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Diurnal Variation of VLF Radio Wave Signal Strength at 19.8 and 24 kHz Received at Khatav India (16º46′N, 75º53′E)

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Abstract

The period from August 2009 to July 2010 was considered as a solar minimum period. In this period, solar activity like solar X-ray flares, solar wind, coronal mass ejections were at minimum level. In this research, it is focused on detailed study of diurnal behavior of VLF field strength of the waves transmitted by VLF station NWC Australia (19.8 kHz) and VLF station NAA, America (24 kHz). This research was carried out by using VLF Field strength Monitoring System located at Khatav India (16º46'N, 75º53'E) during the period August 2009 to July 2010. This study explores how the ionosphere and VLF radio waves react to the solar radiation. In case of NWC (19.8 kHz), the signal strength recording shows diurnal variation which depends on illumination of the propagation path by the sunlight. This also shows that the signal strength varies according to the solar zenith angle during daytime. In case of VLF signal transmitted by NAA at 24 kHz, the number of sunrises and sunsets are observed in VLF signal strength due to the variations of illumination of the D-region during daytime. In both the cases, the signal strength is more stable during daytime and fluctuating during nighttime due to the presence and absence of D-region during daytime and nighttime respectively.

Keywords: *VLF field strength, diurnal variation, ionosphere, solar zenith angle*

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INTRODUCTION

The ionosphere is made up of many gases such as nitrogen, oxygen etc. The solar ultraviolet radiation interacts with the atoms present at this level. This ionizing radiation collides with oxygen molecules. The ultraviolet waves are partly absorbed by the oxygen molecules and so these waves ionize the oxygen molecules [1].

The ionospheric layer breaks down into many layers. These layers are ionized at all times except the D layer. The D layer is close to the earth. It disappears during night. It is due to the sufficient neutral density below 200 km. Due to this, electrons recombine with oxygen within a few hours [2].

The E region ionization decreases in small amount during the night time. The D layer reappears only at that time when the sun rises at the D layer height. The VLF waves travel along the ground as well as they reflect from the ionosphere. That's why these rays are used for communication around the globe and they are also used for monitoring the ionospheric behavior. The VLF waves reflects from the ionosphere, and that's why if something happens in the ionosphere then the VLF radio waves reflecting from the ionosphere will be affected [3–5].

Simple background cosmic radiation also affects continuously on the ionosphere. The energy of cosmic radiation is not strong but they are constantly affecting the ionosphere. But, the solar radiation affects diurnally as well as it affects the ionosphere during solar flares and magnetic storms [6, 7].

So, the solar flare effects are only discrete events during the day time only. During the night time, VLF waves travel up to 90 km to the E layer in the ionosphere and then reflects towards earth. During the daytime the D layer is partially ionized. The VLF radio waves travels through the D layer and so lose some energy in the travel way. The strength of the signal of the VLF waves is stronger at night time than the daytime [8]. The VLF waves respond in different way to different solar activity. In our study, we have recorded VLF data since 2007 and it is observed that VLF radio wave signal strength is affected with the disturbances occurred in the ionosphere and this ionospheric disturbance can be affected on human life [9, 10].

When we use VLF radio waves for communication purposes, solar activity can affect the VLF signal strength. Therefore, the purpose of this study was to investigate how VLF radio waves are impacted by the radiation given off by the sun at various times.

THE VLF EXPERIMENT

For the study of effect of solar activities on the ionosphere, Stanford University, USA, has set up a program. This University has distributed inexpensive SID monitors to space researchers and college as well as University students throughout the world [10, 11]. By using the SID monitors and VLF loop antenna, it is easy to record VLF radio waves transmitted by particular VLF transmitting station.

The VLF field strength monitoring system at Khatav, India (16°46' N, 75°53' E) is shown in Figure1. Experimental set up -two channel VLF field strength monitoring system is shown in Figure 2. Figures 3 (a) and (b) shows loop antennas.

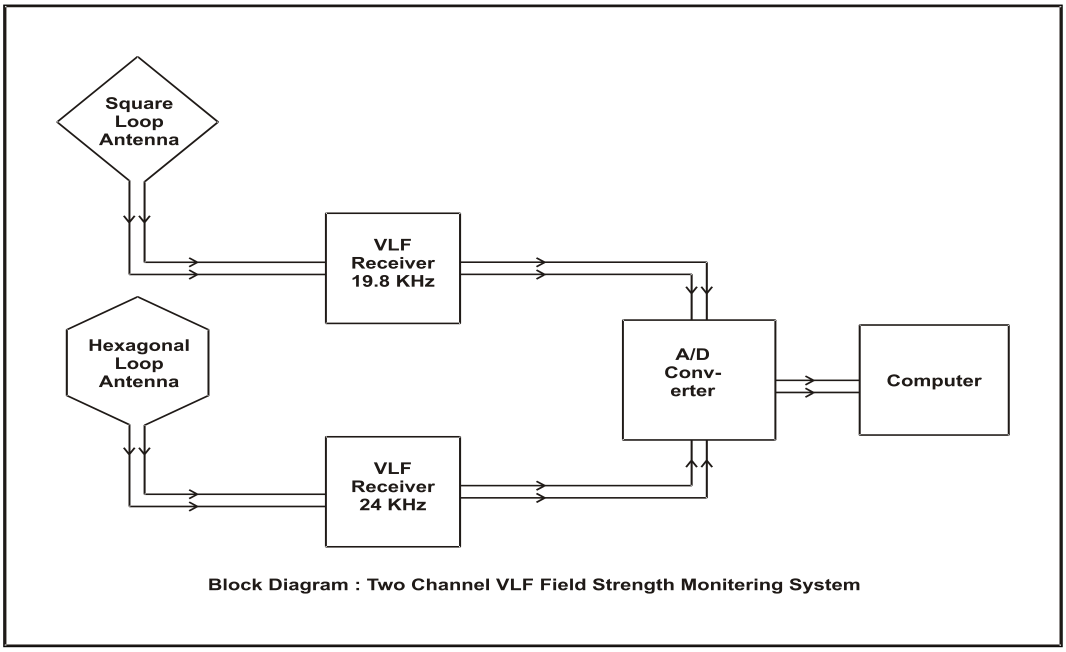

Fig. 1: *Block Diagram of VLF Field Strength Monitoring System which Consists of Loop Antennas, SID Monitor, A/D Converter and Computer.*

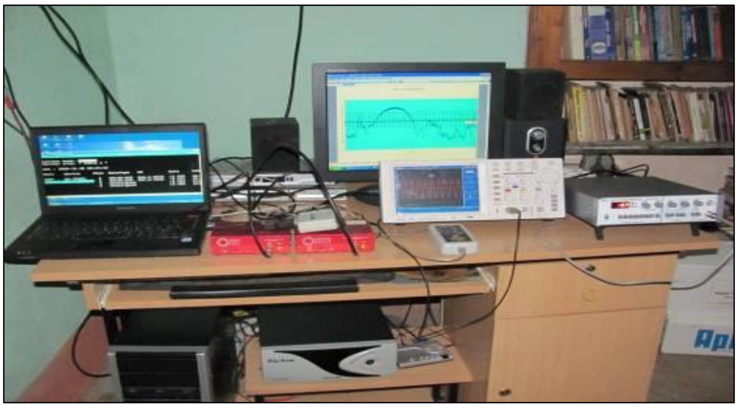

Fig. 2: *Experimental set up—Two Channel VLF Field Strength Monitoring System.*

***Fig. 3:** Loop Antenna: (a) Hexagonal Loop Antenna (b) Square Loop Antenna.*

By monitoring the signal strength of the VLF radio waves reflecting over a period of time, it is possible to draw many conclusions about the characteristics of the ionosphere. It is because of the fact that the radio waves and the ionosphere are so closely related with each other. If there is a change in the VLF signal strength over the daytime, then it is called as sudden ionospheric disturbance (SID). During the SID, the numbers of ionized particles present in the ionosphere increases or decreases and that's why VLF radio waves to be reflect either more or less. The reason of the SID can be determined by comparing SID data to GOES satellite data. GOES satellite directly and continuously monitors the sun and records solar flares [11–13]. If the SID and solar flare occurs at the same time which is found by using GOES satellite data, then there is direct correlation in between ionosphere, sun and the VLF radio waves. In this way, sun and solar flares affect the VLF radio waves which is useful because indirect observations of the ionosphere as well as the sun is possible. The collection of the VLF data by using SID monitor is possible from several different locations. Thus monitoring of VLF waves is very useful not only in understanding the impact of sun on VLF radio waves which relies on the ionosphere but also the understanding of ionosphere. It is very important to study VLF radio wave technology and the ionosphere because the level of ionization of particles in the ionosphere does not remain constant for a long time. When the level of ionization of particles in the ionosphere changes, then we should be aware of the fact that the signal strength of VLF radio waves will also change.

THE SOLAR BASELINE EFFECT ON THE IONOSPHERE OF THE EARTH

During the period 2009–10, sun was relatively calm because there was a very low level of SID activities in the ionosphere of the earth. If due to the solar activity, there is a change in the characteristics of ionosphere then there will be change in the signal strength of VLF radio waves. There is 11-year cycle for solar activity which corresponds to the reversal of sun's magnetic field [3]. However, it is not possible to predict when individual solar flares are going to occur, with a high level of accuracy. During the period 2009–10, the suns activity was at its lowest point of the 11-year cycle. Hence, there were not a big number of solar flares, or SIDs observed during this period. Hence, it was important to take advantage of the lowest solar activity period to understand the sun's baseline effect on the ionosphere of the earth as well as on the VLF radio waves during sun's minimum activity level [14]. If we are able to understand what has happened in the ionosphere without or minimum solar activity then could be easy to solve the issues of the technology accuracy. Further we will be prepared to handle the technology and accuracy issues when the solar activity are frequent or more. Around the world, more and more scientists are recording

SID monitor data and they noticed the effect on radio communications. For this study a SID monitors was used to record VLF radio waves from US navy transmitters NAA (24 kHz) and NWC (19.8 kHz) and monitors changes in the ionosphere [15, 16]. The SID monitors data for above mentioned frequency was collected since 2007 and analysis as well as comparison was done.

The signal strength varies in a characteristic way for each station during sunrise and sunset due to the variations in the ionization level of the ionosphere. By studying the effect of solar radiation on the ionosphere at a specific moment, the conclusion is that the ionosphere is affected by the solar radiation and specifically by the zenith angle of the sun with respect to certain location. There is effect of solar radiation on the VLF radio waves reflected from the ionosphere of the earth.

Sudden ionospheric disturbance (SID) monitors of VLF frequencies 24 kHz and 19.8 kHz were obtained from Solar Center Department of Stanford University, USA [17, 18]. These VLF monitors were made available to the research institutions. The goals of the SID monitor program were to distribute SID monitors to researchers around the world have them monitor SIDs and do research and share the data collected.

During the nighttime the VLF signal strength observed is lower as compared to the maximum strength observed at maximum zenith angle during daytime. But the VLF signal strength varies from night to night and day to day. However, there is definite dip, or decrease in VLF signal strength, just before sunrise which is followed by a recovery and a more subtle decrease in VLF signal strength.

SUNRISE AND SUNSET PATTERN OBSERVED IN VLF RADIO WAVE SIGNAL

To find out sunrise and sunset pattern in VLF radio wave signal in our SID data, we have considered VLF data from 31st July, 2009 to 30th July 2010 and compared the local sunrise/sunset time, as well as the sunrise /sunset time in ionosphere [1]. It is observed that the ionosphere is ionized before the sun rises and after the sun sets because there is a change in radio signal strength meaning that there is a change in the level of ionization in ionosphere. The goal of this study was to use VLF radio waves as a tool to monitor the ionosphere and to observe how radiation from the sun affects the strength of VLF radio waves and how the solar flare affects on the ionosphere. During the minimum solar activity period there was a very low solar activity in the form of solar flares. That's why we have focused our concentration to the analysis on how sunrise and sunset affect on the ionosphere and VLF radio waves which are reflected by the ionosphere.

As a sunrise effect, the sunset effect can also be explained in a similar way. The sunset occurs first at the receiver. The Earth blocks the VLF radio rays as the sun sets on the ionosphere. Consequently the solar radiation cannot reach the ionosphere, and hence the signal strength decreases drastically in a short period of time.

By comparing our data with other data from across the globe, it is noticed that graphs have differences in terms of shapes, sunrise and sunset times and signal strength level. The calibration of the individual SID monitor is major cause of the differences. We have to calibrate the SID monitor for + -5V. A very small difference in calibration can cause much difference in the results.

This is due to differences in calibration or the variation at local signal strength. The signal strength difference is not so important because it is the change in signal strength, not the actual reading that matters. It is also observed that a longitudinal difference affects more than the latitudinal differences.

This study shows how many interesting characteristics of VLF radio waves depend on the behaviors of the ionosphere which depend on the solar radiation. However, there are lot of things that are not known about VLF radio waves and their relationship with the ionosphere. As further research it would be interesting to study why the signal strength at night fluctuating. It would also be interesting to study effects of solar flares on VLF radio waves in different locations around the world.

DIURNAL VARIATION OF VLF FIELD STRENGTH–NWC (19.8 kHz)

The distance between NWC Cape North 19.8 kHz transmitting station in Australia and Khatav (India) is around 6184 km. Since single-hop VLF radio wave reflection via D-layer does not reach beyond 2000 km and assuming earth-ionosphere waveguide mode of propagation, there must be at least three-hop propagation between Australia and India during daytime over reflection points in the ionosphere [1, 9]. During nighttime, however, propagation can be complex because reflection takes place from higher heights via E and/ or F layers. The meaning of diurnal variation is nothing but variation during whole day. For the ionospheric layers, during the daytime the critical frequency depends upon the zenith angle of the sun on the earth [19]. Diurnal variations of VLF signals propagated over long distances (>5 Mm) were studied by Yokoyama as well as Tanimura in 1933 with diurnal phase variations first reported by Pierce in 1955 and Crombie *et al.* [20]. In 1958 during night-time, the ionosphere has only the F and E layers which reflect VLF transmission. During daytime, the solar X-rays and UV rays ionize neutral atmosphere creating the D, E and F layers. The D layer is created due to ionization of NO by solar H-α (1216Å) radiation. During nighttime, E and F layers reflects VLF signal. But, it is also observed that, as the sun changes its angle of radiation to the reflection point, the signal strength increases and it is a maximum to the solar azimuth angle at reflection point. For further change in solar radiation angle from the azimuth towards setting side, the signal strength decreases. The Figure 4 shows variation in field strength of 19.8 kHz radio wave on July 31 to Aug 1, 2009 at Khatav, India.

TYPICAL DIURNAL CURVE OF VLF SIGNAL AT 19.8 kHz

Figure 4 shows sunrise and sunset effect as well as variation of signal strength over day and night time. The distance between the transmitter (NWC Cape North Australia) and receiver (Khatav, India) is 6184 km. Fig. 4 shows first sunrise SR_1 observed at 23:23 UTC (31, July 2009) second SR_2 at 00:03 UTC and third one SR_3 observed at 03:04 UTC (Aug 1, 2009). After sunrise, the electron density in the D-layer first decreases and then started to increase as suns elevation angle goes on increasing. Figure 5 shows VLF radio wave propagation from NWC to Khatav (India). The distance between NWC transmitting station and Khatav is around 6184 km [1].

Since, single-hop VLF radio wave reflection *via* D-layer does not reach beyond 2000 km so there are at least three reflection points R1, R2 and R3 are shown in Figure 5; T is transmitter at NWC and R is receiver at Khatav. As the sun goes down from noon to evening, VLF signal strength decreases until sunset. The first sunset SS_1 the second SS_2 and third SS_3 is observed at 10:19 UTC, 10:54 UTC and 12:22 UTC respectively on Aug 1, 2009. After sunset, the reflection of VLF signal occurs from E and F regions. Since, there is no source of ionization after sunset, the VLF signal strength is highly variable throughout the night until next sunrise at the reflection point.

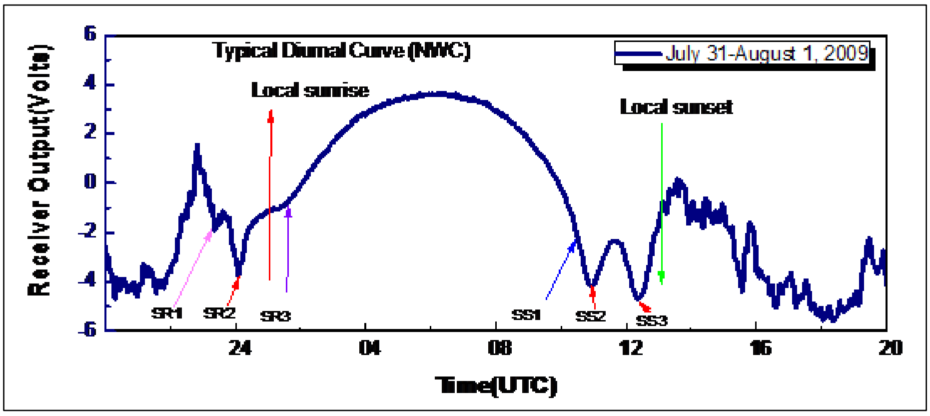

Fig. 4: *Typical Diurnal Variation of NWC Signal Strength (19.8 kHz) Received at Khatav (India) Clearly Shows Sunrise and Sunset on July 31 to Aug 1, 2009.*

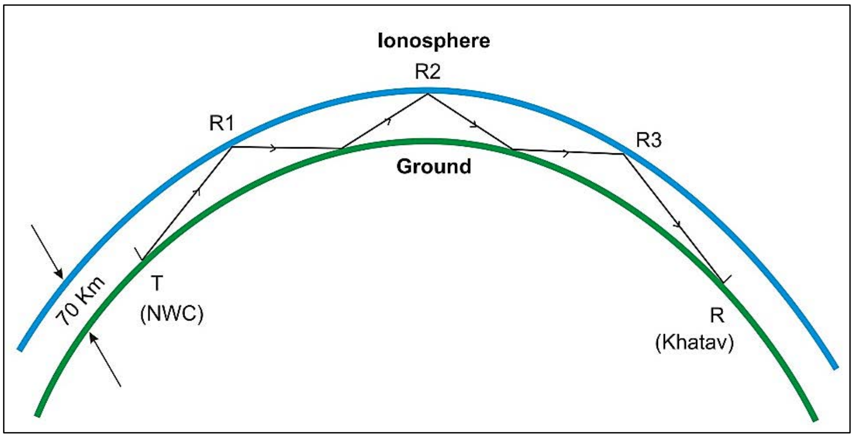

Fig. 5: *NWC (Australia) to Khatav (India) VLF Path.*

The local sunrise and sunset is also shown at 00:28 UTC and 13:29 UTC respectively. It is observed that the field strength variation is proportional to the elevation angle of the sun at the reflection point. When sun is at azimuth, then the solar radiation is maximum. It enhances the electron density at noon and so field strength is observed to be maximum at noon to the reflection point.

We propose the following model of propagation of radio signals between Australia and India to explain the diurnal trend of variation in the observed signal strength. We assume that, at least three reflection points in the ionosphere along the great circle. The sunrise takes place at these reflection points successively. Furthermore, sunrise takes place first at F-layer and finally at D-layer. This means that, as a result of ionization electron density of F –layer begins to increase. This is followed by increase of electron density of E-layer and finally that of D-layer. This sequence of ionization first takes place at the first reflection point in the ionosphere and subsequently at the second and third reflection points. As a result of changes in reflection levels before ground sunrise, we observe somewhat irregular changes in the received field strength of signal. Once all the three reflection points are illuminated by solar ionizing radiation, then only signal strength begins to increase monotonically until the sun's elevation angle attains maximum value. Thereafter, signal strength begins to decline monotonically until the sun sets at three reflection points in the ionosphere sequentially at different ionospheric layers. Finally during nighttime, signals are reflected normally from F-layer or E-sporadic layer. At night, signal strength is highly variable due to variations in electron density and heights of F-layer. This diurnal trend in the signal strength variation is typical one that repeats day after day. This change in signal strength depends upon intensity of solar radiation, various seasons occurred on the earth's surface, various solar and geophysical activities that are continuously taking place on the surface of the sun as well as on the surface of the earth. The other important astronomical activities such as Gamma Ray Bursts (supernova explosion) can also affect on the VLF signal strength.

DIURNAL CURVES OF VLF FIELD STRENGTH–NWC (19.8 kHz) RECEIVED AT KHATAV

Diurnal Variation of NWC Signal for the Month of August 2009

Figure 6 shows the Diurnal variation in the field strength (August 2009) of NWC Cape North VLF radio station received by VLF field strength monitoring system at Khatav. From 00 UTC to 10 UTC, the field strength of 19.8 kHz shows semicircular path. It reaches to maximum value at around 6 UTC. The various peaks are observed on the curves during 00 UTC to 10 UTC which are due to the lightning and local disturbances. The downward spikes are observed due to the sudden loss of signals. The diurnal trend in each curve is similar which indicate the effect of sunrise and sunset on the VLF signal strength. It is also observed that the signal strength is maximum at 7 UTC. There is a fluctuation in signal strength observed at night because solar radiation is unavailable during nighttime and radio rays reflect from F region of the ionosphere. Figure

7 shows monthly average curves of diurnal variations of August, 2009. In both these Figures 6 and 7, it is seen that the signal strength during daytime is more stable and during nighttime, the signal strength is more fluctuating.

The navigational transmitters which operate in very low frequency (VLF) band are used for long distance communication, positioning and timings. The VLF signals generated by navigational transmitters propagate in the guided mode between the earth's surface and the lower region of the ionosphere which form the earth-ionosphere waveguide (EIWG). At VLF, the earth's surface and the lower ionosphere act as good conductor. Therefore, the guided VLF propagation occurs with low attenuation and can be received literally around the world. Yokoyama and Tanimura first observed and studied diurnal variation of amplitude of 17.7 and 22.9 kHz VLF signals propagated over long distances (> 5 Mm), with diurnal phase variations [21]. Their results showed that the phase advanced during sunrise, with pronounced steps coincident with amplitude minima. Some researchers have reported the diurnal variation of VLF transmitter signal amplitude/phase showing the sunrise and sunset effects [22, 23].

Here analysis of VLF field strength of 19.8 kHz signal from NWC (21.8°S, 114.1°E, 1 MW) transmitter to Khatav (India) is discussed during the period of July 31 2009 to August 30, 2010. We have used VLF field strength data recorded at 5 second resolutions. We can also choose resolutions less than 5 seconds or more than 5 seconds.

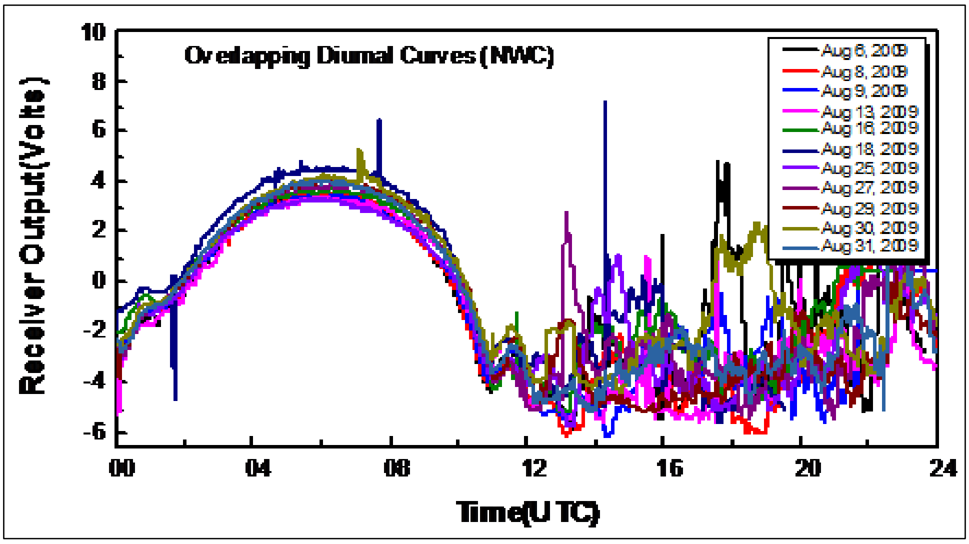

Fig. 6: *Overlapping Curves of Diurnal Variations of August, 2009.*

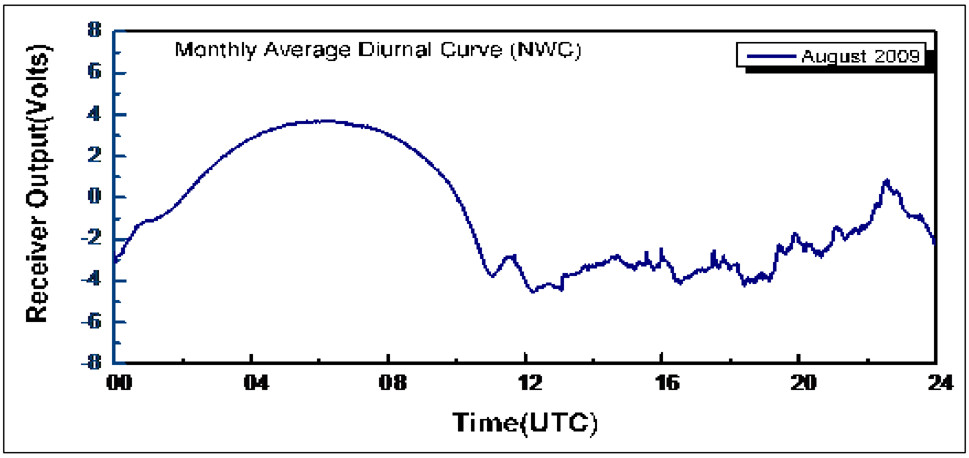

Fig. 7: *Monthly Average Curves of Diurnal Variations of August, 2009.*

Diurnal Variation at 24 kHz Signal

The distance between NAA transmitting station, USA and receiver at Khatav is around 12156 km. The limit of single-hop VLF radio wave reflection *via* D-layer is around 2000 km. Due to this region many signal minima and maxima are observed.

Initially, one SID Monitor was installed and many loop antennas were constructed to receive good signal strength. Different types of copper wires including 26 AWG to 20, 19, 16, and even 12 AWG wires were used to build loop antenna. Along with these different wires, different diameters of wooden frames were used to receive required signals.

Figure 8 shows the Diurnal variation of NAA signal received by VLF field strength monitoring system at Khatav, India on September 26, 2009. From 00 UTC to 10 UTC, the field strength of 24 kHz does not shows semicircular path as NWC. It reaches to maximum value and minimum value for many times. The various minima are observed due to sunrises on the curve. Some spikes are observed which are due to the lightning and local disturbances. The downward spikes are observed due to the sudden loss of signals. In both these figures, it is seen that the signal strength during daytime is more stable and during nighttime, it is more fluctuating. Figure 9 shows overlapping curves of NAA signal of some quite days in the month of August 2009. From this figure, it is observed that the signal strength of NAA shows almost similar diurnal pattern for each day.

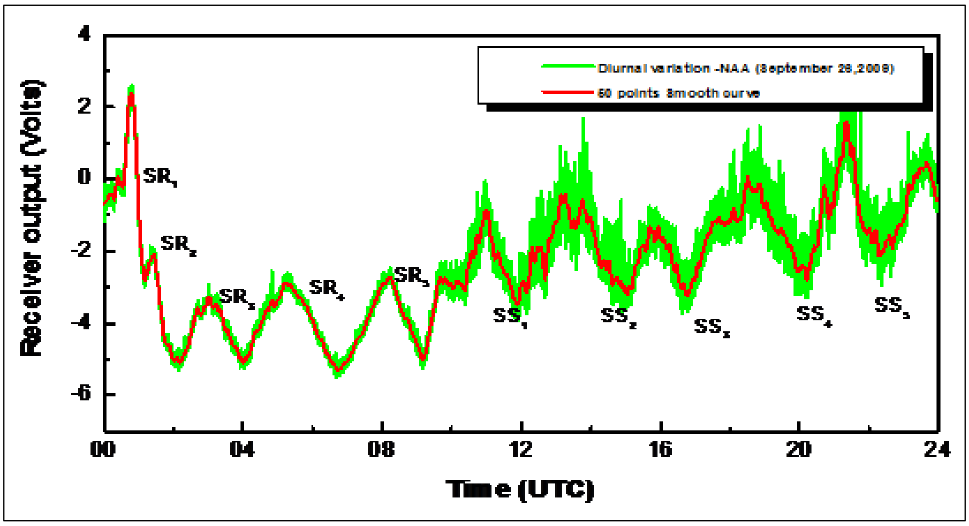

Fig. 8: *NAA Signal Received at Khatav on September 26, 2009.*

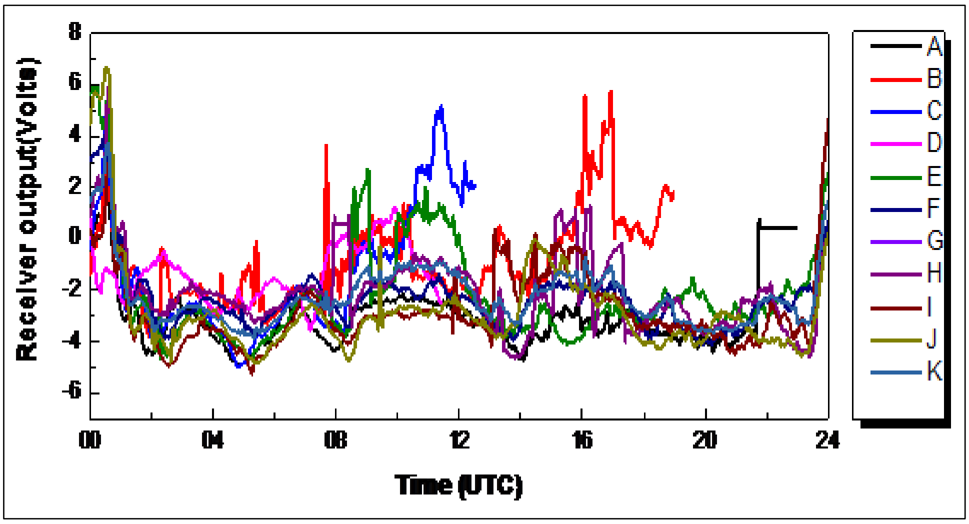

Fig. 9: *Monthly Average Curves of Diurnal Variations of August, 2009.*

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In Figure 9, A- August 1, B- August 2, C- August 5, D- August 6, E-August 8, F- August 11, G- August 13, H- August 15, I-August 21, J- August 23, K- August 28.

Comparison between Diurnal Variations of NAA (24 kHz) and NWC (19.8 kHz)

The original overlapped VLF diurnal curves continuously recorded by using AFMC data logger for NAA and NWC signal during December 7, 2009 to December 10, 2009 is shown in Figure 10. From these curves, it is observed that NWC signal shows semicircular curve during daytime and NAA signal shows many peaks during daytime. It is also observed that, well before local sunrise time at receiver, NWC as well as NAA shows maximum signal strength peaks. For the case of NAA signal, there is increase and decrease in signal strength for many times up to the local sunset is observed.

Figure 11 shows the comparison of diurnal curves of the field strength of NAA and NWC received at Khatav on August 18, 2009. From the figure it is clear that NWC signals shows clearly the sunrise and sunset pattern while NAA signals shows many fluctuations. From comparison between the two overlapped curves, it is observed that two and or three sunrises and the same number of sunsets are observed in NWC signal at 19.8 kHz while about 6 sunrises and 6 sunsets are observed in NAA signal at 24 kHz.

The signal at 19.8 kHz shows maximum value at 7 UTC and at the same time NAA signal also shows its one of the maximum points. It indicates that NAA and NWC signals are coming to the receiver antenna from east and from west. In general, the average day signal exceeds the average night signal in strength. This is due to the higher attenuation of modes in the nighttime than that in the daytime. The signal emerging from the sunrise and sunset transition is associated with amplitude fadings (minima) and changes in the signal phase occurring around local sunrise or sunset. Around the time of sunrise and sunset along the transmission path three amplitude minima at sunrise labeled as SR_1, SR_2, and SR_3 and three amplitude minima at sunset, SS_1, SS_2, and SS_3 are observed. As seen from curves, the rapid change of field strength takes place at the time of the sunrise.

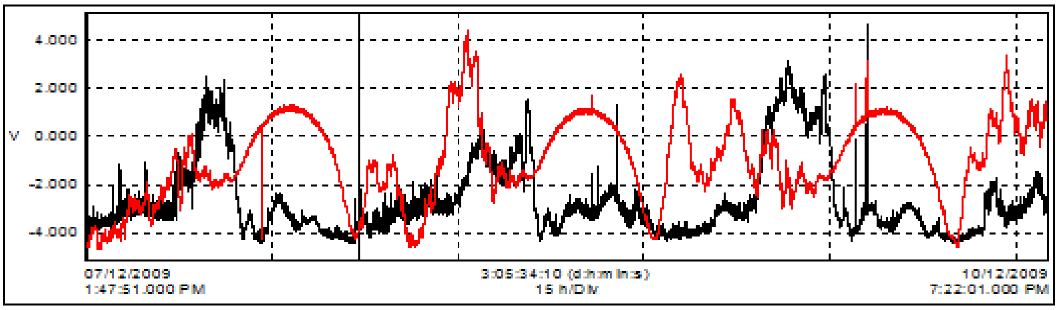

***Fig. 10:** Original Overlapped VLF Diurnal Curve Continuously Recorded by Using AFMC Data Logger for NAA and NWC Signal During December 7, 2009 to December 10, 2009.*

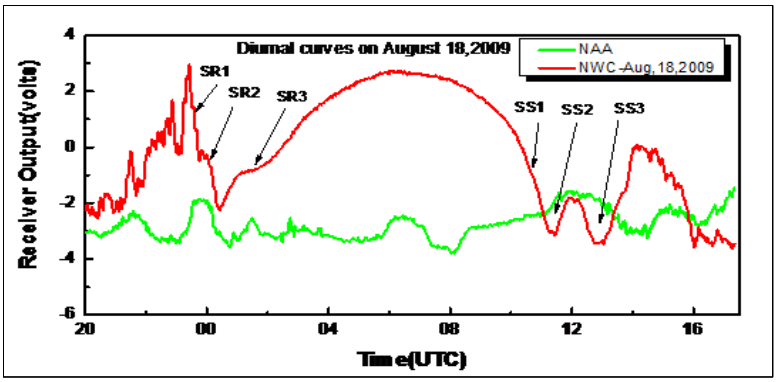

***Fig. 11:** Diurnal Variations of NAA (24 kHz) and NWC (19.8 kHz).*

The signal variability is more in night than in day indicating that propagation path is more stable in the day, suggested that at sunrise, for east to west-transmission, two waveguide modes are present in the dark part of the path between the transmitter and the dawn discontinuity and at the discontinuity the second mode is converted to first mode so that no second mode exists in the daylight part of the path [24].

Crombie showed that the consequences of these assumptions are that, when destructive interference takes place between modes resulting minimum in VLF signal amplitude, the rapid amplitude and phase change is also observed [25]. In our case for NWC the rapid amplitude during sunrise and of increasing amplitude during sunset which is in agreement with Crombie's theory. It is found that the number of signal minima at sunrise and sunset depend on the extent of the distance traversed by the signals in east-west direction under their (Transmitter Receiver Great Circle Path) TRGCP. Generally, if the signal traverses greater component in the east-west direction or vice versa, then more number of minima would be observed. It is interesting to note that the depth of fading at sunset is greater than at sunrise.

Thus, there is a likely difference between the sunrise and sunset mode conversion efficiencies. According to Crombie, the depth of fading should increase as the sunrise terminator approaches the transmitter because the path under illumination is elongating hence increase in attenuation of the second order mode [26]. Conversely, the depth of fading should decrease as the sunset terminator moves to the transmitter because of decrease in the illuminated path length hence, low attenuation of the second order mode.

This is contrary to our results which show that, the depth of fading of the NWC signal at sunrise decreases as the terminator moves from the receiver to the transmitter and increases at sunset. This disparity between the depth and pattern of minima indicates the more complex propagation conditions probably involving more than two modes at night and dominant day mode at the terminator converted into a series of night time modes on the paths like NWC-Suva during sunrise and sunset as has been also reported by Clilverd [27].

CONCLUSIONS

Due to the distance between NWC Cape North transmitting station in Australia and receiver at Khatav (India) which is around 6184 km, the signal strength variation shows few minima during sunrise and sunset. This VLF propagation is trans-equatorial. In case of VLF signal transmitted by NWC at 19.8 kHz, the deepest minima occur three times. During sunrise at about 24 UTC deep minima is observed (SR_2). During sunset, two or sometimes three deep minima are observed. During sunrise times other two minima shows signal strength fading (SR_1 and SR_3).

During sunset the two other deep minima are also observed (SS_1 and SS_2). The pattern of minima indicates the complex propagation conditions may be due to more than two modes. During sunrise and sunset terminator time, interference of various modes shows minima. It is quite well known that the D-region ionospheric layer changes its properties diurnally and this change particularly in electron density depends on the illumination of the region by the sunlight.

The signal strength is observed to be increased from third sunrise SR_3 up to 6.30 UTC. This shows that the signal strength increases according to the solar zenith angle. The VLF signal strength reaches to its maximum value during daytime when sun reaches to 0 degree zenith angle. This is observed when maximum reflections of VLF waves take place due to maximum illumination. After 6.30 UTC, the illumination of the D-region decreases as solar zenith angle changes from 0 degree to the -90 degrees.

In case of VLF signal transmitted by NAA at 24 kHz, Due to the great distance of the order of 12156 km between NAA transmitting station, USA and receiver at Khatav, the number of sunrises and sunsets are observed in VLF signal strength. There are five sunrises and five sunsets observed in a VLF signal strength graph. This is due to the variations of illumination of the D-region due to sunlight for a long TRGCP between NAA and Khatav.

The signal strength is more stable during daytime and fluctuating during nighttime. It is due to the presence and absence of D-region during daytime and nighttime respectively.

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