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One-to-one relationship between low latitude whistlers and conjugate source lightning discharges and their propagation characteristics

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Abstract

One-to-one relation with its causative lightning discharges and propagation features of night-time whistlers recorded at low-latitude station, Allahabad (geomag. lat. 16.05°N, $L = 1.08$), India, from continuous observations made during 1–7 April, 2011 have been studied. The whistler observations were made using the Automatic Whistler Detector (AWD) system and AWESOME VLF receiver. The causative lightning strikes of whistlers were checked in data provided by World-Wide Lightning Location Network (WWLLN). A total of 32 whistlers were observed out of which 23 were correlated with their causative lightnings in and around the conjugate location (geom. lat. 9.87°S) of Allahabad. A multi-flash whistler is also observed on 1 April with dispersions 15.3, 17.5 and 13.6 $s^{1/2}$. About 70% (23 out of 32) whistlers were correlated with the WWLLN detected causative lightnings in the conjugate region which supports the ducted mode of propagation at low latitude. The multi-flash and short whistlers also propagated most likely in the ducted mode to this station.

Keywords: Lightning discharge; Low latitude whistlers; Radio atmospherics; Tweeks

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1. Introduction

Return strokes of lightning discharges are most powerful natural transmitters of electromagnetic waves in a wide frequency range with peak spectral power density in the range 5–10 kHz (Prasad and Singh, 1982). Major part of the extremely low-frequency (ELF: 30–3000 Hz) and the very low-frequency (VLF: 3–30 kHz) waves propagate in the Earth-Ionosphere Waveguide (EIWG) as impulsive signals (sferics or tweeks). A small part of the ELF-VLF radiation can penetrate into the dispersive regions of the ionosphere and the magnetosphere and is received as tones of descending and ascending frequencies called whistlers (Helliwell, 1965). Earlier, whistlers were believed to be high and mid latitude phenomena. However, wide variety of whistlers have been recorded at low latitude stations mainly in India, China and Japan during the last five decades (e.g., Singh et al., 1972, 1998, 2004, 2012; Hayakawa and Ohtsu, 1973; Hayakawa et al., 1985, 1990, 1995; Ondoh et al., 1979; Singh and Hayakawa, 2001; Kumar et al., 2007).

Unlike high and mid-latitude whistlers, propagation features of low-latitude whistlers are not properly understood. Hayakawa and Tanaka (1978) have made a comprehensive review of the propagation of low-latitude whistlers, and concluded that the whistlers observed at geomagnetic latitudes less than 20° propagate in non-ducted mode of propagation and are poorly understood. Ondoh et al. (1979) found remarkable difference between low and mid-latitude whistlers and suggested possibility of ducted propagation for low latitude whistlers also, but later works such as by Andrew (1979), Liang et al. (1985), and Thomson (1987) suggested non-ducted propagation for low latitude whistlers. The simultaneous determination of the ionospheric exit region of whistlers and of their causative atmospherics was suggested to be important to study the propagation of whistlers along path from the source to the receiver (Hayakawa and Tanaka, 1978). However, significant work on the simultaneous location of ionospheric exit regions of whistlers and their causative atmospherics has so far been lacking (Shimakura et al., 1991), which would be of great importance to examine the propagation mechanism of low latitude whistlers.

In a recent study on whistlers and its causative lightnings using the Global Lightning Dataset 360 (GLD360) network data, Singh et al. (2012) found that simultaneous whistlers recorded at two low latitude stations Allahabad (L = 1.08) and Nainital (L = 1.13) were found to be associated with lightnings having peak currents larger than 30 kA and located at and around the conjugate locations of recording stations. In this paper we present night-time observations of whistlers and their dispersion characteristics at Allahabad, a low-latitude station (geomag. Lat.16.05°N, L = 1.08) in India. This is a case study based on the observations of whistlers during 1–7 April 2011 following the work done by Singh et al. (2012).We have critically analysed the origin of these whistlers using the World Wide Lightning Location Network (WWLLN) data and present arguments on the propagation mechanism of these whistlers. We have also determined the distance of lightnings from the station using the WWLLN locations and the tweek dispersion method using the causative tweeks of whistlers to further confirm the true locations of causative lightnings of whistlers. Due to increasing importance and veracity of the whistler technique, it has become essential to understand whistler propagation at the low latitudes.

2. Summary of the formulae used

2.1. Determination of distance travelled by causative tweeks of whistlers

The distance travelled by causative tweeks of whistlers has been determined by two different methods:

2.1.1. Tweek dispersion method

For distance (>2000 km), the spherical model of the EIWG is considered where curvature of the Earth is taken into consideration for calculating group velocity (V_{gn}) and propagation distance (d') of tweeks. The V_{gn} in the homogeneous spherical EIWG is given (Ohya et al., 2008) as

$$V_{gn} = \frac{c\left[\left(1-\left(f_{cn}/f\right)^2\right)\right]^{1/2}}{\left(1-\left(nc/2R\, f_{cn}\right)\right)} \tag{1}$$

where c is the velocity of light in free space, R is the radius of the Earth and f_{cn} is the cut-off frequency of nth mode.

From difference in propagation times, $\delta\ t = t_1 - t_2$ of two frequencies f_1 and f_2 close to f_{cn} from tweek spectrograms and V_{gn}, the distance, d' (in km) by tweek in spherical waveguide were calculated using

$$d\prime = \delta t\left(\frac{V_{gf1} \times V_{gf2}}{V_{gf1} - V_{gf2}}\right) \tag{2}$$

where V_{gf1} and V_{gf2} are the group velocities of waves centred at frequencies f_1 and f_2, respectively (Prasad, 1981).

2.1.2. WWLLN lightning locations method

We calculated the distance d (in km) from the locations for which the WWLLN was able to detect the lightnings closely matched with the whistler causative sferic time using,

$$d = 1.60934 \times \sqrt{x^2 + y^2} \tag{3}$$

where $x = 69.1 \times (\text{lat2} - \text{lat1})$ and $y = 69.1 \times (\text{lon2} - \text{lon1}) \times \cos\ (\text{lat1}/57.3)$. The lat1, lon1 are the geographic coordinates of Allahabad and lat2, lon2 are the coordinates of respective WWLLN detected lightning locations. The details about this formula can be found on http://www.drivehq.com/file/df.aspx?isGallery=true&shareID=10033140&fileID=1066758862.

2.2. Determination of L-shell parameter values

To find the L-shell values, we used following two methods;

(a) We have used linear Q-technique suggested by Dowden and Allcock (1971) for the determination of nose frequency f_n which is determined from measurements of group delay at frequencies along the observed whistler trace. The plot of the reciprocal of the dispersion is

$$Q(f) = \left(tf^{1/2}\right)^{-1} \tag{4}$$

where t is the group propagation time per hop at frequency f. A plot between $Q(f)$ and f produces a straight line which intercepts the $Q = 0$ axis at f_0. The nose frequency f_n can be determined by using,

$$F_x = \frac{f_0}{3.06} \tag{5}$$

The L shell values can be calculated by using

$$L = \frac{9.56}{\left(\frac{f_n}{400}\right)^{1/3}} \tag{6}$$

as described by Park (1972).

(b) The second method follows the determination of L-values (L') using the formula given by Campbell (2003, p. 15)

$$L' = \frac{1}{cos^2\phi} \tag{7}$$

where ϕ is the geomagnetic latitude calculated from the WWLLN detected geographic locations of lightnings that have produced whistlers at the Allahabad Station.

3. Experimental set-up and data

The recording system consists of a Stanford University built AWESOME VLF receiver (Cohen et al., 2010) with two orthogonal crossed loop antennas with base of 10 × 10 m with five turns, to receive East–West and North–South horizontal magnetic field components. A dual pre-amplifier is kept near the antennas for impedance matching to ensure maximum power transfer and pre-amplification of received signal. It is connected with line receiver by a long cable of about 300 m. The line receiver performs anti-aliasing filtering, GPS time synchronization and post processing of the data. The acquired data are sampled by 16-bit analogue-to-digital converter at 100 kHz sampling frequency. The frequency response of the receiver is flat in the frequency range of 300 Hz to 47.5 kHz. Detailed information about the experimental setup in India can be found in Singh et al. (2010). The broadband VLF data was recorded in continuous mode during the period of observation. Automatic Whistler Detector (AWD) was used along with AWESOME VLF receiver to detect the whistlers from AWESOME broadband data. The AWD system has false-positive and false-negative rates of 20% to 50% and 10% respectively meaning that it is unlikely to miss a whistler if there is indeed one present in the data, but more often mistakenly indicates a whistler when there is not actually one present in the data. The detailed information about AWD system can be found in Lichtenberger et al. (2008). To find the causative lightning strikes corresponding to whistlers, lightning data from WWLLN has been used. The World-Wide Lightning Location Network (WWLLN) currently detects the lightnings with peak currents larger than 50 kA within the spatial and temporal accuracy of 10 km and 10 μs and has the global detection efficiency of about 10% (Rodger et al., 2009).

4. Observations and discussion

In the present report of whistlers from Allahabad (L = 1.08) we received a total of 32 whistlers during the nights of 1–7April 2011: on the nights of 1 April (6 whistlers), 4 April (6 whistlers), 5 April (1 whistler), 6 April (13 whistlers), 7 April (6 whistlers). No whistler activity was found in the daytime. This may be attributed to the heavy absorption of ELF-VLF waves by the daytime D-region. The conjugate point of Allahabad (Geog. lat. 9.87°S; Geog. long. 83.59°E) lies over the ocean and hence thunderstorm activity is relatively low as compared to that over the land (Christian et al., 2003). This may be one of the reasons for overall low whistler activity at Allahabad. The period of observations is geomagnetically quiet except a moderate storm on 6 April with $K_p = 6$.

Whistler activity is generally believed to depend mainly on lightning activity in the conjugate region in the opposite hemisphere. In order to understand the correlation of whistler occurrence with the lightning activity around the conjugate point, we took a period of one month, April 2011. There are four pairings between whistler occurrence and lightning activity as whistler-lightning: Yes–Yes; Yes–No; No–Yes and No–No. For Yes–Yes case, in total we found five whistler activity days with an average of ~59 lightnings per day with a radial extent of ~700 km around the conjugate region of Allahabad. The correlation coefficient for this case is found to be 0.88 which is good enough to show positive correlation between whistler activity and its source lightning activity. There are total of 21 days where lightning is seen at or around conjugate region but no whistler is detected (No–Yes case). There are ~16 lightnings per day for this case. Such a low lightning activity may be the possible reason for no whistler activity. As well the characteristics of lightning like peak current, orientation and the ionospheric conditions may have played important role for giving no whistler activity on these days. This will be the part of our future analysis. There are total of 4 days where no lightning and no whistlers are observed. (No–No case), which also gives 100% correlation between whistler activity and its source lightning activity. Not a single case is found where whistler is found without any lightning in the conjugate region (Yes–No case) which also strengthens the whistler-lightning correlation.

Previous work by Ohta and Hayakawa (1990) did not find any correlation between the two when they compared whistler activity at Yamaoka ground station (geomag. lat. 25°N) with thunderstorm activity in the conjugate region. Also Kumar et al. (2007) using a small set of whistler data reported similar results for whistlers observed at low latitude station Suva, Fiji (geomag. lat. 22.1°S). Collier et al. (2009) carried out correlation between global lightning and whistlers observed at Tihany, Hungary and found relatively low correlation coefficient of about 0.065 in the ~1000 km of area around conjugate point. They also found a positive correlation area extending to South America and Maritime Continent. In their study, they observed a negative correlation of lightning activity observed in northern hemisphere with the whistlers recorded at Tihany. These studies suggested that whistler occurrence at any station is controlled more by the propagation effects in the ionosphere and magnetosphere than by the lightning activity in the conjugate region. Singh et al. (2012) observed a large number of 864 whistlers at Allahabad, on the night of 26 January 2011 and using lightning data from GLD360 geo-location network, they showed that 311 (36%) of whistlers were associated with coincident lightnings within 200 and 450 km from the conjugate point of Allahabad. In our case, more than 70% of causative sferics of whistlers were observed to match closely with the times of WWLLN detected lightnings within the propagation times of causative tweeks.

The dynamic spectra of some of the whistlers recorded on 1 April 2011, 4 April 2011, 5 April 2011, 6 April 2011 and 7 April 2011 are shown in Fig. 1(a–e). The L-values, dispersions and distance travelled by whistlers are given in Tables 1. and 2. Using the method described in Section 2 the L-values are found in the range of 1.25–4.66. Most of the whistlers are found to be associated with sferics/tweeks. For identifying the causative sferics, selection of different f–t pairs from spectrogram were done and then plotted as time t versus $f^{-1/2}$. The plot is extrapolated to meet time axis, and the point on the time axis where it intersects is denoted by t_H. Hence, t_H is the time of causative sferic calculated by the Helliwell method. (Helliwell, 1965). After determining t_H, we looked for a sferic in the whistler spectrogram whose time is close to t_H. This sferic arrival time obtained from whistler spectrogram is denoted by t_0. As an example, the determination of causative sferic by above method for the whistler shown in Fig. 1(c) is given in Fig. 2. The equation of the straight line is $y = 16.504x + 0.14431$, where slope, 16.504 is the dispersion (D) for the whistler and the intercept 0.14431 on time axis gives t_H. Corresponding to t_H, the sferic arrival time t_0 from the spectrogram is 0.14461 s. Hence, the dispersed sferic at time $t_0 = 0.14461$ s has initiated the whistler given in Fig. 1(c). The intercept on the time axis at 0.14431 s, shown in Fig. 2, suggests that the time of causative sferic (t_H) was about 0.3 ms earlier than the sferic arrival time traced in spectrogram (t_0) and the average difference for all the observed whistlers was within 8 ± 6 ms. The distance travelled by causative sferics of the whistlers in the EIWG, calculated using the method used by Kumar et al. (1994) is found to be in the range of 3990–6090 km as listed in Table 2.

From the empirical relationship $D = 1.22(\phi - 0.72)$ obtained by Hayakawa and Tanaka (1978) where ϕ is the geomagnetic latitude in degree, the maximum D of the

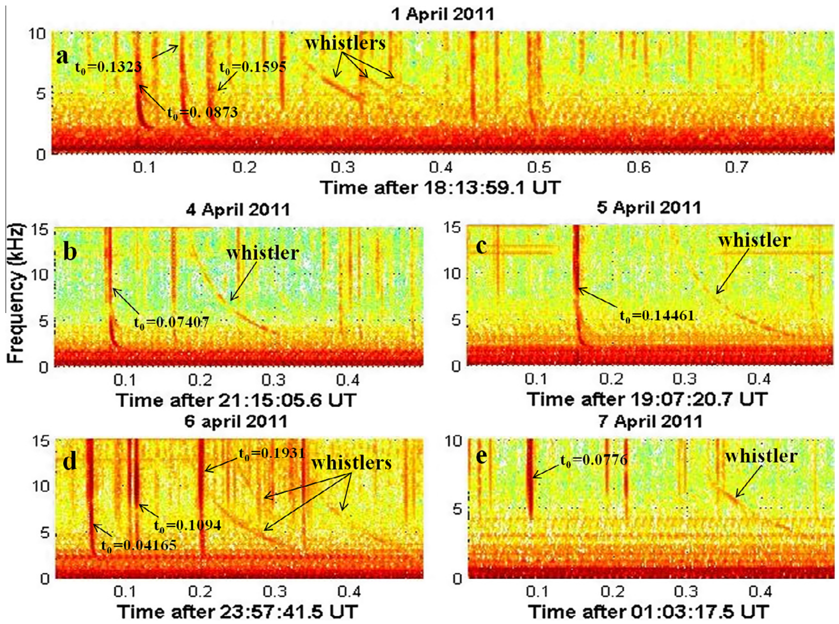

Fig. 1. Dynamic spectra of the whistlers observed on (a) 1 April 2011 (triplet), (b) 4 April 2011, (c) 5 April 2011, (d) 6 April 2011, (e) short whistler observed on 7 April 2011.

Table 1
Number of whistlers and their dispersion ranges, L-value ranges calculated from Q-technique (L) and from Eq. (7) (L′).

Date	No. of whistlers	Dispersion ($s^{1/2}$)	L	L′
01/04/2011	6	13.63–17.51	1.27–3.46	1.121–1.122
04/04/2011	6	12.11–14.61	2.55–3.26	1.099–1.181
05/04/2011	1	17.21	2.80	1.133
06/04/2011	13	13.65–16.59	1.25–4.66	1.108–1.133
07/04/2011	6	14.13–21.63	1.91–3.50	1.106–1.117

whistlers observed at Allahabad should be 18.70 $s^{1/2}$. We have found D in the range of 12.10 to 21.63 $s^{1/2}$ for the period of observations in this work. It follows that the whistlers observed from 1–7 April, listed in Table 2 are low-latitude whistlers. From the detailed spectral analysis, it is found that the whistlers listed in Table 2 obey Eckersley law given by $D = (t - t_0) \times \sqrt{f}$, which states that the dispersion of the whistler is product of travel time and square root of the frequency component (Eckersley, 1928).

The whistler triplet shown in Fig. 1a was recorded on the night of 1 April 2011, whose causative sferics are at 18:13:59.1873UT, 18:13:59.2323UT and 18:13:59.2595UT. Local time (LT) = UT + 5.5 h. The WWLLN detected only one lightning strike at 18:13:59.222370 UT closely matching with the second causative sferic within a time difference of 1 ms and was located at 9.77°S, 91.53°E which is displaced by ~134 km from the conjugate point of Allahabad. The time delay between the 1st and 2nd causative sferics is estimated as 45 ms and that between 2nd and 3rd as 27.2 ms. The time delays between the corresponding whistlers are found 39 ms and 27 ms but with decreasing intensity suggesting that these whistlers generated from subsequent flashes of same lightning strike or two closely occurring lightnings. Kumar et al. (2007) found the time delay of 32 ms for two component whistlers observed at Suva. They found a time delay of 16.4 ms for the corresponding whistlers and concluded that those whistlers were associated with two closely separated lightning strikes and also propagated in two close paths.

Table 2
Whistlers with their causative sferic times (t_0), WWLLN time with locations and distances calculated from location (d) and tweek dispersion method (d'). ND indicating the lightning that has not been detected by WWLLN and NA to indicate Not Applicable.

Date	t_0	WWLLN detected lightning time	Lightning detected by WWLLN & it's location	d (km)	d' (km)
01/4/2011	18:13:59.1873	ND	No	NA	NA
	18:13:59.2323	18:13:59.222370	−9.77, 91.53	4057	3029
	18:13:59.2595	ND	No	NA	NA
	18:14:55.07375	18:14:55.067590	−9.84, 91.81	4069	3581
	18:15:49.51055	18:15:49.506259	−9.74, 91.54	4050	3685
	18:15:49.612	18:15:49.606575	−9.81,91.55	4049	3550
04/4/2011	21:12:01.8129	21:12:01.811559	−13.64, 91.24	4459	3229
	21:15:05.67407	21:15:05.664231	−12.82, 85.60	4272	3763
	21:15:05.75834	21:15:05.748137	−12.82, 85.62	4272	4026
	21:25:15.97142	ND	No	NA	3952
	21:46:47.19553	21:46:47.190547	−8.06, 91.21	3856	2883
	21:51:26.25171	21:51:26.246801	−8.06, 91.28	3858	4270
05/4/2011	19:07:20.84461	19:07:20.839174	−10.90, 86.31	4068	3427
06/04/2011	22:59:04.97644	22:59:04.971270	−9.56, 79.36	3902	3347
	23:02:50.70517	ND	No	NA	NA
	23:13:46.40721	23:13:46.399396	−9.52, 84.37	3896	4540
	23:18:49.48848	23:18:49.482676	−9.50, 84.37	3893	3197
	23:19:16.22362	23:19:16.218923	−10.71, 76.97	4057	3062
	23:19:42.11327	23:19:42.106821	−10.59, 78.57	4023	2583
	23:22:12.9196	23:22:12.914637	−9.58, 79.26	3905	4110
	23:23:50.2166	23:23:50.210953	−9.55, 79.14	3903	3307
	23:24:36.39618	23:24:36.379393	No	NA	4250
	23:52:39.51757	2352:39.510329	−10.60, 77.95	4032	4650
	23:57:41.54165	23:57:41.539256	−9.47, 79.32	3892	3229
	23:57:41.6094	ND	No	NA	NA
	23:57:41.6931	23:57:41.686352	−9.49, 79.27	3895	4647
07/04/2011	20:57:46.68511	ND	No	NA	NA
	01:00:42.43731	ND	No	NA	NA
	01:00:05.43631	ND	No	NA	NA
	01:02:07.63394	01:02:07.629060	−9.99, 78.64	3956	NA
	01:02:33.6399	01:02:33.638180	−9.41, 79.27	3887	NA
	01:03:17.5776	01:03:17.574607	−10.34, 78.52	3997	NA

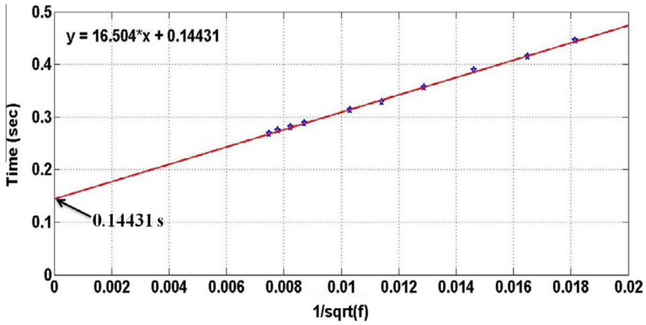

Fig. 2. Plot of time t versus $f^{-1/2}$ for whistler observed on 5 April 2011 at 19:07:20.84431 UT. The intercept of extrapolation of $f^{-1/2}$ points on time axis gives the time of causative lightning of whistler and the slope of the line gives the dispersion.

Fig. 1(b)–(d) show whistlers observed on the nights of 4, 5 and 6 April 2011, respectively. Five whistlers were recorded on 4 April. The whistler shown in Fig. 1b was received after 21:15:05 UT. The causative sferic corresponding to this whistler arrived at 21:15:05.67407 UT. The WWLLN detected a closely matched lightning at 21:15:05.664231 UT at the location, 12.8°S; 85.6°E. On the night of 5 April, only one whistler was received. We checked the WWLLN data and found a lightning at 19:07:20.839174UT, for the sferic that arrived at 19:07:20.844610 UT (as shown in Fig. 1(c)), in the vicinity of conjugate point at 10.9°S; 86.3°E as listed in Table 2. On the night of 6 April 2011, highest whistler activity with 13 whistlers was observed after 22:29:00 UT. One of the possible reasons for high activity can be the moderate storm with maximum $Dst = -61$nT at 20:00 UT and $K_p = 6$ at 23 UT. The whistler activity on 6 and 7 April was observed during the recovery phase of the geomagnetic storm. Fig. 1d shows the dynamic spectra of three such whistlers whose causative sferics arrived at 23:57:41.54165 UT, 23:57:41.6094 UT and 23:57:41.6931 UT, respectively. The WWLLN detected the lightning discharges close to 1st and 3rd sferics at 23:57:41.539256 UT and 23:57:41.686352 UT just 28 km away from the conjugate point. The dispersion of all the whistlers on this particular day varied from 13.6 to 16.6 $s^{1/2}$, which indicates that these whistlers propagated in the low latitude region.

The short whistlers were observed on the nights of 1, 6 and 7 April 2011. Here, by short whistlers we mean the whistlers that are received with fewer frequency components unlike the whistlers whose traces cover the range up to ~20 kHz. Previous observations of short whistlers at low latitudes showed the frequency components ranging in 1.7–3.0 kHz and 3.0–4.5 kHz (Singh et al., 2004) and 4.4–5.2 kHz (Kumar et al. 2007). Kumar et al. (2007) found no causative sferics of a short whistler in the spectrogram and concluded that short whistler received at their station might have originated at mid latitude which initially propagated in ducted mode in the magnetosphere. Some of its frequency components leaked from the duct and penetrated the ionosphere and were trapped in the EIWG, which were received as short whistler at Suva, Fiji, a low latitude station in the South Pacific region. One of such example of short whistler received at our station is shown in Fig. 1e. It was observed after 01:03:17 UT on the night of 7 April 2011. The frequency components for this particular whistler are in the range of 3.5–6.2 kHz with the $D = 20.91$ $s^{1/2}$. The WWLLN was able to detect a lightning strike at 01:03:17.574607 UT for which the spectrogram showed a sferic at 01:03:17.5776 UT located at 10.3°S;78.5°E. Total of 8 such short whistlers were found whose frequency components were in the range of 3.0–6.5 kHz with D varying 12.11–20.91 $s^{1/2}$. Out of 8 whistlers, WWLLN was able to locate 6 lightning strikes corresponding to the causative sferics in the vicinity of the conjugate point. As no difference is found in the dispersion ranges as well as their sources of origin of long and short whistlers, we expect the ionospheric variation may be one of the reasons for attenuation of some of the frequency components.

One of the advantage of low latitude whistlers while establishing one to one correlation between whistler and lightning activity is that the propagation delay for the causative sferics is much less as compared to mid and high latitudes. Hence, uncertainty in identifying the occurrence time of causative sferics is very less. For sferics associated with lightning strikes in the conjugate region, it takes nearly ~13 ms to cover distance of ~3900 km in propagation to Allahabad station and the WWLLN lightning strikes listed in Table 2 occurred with a maximum of 17 ms prior to the causative lightning identified by time t_0, indicating time t_0 as the accurate time for causative sferic traced in spectrogram which produced whistlers.

Unlike middle and high latitude whistlers, the propagation mechanism of low-latitude whistlers has been a subject of controversy over the years. While many workers have favoured ducted propagation for low latitude whistlers on the basis of ground data and direction finding measurements (Somayajulu and Tantry, 1968; Hayakawa and Ohtsu, 1973; Hayakawa et al., 1985; Ohta et al., 1989), others have not found any convincing evidence in its support on the basis of ray tracing analysis and satellite measurements (James, 1972; Cerisier, 1973; Singh and Tantry, 1973; Hayakawa and Iwai, 1975; Tanaka and Cairo, 1980). Hayakawa and Tanaka (1978) have classified whistlers into two categories, ducted whistlers which are observed between 20° and 30° geomagnetic latitude and Pro-longitudinal (PL) whistlers which are observed below 20° geomagnetic latitude. The geomagnetic latitude of Allahabad (16.05°N) implies non-ducted propagation of whistlers. We analysed whistler occurrence and WWLLN data for lightning occurrence in the conjugate area and found one to one correlation between the whistlers and their causative lightnings in the conjugate region for more than 70% of total 32 whistlers and hence suggesting PL or ducted mode propagation.

The lightning locations detected by WWLLN around the conjugate point of Allahabad during all the five whistler nights are plotted in the Fig. 3. Fig. 4 shows the zoom

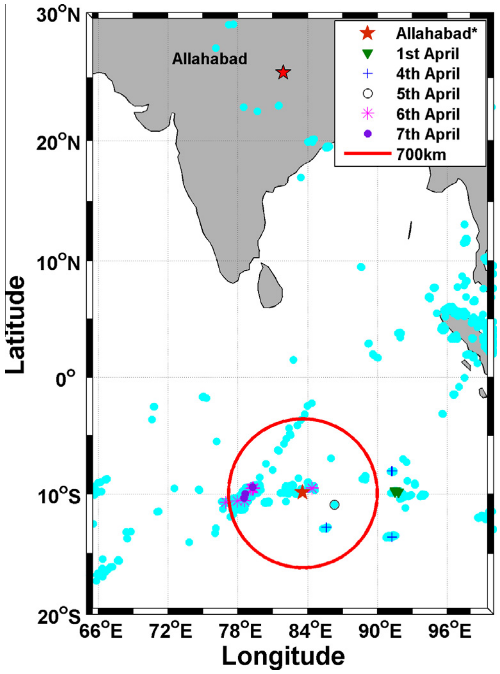

Fig. 3. WWLLN detected lightning locations at conjugate region (circle of 700 km radius) of Allahabad for whistlers observed during 1–7 April 2012.

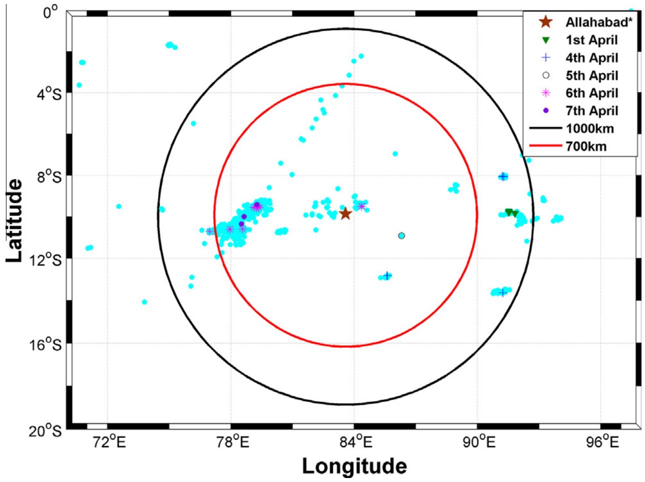

Fig. 4. Zoom in plot of WWLLN lightning detection shown in Fig. 3 within circles of 700 and 1000 km around the conjugate point.

in view of the WWLLN detected lightnings in the conjugate location of Allahabad which occurred close to the causative sferics. All of the lightnings originated from the region within 700 km radius circle from the conjugate point, with some exceptions within 1000 km. The distances travelled by the causative sferics were calculated using two different methods: (a) Tweek dispersion method (d') and (b) WWLLN detected lightning locations with respect to Allahabad (d) determined using Eq. (3). The distances travelled by the causative sferics using tweek dispersion method were calculated using Eq. (2) and are given in Table 2. The estimated distance using WWLLN locations and tweek dispersion are in good agreement within 500 km with few exceptions. To find the L-shell parameter values (L) from the whistler traces we followed the Q-technique for the determination of nose frequency (f_n) and used the Eq. (6). The L-values were found in the range 1.25–4.66. But for the whistlers whose locations of causative lightning were detected by WWLLN, we determined the L-values (L') using Eq. (7), and found in the range 1.099 to 1.181 with an average of ~1.12.The discrepancy in L-values using two methods urges a detailed study of this using more appropriate method with more events to compare, that will be taken in our future study.

5. Conclusion

From the data analysis for the period of 1–7 April 2011, we found 23 out of 32 (about 72%) observed whistlers were associated with lightning discharges detected by WWLLN and hence the locations of the causative lightning discharges were identified. The locations were found to lie near the conjugate point of Allahabad in the Indian Ocean within the circle of ~700 km radius with few exceptions. The proximity of causative lightning discharges found near to the conjugate region may lead towards the consideration of ducted mode of propagation of whistlers in low latitude region and hence the possibility of low latitude whistlers to be used as a diagnostic tool to determine the ionospheric and plasmaspheric parameters along the propagation path in low latitude region.

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