emissions is explained in terms of a quasilinear electron cyclotron instability model for wave excitation [15].
(vii) The computed maximum spectral power density $<B_f^2>_max$ of the wave varies between $1.8 \times 10^{-21}$ and $4.08 \times 10^{-22}$ Gauss$^2$/Hz.
(viii) The computed frequency drift rates of these drifting VLF emissions are found in reasonably good agreement with that of observed values.

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