Very low latitude whistlers ($L = 1.08$): arrival azimuth determination

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Since last four decades and more generation and propagation mechanism of very low latitude ($L < 1.4$) whistlers has been studied by many workers in low-latitude regions and especially in India. The key questions that remain unanswered include: (1) Where are the lightning discharges, the source of whistlers located? (2) Do the whistler waves at low latitudes propagate along the magnetic field lines in low latitude ionosphere? We reported that the lightning discharges that have generated whistlers are located in the conjugate region in the Indian Ocean and suggested the whistlers at these stations propagate along the magnetic field lines in the low latitude ionosphere. In this communication, we present the arrival azimuth determination technique adopted to confirm the location of the lightning discharges which generated the observed whistlers and the technique is validated with real-time lightning data. The technique adopted to determine the arrival azimuths of low latitude whistler causative lightning discharges is of significance and will help in resolving the unanswered questions of low latitude whistler phenomena.

Keywords: Arrival azimuth, ionosphere, lightning, low latitude, whistlers.

WHISTLERS are very low frequency (VLF: 3–30 kHz) waves of the electromagnetic spectrum that are generated from lightning flashes. The whistler waves travel along the magnetic field lines and can be received in the opposite hemisphere as a descending tone due to the properties of the dispersive medium[1]. The whistler waves essentially carry information about the medium through which they propagate[2]. This unique property of whistlers has been utilized by many workers to probe the magnetosphere or plasmasphere[3–7]. The propagation of these waves is well understood at mid ($1.4 > L < 2.4$) and high ($L > 2.4$) latitudes, but propagation at low latitudes ($L < 1.4$) is still not well studied. There has been perplexity between ducted[8–14] and non-ducted propagation[15,16] of whistlers in low latitude. The pro-longitudinal mode of propagation has also been proposed for low latitude whistler propagation[6,17]. To resolve this ambiguity, Singh *et al.*[18] suggested identifying the source region of causative lightning flashes of low latitude whistlers. They have by far reported the highest whistler activity during a single night observed on a geomagnetically quiet day of 26 January 2011 at Indian low latitude station, Allahabad ($L = 1.08$). The simultaneous whistler recording from Nainital ($L = 1.16$) was also analysed. Utilizing GLD360 lightning data, Singh *et al.*[18] found the source region of causative lightning discharges of the whistler to lie at a distance of ~200–450 km around the conjugate point in the Indian Ocean. By studying the one-to-one relation between whistlers observed at Allahabad during April 2011, Srivastava *et al.*[19] confirmed the source region to be located around the conjugate point of Allahabad with a radius of ~700 km. Gokani *et al.*[20] conducted a study of correlation of whistlers observed at Allahabad for a period of one year and lightning activity in the conjugate region. They found that majority of the lightning discharges which produced whistlers are generated in the region 200–800 km from the conjugate point.

Since it is also reported that source lightning discharges of whistlers are located away from the conjugate point[21], and that it is possible to have many lightning discharges at the same time in different areas all over the globe, the direction finding of the source lightning discharges becomes important to confirm the source. Here we present a technique to determine the arrival azimuths of low latitude whistler causative sferics or

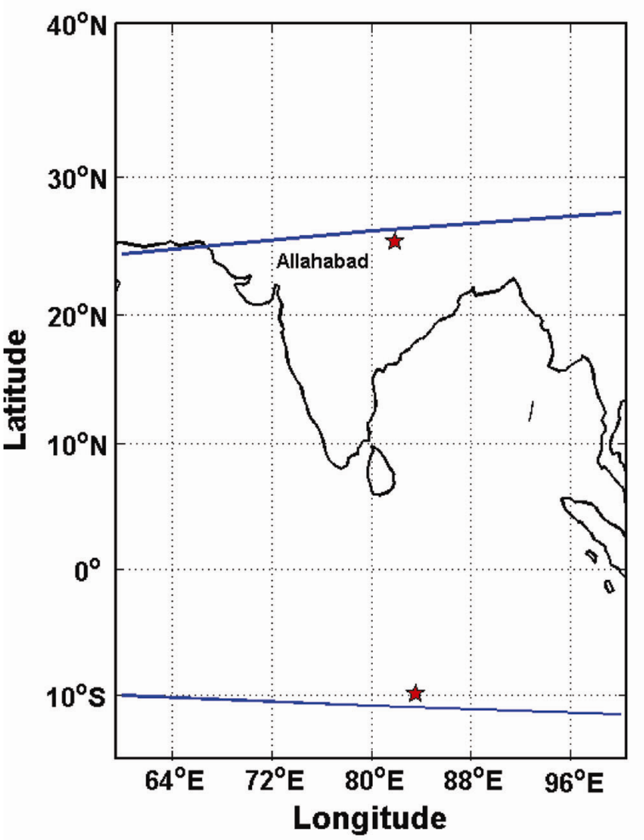

Figure 1. Map showing VLF station, Allahabad and its conjugate point along with L-value.

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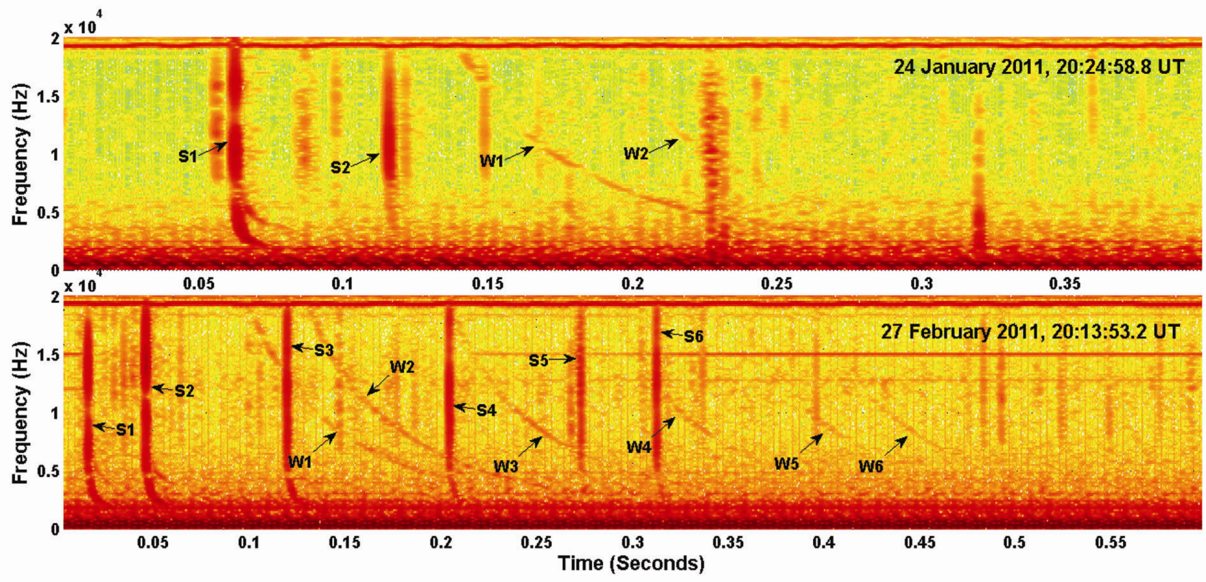

Figure 2. Example of whistlers recorded on the nights of 24 January 2011 at 20:24:58.8 UT and 27 February 2011 at 20:13:53.2 UT.

lightning discharges. The arrival azimuth technique is demonstrated with whistler observations made at Allahabad (25.40°N; 81.93°E; $L = 1.08$) station on two nights: 24 January 2011 and 27 February 2011. The results obtained are validated with World Wide Lightning Location Network (WWLLN) real-time lightning data[22]. Figure 1 shows the location of Allahabad and its conjugate point (9.87°S; 83.59°E) with L-shell values.

A total of 129 and 356 whistlers were observed on the night of 24 January 2011 and 27 February 2011 respectively. Figure 2 shows example of whistler traces for the two event days. The whistlers are indicated by W1, W2, W3, etc. and the causative sferics are indicated by S1, S2, S3, etc. according to the method suggested by Srivastava *et al.*[19]. The whistlers were recorded at Allahabad using AWESOME VLF receiver. Details about the experimental set-up can be found in Singh *et al.*[23]. An automatic whistler detector (AWD) was used to identify whistlers from a continuous stream of broadband data[24]. WWLLN data were used to validate results of the arrival azimuth technique.

The arrival azimuth methodology adopted is twofold: (1) arrival azimuth determination of the causative sferics of whistlers and (2) arrival time determination of the causative sferics of whistlers. The techniques described by Wood[25] and Said[26] have been implemented to find the arrival azimuth of source lightning discharges of the observed whistlers. This technique utilizes the direction finding of the detected sferic in the Fourier domain. The method assumes transverse magnetic (TM) waveguide mode for the sferics and the arrival azimuths can be accurately determined by measuring horizontal magnetic field component of the incoming wave. The azimuth is then calculated by using

$$\theta_{\text{calc}} = \frac{\sum_{n=1}^{N} \arctan\left(\frac{|B_{\text{EW}}[n\Delta f]|}{|B_{\text{NS}}[n\Delta f]|}\right) B_{\text{total}}[n\Delta f]}{N \sum_{n=1}^{N} B_{\text{total}}[n\Delta f]}, n\Delta f = f_2 - f_1, \tag{1}$$

where Δf is the frequency resolution, $B_{\text{EW}}[n\Delta f]$ and $B_{\text{NS}}[n\Delta f]$ are the Fast Fourier Transforms (FFT's) of the E/W antenna and N/S antenna discrete time signals respectively, and

$$B_{\text{total}}[n\Delta f] = \sqrt{(B_{\text{EW}}[n\Delta f])^2 + (B_{\text{NS}}[n\Delta f])^2}. \tag{2}$$

The azimuth determined using this technique introduces an ambiguity of 180°, as the Poynting vector cannot be determined uniquely with only magnetic field measurements. After taking account of site error corrections, the azimuth can be determined accurately by using

$$\theta_{\text{true}} = \arctan\left[\alpha \frac{\tan \theta_{\text{calc}}}{\cos \varepsilon} - \tan \varepsilon\right] + \rho, \tag{3}$$

where α is the ratio of gain in the N/S channel to gain in the E/W channel ($G_{\text{NS}}/G_{\text{EW}}$), ρ the offset in antenna alignment with respect to exact geographic north, and ε is the angle by which the two antennas are skewed from orthogonality. The arrival azimuth calculated is designated as A_z throughout the text. Figure 3 shows the arrival azimuth directions (blue lines) for the causative sferics of 129 whistlers observed on 24 January 2011 (left panel) and 356 whistlers observed on 27 February 2011 (right panel). The magenta lines are the arrival azimuth paths for the whistler causative sferics marked as S1, S2, S3, etc. in Figure 2. Around ~72% and ~78% causative sferics of whistlers observed on the two days are found to have their arrival azimuth direction towards conjugate point of Allahabad in the Indian Ocean. The average arrival azimuth for the whistler causative sferics of 24 January 2011 is found to be ~171° and that of 27 February 2011 ~175°. The standard azimuth for Allahabad conjugate point (9.87°S; 83.59°E) is 175.5°. The arrival azimuths obtained are in good agreement with this standard azimuth.

To validate the calculated arrival azimuths of observed causative lightning discharge of whistlers obtained using arrival azimuth determination technique, we determined the location of source lightning discharge or observed sferics by matching its arrival time with that of causative sferics observed in the spectrogram. Unlike mid and high latitude whistlers, the propagation delay for whistler causative sferics is much less as the distance between the receiving station and its conjugate point is less[19], around ~4000 km. Hence one can precisely identify the whistler causative sferics in the spectrogram. To determine the time and location of source lightning discharge from real-time lightning data, we first determined the tentative time (t_H) of the whistler causative sferic using the method of Helliwell[2]. Next, the spectrogram containing the whistler was scanned and the sferic whose time (t_s) matched with t_H was identified. The WWLLN data were checked carefully for the lightning discharge whose time matched with t_s within a window[19] of 17 ms and designated as t_{wwlln}.

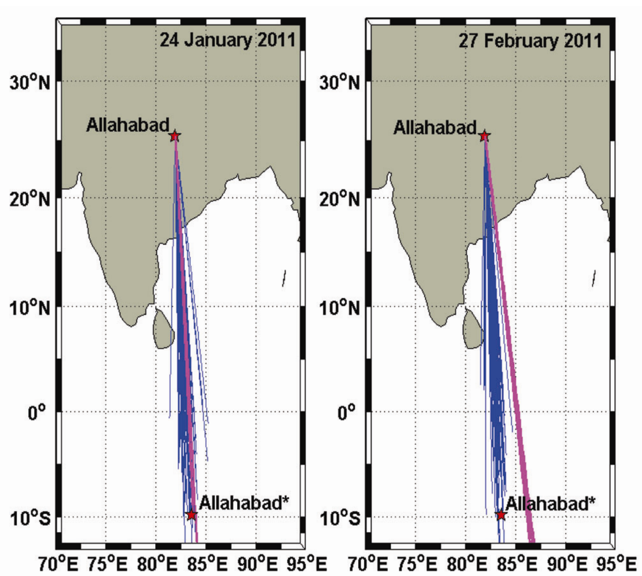

Figure 3. Directions of arrival azimuth of whistler causative sferics recorded on the night of 24 January 2011 and 27 February 2011. Magenta lines present the arrival azimuth paths for the whistlers shown in Figure 2.

Figure 4 shows the total lightning activity (L_t, cyan spheres) on the nights of whistler activity days considered in this study. Magenta circles represent the locations of all the source lightning discharges of whistlers determined from time-matching method (L_w). Blue stars are locations of the source lightning discharges (L_{we}) of the whistlers presented in Figure 2. The circle is drawn with 1000 km radius. Around 75.5% and 82.8% source lightning discharges of whistlers observed on 24 January 2011 and 27 February 2011 respectively, are found to be located around the conjugate point. We have also calculated the azimuths of these lightning discharge locations and designated them as A_{zw}. The average arrival azimuth (A_z) of the causative sferics for whistlers W1 and W2 of 24 January 2011 (Figure 2) is 176.7°, whereas the average azimuth of the WWLLN-detected source lightning discharges (A_{zw}) is 178.2°. Similarly, A_z for the whistlers W1–W6 of 27 February 2011 (Figure 2) is 172.6°, whereas A_{zw} is 167.1°. The average azimuth (A_{zw}) for all the source lightning discharges of the whistlers observed on the night of 24 January 2011 is ~174.4° and that for the whistlers observed on the night of 27 February 2011 is ~172°. The difference ($|A_z - A_{zw}|$) in the azimuth values is only ~3°, which is well within the error limits.

The arrival azimuths determined for whistler causative sferics are in agreement with the locations of WWLLN-detected parent lightning discharges of whistlers. Hence this confirms the source location of causative sferic of whistlers observed at Allahabad in the neighbourhood of its magnetically conjugate point. Thus, the arrival azimuth technique confirms that source lightning discharges

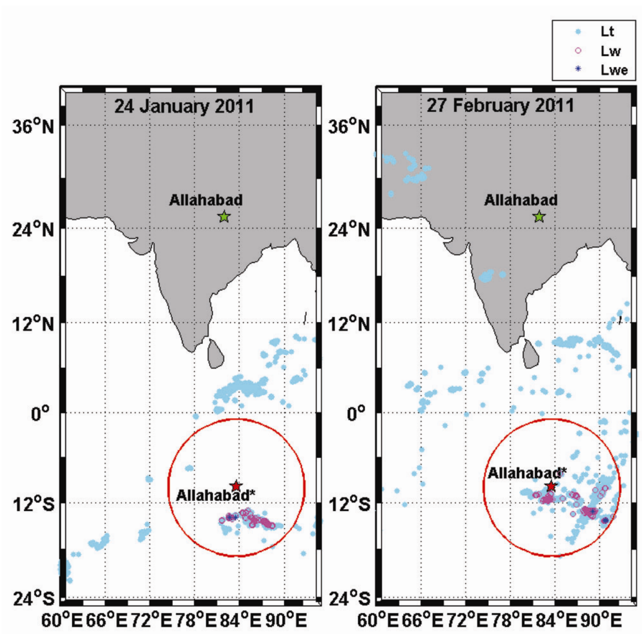

Figure 4. WWLLN-detected lightning activity (L_t – cyan spheres) on the nights of 24 January 2011 and 27 February 2011. Magenta circles (L_w) are the source lightning discharges for the whistlers observed on these two days. Blue stars (L_{we}) are the source lightning discharges for the whistlers shown in Figure 2.

of very low latitude whistlers are located around the conjugate point in the Indian Ocean. Recent results suggest that the path of propagation, i.e. geomagnetic field lines connecting the conjugate points should lie in the ionosphere, and ducted or pro-longitudinal mode of propagation is more likely to occur[18–20]. Studies are pursued and the results obtained will enhance the existing knowledge on the intricacies involved with low latitude whistlers.

1. Storey, L. R. O., An investigation of whistling atmospherics. *Philos. Trans. R. Soc. London, Ser. A*, 1953, **246**, 113–141.
2. Helliwell, R. A., *Whistlers and Related Ionospheric Phenomena*, Stanford University Press, Stanford, California, USA, 1965.
3. Carpenter, G. B., An FM technique for observation of VLF whistler-mode-propagation. Technical Report No. 3, Nonr-225(27), Technical Report No. 3412-2, AF-AFOSR-62-370, Radioscience Lab., Stanford Electronics Labs, Stanford University, California, USA, 1963.
4. Hayakawa, M. and Tanaka, Y., On the propagation of low latitude whistlers. *Rev. Geophys. Space Phys.*, 1978, **16**, 111–125.
5. Sazhin, S. S., Hayakawa, M. and Bullough, K., Whistler diagnostics of magnetospheric parameters: a review. *Ann. Geophys.*, 1992, **10**, 293.
6. Singh, B. and Hayakawa, M., Propagation modes of low and very-low-latitude whistlers. *J. Atmos. Sol.–Terr. Phys*., 2001, **63**, 1133–1147.
7. Singh, R. P., Singh, R. L., Hamar, D. and Litchtenberger, J., Application of matched filtering to short whistlers recorded at low latitudes. *J. Atmos. Sol.–Terr. Phys*., 2004, **66**, 407–413.
8. Cerisier, J. C., A theoretical and experimental study of non-ducted VLF waves after propagation through the magnetosphere. *J. Atmos. Terr. Phys*., 1973, **35**, 74.
9. Hayakawa, M., Tanaka, Y. and Ohta, K., Absolute intensity of low latitude whistlers as deduced from the direction finding measurements. *Radio Sci*., 1985, **20**, 985.
10. Ondoh, T., Kotaki, M., Murakami, T., Watanabe, S. and Nakamura, Y., Propagation characteristics of low latitude whistlers. *J. Geophys. Res*., 1979, **84**, 2099–2104.
11. Singh, B. and Tantry, B. A. P., On ducting of whistlers at low latitudes. *Ann. Geophys*., 1973, **29**, 561–568.
12. Hayakawa, M. and Iwai, A., Magnetospheric ducting of low latitude whistlers as deduced from the rocket measurements of wave-normal direction. *J. Atmos. Terr. Phys*., 1975, **37**, 1211.
13. Tanaka, Y. and Hayakawa, M., The effect of geomagnetic disturbance on duct propagation of low latitude whistlers. *J. Atmos., Terr. Phys*., 1973, **35**, 1699–1703.
14. Tanaka, Y. and Cairo, L., Propagation of VLF waves through the equatorial anomaly. *Ann. Geophys*., 1980, **36**, 555–575.
15. Andrews, M. K., Non-ducted whistler mode signals at low latitudes. *J. Atmos. Terr. Phys*., 1978, **42**, 1–20.
16. Thomson, N. R., Ray-tracing the paths of very low latitude whistler-mode signals. *J. Atmos. Terr. Phys*., 1987, **49**, 321–338.
17. Kumar, S., Anil, D., Kishore, A. and Ramachandran, V., Whistlers observed at low-latitude ground-based VLF facility in Fiji. *J. Atmos. Sol.–Terr. Phys*., 2007, **69**, 1366–1376.
18. Singh, R. *et al.*, Very low latitude ($L = 1.08$) whistlers. *Geophys. Res. Lett*., 2012; doi:10.1029/2012GL054122.
19. Srivastava, P. R. *et al.*, One to one relationship between low latitude whistlers and conjugate source lightning discharges and their propagation characteristics. *J. Adv. Space Res*., 2013, **52**, 1966–1973.
20. Gokani, S. A. *et al.*, Very low latitude ($L = 1.08$) whistlers and correlation with lightning activity. *J. Geophys. Res. Space Phys.*, 2015, **119**; doi:10.1002/2015JA021058.
21. Collier, A. B., Bremner, S., Lichtenberger, J., Downs, J. R., Rodger, C. J., Steinbach, P. and McDowell, G., Global lightning distribution and whistlers observed at Dunedin, New Zealand. *Ann. Geophys*., 2010, **28**(2), 499–513.
22. Rodger, C. J., Brundell, J. B. and Holzworth, R. H., Improvements in the WWLLN network: bigger detection efficiencies through more stations and smarter algorithms. In Paper presented at the 11th Scientific Assembly, International Association of Geomagnetism and Aeronomy, Sopron, Hungary, 2009.
23. Singh, R. *et al.*, Initial results from AWESOME VLF receivers: set up in low latitude Indian regions under IHY2007/UNBSSI program. *Curr. Sci*., 2010, **98**(3), 398–405.
24. Lichtenberger, J., Ferencz, C., Bodnár, L., Hamar, D. and Steinbach, P., Automatic whistler detector and analyser system: automatic whistler detector. *J. Geophys. Res*., 2008, **113**, A12201; doi:10.1029/ 2008JA013467.
25. Wood, T. G., Geo-location of individual lightning discharges using impulsive VLF electromagnetic waveforms. Ph D theses, Stanford University, California, USA, 2005.
26. Said, R. K., Accurate and efficient long range lightning geolocation using a VLF radio atmospheric waveform bank, Ph D theses, Stanford University, California, USA, 2009.

ACKNOWLEDGEMENTS. We thank the Director, Indian Institute of Geomagnetism (IIG), Navi Mumbai, for support and encouragement. The whistler data used in the present study are taken from the IIG (http://iigm.res.in/) operated VLF stations in India. We also thank Robert Holzworth, University of Washington, USA (bobholz@ess.washington.edu) for providing WWLLN data (http://webflash.ess.washington.edu/), and the International Space Weather Initiative Program and United Nations Basic Space Sciences Initiative programme for their support to VLF project activities in India.

Received 7 December 2015; revised accepted 15 February 2016

doi: 10.18520/cs/v111/i1/198-201

A synoptic-scale perspective of heavy rainfall over Chennai in November 2015

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The South Indian city of Chennai experienced three phases of heavy rainfall that resulted in devastating flood during November and early December of 2015. We find that propagating convective systems from the west Pacific Ocean intensified further over the warm Indian Ocean before moving north towards Indian land region. This northward propagation was guided by two highs of mid-troposphere to the east and west

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