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: Re:
: Some AWESOME VLF results.
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Dear ISWI Participant:

I was asked (by UNOOSA) to circulate the attached paper, which has this title:
: "Initial results from AWESOME VLF receivers:
: set up in low latitude Indian regions under
: IHY2007/UNBSSI program"

Please let me know if you wish to have an IHY/ISWI paper circulated via this newsletter.

Most faithfully yours,
: George Maeda
: The Editor
: ISWI Newsletter

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on 21 January 2011.

Initial results from AWESOME VLF receivers: set up in low latitude Indian regions under IHY2007/UNBSSI program

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This article delineates preliminary results obtained from three newly set up very low frequency (VLF) radio receiver observation stations at low latitude Indian sites Allahabad (16.49°N), Nainital (20.48°N) and Varanasi (15.41°N), during 2007. These stations were set up by collaboration between the Indian Institute of Geomagnetism, Mumbai and Stanford University, USA under the International Heliophysical Year 2007/United Nations Basic Space Science Initiative (UNBSSI) program. VLF stations are part of Atmospheric Weather Electromagnetic System for Observation, Modeling and Education (AWESOME) network being operated globally to study the ionosphere and the magnetosphere with the help of electromagnetic waves in extremely low frequency (ELF) and VLF bands. The new set up of VLF receiver is a marked improvement over the traditional recording and analysis systems in India. It provides additional facilities to study the VLF phenomena at low latitudes which were not studied earlier, like direction finding of events like whistlers, emissions, etc. and *D*-region ionospheric perturbation caused by the geophysical phenomena such as solar flares, lightning induced electron precipitations, cosmic gamma ray flares, terrestrial gamma rays flares, geomagnetic storm effect, etc. Simultaneous observation at multiple sites will provide opportunity to study in more detail the application of ELF/VLF data as earthquake precursors. Some of the initial results obtained from the preliminary analysis are presented to show the probing potentiality of ELF/VLF waves in ionosphere/magnetosphere studies.

Keywords: Radio atmospherics, *D*-region ionosphere, very low frequency, VLF emissions, whistlers.

LIGHTNING discharges from thunderstorms are nature's most significant source of electromagnetic radiation, the energy in these pulses vary over a wide frequency range from a few Hz to several megahertz; ultra low frequency (ULF; 1–30 Hz), extremely low frequency (ELF; 30–3000 Hz), very low frequency (VLF; 3–30 kHz), low frequency (LF; 30–300 kHz), medium frequency (MF; 0.3–3 MHz), high frequency (HF; 3–30 MHz) and ultra high frequency (UHF; >30 MHz). However, maximum energy radiation is contained in the ELF/VLF band[1]. Continuous monitoring of these ELF/VLF waves provides a powerful remote sensing tool for understanding the processes in ionosphere and magnetosphere. Since both the Earth and the ionosphere are good reflectors at these frequencies, the lightning radiated impulses, commonly known as radio atmospheric or sferics (short form of atmospherics), travel thousands of kilometres in the so-called earth-ionosphere waveguide (EIWG) with little attenuation (~2–3 dB/1000 km). When this radiated energy is received at VLF/ELF bands, the received signals do not exhibit any dispersion, except near the cut-off frequency of the waveguide and are known as sferics/tweeks. Part of the radiated energy also penetrates the lower boundary of the ionosphere and is guided through the magnetosphere by field-aligned irregularities called ducts with no appreciable attenuation, before re-entering the EIWG to be received as whistlers, emissions, etc. This mode of propagation in magnetized plasma is called the whistler-mode[2]. The phenomenon of whistler waves was one of the first observed wave modes from the space and is widely studied[2,3].

Because of the ability of ELF/VLF waves to penetrate deep into seawater due to its high skin depth, about ~24 VLF transmitters in the frequency range 10–50 kHz are being operated globally by different countries to communicate with submarines, ships and for global navigation. Examples on global scale are the decommissioned 'Omega' by USA and in operation 'Alpha' system by Russia, besides individual transmitters by several countries; a VLF transmitter, VTX with transmitting frequency 18.2 kHz located at Katabomman (lat. 8.47°N, long. 77.40°E) is operated by India. Since ELF/VLF waves are reflected by *D*-region ionosphere and propagate through EIWG to large distances, transmitted signals from these

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transmitters can be used for the study of *D*-region ionospheric disturbances caused by various geophysical phenomena like solar flares[4,5], lighting induced electron precipitations (LEP's), cosmic gamma ray flares, effect of geomagnetic storms, earthquake precursors, etc. It is important to mention that the altitude of *D*-region ionosphere is too low for satellites and too high for balloons to make any reasonable measurements. Also, ground-based experiments using ionosondes and incoherent scatter radar do not receive echoes due to low electron densities ($<10^3$ el/cm^3) of the *D*-region ionosphere. So, for the studies of *D*-region ionosphere, VLF signals are extremely important because of their propagation in waveguide formed by Earth and lower *D*-region ionosphere. Studies to understand the intricacies of the associated phenomena, have led to contributions in development of plasma physics and space physics.

History of VLF measurements in India

Encouraged by mid- and high-latitudes studies of ionosphere/magnetosphere with the help of VLF/whistler-mode waves[2], research was started in Indian low latitude region in 1963 by a research group at Banaras Hindu University, Varanasi. The observations were first carried out at the highest available location in India at Gulmarg (lat. 24.16°N). The results obtained from the first station were encouraging[6]. This prompted the setting up of stations at lower latitudes in Nainital (lat. 20.48°N) in 1971 (ref. 7) and Varanasi (lat. 15.41°N) in 1976 (ref. 8). Further, the studies were also extended to Agra (lat. 17.2°N), Jammu (lat. 22.44°N) and Bhopal (lat. 13.78°N). Very interesting records of whistlers and VLF emissions were recorded at these stations which included whistlers of different types like short, diffused, multiflash, multipath, twin, synchronized, low dispersion, etc. and emissions like hiss, pulsing hiss, risers, triggered, periodic, quasi-periodic, etc. as described in various review articles[3,7,9,10]. Singh *et al.*[11] have reported the observation of whistler triplet bands and have studied temporal fine structure of whistlers at Agra. Singh *et al.*[12] reported observation of hiss triggered emission from Gulmarg and discussed its generation mechanism. Observations of very rare phenomena of hisslers from low latitude have also been reported[13].

Similar analogue experimental set-ups were used at all stations which consisted of T-type antenna, pre- and main-amplifiers, and magnetic cassette tape recorder. Initially recorded data was analysed on sonograph machine and later on AVDAS (advanced VLF data analysis system) available at Physics Department, Banaras Hindu University (BHU) at Varanasi. Recently loop antenna in place of T-type and an improved experimental set-up compared to old has been deployed at Agra site[14]. Loop antenna has an advantage over T-type antenna because background noise and electrical interferences can be avoided. T-type antennas records E_z components of the waves and are heavily masked by local noises compared to loop antenna. Since 1963, experimental set-ups have produced bulk of whistlers and VLF emission data, whose analysis has produced important results in low latitude whistlers and emission studies[3,7,9,10]. The studies were done with some limitations because most of the sites used analogue system of observation and single channel E_z measurements, which limits scientific application and interpretation of the data. For instance, direction finding is essential to determine the generation and propagation path of the observed whistlers and emissions in low latitudes, because these are essentially considered as mid- and high-latitude phenomena. Further, traditional systems designed for whistler studies could not use VLF transmitter signals as there was no facility to monitor transmitter signals. Because of this limitation, till now *D*-region ionospheric studies have not been given due attention in the Indian low latitude region. To overcome these limitations at Agra station, loop antenna with improved recording system, and OmniPal and AbsPal receivers for VLF transmitter signals monitoring have been used.

Studies till now have emphasized the occurrence and importance of VLF activity studies in the Indian low latitude region. With the objective of detailed study with simultaneous observation at different sites, three AWESOME receivers were set up at three sites in 2007, by Indian Institute of Geomagnetism in collaboration with Stanford University, USA under International Heliophysical Year 2007/United Nations Basic Space Science Initiative (UNBSSI) program[15]. The stations are located at KSK Geomagnetic Research Laboratory, Allahabad (a regional centre of Indian Institute of Geomagnetism), Aryabhatta Research Institute of Observational Sciences (ARIES) at Nainital and Banaras Hindu University at Varanasi. Figure 1 shows the location of the stations and great circle paths of some of the VLF transmitter signal being monitored continuously at these sites. This article intends to describe the experimental set-up used for observation at the sites and probing potentiality of the acquired VLF data for ionosphere and magnetosphere studies. Observations of broadband lightning discharge generated radio atmospherics have been used in studying the lower boundary of the ionosphere *D*-region. Some observations of magnetospheric events whistlers and chorus emissions are also presented.

Description of AWESOME VLF-receiver

The system consists of crossed magnetic loop antennas, matched pre-amplifier and line receiver. Figure 2 shows the block diagram and photograph of the system. The antennas are orthogonal to each other and directed in North–South (N–S) and East–West (E–W) magnetic plane,

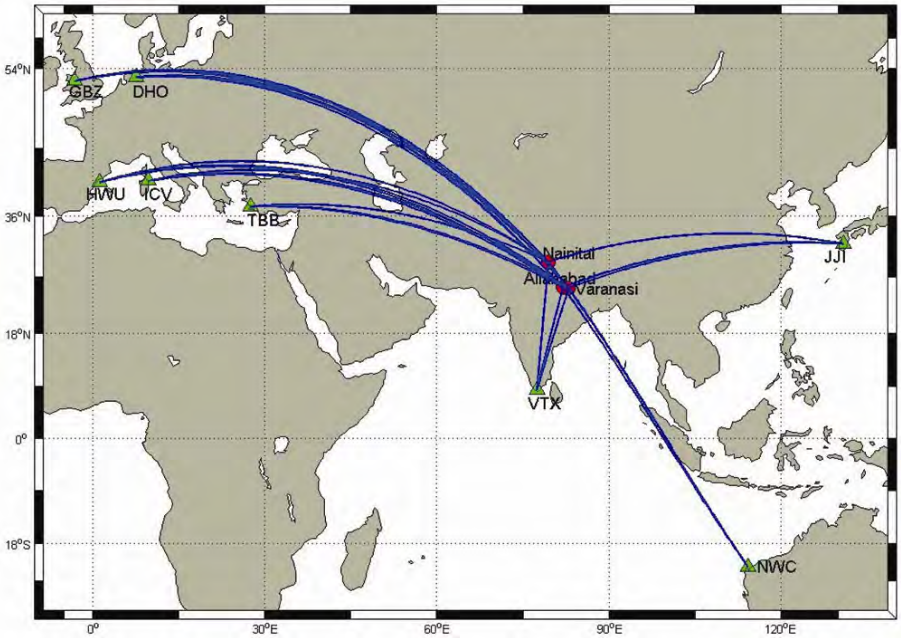

Figure 1. Location of the Allahabad, Nainital and Varanasi sites on the global map. The great circle paths of some of the VLF transmitter signals being monitored continuously at the sites is also shown.

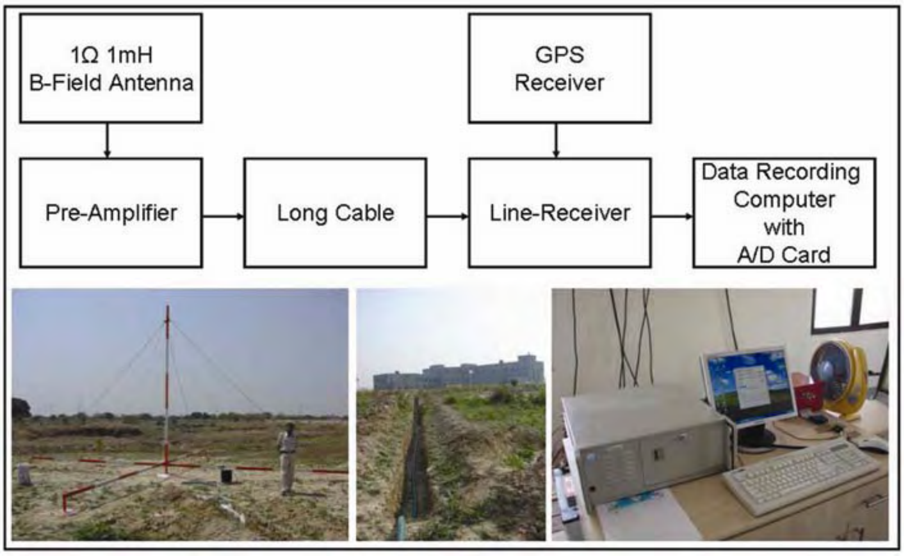

Figure 2. Block diagram of AWESOME VLF receiver system and some photographs from the site.

so that the receiver picks up magnetic fields (horizontal) parallel to the ground from any direction. The antenna corresponds to right isosceles triangles covering a geometrical area of roughly 25 m^2 and base 10 m. The impedance of the antenna is 1 Ω and 0.5–1.0 mH. The pre-amplifier is placed near the antenna with the impedances matched to enable maximum power transfer from antenna to receiver. The pre-amplifier is connected to the line receiver by long cable ~300 m. Apart from data transfer, the power ~± 15 V to the pre-amplifier is fed by same cable from line receiver. The line receiver is kept inside the building which performs anti-aliasing filtering, GPS time synchronization and post processing of the data. The line receiver then sends the acquired analogue data to the computer for digitization which is done by A/D card fitted in the PCI slot of the computer. The acquired data is sampled at 16-bit and 100 kHz. The sampling of 100 kHz enables signal detection up to 50 kHz. The lower and upper cut-off frequency of the receiver designed is between ~800 Hz and 47.5 kHz. For time stamping on acquired data the line receiver is also connected to the GPS device which provides better than 100 ns timing accuracy. The

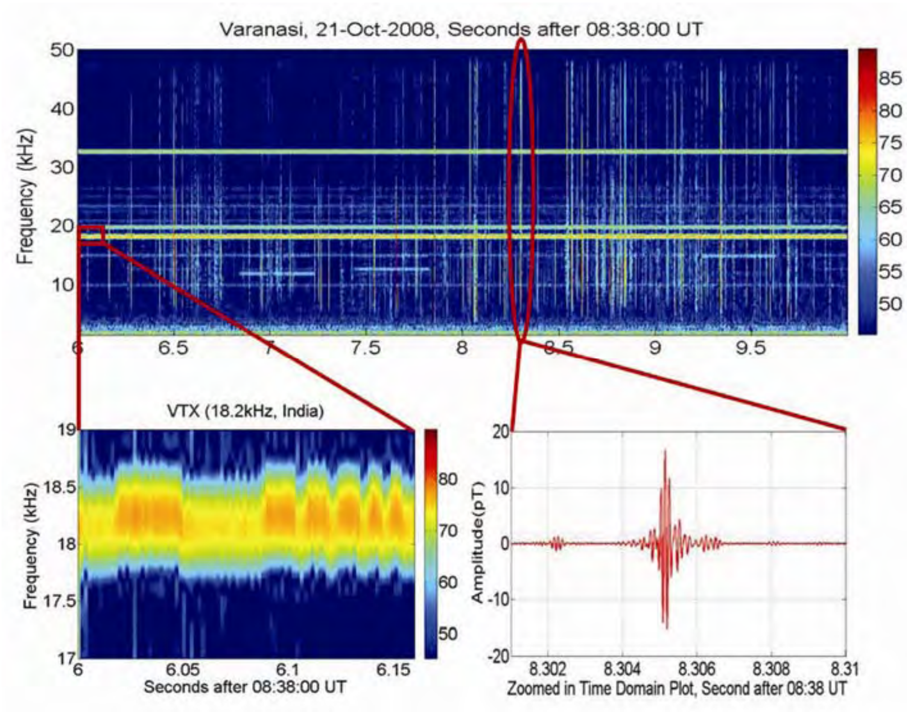

Figure 3. Sample data taken from the AWESOME receiver. Top panel: An ELF/VLF spectrogram of the data, the numerous vertical lines are signatures of lightning generated signals called 'radio atmospherics', and horizontal lines between ~10 and 30 kHz are signals from fixed frequency VLF transmitters being operated globally for marine communication and navigation. Bottom left panel: A zoom-in of a VLF transmitter signal being sent from Katabomman, India and named as VTX, at 18.2 kHz. Bottom right panel: A time domain close-up of a radio-atmospheric, lasting ~1 ms.

recording of the data is supported by data acquisition software developed by Stanford University which gives flexibility in the recording schedule, the type of data recorded, where the data is kept and sent, etc. Primarily two types of data are collected, first is broadband in which entire data stream is saved as single long waveform at 16 bits, 100 kHz. The data accumulates quickly at the rate of about 1.5 GB per hour, for two antennas combined. Because of this, broadband data is often collected only in 'synoptic' format, for example, 1 min out of every 5 min. During special campaign and experiment, data can be acquired in continuous format. The second type of data collected is narrowband, in which case the amplitude and phase of a single frequency, corresponding to a VLF transmitter is monitored. The software also demodulates the communication algorithm that is used by many of these transmitters, in order to accurately track the phase of the signal[16].

Sample data from receiver

Figure 3 shows the typical sample data taken from one of the AWESOME receivers set up at three locations Allahabad, Nainital and Varanasi. The top panel shows the 4 s data segment from one of the two antennas aligned in N–S and E–W plane. The sample data shown here is represented in spectrogram format (frequency versus time). The numerous slim vertical lines in the top panel are signatures of lightning generated signals called 'radio atmospherics'. The source lightning discharge can be near or thousands of kilometres away. The close-up in time domain of one of the radio atmospheric, lasting ~1 ms is shown in bottom right panel. Horizontal lines between 10 and 30 kHz correspond to VLF transmitter signals operating globally for marine communications. Between 10 and 15 kHz, the pulsed signals originate from a set of three transmitters known as the 'Alpha' network, operated by Russia. The horizontal line at 18.2 kHz is the signal from VTX transmitter operated by India at Katabomman (lat. 8.47°N, long. 77.40°E). The zoom-in of VTX signal is shown in bottom left panel.

Ionosphere/magnetosphere probing potentiality of VLF data

In this section the preliminary results obtained from the analysis of acquired data is presented to demonstrate the probing potential of ionosphere and magnetosphere. Features of the lightning discharge generated radio atmospherics are discussed, and its effectiveness in *D*-region ionosphere diagnostics is explained. In addition, sometimes waves from lightning discharge propagating through EIWG leak some energy upward through the ionosphere, which propagate through the magnetosphere along geomagnetic field lines in the form of whistler mode waves. As it propagates towards the conjugate hemisphere, dispersion is introduced so that the received signal is no longer impulsive, but has a distinct frequency–time characteristic, known as a whistler. The observation of some whistlers from one of these newly set-up station is presented. The chorus and hiss emission are also generated because of interaction between Van Allen radiation belts electrons and VLF whistler mode waves particularly at mid- and high-latitudes. The observation of these emissions has often been reported in Indian low latitude region, the explanation of their occurrence in low latitudes is still an interesting problem to study and typical example of recent observation of chorus is also discussed.

Radio atmospherics and *D*-region ionosphere remote sensing

Sferics radio signals from lightning discharges propagate in the Earth-ionosphere waveguide with low attenuation, typically ~2–3 dB/1000 km (ref. 17). The waveform, spectrogram and power spectrum of a typical sferic is shown in Figure 4 *a*–*c*, this was recorded on 26 March 2008 at a low latitude station in Allahabad. The spectrum shows greater dispersion at lower frequencies. From power spectra it can be seen that major portion of the wave energy lies in the frequency range 5–15 kHz. The spike at 18.2 kHz is due to strong VTX-VLF transmitter signal operated in India. Because of the fact that major portion of VLF signals energy lies in audio range, the signals when put to suitable amplifier are audible to human ears. The morphological features of sferics have been used to estimate the distance and geographic bearing of the source discharges, ionospheric reflection height and *D*-region electron density along the propagation path. Cummer *et al.*[18] developed a technique, which is based on wideband, long distance VLF propagation effects observed in sferics. This technique measures average electron density profile across the entire path and is therefore capable of estimating the electron density of large region. Some recent work with sferics has focused on understanding the delayed sferic component called a 'tweek'[19–22]. Ohya *et al.*[23] estimated equivalent night-time electron densities at reflection heights in the *D*-region ionosphere at low-middle latitudes by accurately reading the cut-off frequency of tweek atmospherics. They reported the equivalent electron densities ranged from 20 to 28 el/cm^3 at ionospheric reflection height of 80–85 km. Ohya *et al.*[24] examined the response of the night-time *D*-region ionosphere to the great magnetic storm of 2–11 October 2000 using an accurate analysis of the cut-off frequency of tweek atmospherics.

In the present study, tweeks recorded during the night of 13 June 2007 at Allahabad and Nainital have been analysed to understand the night-time behaviour of lower *D*-region (<90 km) ionosphere in low latitude region. Dynamic spectrogram of some of the tweeks observed simultaneously is shown in Figure 4. The time duration of the tweek events considered for present study is 4 h from 8.30 pm (Indian Standard Time, IST) in evening to 0.30 am (IST). During the period a total of 1052 tweeks observed at Allahabad and Nainital were analysed. Figure 5 shows examples of tweeks up to third modes. Following

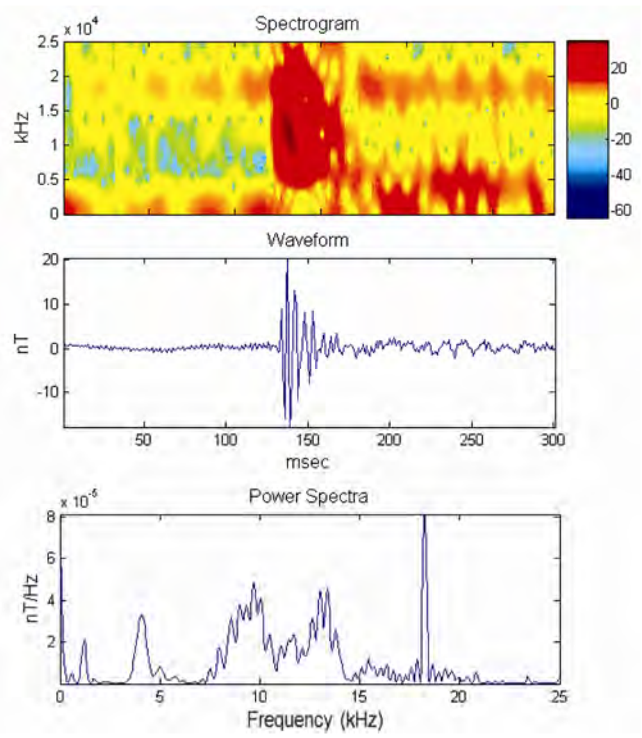

Figure 4. The waveform, spectrogram and power spectrum of a typical radio atmospheric recorded on 26 March 2008 at a low latitude station in Allahabad.

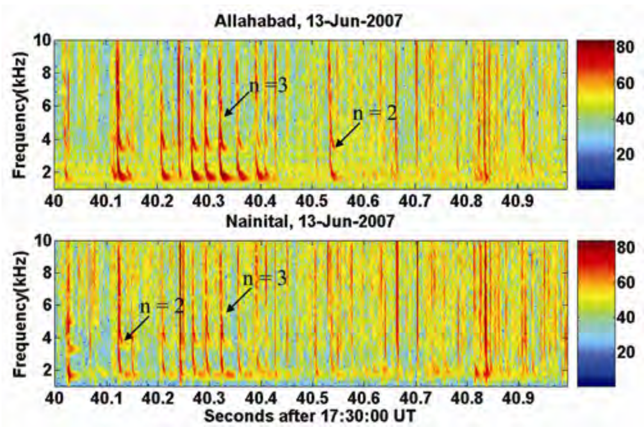

Figure 5. Examples of dynamic spectrograms of tweeks observed simultaneously at Allahabad and Nainital sites on 13 June 2007.

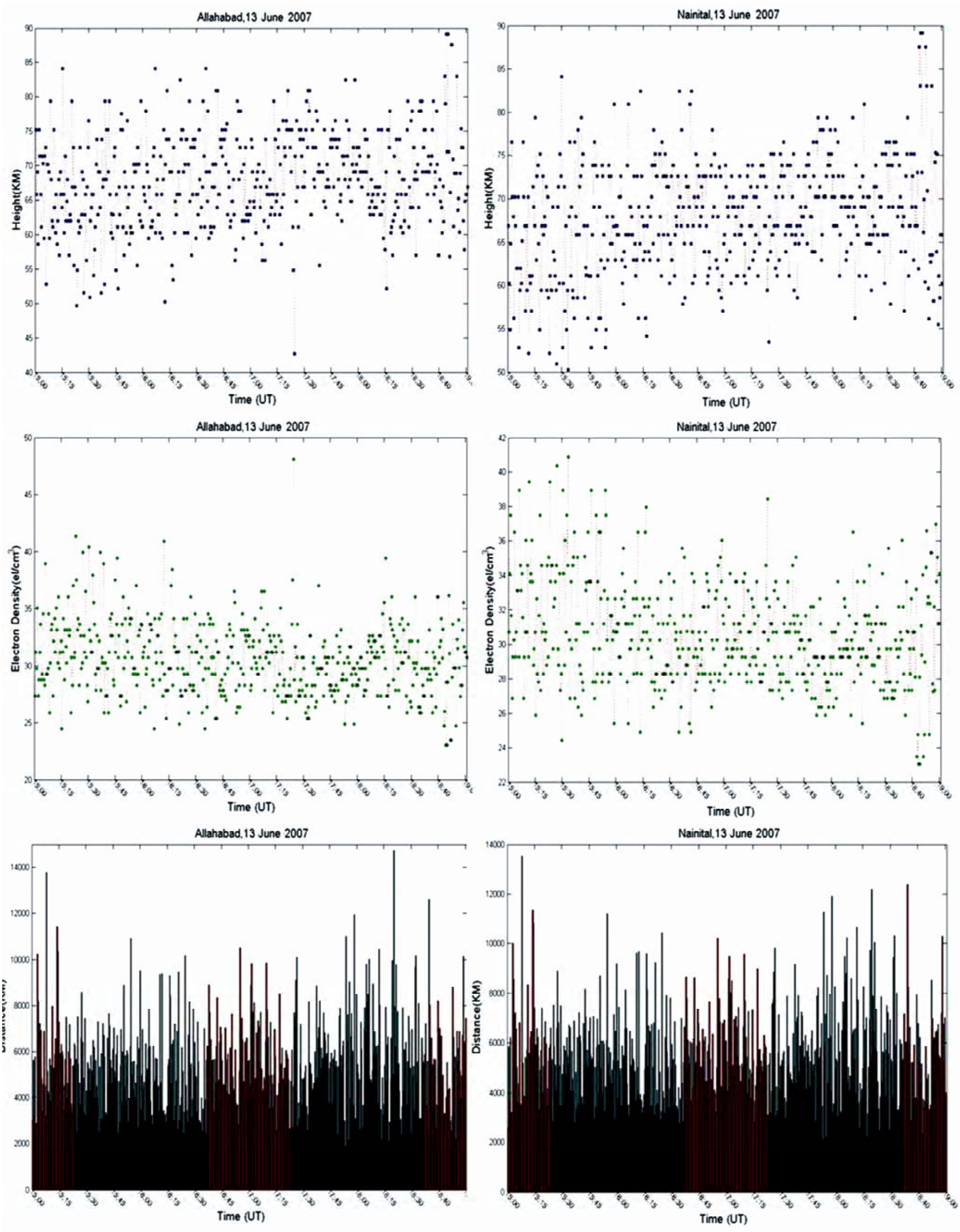

Figure 6. Panels 1 and 2 of the figure shows the ionospheric reflection (in km), electron density at these height (el cm^{-3}) and distance travelled from source lightning discharge in EIWG (in km) with reference to Allahabad and Nainital sites.

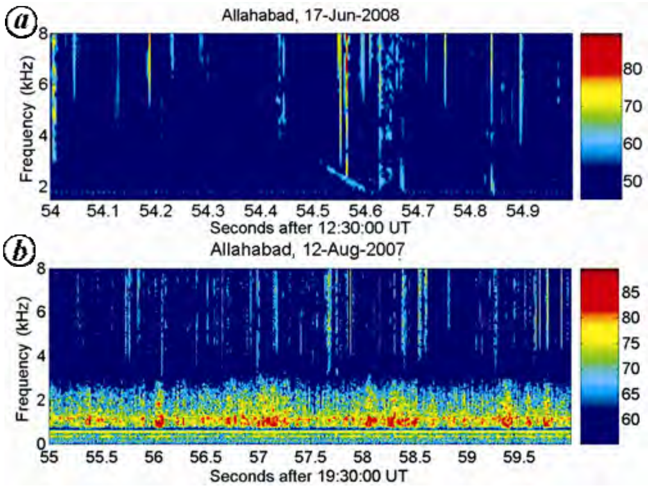

Figure 7. Spectrogram of whistler and chorus observed at Allahabad on 17 June 2008 (***a***) and 12 August 2007 (***b***).

the method of tweek analysis described in detail[23–28], we have computed ionospheric reflection height of tweeks and electron densities at these heights for fundamental mode ($n = 1$). The distance travelled in EIWG from source lightning discharge to the observing site has also been calculated (Figure 6).

Figure 6 shows the temporal evolution of night-time lower boundary of ionosphere like reflection height, electron density and distance travelled by signals from source lightning discharge in EIWG during the night of 13 June 2007. The ionospheric reflection of the tweeks analysed observed at Allahabad and Nainital was found to vary between ~60 and 85 km. Electron densities lie between 25 and 35 el/cm^3 at reflection height of ~60–85 km during the night of 13 June 2007. Estimated electron densities were equivalent to the reflection height of first-mode propagation of tweeks. The results are in good agreement with previously reported profiles from IRI model[23], MF radar[29] and rocket experiments[30,31]. The inferred features are in consistent with the behaviour of ionosphere during perfect quiet geomagnetic conditions. The calculated distance with reference to Allahabad and Nainital site is shown at the bottom panels 1 and 2 of Figure 6. Propagation distance was found to vary in the range ~2000–12,000 km. The extent of the travelled distance by the lightning discharge generated tweeks shows their usefulness as a diagnostic tool for the *D*-region ionospheric study of large geographical region around observation site.

Whistler mode waves and magnetospheric probing

Because whistler waves propagate from a lightning discharge to deep into the magnetosphere, they couple energy from the atmosphere to the magnetosphere. As the wave propagates through the ionized medium embedded in the geomagnetic field, it is dispersed and a particular form of whistler spectrogram (dynamic spectrum in the frequency–time domain) is obtained. The dynamic spectra of whistlers are controlled by the path-length, the distribution of electron density and the magnetic field along the path of propagation. The analysis of dynamic spectra of whistlers gives the information about the L value of the path of propagation, the nose frequency and the electron gyro-frequency. From these analysed parameters of the whistlers we can compute magnetospheric parameters like electron density at the equatorial height, total electron content in a magnetic flux tube of unit cross-sectional area at the reference height, movement of flux of ionization, large scale magnetospheric electric field and electron temperature. Figure 7 *a* shows dynamic spectra of whistlers recorded at Allahabad on 17 June 2008, at 12.40 UT. The lower and the upper cut-off frequencies are 1.68 and 5.63 kHz respectively. The calculated dispersion of the whistlers is 16.41 s$^{1/2}$. The characteristic difference between low- and mid-high latitude whistler spectra is (i) the upper cut-off frequency of low latitude whistler is lower than those observed at mid-high latitudes; (ii) the nose-frequency (~0.4 f_{He}, where f_{He} is the equatorial electron gyrofrequency) for low latitude whistler is ~100 kHz or more and hence is not observed due to heavy attenuation (the absorption coefficient is minimum ~5 kHz and increases with frequency), and (iii) the dispersion is smaller than for mid-high latitude whistlers.

Another class of whistler mode waves is VLF emissions having complex structured and unstructured dynamic spectra observed both on the ground and onboard satellites. Unstructured emissions are characterized by a band limited spectrum for times ranging from a few milliseconds to a few hours, they are called as hiss emissions. Hiss emissions can be observed at repeated time intervals as pulsing hiss[3]. Structured emissions exhibit coherent discrete frequency–time characteristics; these are emissions like chorus, periodic emissions and quasi-periodic emissions[2,9,11]. Figure 7 *b* shows the dynamic spectrum of chorus between 0.75 and 3.2 kHz recorded at Allahabad on 12 August 2007. VLF emissions may be generated following lightning discharges, or triggered by VLF waves of natural origin or by transmitted signals. Simultaneous measurements of VLF waves and charged particles onboard rockets and satellites suggest that the main source of energy for VLF emissions are the energetic electrons in the magnetosphere[32,33]. Whistlers and VLF emissions are essentially considered as mid-high latitude phenomena but their sporadic occurrence in low latitudes is an interesting subject which needs to be investigated thoroughly[34,35]. Simultaneous observation at the three newly set up stations will help us in better understanding of this phenomenon.

Summary

A new instrument, AWESOME VLF receiver has been deployed at three low latitude stations Allahabad, Nainital and Varanasi in India during the year 2007 under

IHY/UNBSSI program for sensitive reception of broadband ELF (30–3000 Hz) and VLF (3–30 kHz) radio signals from natural and manmade sources. The receivers are designed and developed by Stanford University, USA. We have described the performance characteristics of the Atmospheric Weather Electromagnetic System for Observation Modeling and Education (AWESOME) VLF receiver setup. We also discussed a broad range of scientific applications of ELF/VLF data involving measurements of both sub-ionospheric (VLF transmitter signals) and magnetospheric propagating signals (whistlers, emissions, etc). Some of the initial results obtained from the preliminary analysis of the VLF data recorded at all the three stations are presented to show the probing potentiality of ELF/VLF waves in ionosphere and magnetosphere studies. The three new VLF stations have been setup in India with the aim of better understanding of lower D-region ionosphere and magnetosphere in the low latitude region during quiet and disturbed geomagnetic condition. The setup of these VLF stations in India coincides with the beginning of solar cycle 24. So it provides the opportunity to study low latitude lower ionosphere and magnetosphere response to the various geophysical phenomena.

1. Uman, M. A., *The Lightning Discharge, International Geophysics Series*, Academic Press, Orlando, 1987, vol. 39.
2. Helliwell, R. A., *Whistler and Related Ionospheric Phenomenon*, Stanford University Press, Stanford, 1965.
3. Singh, D., Singh, A. K., Patel, R. P., Singh, R., Singh, R. P., Veenadhari, B. and Mukherjee, M., Thunderstorm, lightning, sprites and magnetospheric whistlers-mode radio waves. *Surv. Geophys.*, 2008, **29**, 499–551.
4. Mitra, A. P., *Ionospheric Effects of Solar Flares*, D. Reidel Publishing Co, Norwell, Mass, Dordrecht, 1974.
5. Pant, P., Relation between VLF phase deviations and solar X-ray fluxes during solar flares. *Astrophys. Space Sci.*, 1993, **209**, 297–306.
6. Somoyajulu, V. V., Studies on low latitudes whistlers, Ph D dissertation, Banaras Hindu University, Varanasi, India, 1968.
7. Somoyajulu, V. V., Rao, M. and Tantry, B. A. P., Whistlers at low latitude. *Indian J. Radio Space Phys*., 1972, **1**, 102–118.
8. Singh, R. N., Lalmani and Singh, R. P., Whistlers recorded at Varanasi. *Nature*, 1977, **266**, 40–41.
9. Singh, R. P., Whistler study at low latitude, a review. *Indian J. Radio Space Phys*., 1993, **22**, 139–155.
10. Singh, B., Forty years of whistler research in India. *Indian J. Radio Space Phys*., 2007, **36**, 466–473.
11. Singh, B., Singh, R. and Singh, R., Whistler triplets, bands and fine structures observed in low latitude ground station. *Geophys. Res. Lett.*, 1997, **24**, 2507–2510.
12. Singh, R., Patel, R. P., Singh, R. P. and Lalmani, An experimental study of hiss-triggered chorus emission at low latitude. *Earth Planet Space*, 2000, **52**, 37–40.
13. Singh, K. K., Singh, R., Singh, R. P. and Shyampati, Hisslers: quasi-periodic VLF noise forms observed at low latitude ground station (L = 1.17). *Geophys. Res. Lett.*, 2004, **31**, L19802.
14. Singh, V., Kumar, M. and Singh, B., A new whistler recorder and analyser developed at Agra. *Indian J. Radio Space Phys.*, 2005, **34**, 349–352.
15. Scherrer, D., Cohen, M., Hoeksema, T., Inan, U. S., Mitchell, R. and Scherrer, P., Distributing space weather monitoring instruments and educational materials worldwide for IHY 2007: the AWESOME and SID project. *Adv. Space Res.*, 2008, **42**, 1777–1785.
16. Cohen, M. B., Inan, U. S. and Paschal, E. W., Sensitive broadband ELF/VLF radio reception with the AWESOME instrument. *IEEE Trans. Geosci. Remote Sens.*, 2010, **48**, 3–17.
17. Davies, K., *Ionospheric Radio*, Peregrines, London, 1990.
18. Cummer, S. A., Inan, U. S. and Bell, T. F., Ionospheric D-region remote sensing using VLF radio atmospherics. *Radio Sci*., 1998, **33**, 1781–1792.
19. Outsu, J., Numerical study of tweeks based on waveguide mode theory. In *Proceeding Research Institute Atmospherics*, Nagoya University, 1960, vol. 7, pp. 58–71.
20. Yamashita, M., Propagation of tweek atmospherics. *J. Atmos. Terr. Phys*., 1978, **40**, 151–156.
21. Yano, S., Ogawa, T. and Hagino, H., Waveform analysis of tweek atmospheric. *Res. Lett. Atoms. Electr*., 1989, **9**, 31–42.
22. Yedemsky, D., Raybov B. S., Shchokotov, A. and Yarotsky, V. S., Experimental investigation of the tweek field structure. *Adv. Space Res*., 1992, **12**, 251–254.
23. Ohya, H., Nishino, M., Murayama, Y. and Igarashi, K., Equivalent electron densities at reflection heights of tweek atmospherics in the low-middle latitude D-region ionosphere. *Earth Planets Space*, 2003, **55**, 627–635.
24. Ohya, H., Nishino, M., Murayama, Y., Igarashi, K. and Saito, A., Using tweek atmospherics to measure the response of the low-middle latitude D-region ionosphere to a magnetic response. *J. Atmos. Solar-Terr. Phys*., 2006, **68**, 697–709.
25. Singh, A. K. and Singh, R. P., Propagational features of higher harmonic tweeks at low latitudes. *Earth, Moon Planets*, 1996, **73**, 277–290.
26. Ohya, H., Shokawa, K. and Miyoshi, Y., Development of an automatic procedure to estimate the reflection height of tweek atmospherics. *Earth Planets Space*, 2008, **60**, 837–843.
27. Kumar, S., Kumar, A. and Ramachandran, V., Higher harmonic tweek sferics observed at low latitude: estimation of VLF reflection heights and tweek propagation distance. *Ann. Geophys*., 2008, **26**, 1451–1459.
28. Maurya, A. K., Singh, R., Veenadhari, B., Pant, P. and Singh, A. K., Application of lightning discharge generated radio atmospherics/tweek in lower ionospheric plasma diagnostics. *J. Phys. Conf. Ser.*, 2009.
29. Igarashi, K., Murayama, Y., Nagayama, M. and Kawana, S., D-region electron density measurements by MF radar in the middle and high latitudes. *Adv. Space Res*., 2000, **25**, 25–32.
30. Maeda, K.-I., Study of electron density profile in the lower ionosphere. *J. Geomag. Geoelectr*., 1971, **23**, 139–159.
31. Nagano, I. and Okada, T., Electron density profiles in the ionospheric D-region estimated from MF radio wave absorption. *Adv. Space Res*., 2000, **25**, 33–42.
32. Cornilleau-Wehrlin, N., Solomon, J., Korth, A. and Kremser, C., Experimental study of the relationship between energetic electrons and ELF waves observed on board GEOS: a support to quasi-linear theory. *J. Geophys. Res*., 1985, **90**, 4141–4154.
33. Singh, D., Singh, R. P., Kamra, A. K., Gupta, P. N., Singh, R., Gopalakrishnan, V. and Singh, A. K., Review of electromagnetic coupling between the Earth’s atmosphere and the space environment. *J. Atmos. Solar-Terr. Phys*., 2005, **67**, 637–658.
34. Singh, R., Singh, A. K. and Singh, R. P., Synchronized whistlers recorded at Varanasi. *Parmana – J. Phys.*, 2003, **60**, 1273–1277.
35. Singh, A. K., Singh, R., Singh, K. and Singh, R. P., An explanation of the observation of pulsing hiss at low latitude. *Adv. Space Res.*, 2008, **41**, 1695–1698.

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