Effect of geomagnetic storms on VLF waves at low latitudes based on the analysis of whistlers and VLF emissions observed at Indian ground stations: A Review

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Abstract. A review of the effect of geomagnetic storms on very low frequency (VLF) waves (whistlers and emissions) at low latitudes is presented, based on the spectral analysis of the storm-time VLF data collected over a period of about four decades at our low latitude ground-based Indian stations. The review begins with an introduction about the characteristics of whistlers and VLF emissions and the importance of storm-time VLF events for the developments of our theoretical knowledge in plasma physics. This is followed by four different sections (2-5) in order to understand and explain the physics of VLF events observed at low latitudes during magnetic storms. All aspects of whistler duct and geomagnetic activity are described in section 2 whereas section 3 deals with VLF wave (whistlers and emissions) activity and whistler dispersion. Section 4 presents method of analysis of whistler duct alongwith duct lifetime and VLF emission source used in the spectral analysis of storm-time VLF data reported in the present paper. Section 5 describes in brief the experimental setup used in recording of VLF data at our Indian ground stations with a presentation of some selected storm-time whistlers and emissions alongwith their detailed spectral analysis of the observed salient features. Spectral analyses of the storm-time whistlers and emissions using VLF data from our Indian stations have provided the following results (section 6): (1) It may now be established that in general unusual high dispersion whistler observed during magnetic storm periods at low latitude, are mid/high latitude whistlers which have propagated in different ducts along higher and closely spaced $L$-values and after exiting from ducts, they penetrated the ionosphere and are trapped in the Earth-ionosphere waveguide to be received at low latitude ground stations. (2) In case of VLF emissions it may be established that various types of VLF emissions recorded during magnetic storm periods at low latitude ground stations are mid/high latitude emissions generated in the equatorial region of higher $L$-values through the process of Doppler-shifted cyclotron resonance mechanism and propagated along the higher field lines in different ducts formed by disturbances during magnetic storm and after exiting from the ducts, they penetrated the ionosphere and are trapped in Earth-ionosphere waveguide and after propagating in the waveguide are thus recorded at low latitude ground stations. (3) The increased intensity of whistler and emission activities during magnetic storm periods are due to the formation of additional ducts by the enhanced flux of energetic electrons during magnetic storm periods.

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1. Introduction

The investigation of magnetic storms is one of the great importances not only for the development of our theoretical knowledge in plasma physics, but for practical purposes, i.e. diagnostics and prediction of the processes in the magnetosphere and ionosphere during geomagnetic storms. An intense reconfiguration of the magnetosphere takes place during geomagnetic storm periods as a result of charged particles injection, large-scale electric field generation etc. Such changes in the magnetosphere affect the character of the very low frequency (VLF) waves excited in the magnetospheric plasma. For the reason, it is quite necessary to investigate whistlers and all kinds of VLF emissions connected with magnetic storms both in magnetosphere and on the ground at low latitudes.

The two principal classes of magnetospheric radio noise phenomena are whistlers and VLF emissions which occur in the very low frequency range (1 - 30 kHz). Whistlers are VLF electromagnetic waves whose energy originates from lightning discharges and which have propagated through the magnetosphere (Storey, 1953). The radiated VLF wave energy from lightning discharge propagates in the Earth-ionosphere waveguide. Part of VLF wave energy propagates along geomagnetic field lines and is dispersed due to interaction with the plasma present in the magnetosphere. Such a wave known as whistler propagates back and forth along the field lines several times with little attenuation. This is attributed to the trapping of wave energy in the plasma duct aligned along geomagnetic field lines.

The whistler activity depends on the lightning source and the conditions determining whistler propagation below, through and above the ionosphere, which depends on solar and geomagnetic conditions. Whistler activity varies with latitude having maximum around 50° geomagnetic latitude (Helliwell, 1965; Lalmani and Singh, 1977). The whistler occurrence rate is low at low latitudes (Singh, 1993), but it enhances during the magnetic storm period. This was explained in terms of the formation of additional ducts during magnetic storm periods, supporting whistler mode propagation (Somayajulu and Tantry, 1968; Singh, 1993). Somayajulu and Tantry (1968) also observed increased diffuseness in the whistler traces, indicating that the waves propagated through the wide ducts with diffuse boundaries.

Based on the minimum critical frequency of the F2-Layer and the electron number density at the equatorial height of the geomagnetic line of the force corresponding to the geomagnetic latitude of whistler observation, the normal dispersion values of whistler observed at a particular latitude from Allcock's formula (Allcock, 1960) is equal to the value of that particular latitude. In view of this, high dispersion whistlers (>25 $s^{1/2}$) are observed normally at middle and high latitudes (Helliwell, 1965). It is worthwhile to mention here that dispersion of whistlers usually recorded in various low latitude Indian ground stations are almost lesser than 25 $s^{1/2}$ (Somayajulu et al., 1973). From the detailed spectral analysis of the whistler data observed in Japanese, Chinese and Indian ground
stations, it is seen that high dispersion whistlers are recorded at low latitudes only during the periods of severe magnetic disturbance (Singh et al., 2010). High dispersion whistlers during geomagnetic storm periods at low latitudes have been interpreted in terms of increase in $f_{0}F_2$ (Hayakawa and Tanaka, 1978; Bao et al., 1983; Chauhan and Singh, 1992). From the dispersion analysis of storm-time high dispersion whistlers observed at low latitudes using various nose-extension methods (Dowden and Allcock, 1971; Tarcsai, 1975), it is shown that these are middle and high latitude whistlers which have propagated in different ducts along the high geomagnetic field lines and after exiting from the ducts, they penetrated the ionosphere and are trapped in the Earth–ionosphere waveguide to be received at low latitude ground stations.

Like whistlers, VLF emissions are a class of natural electromagnetic wave phenomena (Helliwell, 1965). These emissions have over the past decades become an important diagnostics tool for probing the plasmasphere and beyond. These emissions although less well understood than whistlers are believed to have their origin in the ionosphere–magnetosphere coupled system and may be due to plasma instabilities or in situ electromagnetic radiations from high-energy particles. It is now well established that VLF waves originating from lightning can trigger whistler-mode instabilities under wave–particle interactions occurring in the magnetosphere and generate a variety of VLF emissions of new waves that are much stronger than the input waves. Helliwell (1965) has classified these emissions into hiss, discrete, chorus, periodic and triggered emissions.

VLF emissions are often observed during periods of disturbed magnetospheric conditions (Helliwell, 1965; Tsurutani and Smith, 1974; Inan et al., 1978; Sazhin, 1982; Sazhin, and Hayakawa, 1992; Lauben et al., 1998). Substorm associated VLF emissions could be easily associated with the injection of plasma-sheet electrons into the inner magnetosphere. During the magnetic storm periods more particles are injected and hence, the occurrence probability of new variety of emissions generated by the injected intense electron fluxes in the magnetosphere is increased. Therefore, an investigation of VLF emissions observed during geomagnetic storm periods both in magnetosphere and on the ground is of importance not only for the development of our theoretical knowledge in the plasma physics, but for practical purpose i.e. diagnostics and prediction of the wave–particle interaction process in the ionosphere and magnetosphere, the injection and drift process of particle during sub storm, the magnetosphere plasma structure etc.

During geomagnetic storm periods, VLF emissions are intensified and their occurrence probability is increased due to the injection of more particles during magnetic disturbances. These emissions exhibit a regular frequency drift in the dawn sector which has been interpreted in terms of combined effect of the velocity dispersion during the eastward longitudinal drift of energetic electrons injected near the mid-night sector and a quasi-linear electron cyclotron generation of VLF waves (Carpenter et al., 1975; Hayakawa et al., 1986). Hayakawa et al. (1986) have shown that the occurrence probability of auroral hiss emission increased when the $K_p$ index increased from 0 to 5 and decreased when $K_p$ value increased further. Tsurutani et al. (1975) examined the dependence of inner zone hiss emission on the level of geomagnetic activity using AE (to identify substorm) and $D_{st}$ (to identify storms) indices. They have reported that? percent
of the hiss emission events occurred during active interval containing a sub-storm (AE > 100), a magnetic storm or in most cases both. Fifty five percent of the events occurred during intense magnetic storms with peak $|D_{st}| > 45$. Smith et al., (1974) have reported that most of the storm time events occurred during the recovery phase of the storm and most intense emissions occurred soon after the onset of a storm recovery phase. Etcheto et al. (1975) has shown that the trapped flux increases rapidly for $K_p > 3 \cdot 4$.

From the observation of VLF emissions at low latitudes, it is shown that their source region is located at mid-latitude and at the equatorial zone (Singh et al., 1999; Hayakawa and Sazhin, 1992). Hayakawa et al., (1975) reported storm-time VLF hiss emission centered around 5 kHz at low latitudes and have shown that they are mid-latitude emission generated around the plasmapause and were observed at low latitudes after penetrations at mid-latitudes, followed by the Earth-ionosphere waveguide propagation. Hayakawa, (1993) had suggested that the hiss emission events reported by Khosa et al., (1981) could be storm-time plasmaspheric/mid-latitude hiss emission.

An intensive investigation on the effect of geomagnetic storms on VLF (whistler and emission) data observed at middle / high latitudes has been made in the past (Carpenter, 1962; Helliwell, 1965; Sazhin and Hayakawa, 1993; Thomson et al., 1997 etc.). As a result of this study, it was found that the whistler activity during the magnetic storm periods are enhanced due to the formation of additional ducts supporting the whistler ducted mode propagation. During the magnetic storm periods, the efficiency of both duct sizes and scatter in duct sizes are observed to increase with the increasing magnetic activity ($K_p$). The duct efficiency increase and their increased scatter are due to the plasmaspheric amplification resulting from enhanced magnetic activity, increasing the range of anisotropy and particle energy fluxes. As a result of this, the transmission of whistler wave energy is found to increase as magnetic activity increased (Thomson et al., 1997 and references therein).

Unlike mid-and high latitudes, low latitude whistlers and VLF emissions have not been used much for exploring the inner magnetosphere. The main reason for this is that at latitudes, the occurrence rate of whistlers and VLF emissions is very low and sporadic. But they occur in significant numbers during geomagnetic storm periods. Some studies to decipher the effect of geomagnetic storms on low latitude whistlers and VLF emissions observed in Japanese, Chinese and Indian ground stations have been made (Somayajulu et al., 1972; Rao and Lalmani, 1975; Hayakawa and Tanaka, 1978; Bao et al., 1983; Chauhan and Singh, 1992; Singh and Singh, 2002; Singh et al., 2010 and references therein), but not enough to come to a conclusion in this regard.

In order to establish the effect of geomagnetic storms on the observation of VLF waves at low latitudes, we have made a spectral analysis of the whistlers and VLF emissions recorded during geomagnetic storm periods at our various low latitude Indian ground stations. Such an analysis will help in understanding the real VLF source and the mechanism of generation and propagation of the ground observed VLF waves during geomagnetic storm periods at low latitudes. It will also add in determining the magnetospheric plasma parameters.

In this review, first we have presented an introduction about the characteristics
of whistlers and VLF emissions and importance of storm-time VLF events for the development of our theoretical knowledge in plasma physics and its investigation for practical purposes i.e. diagnostics and prediction of processes in ionosphere and magnetosphere during geomagnetic disturbances. Section 2 describes all aspects of whistler duct and geomagnetic activity whereas section 3 deals with VLF whistler wave activity and geomagnetic activity in order to understand the physics of VLF events observed at low latitudes during geomagnetic storms. Section 4 presents method of analysis of whistler duct and VLF emission source to be used for the spectral analysis of storm-time VLF events reported in this paper. Section 5, describes in brief the experimental setup used in recording of whistlers and VLF emissions at our various Indian ground stations with the spectral analysis of some selected storm-time VLF data recorded at our Indian stations in order to establish the effect of magnetic storms on low latitude whistlers and VLF emissions. The analyzed results are discussed in Section 6. Finally, section 7 reports the conclusion of the study.

2. Whistler duct and geomagnetic activity

It is now well established that whistlers result from the penetration of lightning discharge produced electromagnetic radiation through the ionosphere and magnetosphere (Helliwell, 1965). The geomagnetic field is not sufficient to guide the signal into the conjugate hemisphere and allow ground-based reception of whistlers in that hemisphere. But in fact reception of whistlers in the conjugate hemisphere is generally common with the signals showing evidence of propagation along distinct field-aligned paths. It was, therefore, suggested that field-aligned ionization irregularities (ducts) might trap and guide whistler signals from one hemisphere to other (Smith et al., 1960; Helliwell, 1969). Ducts are regions of enhanced or depletion from normal ionization densities and hence have different values of refractive index from the surrounding plasma. Such irregularities have been observed using satellites (Angerami, 1970) and by highly sensitive measurements of signal delays on VLF transmissions (Thomson, 1975). Either enhancements or depleted regions of (cold) plasmaspheric plasma are capable of guiding VLF whistler waves in the required manner. The formation of field-aligned electron density irregularities termed “whistler ducts” by interchange of plasma in flux tubes was first suggested by Cole (1971), who suggested that large-scale irregularities (conjugate ducts) arise due to the interchange of plasma in geomagnetic flux tubes. The interchange is driven by a spatially varying electrostatic field (EXB) orthogonal to the geomagnetic field. Park and Helliwell (1971) have suggested that the source of such electrostatic field might be charge enters in thunderstorms. The electrostatic fields from the thunderstorms penetrate the ionosphere and magnetosphere and causing mixing of electrons in flux tubes around the equatorial plane. EXB forces as a whistler duct creation mechanism was first identified by Cole (1971). In the Cole model irregularities in the E-region electron density leads to the orthogonal electrostatic field caused by variations in the ionosphere. Variability in the spatial wind in the dynamo region and gravity waves are suggested both producing ionospheric irregularities and hence irregular magnetospheric electric field. Walker (1978) has presented order of magnitude calculations to show that when the ring
current overlaps in the outer plasmaspheric irregularities in the current cause field-aligned currents to flow down to the ionosphere. These currents would be continuous with horizontal electric field maps up into the equatorial region producing, flux-tube interchange, and once again the formation of whistler ducts. This mechanism would lead to duct formation on a time scale of 30 min, which would be expected to decay on a time scale of days (Walker, 1978).

Several duct formation mechanisms have been proposed to date (Park and Helliwell, 1971; Cole, 1971; Walker, 1978; Thomson, 1978; Lester and Smith, 1980). An essential point common to several theories is that large-scale electric fields perturbing the magnetospheric plasma play a dominant role in whistler duct formation. Such magnetospheric large-scale electric fields during magnetic storm periods using whistlers observed on the ground stations can be estimated from radial motions of discrete field-aligned whistler ducts as indicated by changes in nose frequencies (Block and Carpenter, 1994). Park (1976) has shown that the observed changes in whistler nose frequencies were due to cross-L drift of ducts. The whistler nose frequency $f_n$ and the minimum equatorial gyrofrequency $f_{Heq}$, along the path of propagation are related (Block and Carpenter, 1974; Park, 1976) as

$$f_n \approx k f_{Heq} = k f_{Heq} (R_0/R)^3$$  \hspace{1cm} (1)

Where $k=0.38$ for diffusive equilibrium model of field-line distribution of ionization $f_{Heq}$ and $f_{Heq}$ are the equatorial geocentric distance $R$ and $R_0$ (Earth’s surface) respectively.

Specializing the hydromagnetic drift relation $V = E_x B/B^2$ to the magnetic equator, we obtain (in MKS units)

$$dR/dt = -(E_x/B_0)(R_0/R)^{-3}$$  \hspace{1cm} (2)

where $B_0$ represents the geomagnetic field strength at the Earth’s surface and $E_x$ is the westward component of the magnetospheric electric field. From eqns. (1) and (2) the magnetospheric electric field in a dipole model, in the equatorial plane is given (Block and Carpenter, 1974; Park, 1976) as

$$E_x = 2.07 \times 10^{-2} \frac{d(f_n^{2/3})}{dt} \hspace{1cm} Vm^{-1}$$  \hspace{1cm} (3)

Thus, from eq. (3) one can directly estimate the electric field from the slope $f_n^{2/3}$ required for the duct formation.

It is now well established that most ground-observed whistlers are guided between opposite hemisphere by magnetic field-aligned enhancement of ionization termed “plasma ducts”. This is attributed to the trapping of whistler wave energy in the plasma duct. Applying this hypothesis, the occurrence of train of nose whistlers in which the frequency gradually descended with time was explained initially. Smith (1960) studied in a more quantitative way the mechanism of trapping of whistler energy in the field-aligned ducts of enhanced or depressed ionization. The theory of trapping and propagation of whistlers in ducts has been discussed by several authors (e.g. Smith, 1961; Helliwell, 1965; Walker, 1972; Liard and Nunn, 1975). The existence of such ducts implies that a cross-section of the magnetospheric electron density varying with height in a wave-like pattern. Though a direct verification of such a structure in the magnetospheric electron density has yet to be made, there is ample indirect experimental evidence from.
ground-based observations and in situ observations on board OGO-I (Smith, 1961; Smith and Angerami, 1968) to suggest the existence of ducts. However, Walker (1976) showed that there remain many unsolved problems in the whistler propagation in the ducts itself, especially in the lower exosphere and ionosphere, such as the excitation of ducts and their lifetimes, leakage from them, and the transmission properties through the ionosphere.

During a magnetic storm period, the magnetic disturbance produced in the ionosphere and magnetosphere forms the “whistler duct” which is believe to be an enhancement of electron density along a magnetic line of force. The magnetic disturbance which result in producing the ducts occur one to three days after storm sudden commencement (SSC) of a magnetic storm, or after a maximum of the daily sum of $K_p$-index (Outsu and Iwai, 1962). Laaspere et al. (1963) have suggested that there is link between spread-F irregularity and magnetospheric whistler duct, both being produced by the same cause magnetic storm.

During magnetic storm period, both the duct efficiency and scatter in the duct efficiently are observed to increase with the increasing magnetic activity $K_p$ as a measure of geomagnetic activity (Thomson et al., 1997). The duct size and scatter in duct size are found to increase with the increasing $K_p$. Duct efficiency increases by a factor of about 30 with $K_p = 2 \cdot 8$. The duct efficiency increases (and their increased scatter) are due to plasmaspheric amplification resulting from enhanced magnetic activity increasing the range of anisotropy and particle energy fluxes (Thomson et al., 1997). As a result of this, the transmission of whistler wave energy is found to increase as magnetic activity increased. An evidence of more efficient whistler-mode transmission during magnetic storm period has been observed by means of whistler-mode signals received at Faraday, Antarctica (geomag. lat., 46°S; 171°E) (Thomson et al., 1997).

3. VLF whistler wave activity (occurrence and dispersion of whistlers, and VLF emission occurrence) and geomagnetic activity

Whistler activity depends on the propagation condition in the exosphere as well as on the thunderstorm activity in source region of whistler. The source of whistlers has nothing to do with geomagnetic activity but the propagation condition of whistlers is modified by the geomagnetic activities. During magnetic storm periods, some changes of physical state appear in the exosphere which effects on the occurrence rate and on the dispersion of whistlers.

From the statistical analysis of whistler data observed at middle and high latitude stations, Allcock (1966) has shown that whistler activity reached a maximum when the planetary magnetic index $K_p$ attained to a certain value during magnetic storm. He has also shown that parameters “whistler rate” as well as “percentage occurrence” is the good indicators for representing the propagation conditions. The rate of occurrence of whistlers at low latitudes is normally quite low, which gets enhanced during magnetic storm periods as the whistler activity depends on the solar and geomagnetic conditions (Singh, 1993). The enhanced whistler activity observed during magnetic storm periods at low latitude stations was explained in terms of the formation of additional ducts supporting the whistler mode propagation (Somayajulu and Tantry, 1968; Singh, 1993). From the
analysis of whistler data recorded during magnetic storm periods at low latitude stations, it was found that whistler occurrence rises rapidly from the beginning of a magnetic storm and reaches a maximum when $\sum K_p$ attained a maximum, and whistler activity lasts about a few days (Outsu and Iwai, 1962; Somayajulu et al., 1972; Ohta et al., 1989; Hayakawa, 1991; Singh, 1993).

It is well known that whistler activity depends on the propagation condition in the exosphere as well as on the thunderstorm activity in the source region of whistler. Whistler activity is observed in the various satellites also by space based measurements which have provided the observation of various types of whistlers like ducted and non-ducted whistlers, protonospheric (SP) whistler, magnetospheric reflected (MR) whistlers (Smith and Angerami, 1967, 1968; Ondoh, 1976; Parrot, 2006; Chum et al., 2009; Pandey et al., 2012, 2013). Satellite observed whistlers have been used to find out their propagation characteristics and to identify individual ducts (Smith, 1961; Angerami, 1970; Ondoh (1976). Simith and Angarami(1967) analyzed frequency spectra of whistlers recorded on board OGO-III satellite identified different ducts and measured their size and spacing From the analysis of OGO-I observation of ducted and non-ducted whistlers, Smith and Angerami (1967) have deduced the properties of the magnetosphere. Recently Pandey et al., (2013) have analyzed the satellite DEMETER (Detection of Electromagnetic Emissions Transmitted from Earthquake Regions) data for a period of three and half months between 01 September and 16 December 2010 in search of whistlers and VLF emissions. Their analysis showed records of large number of first component of magnetospheric reflected (MR) whistlers whose number decrease as the latitude increases mostly when the satellite is in low latitude ionosphere. These MR whistlers together with normal whistlers observed in the DEMETER satellite are not observed on the ground as revealed by simultaneous ground observations at low latitude Indian ground station Agra (Pandey et al., 2013) which confirms them to be non-ducted whistlers which are reflected and observed in the ionosphere and magnetosphere.

It is well known that the dispersion of the whistlers is given by (Helliwell, 1965)

$$D = \frac{1}{2c} \int_{\text{path}} \frac{f_p}{f_H} ds$$  

(4)

Where $f_p$ is the electron plasma frequency and $f_H$ is the electron gyrofrequency, and the integration is carried out along the path(s) a whistler propagates. As evident from whistler dispersion formula (eq.4), the dispersion of the whistlers is affected by electron density distribution, propagation path length etc. So the investigation of characteristics of the dispersion ($D$) in magnetic storm periods will be useful to the study of the mechanism of formation and decay of ducts and lifetime of ducts which control the whistler propagation.

From the dispersion analysis of the whistler data observed during magnetic storm periods at low latitude ground stations, it is found that the dispersion of whistlers increases during magnetic storm periods and the minimum difference between the normal and increased dispersions values is about 20 sec$^{1/2}$ (Outsu and Iwai, 1962). The existence of whistlers with “discrete dispersion” within the observation period of about 5h was found which implies the presence of different additional ducts during magnetic storm period.
VLF emissions are another class of natural electromagnetic wave phenomena which are similar to whistler wave generated during atmospheric lightning, as waves share the same frequency, polarization, wave normal distribution and propagation ducted mode (Helliwell, 1965). VLF whistler wave originating from lightning and ground-based VLF transmitter can trigger whistler mode instabilities through cyclotron resonance interactions between wave and particles in the magnetosphere and stimulate VLF emissions of new waves that are much stronger than input waves (Helliwell and Katsufrakis, 1974).

During magnetic storms, an intense reconfiguration of the magnetosphere takes place as a result of the charged particle injection, large-scale electric field generation etc. Such changes must affect the character of the waves excited in the magnetospheric plasma. For this reason, it is quite necessary to investigate all levels of VLF emissions connected with magnetic storms both in the magnetosphere and on the ground. Simultaneous measurements of VLF emissions and electron fluxes supported the idea that VLF emissions are generated from electron fluxes present in the magnetosphere and ionosphere (Hayakawa et al., 1975). Based on statistical analysis of VLF emissions, Hayakawa et al., (1986) has shown that emissions are closely associated with geomagnetic storms. VLF chorus emission is especially important for the physics of the Earth's magnetosphere since it can significantly influence the distribution functions of the energetic electrons in the outer radiation belt (Meridith et al., 2003). During magnetic storms more particles are injected and hence, the occurrence probability of VLF emissions is increased. Analyzing the VLF emission data observed at Syowa ground station in Japan, Hayakawa et al., (1975) have shown that the occurrence probability of our auroral hiss emission increased when the $K_p$-index increased from 0 to 5 and decreased when $K_p$ value increased further. It is now widely accepted that the magnetic storm-associated VLF emissions are associated with the injection of plasma-sheet electrons into the inner magnetosphere (Carpenter et al., 1975; Hayakawa et al., 1986). Hence, storm aspects of VLF emissions make it possible to investigate the wave-particle interaction process, the injection and drift process of particle during magnetic storm, the magnetospheric plasma structure etc.

4. Method of analysis of (a) whistler duct and (b) VLF emissions source

(a) Whistler duct

It is well established that most ground-observed whistlers at low as well as at high latitudes are guided between opposite hemispheres by magnetic field-aligned enhancements of ionization termed “whistler ducts” (Helliwell, 1965). Both ground and in situ observations have been used to identify individual ducts (Smith, 1961; Angerami, 1970; Ondoh, 1976; Hayakawa and Iwai, 1975). Smith and Angerami (1967) analyzed frequency spectra of whistlers recorded on board OGO-III, indentified different ducts and measured their size and spacing. Park (1970) in his studies of the interchange of ionization between ionosphere and protonosphere identified
the individual ducts. Now it is also well established that whistlers observed during magnetic storm periods propagate in whistler ducts along higher $L$-values and after exiting from the duct, they penetrated the Earth-ionosphere waveguide. The wave-normal at the entrance into the waveguide is such that they propagate towards the equator and are received at low latitude ground stations (Singh, 1993; Singh et al., 1993).

Somyajulu and Tantry (1968) have reported the first low latitude (Gulmarg-geomag.lat., 24°10′ N) ground observations of whistler ducts who suggested that it might take less than 1 hr for ducts to form and that once the duct had formed it might stay “alive” for a time period measured in days. However, Okuzawa et al. (1971) have questioned this suggestion and have, in turn, suggested that the process of duct formation and decay is a kind of cyclic phenomenon whose period ranges between 30 min to few hours.

In order to examine the suggestion of Okuzawa et al. (1971) and to estimate the duct lifetime from the analysis of the whistlers recorded during magnetic storm periods at low latitude Indian ground stations, the power spectrum analysis method (Madden, 1964) have been used which can be described in brief as follows: On certain occasions during magnetic storm periods, whistler occurrence rate at low latitude ground stations are found to exhibit some periodicity. It was suggested that this period is an indication of duct lifetimes at low $L$-values (Rao and Lalmani, 1975; Somayajulu and Tantry, 1968; Singh, 1993, 1997, 2007; Singh et al., 2008, 2009, 2011, 2013). For this, let us consider an ideal situation in which only one duct is contributing to the whistler occurrence rate at a ground station and also suppose that this duct takes a finite time to grow to its mature state and to decay, finally merging with the background ionization. We should then expect the whistler occurrence rate recorded on the ground to show the corresponding rise and fall with time. If, as suggested by Okuzawa et al. (1971), the growth and decay of ducts are cyclic, it follows that the whistler occurrence rate shows a kind of periodicity. This ideal case can, in fauciable conditions, be extended to a realistic situation in which few active ducts are “simultaneously” contributing to the occurrence rate. The presence of any periodicity in the combined occurrence rate can be detected by the standard technique of “Power spectrum analysis” as suggested by Madden (1964).

Power spectrum analysis consists of four discrete steps. The first step called the digitization of the data which corresponds to the measurement of the time function at discretely chosen time intervals. The second step called selection of finite interval is applicable only when the data is recorded continuously over very long period. The third step consists of autocorrelation function for the data included in finite interval mentioned in second step. The fourth step called the window shaping is a simple multiplication of autocorrelation function of the form $\sin (\Delta \omega / 2t) / t$, where $\omega$ is radiation frequency and $t$ is the time. The final step in the power spectrum density computations consists of obtaining the cosine transform of the autocorrelation function after passing through the window. Thus the final expression for the power spectrum can be written as (Madden, 1964):

$$P(\omega) = \int_0^\infty \rho(\tau) \sin((\Delta \omega / 2t) / t) \cos \omega t \ \mathrm{d}t \quad \text{................................................. (5)}$$
Where $\rho(\tau)$ is autocorrelation at time interval $\tau$.

Eq. (5) is numerically integrated. The computed power spectrum of the whistler occurrence rate observe at Indian ground stations showed peaks at a radian frequency and its harmonics, and the time interval corresponding to frequency separation between peaks was remarkably constant and was around one hour. This result seems to indicate that some physical process with a periodicity of about 1 hr is present in the whistler occurrence rate at low latitude ground stations. It is suggested that this periodicity signifies that continuous process of growth and decay of ducts as envisaged by Okuzawa et al., (1971). The period of about 1 hour obtained from power spectrum analysis is taken to represent the order of lifetime of ducts. This result was confirmed by the dispersion analysis of these whistlers.

The study of whistler waves at low latitudes shows that whistlers observed during magnetic storm periods are ducted whistlers. A number of methods have been used for the determination of whistler propagation path latitude of the ducted whistlers observed at low latitude ground stations (Dowden and Allcock, 1971; Tarcsai, 1975; Hayakawa and Tanaka, 1978). Among all these methods, the simplest one is the method developed by Hayakawa and Tanaka (1978), who have found an empirical relation between dispersion and geomagnetic latitude of whistler propagation based on nighttime whistler data obtained at the Japanese ground stations for the determination of whistler propagation path latitude $L$. This relation is

$$D = 1.22(\phi - 0.72)$$

Where $D$ is the measured dispersion of whistler in sec$^{1/2}$ obtained from the slope of $t$ versus $f^{1/2}$ plot in which time delay $t$ and whistler wave frequency $f$ is measured from the spectrogram of the observed whistlers and $\phi$ is the geomagnetic latitude in degrees.

Although, the method of Hayakawa and Tanaka (1978) for the determination of whistler propagation path latitude $L$ gives good results at low latitudes, its validity may be questioned. To examine its validity, whistlers observed during magnetic storm periods at low latitude ground stations were analyzed for the determination of whistler propagation path latitude $L$ using two methods: (a) linear extended Q-technique as developed by Dowden and Allcock (1971) and (2) curve fitting technique as developed by Tarcsai (1975). Using the above two methods, the computed values of whistler propagation path latitude $L$ were found to be of the same order to that by the method of Dowden and Allcock (1971). All the above three methods yielded results ±10% (Misra et al., 1980; Lalmani, 1984; Singh et al., 1993, 1999, 2000, 2004).

(b) VLF emission source
The sources of VLF emissions are localized near the geomagnetic equator as supported by the most frequent observations of VLF emissions by satellite near the geomagnetic equator (Tsurutani and Smith, 1974: Burtis and Helliwell, 1976). From the study of low latitude VLF emission observations, it is now commonly believed so far that they originate in the equatorial magnetosphere and may have propagated along higher $L$-values in ducted mode and exiting from the duct, they penetrated the ionosphere and are trapped in the Earth-ionosphere waveguide and propagated towards the equator and are received at our low latitude ground stations (Singh et al., 2003, 2010).
UBF-method based on the measurement of the upper boundary frequency ($f_{UB}$) of the ground-observed VLF emissions is used for the estimation of $L$-value of the VLF emission source. Such an approach called upper boundary frequency (UBF) method has been developed by Smirnova (1984). In this method, $f_{UB}$ of the ground-observed VLF emissions is determined on the assumption of a dipolar geomagnetic field configuration, by the half electron gyrofrequency in the generation region irrespective of the observation station (Smirnova, 1984). The UBF-method is valid for ducted mode propagation of VLF emissions and hence can be used for the analysis of the ground-observed VLF emissions at low latitudes. The $L$-value of the VLF emission source by the measurement of $f_{UB}$ of the ground-observed VLF emissions is estimated with the help of the relation (Smirnova, 1984).

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

(7)

Where $f_{UB}$ is in KHz. Making use of eq.(7) and the observed parameters, the values of source region of the VLF emissions are computed.

5. Observation and analysis

The present study is based on the VLF data collected over a period of over four decades recorded at our low latitude ground-based Indian stations Gulmarg, Srinagar, Jammu, Nainital, Agra and Varanasi. The whistler-mode signals (whistlers and VLF emissions) are received by a T-type of antenna, amplifiers and tape recorder having band width of 50 Hz - 15 kHz. T-type antenna is 25 m in vertical length and 6 m long horizontally and 3.2 mm in diameter. Its impedance is about 1 mΩ. The antenna is rendered a periodic with the help of suitable $R$-$C$ network, to avoid any possible ringing effect. The antenna is erected at a suitable distance from the main building to reduce the power line hum and any other type of man made noises. Between the antenna and pre/main amplifiers, an active filter unit is introduced to reduce the local noise to a minimum in the frequency range 100 - 500 Hz. The filter is constructed from a suitable $R$-$C$ network alongwith the operational amplifier to be operated in positive feedback mode. The lower cut-off frequency of the filter is about 60 Hz and the voltage gain is 1.2 up to 15 kHz. The gain of the pre/main amplifier is varied from 0 - 40 dB to avoid overloading of the amplifier at the time of great VLF activity. Pre-amplifier is kept at the bottom of the pole at which an antenna is installed to amplify the VLF signal by main-amplifier and recorder using the digital audio tape recorder on magnetic tapes. The observations were taken continuously both during day and night times. The VLF data were stored on the magnetic tapes, which were analyzed using a digital Sonograph machine and also using analysis software ‘Raven’ installed at our observatories. Digitization of the analog signal was carried out at 16 kHz sampling frequency. The inbuilt software in the spectrum analysis of the Sonograph machine provided dynamic spectrum, which updated in real time typically covering 8 kHz in frequency and 2.54 s in time. The frequency range may be varied from 100 Hz to 40 kHz. Raven is a software application for the acquisition, visualization, measurement and analysis of various types of sound signals (www.birdscornelledu/brp/raven/RavenOverview.html).

Under all India coordinated program of ionosphere thermosphere studies (AICPITTS), the observation of whistlers and VLF emissions was conducted at our
mentioned ground based Indian stations e.g. Gulmarg/Srinagar, Jammu, Nainital, Agra and Varanasi during day and night times and a huge amount of VLF data was acquired during this AICPITS campaign. The extensive VLF database, thus, acquired during a period of about four decades from Indian stations, has been searched for the events of whistlers and VLF emissions recorded during geomagnetic storm periods.

In this paper we study the effect of magnetic storms upon VLF waves observed at low latitude Indian ground stations from their spectral analysis. The ground-observed VLF data used here for the spectral analysis are picked up from the various reports recorded at Indian VLF observatories e.g. Gulmarg/Srinagar, Agra, Nainital and Varanasi (Rao and Lalmani, 1975 and Singh et al., 1993; Singh et al., 2013; Singh et al., 2011; Singh et al., 2008, 2009; Singh, 1997, 2007; Singh et al., 1993; Lalmani, 1984: Singh et al., 2000; Singh and Ronnmark 2004; Singh et al., 2004, 2013; Sheikh et al., 2013). These picked up storm-time VLF events are the best examples of storm time VLF events having clear fine structure dynamic spectra selected out of large number of acquired storm-time VLF events which are presented here in this paper along with their description and spectral analysis.

5.1. Storm-time whistler observations at low latitude Indian ground stations and their analysis

(i) Gulmarg station (geomag. lat., 24°10’ N; L=1.28) At the ground station Gulmarg high dispersion whistlers in large numbers were detected during magnetic storm periods on various days. Out of huge amount of whistlers recorded at Gulmarg, some examples of the spectrograms of storm-time whistler events recorded on 9 March 1970 and 8 February 1986 are shown in Figure 1 along with their characteristics and dispersion analysis. In Figure 1(a) we show a sequence of five sonograms corresponding to different times of occurrence recorded at Gulmarg on 9 March 1970 during magnetic storm period, when $K_p$-index was 6 (Rao and Lalmani, 1975). On this day the spurt in activity started around 00:00 IST and lasted for about 5h, and several hundred whistlers were recorded during this 5h period. Dispersion analysis of these whistlers shows a remarkably smooth decrease in dispersion within the observation period of 5h, which clearly show an experimental evidence of the formation of additional ducts during 5h period. The sequence of sonograms shown in Figure 1(a) is diffused in nature. The first sonogram (00:23 IST) shows a sharp whistler with dispersion of about 45 s$^{1/2}$ and finally the last sonogram (04:32 IST) shows a sharp whistler with a dispersion of about 35 s$^{1/2}$. Another example of storm-time whistler events of similar nature recorded on 8 February 1986 at Gulmarg is shown in Figure 1(b). Whistlers in large numbers were observed on this day between 02:54-06:50 IST, during which the $K_p$-index varied between 7 and 9. A sequence of sonograms is shown in Figure 1(b) which is diffused in nature. Similar characteristics of smooth decrease in dispersion of whistlers observed on 8 February 1986 can also be seen in Figure 1(b), which show again an evidence of the formation of additional ducts during 4h period (Singh et al., 1993). The decrease in dispersion of whistlers as seen in Figure 1(a) clearly indicate that some different ducts corresponding to their respective dispersion values have been formed within the portion of fields of view at
Gulmarg. Further, whistler occurrence rate at Gulmarg on 9 March 1970 and 8 February 1986 are found to exhibit some periodicity. This periodicity in the whistler occurrence rate is the duct lifetime at low $L$-value Gulmarg as discussed in detail in section 4. In order to find out the additional ducts formed during the 5 h period of whistler observation at Gulmarg on the above two date and to estimate whistler duct lifetime, we have used the standard techniques of “power spectrum” analysis (eq. 5) as outlined in section 4(a). Our estimated value of duct lifetime at Gulmarg is found to be 50 min in good agreement with the estimated value of about 1h by Rao and Lalmani (1975).

The above estimate of whistler duct lifetime of 50 min was entirely based on the occurrence rate of whistlers observed at Gulmarg. Therefore, it would be desirable to establish this result by dispersion analysis of whistlers observed at Gulmarg. For this purpose, we have made the dispersion analysis of all the several hundred whistlers observed during magnetic storm periods at Gulmarg on 19 March 1970 and 8 February 1986. Our whistler dispersion analysis results show that whistlers with a particular dispersion are observed only during a certain specific period of time of about 1h which

Figure 1. Example of dynamic spectrograms of high dispersion ducted whistlers recorded at our low latitude ground station Gulmarg (a) on 9 March 1970 and (b) on 8 February 1986 during magnetic storm periods (after Rao and Lalmani, 1975 and Singh et al., 1993).
confirm the estimated duct lifetime of about 1h from power spectrum analysis, and different ducts corresponding to their respective dispersion values have existed during the period of whistler observation at Gulmarg and more than one duct are present simultaneously. The electric fields perturbing the magnetospheric plasma play a dominant role in the formation of these ducts. In order to estimate the magnetospheric electric field involved in the formation of additional ducts corresponding to their respective whistler dispersion values during the period of whistler observations, we have used whistlers observed during magnetic storm periods at Gulmarg (shown in Figure 1a and b), from the radial motions of discrete field-aligned whistler ducts, as indicated by changes in whistler nose frequency $f_n$ (eq. 3 given in section 4). The estimated value of electric field $E_W$ at equatorial height of Gulmarg ($L=1.28$) is found to be about 0.8 mVm$^{-1}$ which is sufficient for the formation of different ducts at low latitudes.

(ii) Srinagar station (geomag. lat., 24°10' N; $L=1028$) On certain occasions, whistlers in great numbers were recorded during magnetic storm periods at our low latitude Indian ground stations Srinagar. Out of large amount of storm-time whistler data collected at Srinagar, we have selected some best examples of very interesting and important ducted whistlers for the dispersion analysis in order to study the effect of magnetic storms on VLF wave observed at low latitudes. The selected examples of whistler events are represented in Figure 2 alongwith their spectral characteristics and dispersion analysis (Singh et al., 2013). These were recorded at Srinagar on 25 March 2009 over a period of long duration of about 5h during magnetic storm period with the sum of $K_p$-index 15. During the mentioned period, whistler data were characterized by good whistler intensity and rate with well-defined components and number of whistlers is large enough to be of physical significance. On 25 March 2009, the spurt in whistler activity started around 00:00 IST and lasted for about 5h ending finally at about 05:00 IST. The sequence of whistler sonograms in Figure 2 shows spectrograms of whistlers recorded at srinagar during magnetic storm period on 25 March 2009. The first spectrogram (00:05 IST) shows a diffused whistler with dispersion of about 40 s$^{1/2}$ and finally the last spectrogram (04:00 IST) shows a sharp whistler with the dispersion of about 15 s$^{1/2}$.

The mere occurrence rate of whistlers recorded on 25 March 2009 at Srinagar is very interesting and altogether about hundred whistlers were recorded on this day. From the study of occurrence rate variations of these whistlers, it is find that whistler occurrence rates show a periodicity which is attributed to a cyclic process in the growth and decay of ducts. Power spectrum analysis of the occurrence rate of these whistlers yielded a periodicity of a dominant period of about 1h which is considered to be the whistler duct lifetime of the order of an hour at low $L$-value (Singh et al., 2013). The above estimate of duct lifetime of about one hour was entirely based on the power spectrum analysis of the whistler occurrence rate, which is confirmed by the dispersion analysis of these whistlers. Dispersion analysis of these whistlers. Dispersion analysis of these whistlers showed the existence of separate ducts and remarkably a smooth decrease in dispersion within the observation period of 5h duration which clearly show an experimental evidence of the formation of additional different ducts during magnetic storm period on 25 March 2009. The dispersion analysis of these whistlers has shown that
whistlers of a particular dispersion are observed only during about one hour period of time which confirm. (The whistler duct lifetime of about one hour estimated by power spectrum analysis (Singh et al., 2013). Further, whistler dispersion analysis predicts that more one duct are present simultaneously and whistlers have propagated in the magnetosphere along higher $L$-values ($L=2.8$-$4.12$). Using storm time whistlers observed at Srinagar on 25 march 2009 from eq. (3) the estimated value of electric field $E_w$ is found to be about 0.7 mVm$^{-1}$ which is sufficient for the formation of additional different ducts during the period of observation at Srinagar on 25 March 2009.

(iii) Jammu station (geomag. lat., 19°26' N; $L=1.17$)  
At ground station Jammu, unusual high dispersion whistlers were detected during magnetic storm periods in day and night times. Out of huge amount of storm-time whistler data collected at
Jammu, some examples of important and unusual very high dispersion whistlers are presented in Figures 2 and 3 along with their characteristics and dispersion analysis. During a magnetic storm period, a very important unusual whistler events in the extremely low frequency (ELF) band known as ELF whistlers were observed on 4 March 1986 at Jammu in the day time (Figure 3). The frequency-time spectrograms of storm-time ELF whistler events occurred on 4 March 1998 at 09:31:15 IST is shown in Figure 3. The important features of these events are (1) daytime occurrence of the events with maximum around 09:30 IST, (2) observed during magnetic storm period, (3) frequency range of the event lies in ELF band (1 - 3 kHz), (4) duration of event is only few seconds (0.5 - 3.5 s) and (5) dispersion of ELF whistlers lies in the range $67.4 - 252 \, s^{1/2}$. Lightning seems to be the dominant source for the ELF whistlers. From the dispersion

Figure 3. (a) The frequency-time spectrogram of multiflash ELF whistlers observed in local daytime on 4 March 1998 at 09:31:12 IST at low latitude station Jammu. The corresponding causative spherics is marked by arrows. (b) The frequency-time spectrograms of enlarged four sets of above group of ELF whistlers starting at 09:31:15 IST along with a precursor emission which is marked by arrow (after Singh et al., 2011).
analysis of these ELF whistlers, it is found that the dispersion of whistlers marked W1-W7 of ELF events are in increasing order and are about 101, 121, 122, 139, 152, 200 and 212 s$^{1/2}$ respectively, which gives a clear evidence of the formation of additional ducts during magnetic storm period. Dispersion analysis of these whistlers has qualitatively confirmed the existence of different ducts corresponding to their respective dispersion values during the period of observation at Jammu on 4 March 1998. Further the dispersion analysis shows that these whistlers have propagated in the magnetosphere along higher $L$-values ($L\sim3$-$7$).

In Figure 4 we show few examples of unusual whistler events with very high dispersion observed on 8 March 1999 and 2 February 2003 during magnetic storm period at Jammu in day and night times. Typical examples of daytime whistler doublets (composed of two whistler traces marked by A1, A2 and separated by 0.16 s having dispersions of about 30 and 40 s$^{1/2}$ respectively and whistler triplets (composed three consecutive whistler traces marked by W1, W2, W3 separated by about 0.64 s having dispersions of about 82, 95 and 100 s$^{1/2}$ respectively shown in Figure 4(a) and (b) were observed at Jammu on 8 March 1999 during magnetic storm periods in daytime hours. Whereas, two examples of whistler triplets (WT) from Jammu shown in Figure 4 (c) and (d) were observed during magnetic storm period in nighttime (02:00 IST) on 2 February 2003 in which consecutive whistler traces are separated by very small time intervals. The

![Figure 4](image)

Figure 4. Dynamic spectrograms of Whistler doublet and triplet whistlers observed during magnetic storm periods in daytime and night times at Jammu on 8 March 1999 (a, b) and 2 February 2003 (c, d) (after Singh et al., 2008, 2009).
dispersion of whistlers (W1, W2, and W3) of the first triplet (WT1) are 72, 80 and 88 s\(^{1/2}\) respectively (Figure 4c) and dispersion of whistlers (W1, W2 and W3) of second triplet (WT2) are 70, 76 and 82 s\(^{1/2}\) respectively (Figure 4d). The increasing order of the whistlers of both triplets gives further evidence of the formation of additional ducts during magnetic storm period. Dispersion analysis of these whistlers confirms the existence of different ducts corresponding to their respective dispersion values during the period of observation at Jammu. Further, the dispersion analysis shows that these whistlers have propagated in the magnetosphere along higher geomagnetic field lines (L ~ 6–7).

(iv) **Agra (geomag. lat., 17°12’ N; L=1.15)** During geomagnetic storm on various days, high dispersion whistlers in large numbers were observed at out ground-based station Agra. Out of these collected storm-time high dispersion whistlers along with their dispersion characteristics is represented in Figure 5, along with their dispersion analysis. From the dispersion analysis of storm-time whistlers recorded simultaneously on 2 April 1979 at 03:20 IST (shown in Figure 5(a), it was found that their dispersions are about 67 and 70 s\(^{1/2}\) respectively and further the whistler of dispersion 67

Figure 5. Dynamic Spectrograms of very high dispersion whistlers recorded at Agra during magnetic storms periods in night times: (a, b) on 2 April 1979 (c) 28 February 1996 (after Singh, 1997, 2007).
s$^{1/2}$ occurred earlier than the other whistlers (Singh, 1997). Whereas, Figure 5(b) shows another example of storm-time long enduring whistlers with dispersion of 54 s$^{1/2}$ recorded on the same day 2 April 1979 at 23:13 IST (Figure 5 b). A very unique storm-time whistler event recorded at Agra station on 28 February 1996 at 01:28 IST is shown in Figure 5(c). Dispersion analysis of a group of whistlers in Figure 5(c) shows temporal fine structures in their occurrence at a regular time of interval of about 0.06 s and their dispersions are same of about 42 s$^{1/2}$. The fine structure of these whistlers was interpreted in terms of multiple signals radiated from multi-stroke lightning and are received at Agra after propagating in the same duct (Singh 2007). During magnetic storm period, dispersion analysis of these whistlers has confirmed the existence of different ducts corresponding to their dispersion values during the period of observation at Jammu on 8 March 1997 and 2 February 2003. Further, our dispersion analysis shows that these whistlers have propagated in the magnetosphere along higher geomagnetic fields lines ($L \sim 3.6$).

(v) Nainital (geomag. lat., 19°06' N; $L=1016$) and Varanasi (geomag. lat., 15°06' N; $L=1011$) Out of large amount of whistlers observed at our ground stations Nainital during magnetic storm periods, we here reproduce some examples of storm-time whistler events from Nainital and Varanasi in Figure 6 alongwith their dispersion characteristics (Rao and Lalmani, 1975; Singh et al., 1993; Lalmani, 1984). In Figure 6, we show a sequence of five whistler sonograms corresponding to different times of occurrence during magnetic storms recorded at Nainital on 25 March 1971 (Figure 6a) and Varanasi on 19 March 1977 (Figure 6 b). On 25 March 1971, the spurt in whistler

![Figure 6](image-url)
activities started around 00:20 IST at Nainital and lasted for about 5h, ending finally at 05:20 IST, during this period $K_p$-index varied between 2 and 5. Whereas at Varanasi, the spurt in whistler activities started 00:00 IST and lasted for about 3h ending finally at 03:00 IST, several hundred whistlers were recorded during this 3h period. The similar characteristics of smooth decrease in dispersion of whistler recorded at both stations Nainital (from about 35 s$^{1/2}$ to 25 s$^{1/2}$ within about 5 h period) and Varanasi (from about 25 s$^{1/2}$ to 15 s$^{1/2}$ within about 3h period) is clearly seen in Figure 6 (a) and (b) respectively. The decrease in dispersions shown in Figs. 6(a) and (b) clearly give an experimental evidence of the formation of additional ducts within the portion of observational fields of view.

The occurrence rate of whistlers recorded during magnetic storm periods on 25 March 1971 and 19 March 1977 at Nainital and Varanasi respectively (Figure 6) is very interesting and altogether more than hundred whistlers were recorded on these days. The whistler occurrence rate variations at the above two stations showed a periodicity which is attributed to a cyclic process in the growth and decay of ducts. Power spectrum analysis of the occurrence rate of these whistlers yielded a periodicity of a period of 1h which is considered to be the lifetime of whistler duct of about one hour (Lalmani, 1984; Singh et al., 1998). This estimation of whistler duct lifetime of about one hour is confirmed by the dispersion analysis of these whistlers. Disperse analysis of these whistlers have qualitatively confirmed the existence of separate ducts corresponding to their respective dispersion during the period of observations (Rao and Lalmani, 1975; Lalmani, 1984) and also shows that these whistlers have propagated in the magnetosphere along higher $L$-value ($L \sim 3$-$4$). Using these whistlers observed at Nainital and Varanasi (Figure 6), the estimated value of magnetospheric electric field $E_w$ was found to be in the range of 0.1 to 0.7 m Vm$^{-1}$ which are sufficient for the duct formation at low latitudes (Mishra et al., 1980; Lalmani, 1984; Singh et al., 1993).

5.2. Storm-time VLF emission observations and their analysis

A variety of VLF emissions e.g. hiss, chorus, hissler, periodic, quasi-periodic, hook, inverted hook and triggered emissions are often recorded at our low latitude Indian ground stations during magnetic storm periods, but evidence of their occurrence is very rare during magnetically quiet periods at low latitudes. In order to understand the effect of magnetic storm on VLF waves i.e. increased occurrence probability of these VLF emissions and their propagation characteristics to be received at low latitudes during magnetic storm periods, we have made a spectral analysis of VLF emissions recorded during magnetic storm periods at our ground-based Indian stations which we here reproduce alongwith their characterisics and analysis.

(i) Observations of Chorus emission events

At Gulmarg, VLF emissions of different types have been recorded on various days during magnetic storm periods. Out of these emission data, a best example of storm-time VLF chorus emissions triggered by hiss emission recorded during nighttime between 21:26 UT to 01:23 UT on 7-8 March 1986 at Gulmarg is shown in Figure 6 (Singh et al., 2000; Singh and Ronnmark 2004). The most intense chorus emissions were registered during the night of 7 - 8 March when the magnetic activity was highest ($\sum K_p=34$) during the recovery phase of the sub-storm.
the spectrum analysis, it is found that hiss is seen as an unstructured signal below about 2.5 kHz and the discrete rising tones are chorus emissions. It is also observed that each chorus element, as seen in the figure, originates from the upper edge of the underlying hiss band.

From the analysis of the dynamic spectrums of the chorus emission events (Figure 7), the measured value of the upper boundary frequency ($f_{UB}$) of these emissions is found to be about 7.5 kHz. Making use of UBF-method (eq.7) and the observed parameter $f_{UB}$, the $L$-value of the source region of the reported chorus emissions for $f_{UB}$~7.5 kHz is found to be $L_{source}$=3.9. The computed higher $L$-value of the source region compared to our observation station Jammu ($L$=1.17) clearly shows that these emissions have propagated in ducted mode of propagation towards lower latitudes significantly. Thus, from spectrum analysis of the reported chorus emissions it is found that these emissions generated through cyclotron resonance interactions between whistler waves and particles in the equatorial region of $L$=3.9 have propagated in ducted mode along higher $L$-values and received at Jammu through Earth-ionosphere waveguide propagation.

(ii) **Observations of Hissler emission events**
Out of various types of VLF emissions recorded during magnetic storm periods at Jammu, we here reproduce the observation of “hissers”-the first report from low latitudes which are quasi-periodic

![Figure 7. Frequency-time spectrograms of hiss-triggered chorus emissions recorded at Gulmarg on 7-8 March 1986 during magnetostorm periods (after Singh et al., 2000; Singh and Ronnmark 2004).](image-url)
falling-tone noises during the period of hiss emission activity and appear in minute-long sequences with average spacing between individual bursts of the order of 0.2 seconds and falling tones do not overlap in time. Examples of hustlers are shown in Figure 8, which are easily recognizable on frequency time spectrograms Singh et al., (2004). These were observed in summer local night times during magnetic storm period on June 9, the activity started around 21:00 IST and continued for more than an hour. Typical examples of hissters shown in Figure 8 contain two bands. The hissters shown in Figure 8(a) and (b) are diffused and of longer periods and were observed only in the beginning of the activity and continued for about 30 minutes. The periodicity within the activity period is about 0.23 s. Hissers shown in Figure 8(c) occurs in large numbers during short time period and periodicity is about 0.04 s. Figure 8(d) shows two hiss bands on the spectrogram. Careful analysis shows that these hiss bands start first and after sometime hisser elements appear on the spectrograms. The hiss band structure continued for about an hour after the disappearance of the hissters.

From the dynamic spectrum analysis of hissler emission events (Figure 8), the measured value of upper boundary frequency ($f_{UB}$) of hissler emissions is found to be about 6 kHz. Using UBF-method (eq. 7), the estimated $L$-value of the source region of the reported hissler emissions for $f_{UB}$~6 kHz is found to be $L_{source}=4.2$. The estimated higher $L$-value of the hissler source region compared to the $L$-value of our observation station Jammu ($L=1.17$) clearly shows that hissler emissions generated in the equatorial region
of \( L = 4.2 \) have propagated in ducted mode along higher \( L \)-values and are received at Jammu through Earth-ionosphere waveguide propagation.

(iii) **Observations of Pulsing hiss emission events**

Figure 9, illustrates typical examples of pulsing hiss (PH) emissions observed at our low latitude Indian ground stations Jammu and Srinagar during magnetic storm periods in daytime (Sheikh et al., 2013). PH emission is a band-limited thermal or fluctuation noise irregularly pulsing with almost equal period, consists of repeated noise (hiss) bursts which show a degree of periodicity of somewhat shorter periods (from fraction of a second to several seconds). The investigations of PH emissions are extremely useful in studying wave-particle interaction processes in magnetosphere and particle dynamics responsible for wave excitation. From the detailed frequency spectra of PH emissions shown in Figure 9, it found that PH emissions clearly show band-limited spectra regularly pulsing almost with equal period of few seconds in the frequency range of \( \sim 300 \) Hz - 8 kHz. The PH emissions in Figure 9(a - d) contain equi-spaced pulses of very short duration of about 0.5 s which are non-dispersive discrete rising tones in the frequency range \( \sim 300 \) Hz - 8 kHz. The intensity and bandwidth of PH emissions remain almost constant in the frequency

![Figure 9](image.png)

**Figure 9.** Temporal variation of frequency spectra of pulsing hiss (PH) emissions observed during magnetostorm period at Jammu in daytime (a) 1610 IST (b) 1645 IST (c) 1620 IST and (d) 1658 IST (after Sheikh et al., 2013).
range ~300 Hz - 8 kHz.

The measured value of upper boundary frequency ($f_{UB}$) from the dynamic spectrum of the ground-observed pulsing hiss emissions (Figure 9), is found to be about 8 kHz which is used to estimate the $L$-value of the source region ($L_{source}$) of the reported pulsing hiss emissions at Jammu from UBF-method (eq. 7). The estimated value of $L_{source}$ of the pulsing hiss observed at Jammu is found to be $L=3.8$ for $f_{UB} = 8$ kHz. The estimated higher $L$-value of the pulsing hiss source region ($L=3.8$) compared to the $L$-value of the observation station Jammu ($L=1.17$) clearly indicates that our observed pulsing hiss generated in the quatorial region of $L=3.8$ have propagated in the ducted mode along higher field lines and are received at Jammu through Earth-ionosphere waveguide propagation.

(iv) Observation of Triggered emission

Of particular interest among various types of VLF emissions are triggered emissions that are identified as early as a dominant contributor to the loss of radiation belt particles. Triggered emissions display a variety of dynamic spectral forms and follow their apparent source e.g. a whistler, a discrete emission, hiss, a signal from VLF transmitters. Among various types of triggered VLF emissions, whistler-triggered pulsing hiss emissions is considered to be the most important for the understanding of wave-particle phenomena in the ionosphere and magnetosphere.

Figure 10 shows the well-defined frequency-time spectrograms of whistler-triggered pulsing hiss emissions (WTPHEs) recorded at our low latitude Indian ground stations Varanasi, Nainital and Jammu in the morning local time sector during magnetic storm periods. From Figure 10(a), it is noted that pulsing hiss emission (marked by PH in the frequency band of 2.6 - 2.9 kHz) is triggered from the lower end of the whistler W whose dispersion is about 15 s$^{1/2}$ and corresponding $L$-value of path of propagation is about 2.88. In all spectrograms triggered PH emissions contains about 14 equi-spaced pulses of very short duration of about 0.1 s which are non-dispersive. The present events of whistler triggered pulsing hiss events have been recorded during the great whistler activity during magnetic storm period. The last spectrogram of Figure 10(a) shows a whistler-triggered hiss emission in which a hiss emission in the frequency range 1.05-1.60 kHz is triggered by the lower end of a high dispersion whistler. The dispersion of this whistler is about 50 s$^{1/2}$ and corresponding $L$-value of path of propagation of this whistler is 4.15. Figure 10(b) shows typical examples of whistler-triggered pulsing hiss emissions recorded at Nainital on 25 March 1971 during the strong magnetic storm period 24-28 March 1971 with minimum $D_{st}$-index = -30 nT and maximum $K_p$-index 4 on 25 March 1971 in nighttime at 00:30 IST. From Figure 10(b), it is noted that WTPHEs lie in the frequency range of about 3.5 kHz in which PH emission occurs in two frequency bands which are triggered by two consecutive one-hop whistlers W1 and W2 having equal dispersion of the order of 20 s$^{1/2}$ and the corresponding $L$-value of path of propagation is 3.22. The time period of equi-spaced pulses in lower band in about 0.1 s, whereas time period of irregular pulses in upper band varies from 0.1 - 0.2 s. WTPHEs in Figure 10(b) have been recorded during the great whistler activity period on 25 March 1971. Figure 10(c) shows some unique and unusual events of WTPHEs recoded at Jammu on 18 Feb.
1998 during magnetic storm period 16–20 Feb. 1998 with minimum $D_{st}$-index = -100 nT and maximum $K_p$-index = 7 in the morning local time sector (03:00–04:00 IST). In this case the lower band PHE has a bandwidth of about 0.5 kHz and is triggered by lower end of the

Figure 10. Temporal variation of frequency spectra of whistler-triggered pulsing hiss (PH) and hiss (H) emissions recorded during magnetic storm periods at (a) Varanasi (b) Nainital (c) Jammu (self).
whistler W2 whose dispersion is about 50 s\(^{1/2}\) and the corresponding \(L\)-value of path of propagation is 4.13, whereas upper band PHE has a bandwidth of about 0.2 kHz and is triggered by the lower and of whistler W2 whose dispersion is about 53 s\(^{1/2}\) and corresponding \(L\)-value of this whistler is 4.21. The time period of equi-spaced pulses in lower and upper band PHE is about 0.1 and 0.2 s respectively. In this spectrogram a third un-triggered whistler W3 is also found to occur just after the upper band PHE event whose dispersion and \(L\)-value of path of propagation are of the same order as that of whistler W2.

Our spectrum analysis clearly shows that the sources of whistler-triggered pulsing hiss emissions observed at Varanasi, Nainital and Jammu are in the auroral region as estimated by UBF-method (eq. 7) and measured value of \(f_{UB}\) of the observed WTPHEs (Figure 10). The estimated higher \(L_{\text{source}}\) of the reported WTPHEs shows that these WTPHEs generated in the equatorial region of \(L \sim 3.5 \sim 4.2\) have propagated in the ducted mode along with whistlers along higher \(L\)-values and are received at our above mentioned ground stations through Earth-ionosphere waveguide propagation.

6. Analyzed results of the storm-time whistlers (a) and VLF emissions (b) and their discussions

(a) Storm-time whistlers

At low latitudes, the whistler occurrence rate is very low and sporadic during quiet periods, but it enhances during magnetic storm periods. The increased whistler occurrence rate during magnetic disturbances clearly shows the effect of magnetic storms on the occurrence, dispersion and propagation characteristics of whistlers observed at low latitudes. In order to establish the effect of geomagnetic storms on whistlers, we have made a dispersion analysis of whistlers recorded during magnetic storm periods at our low latitudes Indian ground stations Gulmarg, Jammu, Nainital, Agra and Varanasi under AICPITS program. Some examples of storm-time whistlers out of huge amount of storm-time whistler data from our mentioned Indian stations are reproduced in Figures 1-6 along with their dispersion analysis. The dispersion analysis of the storm-time whistlers observed at mentioned Indian stations, shows, that unusual high dispersion whistlers are registered during magnetic storm periods and their dispersions ranges from about 15 \(\sim 250\) s\(^{1/2}\). From the dispersion analysis of these observed storm-time high dispersion whistlers using Dowder-Allcock method (Dowden and Allcock, 1971) and curve-fitting technique of Tarcsai (Tarcsai, 1975), we find that these whistlers have propagated along the higher geomagnetic field lines in different ducts corresponding to \(L\)-values of 2.88 to 6.52. Hence it may be inferred that storm-time whistlers recorded at low latitudes belong to mid/high latitudes and these whistlers may have propagated in different ducts along higher \(L\)-values and after exiting from ducts, they penetrated the ionosphere and are trapped in Earth-ionosphere waveguide and thereafter propagating in the waveguide they are received at our low latitude Indian ground stations. The wave normal angle (lying in the range of 0.2 \(\sim 2.3\)) at the entrance into the waveguide is such that they propagated towards the equator and are received at low latitude Indian ground stations (Singh et al., 2008, 2009, 2010, 2011).
Further, the spectral analysis of storm-time whistler data recorded at Gulmarg, Srinagar, Nainital and Varanasi also shows that on certain occasions, whistler rate occurrences at these stations during magnetic storm periods are very high and are found to exhibit some periodicity. Figure 1(a, b), 2(a, b) and 6(a, b) show a sequence of five sonograms corresponding to different times of occurrence on 19 March 1970 and 8 Feb. 1986 at Gulmarg (Figure 1a, b) on 25 March 2009 at Srinagar (Figure 2), on 25 March 1971 at Nainital (Figure 6 a) and on 19 March 1977 at Varanasi (Figure 6b). It is at once evident from these figures that smooth decrease in whistler dispersion is clearly seen during the time span of about 5h. This decrease in dispersions seen in Figure. 1, 2 and 6 indicate that some additional ducts formed within that portion of observational fields of view, which are believed to be enhancement of electron density along a magnetic line of force by the disturbances produced in the ionosphere and magnetosphere during magnetic storm periods which result in producing additional ducts. The enhanced whistler occurrence rate at Gulmarg, Srinagar, Nainital and Varanasi stations on various days (Figure. 1, 2 and 6), are found to exhibit some periodicity in the whistler occurrence rate. Using the procedure of Madden (1964), the exhibited periodicity in the whistler occurrence rate was found to be a time period of about 50 min. This period of about 50 min is the duct lifetimes of the additional ducts formed during the periods of observation (Rao and Lalmani, 1975, Lalmani, 1984; Singh et al., 1998; Singh et al., 2013). The electric fields perturbing the magnetospheric plasma play a dominant role in duct formation. Therefore, an attempt was made to estimate the magnetospheric electric field responsible for the formation of additional ducts within the portion of whistler observational fields of view using whistlers observed at Gulmarg, Srinagar, Nainital and Varanasi during magnetic storm periods (shown in Figure 1, 2 and 6) from radial motions of discrete field-aligned whistler ducts, as indicated by change in dispersion (nose frequencies) and the estimated value of electric field (E) at equatorial heights of Gulmarg, Srinagar, Nainital, and Varanasi ground station lies in the range of 0.1 to 0.8 mV/m which are sufficient for the formation of the additional ducts during the period of whistler observation at Gulmarg, Srinagar, Nainital, and Varanasi (Mishra et al., 1980, Lalmani, 1984, Singh et al., 1998).

(b) Storm-time VLF emissions

In order to study the effect of magnetic storm on the low latitude VLF emissions, we have made an intensive investigation of the huge amount of VLF emission data collected over a period of about four decades at our ground-based Indian stations Gulmarg, Jammu, Nainital, Agra and Varanasi. During this investigation, we obtained huge amount of various types of VLF emission events recorded during magnetic storm periods at our Indian stations. Out of the obtained storm-time emission data, some typical examples of various types of storm-time emissions are reproduced in Figure. 7 - 10 alongwith their detailed spectral analysis.

A detailed spectral analysis of VLF chorus emissions observed at Gulmarg during the strong magnetic activity on 7 - 8 March 1986 (represented in Figure 7), shows that each chorus element originates from the upper edge of the underlying hiss emission band. Various temporal and spectral features of these chorus emission was successfully explained by Singh and Romnmark (2004) with the help of a generation mechanism based
on the backward wave oscillator (BWO) regime of the magnetospheric cyclotron maser. This model explained peculiarities of chorus emissions, such as its connection with hiss, the appearance of a succession of chorus element with small repetition frequency and amplitude of a signal (Singh et al., 2000; Singh and Ronnmark 2004). Our computations of $L$-source of chorus emissions by UBF-method (Smirnova, 1984) shows that VLF chorus emissions observed at Gulmarg lies around $L=4$ which clearly shows that these emissions are high latitude chorus emissions generated in the equatorial region of higher latitudes ($L \sim 4$) through the process of Doppler-shifted cyclotron resonance mechanism and propagated along higher field lines in ducted mode and are recorded at our low latitude ground station Gulmarg after propagating through Earth-ionosphere waveguide.

The first observation of hissler at Jammu during magnetic storm period on 9 June 1999 are represented in Figure 8. From the spectral analysis of hissler shown in Figure 8, it is found that these are falling tone noises during the period of hiss activity and appear in minute long sequences with average spacing between individual bursts of the order of 0.2 s and falling tones do not overlap in time. Using upper boundary frequency (UBF) method the values of source region of hissler emission is found to be $L=4$ for $f_{UB}=7.5$ kHz (Figure 8). Thus, we find that hissler observed at Jammu may have generated in the equatorial region of the geomagnetic field at $L=4$ through the process of Doppler-shifted cyclotron resonance mechanism. After generation, hissler emissions propagated along field lines in the duct formed by the disturbance produced in the magnetosphere during a magnetic storm which is an enhancement of electron density along a magnetic lines of force and after exiting from the inosphere must have excited Earth-ionosphere waveguide towards the equator, so that they could be received at Jammu (Siren, 1975; Singh et al., 2004, 2010).

Observation of VLF pulsing hiss emissions at Jammu and Srinagar during magnetic storm periods are represented in Figure 9. From statistical analysis of these observed data, it is found that pulsing hiss (PH) emission is a rare phenomenon at low latitudes. The spectrograms of these storm-time PH emissions clearly show band limited spectrums regularly pulsing with almost equal time period of about 0.5 s in the frequency range of 300 Hz · 8 kHz. By measuring the upper boundary frequency ($f_{UB}$) of the reported PH emission, the $L$-value of source is determined by UBF method (Smirnova, 1984). Using UBF method, the $L$-value of the source region of our storm-time PH emissions observed at Jammu and Srinagar is found to be $L_{source}=4$. These PH emissions are considered to be generated during Doppler-shifted cyclotron resonance interaction. These, storm-time PH emissions observed at Jammu and Srinagar (Figure 9) are generated in the equatorial region of $L=4$ through the process of Doppler-shifted cyclotron resonance mechanism and propagated along the field lines in the ducts formed by the disturbances produced in the magnetosphere during a magnetic storm and after exiting from the duct they penetrated the ionosphere and are trapped in the Earth-ionosphere waveguide. The wave normal (0.2 · 2.3°) at the entrance into the waveguide is such that they propagated towards the equator and are recorded at Jammu and Srinagar ground stations (Singh et al., 2010; Sheikh et al., 2013).

The first observation of whistler-triggered pulsing hiss emissions (WTPHEs) was
obtained during investigation of VLF data collected over a period of about four decades at our low latitude Indian ground stations. The spectral analysis of the obtained WTPHE data shows that these are rare events recorded at low latitudes during the period of great whistler activity in the night times on geomagnetic storm days, some best examples of which are represented in Figure 10. From the detailed spectral analysis of these WTPHE data, it is found that band limited spectra of pulsing hiss (PH) emission triggered by the lower end of the whistler is regularly pulsing with almost equal period of order of a second. Dispersion analysis of triggered whistlers of WTPHEs shows that these whistlers are one hop whistlers having their propagation paths along higher \( L \)-values lying between 2.9 and 4.4, suggesting that these WTPHEs are to be regarded as mid/high latitude VLF emissions generated in the equatorial region of higher \( L \)-values through the process of Doppler-shifted cyclotron resonance mechanism and have propagated in different ducts formed by geomagnetic disturbances during magnetic storms along higher geomagnetic field lines \( 2.9 \leq L \leq 4.4 \) and after exiting from ducts, they penetrated the ionosphere and are trapped in Earth-ionosphere waveguide and are thus recorded at our Indian ground stations after propagating in the waveguide (Singh 2016).

7. Conclusion

A statistical study of VLF (whistler and emission) data collected over a period of about four decades at our low latitudes Indian ground stations e.g. Gulmarg, Srinagar, Jammu, Nainital, Agra and Varanasi under All India Coordinated Program of Ionosphere Thermosphere Studies (AICPITS), shows an intensive effect of magnetic storms on occurrence and dispersion of VLF waves at low latitudes. From our detailed study of the dispersion analysis of storm-time whistlers recorded at our Indian ground stations, it may now be well established that in general unusual high dispersion whistlers observed during magnetic storm periods at low latitudes are mid/high latitude whistlers which have propagated in different ducts along higher and closely spaced \( L \)-values and after exiting from the ducts, they penetrated the ionosphere and are trapped in the Earth-ionosphere waveguide and after propagating in the waveguide they are received at low latitude ground stations. Further, On the basis of spectral analysis of storm-time whistler data recorded at Indian ground stations regarding the occurrence probability of these whistlers at low latitudes, it may be established that increased high whistler occurrence rate during magnetic storm period is caused by the formation of additional ducts within the portion of observational fields of view supporting the whistler mode propagation.

Our spectral analysis of various types of VLF emissions observed at our Indian ground stations during magnetic storm periods (some best examples depicted in Figure 7·10), clearly shows that these emissions are mid/high latitude VLF emissions generated in the equatorial region of higher \( L \)-values \( 2.9 \leq L \leq 4.4 \) through the process of Doppler-shifted cyclotron resonance mechanism and propagated along higher field lines in different ducts formed by disturbances produced in the ionosphere and magnetosphere during magnetic storms and after exiting from duct, they penetrated the ionosphere and are trapped in the Earth-ionosphere waveguide and are recorded at our low latitude
Indian ground stations after propagating through the Earth-ionosphere waveguide. Further, our spectral analysis of the various types of storm-time VLF emissions shows a tremendous increase in the occurrence of these emissions during magnetic storm periods at low latitudes due to the formation of additional ducts by the enhanced flux of energetic electrons during magnetic storm periods.

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