Very low latitude (L = 1.08) whistlers

Rajesh Singh,[1] Morris B Cohen,[2] Ajeet K. Maurya,[1] B. Veenadhari,[3] Sushil Kumar,[4] P. Pant,[5] Ryan K. Said,[6] and Umran S. Inan[2,7]

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[1] For decades, whistlers observed on the ground at mid and high latitudes have been used for diagnostics of Earth's plasmasphere. Whistlers have also been observed at low latitudes however, the propagation characteristics of low latitude whistlers are poorly understood thus they have not been used effectively as a diagnostic for the low latitude ionosphere. One key limitation with past studies has been lack of knowledge of the whistler source lightning location. Here we present the first cases of low latitude ground whistlers most likely linked with their causative lightning discharges in the conjugate zone. The Global Lightning Dataset 360 (GLD360) detected lightning discharges were found to be located close to the conjugate location of the recording stations, providing direct evidence of inter-hemispheric propagation at the low latitudes. A total of 864 whistlers were observed at Allahabad, India (Geomag. lat. 16.05°N; Geomag. long. 155.34°E; L = 1.08) during the night of 26 January 2011. Using GLD360 network data, we show the occurrence of thunderstorm activity between 200 and 450 km from the conjugate point of Allahabad. We also report the distribution of peak currents of whistler-producing lightning, which demonstrate a cutoff at 30 kA. **Citation:** Singh, R., M. B. Cohen, A. K. Maurya, B. Veenadhari, S. Kumar, P. Pant, R. K. Said, and U. S. Inan (2012), Very low latitude (L = 1.08) whistlers, *Geophys. Res. Lett.*, *39*, L23102, doi:10.1029/2012GL054122.

1. Introduction

[2] Whistlers are remarkable burst of Very Low Frequency (VLF, 3–30 kHz) electromagnetic waves generated by lightning return strokes which can be recorded by ground receivers and by satellites. Whistlers observed at mid (∼2.4 < L < ∼3.5) and high latitudes (∼3.5 < L ∼<4.5) have been subsequently used as a powerful tool for the diagnostics of Earth's magnetosphere [*Helliwell*, 1965; *Hayakawa and Tanaka*, 1978; *Singh and Hayakawa*, 2001], using the dispersion characteristics of the received waveform. Initially, whistlers were thought to be a uniquely high- and mid- latitude phenomena. However, ground stations in India, Japan and China showed the occurrence of whistlers at low latitudes (L < ∼2.3) [*Rao et al.*, 1974; *Hayakawa and Tanaka*, 1978; *Xu et al.*, 1989].

[3] The whistlers observed at low latitudes are noticeably different from those of middle and high latitudes. The low latitude whistlers are characterized with very low dispersion. The ducted and non-ducted propagation characteristics associated with mid- and high latitude whistlers along the Earth's magnetic field lines are well established and hence these signals have been used extensively in Earth's plasmaspheric investigations at mid and high latitudes [*Helliwell*, 1965]. For whistler wave propagation, the wave normal angle must lie within the transmission cone defined by wave normal direction and vertical direction [*Helliwell*, 1965], and this transmission cone is much larger in a duct propagation than in non-ducted. At low latitudes (geomagnetic latitude <30°: L < 1.3) the Earth's magnetic field lines have sharp curvature and are embedded in the ionosphere (<1000 km) where ducts are not supposed to regularly exist, so most of the wave energy does not lie within the transmission cone. On the other hand, earlier studies utilized direction finding measurements to investigate the possibility that low latitude whistlers can propagate in the ducted mode [*Ondoh et al.*, 1979; *Hayakawa et al.*, 1990]. It is also not known if low latitude ionospheric equatorial anomalies contribute to the propagation of low latitude whistlers. Furthermore, it is also possible that at least some low latitude whistlers may be intense mid latitude whistlers which propagate in the EIWG after re-entering the atmosphere. The propagation characteristics of whistler waves at low latitudes remain poorly understood, and hence the powerful diagnostic potential of whistlers for the low latitude ionosphere remains unrealized.

[4] In this paper we report the first direct correlation between whistlers observed at a low latitude station, Allahabad (L = 1.08) with their causative lightning discharges located near the conjugate region, in the Indian ocean, as observed by the Global Lightning Dataset 360 (GLD360) lightning location network. On the night of 26 January 2011, 864 whistlers were observed at the station Allahabad, India, in continuous broadband VLF data. The data from second station Nainital (L = 1.13) is also used where recording is done in synoptic mode (1 minute at every 15 minute interval). The observations presented here give direct evidence of inter-hemispheric propagation of whistlers at low latitudes, which may possibly be along low latitude ducts and opens a new window into low

[1]KSK Geomagnetic Research Laboratory, Indian Institute of Geomagnetism, Allahabad, India.
[2]Department of Electrical Engineering, Stanford University, Stanford, California, USA.
[3]Indian Institute of Geomagnetism, Navi Mumbai, India.
[4]School of Engineering and Physics, University of South Pacific, Suva, Fiji.
[5]Aryabhatta Research Institute of Observational Sciences, Nainital, India.
[6]Vaisala, Inc., Boulder, Colorado, USA.
[7]Department of Electrical Engineering, Koc University, Istanbul, Turkey.

Corresponding author: R. Singh, KSK Geomagnetic Research Laboratory, Indian Institute of Geomagnetism, Allahabad, Uttar Pradesh 221505, India. (rajeshsing03@gmail.com)

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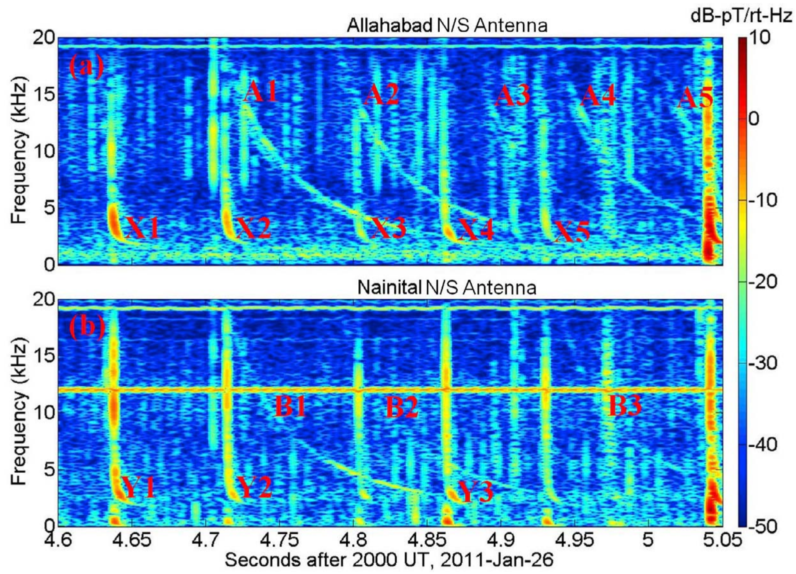

Figure 1. Spectrograms showing whistlers observed simultaneously at both stations (a) Allahabad and (b) Nainital on 26 January 2011 after 20:00:4.5 UT (01:30:4.5 LT). The color scale shows the intensity or amplitude of recorded signal.

latitude ionospheric diagnostics. We present the observed characteristics of both the whistlers and their causative lightning discharges, and the dependence of whistler generation on radiated peak current of lightnings.

2. Experimental Setup and Data

[5] The present study is based on the whistlers recorded at Allahabad (Geog. lat., 25.40°N; Geog. long. 81.93°E; Geomag. lat. 16.05°N, L = 1.08) and Nainital (Geog. lat., 29.35°N; Geog. long. 79.45°E; Geomag. lat. 20.48°N, L = 1.13) during the night of 26 January 2011. The L-values are calculated after *Campbell*, 2003 using the relation $L = {}^{1}/_{\cos^2} \lambda$, where λ is geomagnetic latitude in degree [*Campbell*, 2003, p. 15]. The recording system consists of a Stanford University built AWESOME VLF receiver [*Cohen et al.*, 2010; *Singh et al.*, 2010] with two crossed loop antennas to receive East-West and North-South horizontal magnetic field components. The further details on the AWESOME VLF system can be found in *Cohen et al.* [2010]. We record broadband data in continuous mode at Allahabad site and in synoptic mode (1 minute at every 15 minute interval) at Nainital site.

[6] Lightning Location data are taken from GLD360, a network of VLF receivers across the globe, measuring both time of arrival and direction of incoming sferics, using the methodology developed by *Said et al.* [2010]. The detection efficiency of GLD360 network is ~70%, far higher than any other existing global lightning detection network, and this network is also the first of its kind that gives peak current and polarity of each strike [*Said et al.*, 2010]. Location accuracy is of the order of 1–4 km. However, at the time of these observations, two nearby sensors were temporarily down, so more distant sensors had to be used to determine the geo-location of lightnings. Although, it would have affected the detection efficiency of the network, but it is enough to enable us to carry out a detailed study of the lightning-whistler relationship.

3. Observations

[7] During the night of 26 January 2011 at Allahabad station, intense whistler activity was observed with the occurrence of 864 whistlers between 19:30–23:00 UT. Local time (LT) = UT + 5.5 hrs. At second station Nainital, regular observations are made only in synoptic mode, and hence fewer whistlers were recorded as compared to Allahabad station where data is recorded in the continuous mode. 36 whistlers were simultaneously recorded in the synoptic data window at both stations. All 36 simultaneously recorded whistlers at both stations showed marked difference in their spectral appearance. The whistlers at Allahabad were consistently received with higher signal-to-noise ratio (SNR) as compared to whistlers at Nainital.

[8] Figure 1 presents spectrograms containing whistlers observed simultaneously at both stations Allahabad (Figure 1a) and Nainital (Figure 1b) on 26 January 2011 after 20:00:4.5 UT (01:30:4.5 LT). In this 0.5 second interval, 5 whistlers were recorded whereas at Nainital 3 whistlers were observed. The five Allahabad whistlers are marked by A1 to A5 and three Nainital whistlers by B1 to B3. The causative lightning sferics associated with whistlers are labeled as X1 to X5 for Allahabad and Y1 to Y3 for Nainital whistlers. Due to the proximity of the causative lightnings to the conjugate location (which is not the case for mid latitude whistlers), both the sferics and whistlers are received with very high SNR, allowing unambiguous identification of the causative sferics in the spectrogram.

[9] The dispersion of the observed whistlers is quantified using the method described by *Helliwell* [1965, p. 4] by plotting the time 't' versus '$f^{-1/2}$' of the whistler frequencies 'f' and extrapolating the line to meet the time of the causative

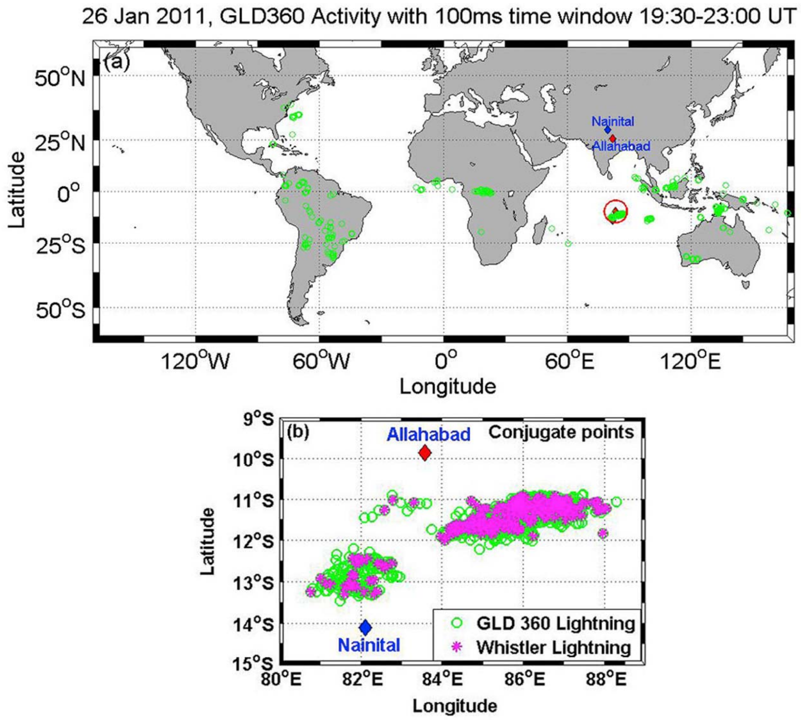

Figure 2. (a) Locations of receiving stations Allahabad and Nainital on global map along with GLD360 detected lightning locations with <=100 ms time window prior to occurrence time of each whistler during 19:30 UT to 23:00 UT (green circles). Red circle of 600 km radius shows a well confined zone of lightning activity surrounding the conjugate point. (b) Zoom in view of the conjugate area to show the conjugate points of receiving stations with respect to GLD 360 detected lightning strikes (green circles) and whistler producing lightning strikes (magenta colored stars).

sferic. The dispersion '*D*' of the whistler is obtained from the product of travel time of the whistler frequency components and square root of frequency components [*Helliwell*, 1965]. The *D* of the five Allahabad and three Nainital whistlers shown in Figure 1 lies between 11.57–12.24 $sec^{1/2}$, and for all the 864 whistlers observed at Allahabad the dispersion varies between ∼11.5–12.5 $sec^{1/2}$. Observations since last five decades have shown that for low latitude whistlers *D* is less than 25 $sec^{1/2}$ except for some rare exceptional high dispersion whistlers. In the present report of 864 whistlers *D* is found in the range of ∼11.5–12.5 $sec^{1/2}$, suggesting that these whistlers have origin in the low latitude region and propagated through low latitude ionosphere along the magnetic field lines connecting the conjugate hemispheres in the ducted or pro-longitudinal (PL) non-ducted mode of propagation [*Smith et al.*, 1960; *Helliwell*, 1965, chap. 3].

[10] The conjugate points of Allahabad (9.87°S; 83.59°E) and Nainital (14.10°S; 82.11°E) lie in Indian Ocean as shown in Figures 2a and 2b. It is well known that the thunderstorm activity over the ocean is about ten times less than on land [*Christian et al.*, 2003], hence lightning discharges in the conjugate region of Indian stations are very less. In order to find the source geographic locations of causative lightings associated with the observed whistlers we have used data from GLD360. A time window extending from 50 ms to 100 ms prior to each whistler is considered to identify the causative sferics, since within this time interval majority of whistler causative lightning strikes are expected to occur. Figure 2a shows the global map of lightning locations (green circles) obtained from GLD360 network data within 100 ms time window prior to occurrence time of each whistler in the interval 19:30 to 23:00 UT (∼3.5 hrs) on 26 January 2011. Figure 2a shows several zones of lightning activity around the globe and a well confined zone within the conjugate area of ∼600 km radius with respect to Allahabad conjugate point. Figure 2b is the zoom view of the conjugate area to show the locations of conjugate points of Allahabad and Nainital stations and locations of well confined zone of lightning activity in the conjugate area. Lightning locations detected by GLD360 network have been represented by green color circles and whistler producing lightning strikes by magenta color stars. The lightning activity zone is closer to Allahabad conjugate point as compared to Nainital conjugate point. From Figure 2b, during 3.5 hrs period of whistler occurrences, 1508 lightning strikes associated with this particular thunderstorm were detected by GLD360 network (shown by green circles), out of which 311 were found to be associated with whistlers (shown by magenta color stars), representing 36% of total 864 whistlers recorded at Allahabad. This is less than the ∼70% detection efficiency of GLD360 as during this period two nearby sensors were temporarily down, but it is still higher than other global lightning geo-location network.

[11] Figure 3 (top) shows the temporal evolution in the occurrence pattern of GLD360 network detected lightning discharges and whistler producing lightnings between 19:30–23:00 UT as the storm in the ocean evolved and moved. The number of lightning strikes shown in Figure 3 (top) is averaged over 15 minute intervals. Taking the bottom of the ionosphere at 80 km, the conjugate location of Allahabad is 9.87°S; 83.59°E and Nainital is 14.10°S; 82.11°E. Figure 3 (bottom) shows the distance to the

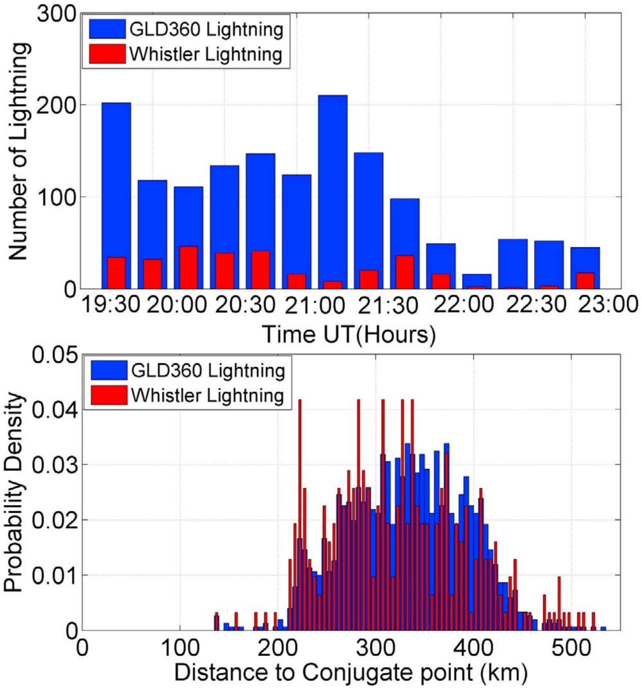

Figure 3. (top) The temporal evolution in the occurrence pattern of GLD360 detected lightning strikes (blue bars) and whistler producing lightnings (red bars) between 19:30–23:00 UT. (bottom) The distance to the conjugate point of the 1508 GLD360 lightning strikes (blue bars) and 311 whistler producing lightning strikes (red bars).

conjugate point of total 1508 lightnings and 311 lightning strikes which were associated with observed whistlers. The intense thunderstorm activity was spread between 200 and 450 km, suggesting that ionosphere over at least a 250 km area was illuminated by lightning strikes. The lightning generated waves penetrated the ionosphere and propagated through and exited finally in conjugate region in an area around the Allahabad station as whistlers. We thus state that at low latitudes, the location of whistlers producing causative lightnings may be located close to the conjugate point.

[12] Figure 4 shows the probability distribution of peak current (kA) of all GLD360 lightning discharges in the storm (blue bars) and whistler producing discharges (red bars). The inference from Figure 4 is that majority (80%) of the whistlers were generated by intense lightning discharges with radiated peak current between ~30–300 kA. 20% of the observed whistlers were associated with lightnings having peak current between 300–500 kA. In this particular case, the lightnings with peak current <30 kA did not produce any whistlers. Further, in Figure 3 (bottom), there are 6 lightnings events located between 100 and 200 km (close to conjugate point) and 4 events between 450 and 600 km, which did not produce any whistlers. The peak currents of these lightnings were checked and we found that these lightnings were associated with peak currents less than 30 kA. Thus it appears that only intense lightnings produce detectable whistlers at low latitudes, with a cutoff of 30 kA peak current. This particular thunderstorm had a large number of extremely strong strikes, thus was associated with a large number of whistlers at Allahabad.

[13] It should be noted that based on above information we cannot distinguish between ducted and non-ducted propagation, both of which may exit the ionosphere close to the conjugate point [*Singh and Hayakawa*, 2001]. But knowledge of the lightning location and delay time to the whistler may enable unambiguous determination of the propagation path. It is possible, however, that these whistlers propagated in low latitude ducts, whose occurrence rate is currently unknown. The simultaneous whistler examples at two stations presented in Figure 1 show the marked difference in their spectral features. The whistlers at Allahabad were more intense with high signal-to-noise ratio compared to whistlers at Nainital. Out of five Allahabad whistlers shown in Figure 1, only three were seen at Nainital with much attenuated wave features. This suggests that the ionospheric exit point of the whistler waves was located closer to Allahabad and whistlers propagated to Nainital station in the Earth-ionosphere waveguide (EIWG). Since whistlers attenuate at a rapid rate of 12 dB per 1000 km in the EIWG [*Walker*, 1974], less number of whistlers were observed at Nainital. The lightnings with same peak current were not able to produce good quality whistlers at Nainital as compared to Allahabad. Further, the conjugate location of Nainital as shown in Figure 2b is not close to the thunderstorm activity as compared to Allahabad conjugate location. The observations presented and examples as shown in Figure 1 suggest the cases where observed whistlers had field-aligned ducted or PL mode of propagation in the low latitude equatorial ionosphere.

4. Discussion

[14] *Hayakawa and Tanaka* [1978] categorized low latitude whistlers into two groups, between 20° and 30° geomagnetic latitude as ducted whistlers (where ducted whistlers can be observed), and non-ducted PL-mode whistlers below 20° geomagnetic latitude. The present report on whistlers is from Allahabad with geomagnetic latitude of 16.05°N, which falls into the category of very low latitude (<20°) site. The results on the whistler ducted propagation at low latitudes below 20° have earlier been presented by Japanese workers [*Ondoh et al.*, 1979; *Hayakawa et al.*, 1990]. *Hayakawa et al.* [1990] showed the field-aligned ducted propagation of whistlers at low latitudes based on the direction finding measurements from the observations carried out at three very

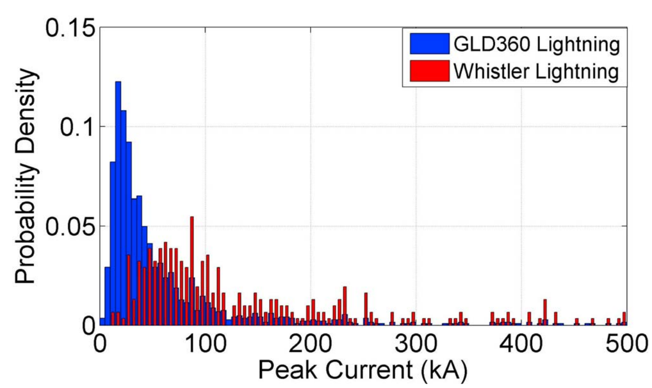

Figure 4. The probability distribution of peak currents (kA) of all GLD360 lightning strikes in the storm (blue bars) and whistler producing strikes (red bars).

low latitude stations in southern China and the presence of intense cloud cover at and around conjugate point.

[15] Correlation study between whistler and lightning activities at low latitude by *Ohta and Hayakawa* [1990] found no correlation between whistler occurrence and lighting strikes near the conjugate point. They suggested the importance of ionospheric absorption for whistler and concluded that lightning activity is only a necessary condition for whistler occurrence. The present work shows that whistler occurrence at low latitudes can depend on lightning strikes around the conjugate point. Other studies on lightning source locations associated with whistlers showed that causative lightning of whistlers were widely distributed around the conjugate point and the distance of the causative sferics from conjugate point varied from 500 to more than 2000 km [*Weidman and Krider*, 1986; *Carpenter and Orville*, 1989]. *Ondoh et al.* [1979] suggested nearly overhead ionospheric exit points for whistlers observed at a Japanese station and proposed ducted propagation. Japanese stations are located in higher low mid-latitude region where ducted propagation is possible. *Yoshino* [1976] observed most of whistlers at Sugadaira, Japan, when there was thick cloud cover ~500 km southwest of conjugate point. *Collier et al.* [2009] have found that whistlers observed at Tihany, Hungary, having source region of ~1000 km surrounding conjugate point, and the source region was not circular rather displaced towards magnetic pole from conjugate point. Further they suggested that results presented were preliminary and more analysis with different set of data is needed. Other studies by *Collier et al.* [2010, 2011] for whistlers observed at Dunedin and Rothera have shown opposite results that the source region is rather towards the equator from the conjugate point.

[16] The present observations show that thunderstorm activity was spread within distances starting from 200 km to 450 km around conjugate point of Allahabad. There seems several zones of lightning activity specially those zones which are located in Asia-Oceania region (Figure 2a) and one cannot completely rule out contribution from these zone but as most of these zones are located far from conjugate area hence most probable lightning source region for whistlers observed at Allahabad lies in the conjugated zone. Further confirmation on whistler associated lightning source region can be obtained by applying direction finding technique which is not the part of present study. Our results obtained for the first time at very low latitudes (L = 1.08) show the dependence of whistler occurrence on lightning activity when the storm is favorably located around the conjugate point of the observing stations. Whistler generation dependence on radiated lightning peak current shows that lightnings with peak current less than 30 kA are not able to produce whistlers. The present observations of whistlers from Indian low latitudes station (L = 1.08) give the first possible suggestion of field-aligned ducted propagation in the low latitude equatorial ionosphere.

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