

## Estimation of magnetospheric plasma parameters from whistlers observed at low latitudes

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**Whistler observations during night-time made at low-latitude Indian ground stations, Jammu (geomag. lat. 29°26'N; L = 1.17), Nainital (geomag. lat. 19°1'N; L = 1.16) and Varanasi (geomag. lat. 14°55'N; L = 1.11) are used to deduce electron temperature and electric field in the vicinity of the magnetospheric equator. The accurate curve-fitting and parameter estimation techniques are used to compute nose frequency and equatorial electron density from the dispersion measurements of short whistlers recorded at Jammu, Nainital and Varanasi. In this communication we estimate the magnetospheric electron temperature and electric field from the dispersion analysis of short whistlers observed at low latitudes using different methods; the results obtained are in good agreement with those reported by other workers. The upper atmosphere environment is impacted by energetic particles, solar radiation and interplanetary magnetic fields that drive 'space weather' disturbances in the region, leading to strong electric currents, order of magnitude changes in neutral density and temperature, and major redistribution of plasma. At the same time, circulation and variability of the upper atmosphere are dramatically impacted by waves carrying energy and momentum upward from hurricanes, thermal tides and surface features. This region is where space and Earth's atmosphere interact, forming a critical boundary that must be studied to advance our understanding of the whole Earth system.**

**Keywords:** Electric field, electron temperature, low-latitude stations, magnetospheric plasma, whistlers.

It is well known that lightning discharges are accompanied by the generation of electromagnetic waves in a wide frequency range<sup>1,2</sup>. Wave energy can penetrate into the magnetosphere and propagate almost along geomagnetic field lines to the opposite hemisphere, where it is recorded by a radio receiver known as a whistler. The dynamic spectrum of the recorded signal is typically dispersed in the spectrogram. These signals sometimes proceeded by an associated signal with an undispersed dynamic spectrum and are generated during the same lightning discharges, but propagate in the Earth-ionosphere waveguide<sup>2,3</sup>. When this signal is recorded and coincides approximately with the moment of light-

ning discharge its time delay does not usually exceed 0.04 sec (ref. 4) as the velocity of wave propagation in the Earth-ionosphere waveguide is close to the velocity of light, it is called an atmospheric or sferic. The whistler signal intensity is normally greatest at few kilohertz (kHz) within the ELF/VLF band; 1–20 kHz.

Whistlers represent an inexpensive and effective method for obtaining various plasmaspheric parameters like electron density, electron temperature, electric field, etc. in the magnetosphere, but the experimental results published up to now refer mainly to higher latitudes<sup>5–7</sup>, and a systematic description of the main features of the plasmaspheric electron density based on large quantities of whistler data is still lacking at high latitudes, with the exception of the work by Park *et al.*<sup>8</sup>. Recently, Tarcsai *et al.*<sup>9</sup> have processed whistlers recorded at Tihany, Hungary ( $L = 1.9$ ) between December 1970 and May 1975 in order to study the distribution of equatorial electron density and total electron content in flux tubes having  $L$ -value lying in the 1.4–3.2 range. At low latitudes, the exploration of whistlers for electron density determination has been carried out by Lalmani *et al.*<sup>10</sup>. In this communication the equatorial electron density, equatorial electron temperature and east–west component of electric field at low latitudes have been estimated using the whistler data observed at our ground stations Jammu, Nainital and Varanasi.

At middle and high latitudes both satellite and ground-based whistler data were exploited fully to reveal new facts about the structure and dynamics of the ionosphere and magnetosphere. These included the discovery of the plasmasphere, plasmopause and bulge<sup>11</sup>, identification of the mechanism of ionosphere–protonosphere coupling<sup>5,12</sup> and the measurement of the magnetospheric electric field<sup>13</sup>. Although the application of whistlers to obtain electron temperature of high latitudes has been discussed since the early 1960s<sup>6,14,15</sup>, this problem still seems at an early stage of development at low latitudes. Whistler data have been used at low latitudes for determining electron temperature, electric field, etc. for understanding the magnetospheric phenomenon.

We consider the methods of 'traditional' diagnostics of magnetospheric parameters, such as electron plasma density, the large-scale electric field and possible temporal variations of the magnetic field at the magnetospheric equator, when both nose frequency,  $f_n$  and travel time,  $t_n$  are known. When one or both of these parameters are not known, the dynamic spectra of whistlers and/or sferics need to be extrapolated. The method of extrapolation is subsequently considered. Then we estimate the equatorial electron density, electron temperature and electric field in the equatorial magnetosphere based on the analysis of the dynamic spectra of whistlers. Studies since 1963 have made significant contribution to the propagation of low-latitude whistlers and understanding of the structure and dynamics of the low-latitude ionosphere<sup>16–18</sup>.

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For the analysis of non-nose whistlers, a number of methods have been proposed<sup>19</sup>. The nose frequency of the whistler data used in estimating electron density, electron temperature and electric field has been computed by means of accurate curve-fitting method developed by Tarcsai<sup>19</sup> based on least squares estimation of the two parameters, zero frequency dispersion  $D_0$  and equatorial electron gyrofrequency  $f_{He}$  in Bernard's approximation. This matched filtering technique developed for the analysis of whistler waves increases the accuracy of analysis and speed of data processing<sup>17,18,20</sup>. The technique employs dispersive digital filters whose frequency-time response of the matched to the frequency-time response of the signal to be analysed. Due to high resolution and time domain many fine-structure components with amplitudes differing in frequency and time are seen in the dynamic spectra<sup>20</sup>. The accuracy and effectiveness of the technique have been discussed at length by analysing a large number of whistlers both on the ground stations (from the low to the high latitudes) and onboard rockets/satellites<sup>18,20-22</sup>.

Electric fields are closely related to and control most of observed geophysical phenomena, such as the bulk motion of the magnetospheric plasma, the current systems in the magnetosphere and the ionosphere, and the acceleration of plasma particles in the Earth's magnetosphere. The role of electric field in controlling the bulk motion of the plasma has been recognized in theoretical studies of the various dynamic processes taking place in the Earth's magnetosphere, although adequate experimental techniques for the precise measurements of such fields in the ionosphere and magnetosphere were not available for quite some time. The observed cross- $L$  motions of the whistler ducts are being used currently for obtaining the east-west component of the electric fields in the plasmasphere during substorm periods as well as quiet periods<sup>4,5</sup>.

The tidal forces in the Earth's atmosphere cause motion of the plasma across the magnetic field lines and give rise to electromotive forces. The generation of electric field by the motion of conducting plasma across the magnetic field is analogous to dynamo action and the theory dealing with the electric field generation by this mechanism is known as dynamo theory. The electric field generation mechanism in the ionosphere has been developed by various workers<sup>23,24</sup>. Electric field measurements have been carried out in the equatorial E-region of the ionosphere by many workers. These measurements reveal the existence of east-west electrostatic field ranging from 1 to 2 mV/m. The whistler method of obtaining the east-west component of the electric field has the advantage of extended time coverage and remarkable property of being directly involved in the motion of magnetospheric tubes or 'ducts' of ionization. Further, the ground-based whistler determinations of electric fields are comparatively easier and the equipment used can be monitored with relative ease on a routine basis. It is precisely for this rea-

son that the ground-based whistler studies of electric fields are still continued at a number of stations spread all over the world.

In this communication we first present the whistler data used for the analysis, recorded at Jammu, Nainital and Varanasi. This is followed by a presentation of an outline of the method developed by Tarcsai<sup>19</sup> from which electron density, electron temperature and electric field in the vicinity of magnetospheric equator are evaluated. Finally, the results are discussed and compared with those reported by other workers.

At low latitudes, the whistler occurrence rate is low and sporadic. But once it occurs, its occurrence rate becomes comparable to that of mid-latitudes<sup>25</sup>. Similar behaviour has also been observed at our low-latitude Indian stations. All the Indian stations are well-equipped for measurements of VLF waves from natural sources. Using VLF wave-recording equipment consisting of a  $T$ -type antenna (25 m in vertical length, 6 m long and 3.22 mm in diameter), transistorized pre- and main amplifiers and a magnetic tape recorder, we conducted routine observations at our low-latitude ground stations, especially in Jammu between December 1996 to December 1999. The observations were taken continuously during day and night hours every day. The accumulated data were analysed on a digital sonograph available at CEERI Centre, New Delhi. The results of the analysis showed a number of whistlers and VLF/ELF emissions recorded at station. Some unique and very interesting events of the whistlers were observed. For the present study, the whistler data chosen correspond to 5 June 1997 for Jammu, 25 March 1971 for Nainital and 19 February 1997 for Varanasi. On 5 June 1997 at Jammu station whistler activity started around 2140 h IST and lasted up to 2245 h IST. During this period about 100 whistlers have been recorded<sup>26</sup>. On 25 March 1971 at Nainital station whistler activity commenced around 0020 h IST and lasted up to 0520 h IST. Altogether more than 100 whistlers were recorded and the occurrence rate showed a feeble but discernible periodicity<sup>27</sup>. On 19 February 1997 at Varanasi station whistler activity started around 2300 h IST and lasted for about one hour up to 0030 h IST. During this period several whistlers were recorded<sup>28</sup>.

Figure 1a presents dynamic spectrum of short whistlers (marked A-G, selected for the analysis) in the frequency band 3-4.5 kHz recorded at Jammu at 2212 h IST on 5 June 1997. In the frequency band 1.7-3 kHz, a large number of frequency components are missing and the signals resemble emissions rather than whistlers. Further, VLF waves in both the frequency bands do not appear simultaneously, rather they appear alternately. Figure 1b shows dynamic spectra of short whistlers (marked 1-4, selected for the analysis) and VLF emissions recorded at Jammu at 2147 h IST. Whistlers are banded and diffused in the frequency range 2.7-3.7 kHz and are repeated in time. The time interval between the events is not

constant. Unusual VLF noises are also seen in the spectrum. Figure 2 shows dynamic spectrum of short whistlers selected for the analysis recorded at Nainital on 25 March 1971. The sonograms of sample whistlers (marked W1–W5) are arranged in a sequence for different times of arrival. Figure 3 *a* and *b* shows the dynamic spectra of short whistlers (selected for analysis) recorded at Varanasi on 19 February 1997 at 0017 h IST and 2338 h IST respectively.

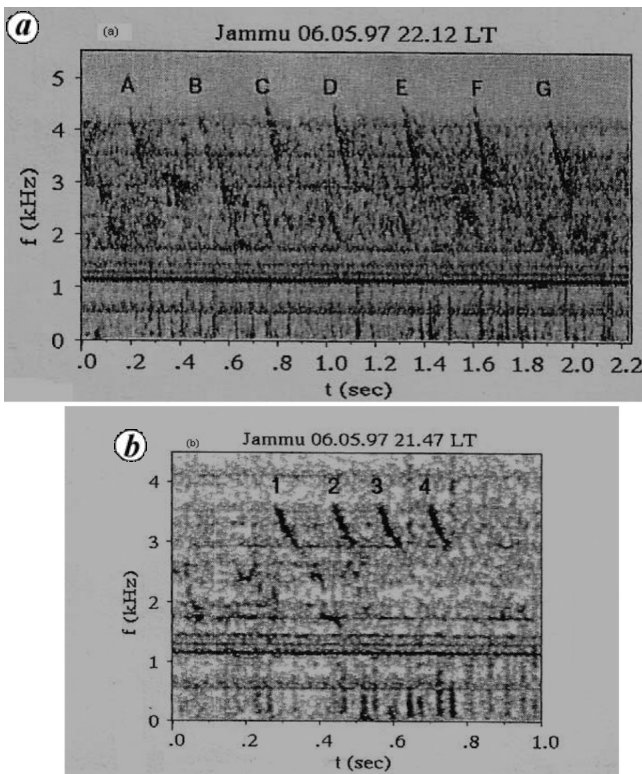
Tarcsai<sup>19</sup> has developed a curve-fitting technique for the analysis of middle and high-latitude whistlers. This technique has also been applied successfully to those low-latitude whistlers whose propagation paths are low, below  $L = 1.4$  (refs 25, 29–31). Further, the technique is found suitable not only for long and good quality whistlers, but also for short and faint whistlers. The computer program for this requires input data such as frequency time ( $f, t$ ) values scaled at several points along whistler trace appropriate for  $F_2$  (ionospheric layers height from the earth's surface), zero frequency dispersion ( $D_0$ ) a suitable ionospheric model, etc. The output results include the  $L$ -value of propagation, equatorial electron density, total tube content, etc. we have adopted this program for the analysis of night-time whistlers recorded at Nainital, Varanasi and Jammu during quiet days.

At low  $L$ -values, the curve-fitting method of Tarcsai<sup>19</sup> would not change too much the equatorial electron density and total electron content values compared to the

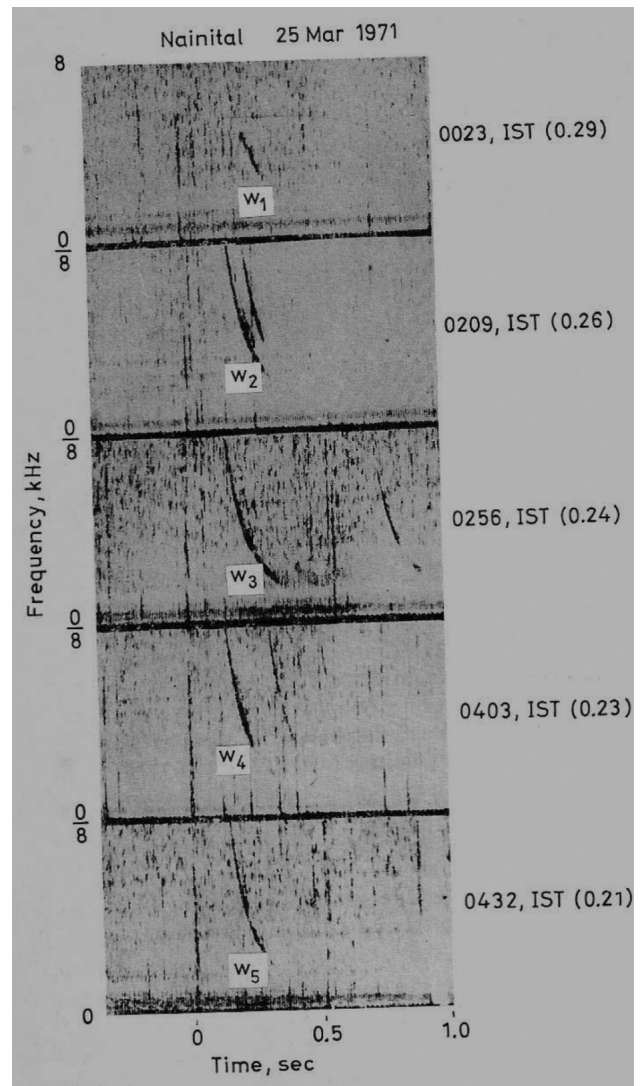
systematic errors which are inherent in all of the existing nose extension methods. These systematic errors originate from the approximations used for the refractive index and for the ray path in the derivation of the analytic expressions for the dispersion and from the difference between the theoretical and actual distribution plasma along the field lines<sup>32</sup>. To examine its validity we analysed few whistlers recorded at Jammu using this method as Dowden–Allcock<sup>31</sup>  $Q$ -technique. Both methods yielded results within  $\pm 10\%$ . Further, it is to be noted that the Tarcsai's method has successfully been used in the analysis of low-latitude whistler.

For the determination of  $D_0 f_n$  and  $t_n$  approximate function for the dispersion of whistlers is given by<sup>19</sup>

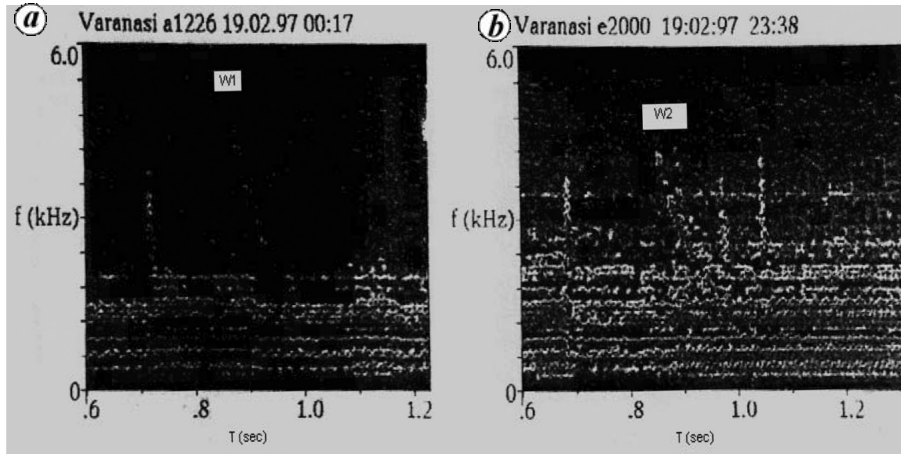
$$D(f) = t(f)f^{1/2} = D_0 \left[ \frac{(f_{\text{Heq}} - Af)}{f_{\text{Heq}} - f} \right], \quad (1)$$



**Figure 1.** Dynamic spectrum of whistlers recorded at Jammu on 5 June 1997. *a*, Whistlers are marked A–G. *b*, Whistlers are marked by 1–4.



**Figure 2.** Dynamic spectrum of whistlers recorded at Nainital on 25 March 1971. Whistlers are marked by W1–W5.



**Figure 3.** Dynamic spectrum of whistlers recorded at Varanasi on 19 February 1997 at (a) 0077 h and (b) 2338 h IST. Whistlers are marked by W1 and W2.

where  $D_0$  is the zero frequency dispersion,  $f_{\text{Heq}}$  the equatorial electron gyrofrequency,  $f$  the wave frequency and  $t(f)$  the travel time at frequency  $f$  and

$$A = \frac{3\Lambda_n - 1}{\Lambda_n(1 + \Lambda_n)} \quad (2)$$

Here

$$\Lambda_n = \frac{f_n}{f_{\text{Heq}}}$$

where  $f_n$  is the nose frequency for which travel time  $t_n$  is written as

$$t_n = \left[ \frac{D_0}{f_n^{1/2}} \right] \left[ \frac{2}{(1 + \Lambda_n)} \right] \quad (3)$$

If the causative spheric is unknown and the travel times at different frequencies of the whistler traces are measured with respect to an arbitrary time origin, then it is necessary to introduce a new parameter  $T$ , which gives the difference in time between the chosen origin and the actual causative spheric. Using  $T$  and eq. (1), the measured travel time  $t^*(f)$  can be written as

$$t^*(f) = t(f) - T = \frac{D_0}{\sqrt{f}} \frac{(f_{\text{Heq}} - Af)}{(f_{\text{Heq}} - f)} - T$$

$$= \left[ \frac{D_0}{\sqrt{f}} \frac{f_{\text{Heq}} f_n (f_{\text{Heq}} + f_n) - f(3f_n - f_{\text{Heq}})}{f_n (f_{\text{Heq}} - f)(f_{\text{Heq}} + f_n)} \right] - T \quad (4)$$

In eq. (4) there are four unknown parameters  $D_0$ ,  $f_{\text{He}}$ ,  $T$  and  $f_n$ . Tarcσαι<sup>19</sup> has developed a computer program to

solve eq. (4) for the unknown using successive iteration method. In this method those values of  $D_0$ ,  $f_{\text{Heq}}$ ,  $T$  and  $f_n$  are searched which give best fit to the measured parameters. After Park<sup>4</sup> and using eq. (3) for  $t_n$ .

$$n_{\text{eq}} = K_e f_n t_n^2 L^{-5} = K'_e D_0^2 f_{\text{Heq}}^{5/3}$$

$$N_T = K_T f_n t_n^2 L^{-1} = K'_T D_0^2 f_{\text{Heq}}^{1/3} \quad (5)$$

$$N = K_1 f_n t_n^2 L^{-5} = K'_1 D_0^2 f_{\text{Heq}}^{5/3}$$

where the constants  $K'_e$  and  $K'_T$  are weakly dependent on  $f_n$  and  $\Lambda_n$  (ref. 19).

Using eq. (5) and analysing whistlers shown in Figures 1–3 recorded at Jammu, Nainital and Varanasi, nose frequency  $f_n$ , equatorial electron density  $n_{\text{eq}}$  and total electron content  $N_T$  in a flux tube of unit cross-section have been evaluated. Then the equatorial electron temperature  $T_{\text{eq}}$  was estimated from nose frequency computed using Tarcσαι<sup>19</sup> method for a given model of electron distribution for our analysis. A diffusive equilibrium model similar to that adopted earlier<sup>5,18,19,28</sup>, was employed which was represented at the height 1000 km by an electron density  $10^3$  electron/cm<sup>3</sup>,  $O^+ = 90\%$ ,  $H^+ = 8\%$  and  $He^+ = 2\%$  at the temperature ( $T_{\text{ref}}$ ) of 1000 K. The electron temperature in the magnetosphere ( $T_e$ ) is related to the electron temperature at the reference level ( $T_{\text{ref}}$ ) by the equation.

$$T_e/T_{\text{ref}} = (R/R_{\text{ref}})^n \quad (6)$$

where  $R$  and  $R_{\text{ref}}$  are the corresponding geocentric distances. We took two values of  $n$  ( $n = 1$  and  $2$ ). For the case of  $n = 0$ ,  $T_e$  remains almost constant and for the case of  $n = 2$ ,  $T_e$  increases rapidly with height, one expects the actual value of  $n$  to lie between these two extremes. The results of the calculation of  $f_n$ ,  $f_{\text{He}}$ ,  $D_0$ ,  $L$ ,  $n_{\text{eq}}$  and  $T_{\text{eq}}$  for the whistlers under consideration are shown in Table 1 (for  $n = 1$  and  $2$ ).

**Table 1.** Parameters of whistlers observed at Jammu, Nainital and Varanasi ground stations estimated from the whistler dispersion analysis using accurate curve fitting technique

<i>W</i>	Station	Date	IST	$D_0$ (s <sup>1/2</sup> )	$f_n$ (kHz)	$f_{Heq}$ (kHz)	<i>L</i> -value	$n_{eq}$ (cm <sup>-3</sup> )	$n = 1$ $T_{eq}$ (eV)	$n = 2$ $T_{eq}$ (eV)
1	Jammu	5 June 1997	21 :40 :25	65.5 ± 1.0	4.2 ± 0.03	11.37 ± 0.07	4.25 ± 0.01	159 ± 3	0.28	0.85
2	Jammu	5 June 1997	21 :47 :42	81.9 ± 1.1	3.39 ± 0.013	10.59 ± 0.034	4.35 ± 0.005	220 ± 5	0.29	0.86
3	Jammu	5 June 1997	22 :47 :50	88.9 ± 1.8	3.82 ± 0.02	10.27 ± 0.05	4.39 ± 0.07	247 ± 8	0.29	0.87
4	Jammu	5 June 1997	22 :47 :55	87.6 ± 1.4	3.85 ± 0.01	10.37 ± 0.03	4.38 ± 0.00	244 ± 6	0.29	0.87
5	Jammu	5 June 1997	22 :12 :20	28.8 ± 1.2	8.15 ± 0.72	21.98 ± 1.95	3.41 ± 0.10	93 ± 6	0.20	0.4
6	Jammu	5 June 1997	22 :12 :51	28.9 ± 0.9	6.29 ± 8.21	16.96 ± 0.55	3.72 ± 0.04	61 ± 1	0.14	0.5
7	Jammu	5 June 1997	22 :13 :22	35.5 ± 1.7	6.13 ± 0.25	16.51 ± 0.66	3.75 ± 0.05	88 ± 2	0.24	0.6
8	Jammu	5 June 1997	22 :13 :53	38.3 ± 1.9	4.61 ± 0.10	12.42 ± 0.28	4.12 ± 0.03	63 ± 4	0.27	0.7
9	Jammu	5 June 1997	22 :14 :24	26.1 ± 0.6	5.76 ± 0.13	15.53 ± 0.35	3.83 ± 0.02	43 ± 4	0.25	0.6
10	Jammu	5 June 1997	22 :14 :55	22.8 ± 1.7	5.99 ± 0.41	16.17 ± 1.10	3.78 ± 0.08	35 ± 1	0.24	0.5
11	Jammu	5 June 1997	22 :15 :26	38.9 ± 1.2	5.06 ± 0.09	13.62 ± 0.24	4.00 ± 0.02	76 ± 3	0.26	0.6
12	Nainital	25 March 1971	00 :23 :00	20.2 ± 2.1	68.33 ± 0.0	204.35 ± 0.84	1.62 ± 0.00	298 ± 0	0.05	0.2
13	Nainital	25 March 1971	02 :09 :00	18.6 ± 0.6	16.85 ± 3.0	45.9 ± 0.82	2.67 ± 0.00	136 ± 3	0.14	0.2
14	Nainital	25 March 1971	02 :56 :00	18.5 ± 0.9	9.72 ± 1.1	26.2 ± 0.381	3.21 ± 0.00	52 ± 6	0.19	0.3
15	Nainital	25 March 1971	04 :03 :00	13.2 ± 0.7	13.24 ± 2.6	35.8 ± 0.72	2.89 ± 0.00	45 ± 1	0.1	0.2
16	Nainital	25 March 1971	04 :32 :00	15.4 ± 0.5	8.53 ± 3.9	23.0 ± 0.10	3.36 ± 0.00	29 ± 1	0.2	0.4
17	Varanasi	19 February 1997	00 :17 :00	11.9 ± 0.3	36.8 ± 2	103.5 ± 60	2.1 ± 0.4	247 ± 24.6	0.1	0.2
18	Varanasi	19 February 1997	23 :38 :00	13.5 ± 0.2	13.1 ± 1.1	35.3 ± 31	2.9 ± 0.01	45 ± 5	0.1	0.2

*W*, Whistler number; IST, Indian Standard Time;  $D_0$ , Dispersion of whistler;  $f_n$ , Whistler nose frequency;  $f_{Heq}$ , Equatorial gyrofrequency; *L*-value, Earth's radius;  $n_{eq}$ , Equatorial electron density;  $T_{eq}$ , Equatorial electron temperature.

The whistler nose frequency  $f_n$  (in kHz) is related to its path *L* by the approximate relation

$$f_n = 3.23 \times 10^5 L^{-3}, \tag{7}$$

and a central dipole magnetic field is used to represent the geomagnetic field. The nose frequency and the minimum equatorial gyrofrequency along the path of propagation are related as<sup>33</sup>

$$f_n = K' f_{Heq} = K' f_{Ho} (R_0/R)^3, \tag{8}$$

where  $K' = 0.38$  for a diffusive equilibrium model of the field-line distribution of ionization,  $f_{Heq}$  and  $f_{Ho}$  are the equatorial gyrofrequencies at geocentric distances of *R* and  $R_0$  (Earth's surface) respectively.

In the equatorial plane, the convection electric field, defines as positive in the eastward direction is given by

$$E = -V \times B/B^2. \tag{9}$$

In the case of magnetic equator we obtain from eq. (8)

$$dR/dt = -(E_w/B_0)(R_0/R)^{-3}, \tag{10}$$

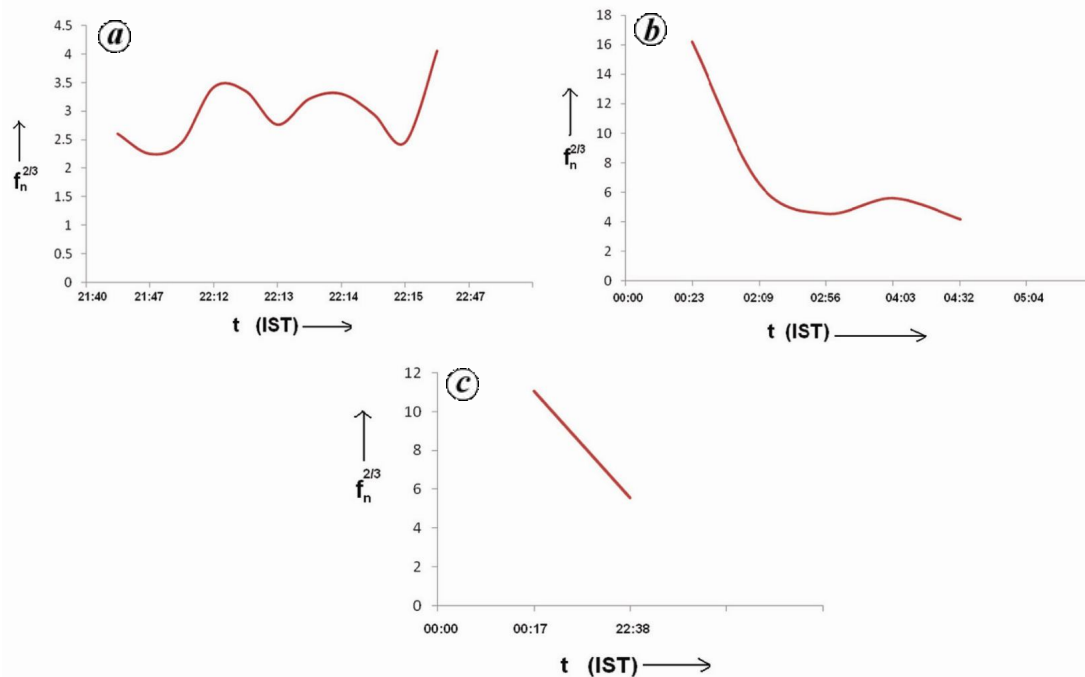
where  $B_0$  represents the geomagnetic field strength at the Earth's surface and  $E_w$  is the westward component of the magnetospheric electric field. With the help of eqs (7) and (8), the convection electric field in a dipole model in the equatorial plane can be obtained as<sup>34</sup>

$$E_w = -2.1 \times 10^{-2} (df_n^{2/3}/dt) \text{ V/m}. \tag{11}$$

with the nose frequency expressed in hertz, one can directly estimate the convection electric field from the slope of  $(f_n^{2/3})$  using eq. (10). The variation of  $f_n^{2/3}$  with time for the whistlers observed at Jammu, Nainital and Varanasi is given in Figure 4 *a-c* respectively.

Several attempts have been made to use whistlers as a diagnostic of the electron temperature of the magnetosphere besides the traditional methods of diagnostics of electron temperature in the magnetosphere. The first such attempt was probably made by Scarf<sup>35</sup> who estimated this temperature from the thermal attenuation of nose whistlers at the upper cut-off frequency. This method was developed by Liemhon and Scarf<sup>36,37</sup>, but to our knowledge was never used in practice, perhaps for two reasons. First, it is difficult to decide whether the whistler upper cut-off frequency is determined by wave attenuation or by propagation effects. Second, the interpretation of the whistler cut-off frequency in Scarf's method is sensitive to the anisotropy of the electron distribution function, which can in general be determined only by *in situ* measurements.

In an alternative approach to this problem, McChesney and Hughes<sup>34</sup> measured the electron density at the magnetospheric equator ( $n_{eq}$ ) by whistler dispersion analysis and in the topside ionosphere from *in situ* observations of LHR noise. The ratio of these densities was fitted to a diffusive equilibrium model of electron density distribution with temperature as a parameter. The main assumption was that the electron temperature did not change along the magnetospheric magnetic field line. However, this assumption seems to be incompatible with satellite measurements of electron temperature; equatorial temperatures



**Figure 4.** Plot between  $f_n^{2/3}$  and  $t$  for the cases observed at (a) Jammu on 5 June 1997; (b) Nainital on 25 March 1971 and (c) Varanasi on 19 February 1997.

can be up to a factor of 10 larger than those at ionospheric altitudes<sup>38,39</sup> and need to be abandoned in further modifications of this method.

A different approach was adopted by Guthart<sup>40</sup>, who attempted to estimate magnetospheric electron temperature from its effect on whistler group velocity, assuming a gyrofrequency model electron distribution. He predicted that the thermal effect on whistler spectra should be largest at frequencies near the upper cut-off frequency of nose whistlers. However, the size of the effect was less than the experimental error associated with whistler spectral analysis. This conclusion enabled Guthart to estimate an upper bound on the magnetospheric electron temperature of  $2 \times 10^4$  K  $\approx 1.7$  eV. By contrast, Kobelev and Sazhin<sup>41</sup> have argued that thermal effects in the vicinity of the plasmopause can be estimated by comparison of observed and theoretical whistler dispersion curves. Assuming an electron density distribution along field lines, they obtained values of electron temperature in the 7–19 eV range, depending on the value of the parameter  $n$ . This temperature corresponds to an average temperature of all electrons, ‘cold’ ones with energies  $\leq 1$  eV plus small, ‘hot’ components with energies of the order of 1 keV. In both these papers the effect of variation of the electron temperature along the magnetospheric magnetic field line was neglected, as was done by McChesney and Hughes<sup>34</sup>. More accurate analysis by Sazhin *et al.*<sup>42</sup>, based on the DE-1, 2, 3, 4 models described earlier, led to a result rather close to that of Guthart<sup>40</sup>, namely the magnetospheric electron temperature was estimated to be

below 4 eV and depends on the choice of the electron distribution model.

Sazhin *et al.*<sup>43</sup> discussed different approaches to this type of diagnostic technique and have concluded that the most effective way to estimate the electron temperature with the help of ground-observed whistlers would be to use nose whistlers with the well-defined upper branch and compare whistler group delay times at the nose and at the upper cut-off frequency. Recently, Sazhin *et al.*<sup>44</sup> have extended this approach of analysis to a larger number of whistlers in order to get statistically more significant results. They have shown that the estimated magnetospheric electron temperature strongly depends on the choice of the model of electron distribution along the magnetospheric magnetic field line.

The whistler data recorded at Jammu, Nainital and Varanasi at different times and for different magnetic activities have been analysed to estimate the magnetospheric electron temperature in the vicinity of magnetospheric equator at low latitudes. We have applied the curve-fitting technique of Tarcsai<sup>19</sup> for our non-nose whistlers at these stations to derive the magnetospheric electron temperatures. The estimated temperature of magnetospheric electrons inferred from the whistler data shown in Table 1 is about 0.8 eV for the value of  $n = 2$  and is about 0.25 eV for the value of  $n = 1$ . Our mean value of  $T_{eq}$  obtained using the diffusive equilibrium model estimated by the method of curve-fitting technique of Tarcsai<sup>19</sup> is  $\sim 0.5$  eV, slightly smaller than other estimates of electron temperature in the equatorial plasma-

sphere<sup>40,42,43</sup>. Magnetospheric temperatures are quite variable, inferred temperatures are between  $5 \times 10^3$  K and  $3 \times 10^4$  K; similar electron temperatures were deduced in a more detailed study by Decreau *et al.*<sup>45</sup> and it would be unwise to attempt to generalize our results.

We have also estimated the above electric field on the basis of dipole geomagnetic field. However, both ground-based and satellite borne magnetometer data show that fast changes in the magnetic field takes place during substorm commencement and substorm expansion and recovery phase. Wang and Kim have discussed the decaying ring current and the electric field that may be associated with that decay. Thus, the departure from the dipole field model gives an induced electric field due to temporal changes in the geomagnetic field.

In the present study the magnetospheric electric field in the plasmasphere at different  $L$ -values is found to be eastward in the pre-midnight sector and westward in the post-midnight sector, in agreement with the published results<sup>12,13,46</sup>. The magnitude of the eastward electric field is about 0.35 mV/m in the equatorial plane of Jammu. The westward electric field is about 0.72 mV/m for Nainital and 0.12 mV/m for Varanasi.

In the electron density, electron temperature and electric field determination, it is assumed that the whistlers have propagated along the geomagnetic field lines. The ducted mode of propagation for low-latitude night-time whistlers has been favoured by many Indian and Japanese workers on the basis of ground observations, and they have studied the duct characteristics and calculated the electric fields in the plasmasphere<sup>16,17</sup>. The nose frequency derived from the whistler spectrograms specifies the path of whistler propagation in terms of  $L$ -value. Thus, measuring the nose frequency  $f_n$  for successively recorded whistlers, the variation of  $L$  with time in the equatorial plane is determined. Using the 'frozen in field' concept, the plasma drift velocity derived from whistler data is related with the magnetospheric plasma drift caused by a large-scale east-west electric field  $E$ . Further, the derivation of magnetospheric electric field from the data assumes that all whistlers of a recording station propagate along the same duct whose position moves under the action of electric field. Here eastward and westward directions represent those of the field because the direction of charged particles changes after mid-night.

Thus the present results of electric field agree with those of ionosonde observations of the night-time  $F$ -layer during substorm, and are in good agreement with the results reported by Park<sup>46</sup>. In the ionosonde studies, it was found that during winter, the  $F$ -layer settles down to a quasi steady-state. Its response to the magnetospheric substorm activity consists of a large-scale distortion with  $F$ -layer lifted upward in the pre-midnight sector and pushed downward in the post-midnight sector. This distortion was interpreted as the result of  $E \times B$  drift by an eastward electric field before midnight and by a westward

field after midnight. This reversal in the electric field direction is confirmed by the low-latitude whistler results reported here. The reversal of the electric field direction near midnight as shown in Figure 4 *a-c* with the westward component during post-midnight hours and an eastward component during pre-midnight hours was also observed by the barium cloud technique and by electrostatic probes on balloons.

The non-nose whistlers recorded at Jammu, Nainital and Varanasi have been analysed to estimate the equatorial electron density, electron temperature and electric field in the equatorial magnetosphere. The estimated temperature and electric field are slightly lower than those reported by other workers. This preliminary test of our method of temperature diagnostic is rather encouraging. However, before this method can be recommended for practical applications, we need to specify more accurately the model of electron density, temperature distribution and electric field in the magnetosphere, have a better estimate for the effect ducted ray paths and increase the precision of determining whistler parameters.

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## Liquid-level sensing based on periodic evanescent field absorption from a multimode optical fibre

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**The working of a robust, long dynamic range, quasi-continuous fibre-optic liquid-level sensor is demonstrated in this communication. The sensor principle is based on periodic evanescent light wave absorption when rising level of liquid gradually replaces the surrounding air medium from a periodically uncladded step-index multimode optical fibre which would cause local variation in normalized frequency parameter ( $V$ ) of the fibre. With our proposed sensor design, liquid-level variation as small as 2.5 cm can be measured with high accuracy and repeatability, which can be further enhanced by reducing the spacing between two adjacent regions of the fibre. Owing to its simplicity and robustness in operation, we envision that the proposed sensing technique could emerge as an alternative to the existing optical-based liquid-level sensors.**

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