Some observed characteristics of daily minimum of an LF signal

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Received 6 February 1996; revised 20 December 1996; accepted 6 February 1997

The daily minimum (DM) of amplitude of a long distance 40 kHz radio signal propagated over a low latitude path shows seasonal variation in its time of occurrence and also in its magnitude. Later occurrence of minimum is observed in winter compared to other seasons. The level of the minimum is lowest in monsoon and highest in winter. The times of occurrence of DM are well correlated with meteorological parameters. During most of the geomagnetically active days DMs disappear.

1 Introduction

In the case of long distance propagation, it is well established that very low frequency (VLF) and low frequency (LF) radio waves are guided between the earth’s surface and the lower ionosphere. Such propagation of VLF and LF radio waves in the earth-ionosphere waveguide is highly dependent on conductivity parameter $1,2$ of the lower ionosphere. The variation of conductivity parameter over 24 hours is mainly responsible for the diurnal variation of the amplitude of an LF signal. Variation of conductivity parameter of the lower ionosphere is appreciable during sunrise and sunset transition periods. After sunrise fade the amplitude of the LF signal increases to a small maximum. After that it gradually decreases showing a minimum. This minimum corresponds to the lowest value of signal strength over a complete day. The level of this minimum is controlled by ionospheric conditions $3$. There is no report regarding the seasonal variation of its magnitude and time of occurrence. The present paper is a short report on the characteristics of daily minimum observed in the case of a 40 kHz signal propagated over a long distance of 5100 km from Sanwa, Japan, to Calcutta, India. This is a low latitude path. The effect of geomagnetic storms has also been discussed in relation to extra-ionization in the lower ionosphere.

2 Observations and results

The field strength of the 40 kHz signal ('call sign: JG2AS/JJF-2') transmitted from Sanwa (36°11'N and 139°51'E), has been recorded round-the-clock in our laboratory in Calcutta for a period of two years from April 1981 to March 1983. The receiving system consists of a loop antenna feeding a number of operational amplifiers used in tuned radio frequency mode. The output is then detected and further amplified to drive a pen recorder. The maximum gain of the amplifier is 120 dB at low input (1 $\mu$V). The band-width is 200 Hz. The reflection height for LF radio waves is 70 km at day and 90 km at night $4,5$. The geographic position of transmitter (T) and receiver (R) along with waveguide propagation path is shown in Fig. 1. The path is mainly over land, and a small part is over the sea of Japan.

The 40 kHz signal under analysis is characterized $6$ by a lower daytime level compared to nighttime level. Figure 2 shows full diurnal record of field strength variation of 40 kHz signal. In Fig. 2, A and B represent sunrise and sunset fades, respectively. After the sunrise fade the signal gradually rises exhibiting a small peak which is called post-sunrise maximum. After post-sunrise maximum the signal level again fades out showing a minimum. The record shows that the level of this minimum is the lowest value of amplitude over a complete day. We assign it as ‘daily minimum' (DM). Though the daytime signal level is appreciably smaller compared to nighttime level, DM is not distinct in some days. Even then DM was clearly identified from its valley-like shape indicated by an arrowhead in Fig. 2. The time of occurrence of daily minimum is repeated after each
Fig. 1—Geographic locations of transmitting station (T) Sanwa and receiving station (R) Calcutta. (The curve shows the wave guide propagation path approximately along W-E direction.)

Fig. 2—Full diurnal record of 40 kHz signal showing the occurrence of daily minimum (DM) indicated by an arrowhead. [A and B represent sunrise and sunset fades respectively.]
24 h with a gradual seasonal variation. But on some days of each month DMs were absent. It is worth mentioning that the missing DMs were closely related to the principal geomagnetic storms reported in Solar Geophysical Data Book brought out by NOAA. Details of DM over the two-year period are shown in Table 1. It is clear from Table 1 that the absence of DM is moderately correlated (60% correlation) with geomagnetic storm. To get a quantitative idea about the effect of geomagnetic activity on the 40 kHz signal on the days of absence of DM, we have evaluated the correlation coefficient between the average level of the signal and the average Dst value. Averages of both have been considered over the period 0700-1200 hrs LT. The correlation coefficient is 0.72 on the days of absence of DM and it is 0.26 on the days of occurrence of DM. However, the time delay observed between the commencement of principal geomagnetic storms and missing of DMs ranged from 5 to 21 h. The time of missing DM has been considered as the average time of DMs occurred within ±3 days of missing DM.

The month-to-month variation of the time of occurrence of DM at mid-point of propagation path, is shown in Fig. 3. In December, January and February DMs occur slightly after the noon period at mid-point of propagation path and in all other months DMs occur at pre-midday at the mid point of propagation path. The maximum uncertainty in the recorded time is ±3 min. The time of occurrence of DM is far away from sunrise time at the transmitter and receiver. The time differences between sunrise at the receiver, and occurrence of DM along with sunrise time at the transmitter and receiver in different months have been shown in Table 2. It is clear that the daily minimum occurs earlier in May, June, July and August. Very late occurrence of DM is observed in December, January and February. Interestingly it is noted that occurrence of DM is shifted rapidly towards midday during the period November-December. Reverse shifting from midday zone towards morning zone occurs during the period February-March.

The level of DM exhibits a month-to-month variation in the case of the present low latitude propagation. In Fig. 4 monthly variations of average values of level of DM are shown. The magnitude of DM is high in December and January, whereas it is remarkably low in July, August and September. The level is moderate in April, October and November. The lower level of DM in the curve during the period of July, August and September is the characteristic feature of the present LF propagation at 40 kHz. A small dip is noted in April.

Figures 3 and 4 clearly indicate that the results are appreciably controlled by the position of the sun and climatic conditions. In order to investigate the effect of climate, a year is divided into
Table 2—Time of sunrise at transmitter and receiver, and time difference between commencement of DM and sunrise at receiver

<table>
<thead>
<tr>
<th>Months</th>
<th>Sunrise time (hrs IST) at Transmitter</th>
<th>Sunrise time (hrs IST) at Receiver</th>
<th>Mean difference between commencement time of DM and sunrise time at the receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0345</td>
<td>0620</td>
<td>5 h 10 min</td>
</tr>
<tr>
<td>February</td>
<td>0325</td>
<td>0610</td>
<td>5 h</td>
</tr>
<tr>
<td>March</td>
<td>0345</td>
<td>0545</td>
<td>2 h 25 min</td>
</tr>
<tr>
<td>April</td>
<td>0200</td>
<td>0520</td>
<td>2 h 40 min</td>
</tr>
<tr>
<td>May</td>
<td>0130</td>
<td>0455</td>
<td>2 h 35 min</td>
</tr>
<tr>
<td>June</td>
<td>0120</td>
<td>0450</td>
<td>2 h 30 min</td>
</tr>
<tr>
<td>July</td>
<td>0130</td>
<td>0500</td>
<td>2 h 30 min</td>
</tr>
<tr>
<td>August</td>
<td>0155</td>
<td>0515</td>
<td>2 h 15 min</td>
</tr>
<tr>
<td>Sept.</td>
<td>0215</td>
<td>0525</td>
<td>2 h 35 min</td>
</tr>
<tr>
<td>October</td>
<td>0240</td>
<td>0535</td>
<td>2 h 45 min</td>
</tr>
<tr>
<td>November</td>
<td>0310</td>
<td>0550</td>
<td>2 h 30 min</td>
</tr>
<tr>
<td>December</td>
<td>0240</td>
<td>0610</td>
<td>5 h</td>
</tr>
</tbody>
</table>

Fig. 4—Monthly variation of average value of the level of DM in terms of induced voltage at the input of the receiver

Figure 5 shows seasonal variation of magnitude of DM exhibited by 40 kHz radio signal and variation of meteorological parameters over receiving station. The level is extremely low in monsoon compared to that in other seasons. The level is
highest in winter. Pre-monsoon level is comparable to post-monsoon value. The DM-curve is almost an inverted form of temperature-humidity product curve. Correlation coefficients between DM and temperature, between DM and relative humidity, and between DM and relative humidity-temperature product are -0.60, -0.84 and -0.81, respectively.

3 Discussion
During sunrise the signal exhibited steep fading due to interference of different order of modes. The effect of mode conversion and mode interference are particularly evident at sunrise and sunset (fade A and B in Fig. 2). In the present observation DMs occur much after the sunrise. During DM the whole path is covered with day. So a DM cannot be due to modal conversion or interference with higher order modes.

The boundary of the ionosphere at 70 km plays the role of a waveguide reflector, and the region between 55 and 65 km plays the role of absorber. The origin of DM lies in two factors, namely, (i) the variation of conductivity parameter \( \Delta \omega_r \) at ionospheric reflection zone near 70 km during the period from morning to midday and (ii) increase in electron density in the absorption region below 70 km. In waveguide mode theory the conductivity parameter is defined as \( \omega_r = \omega_0^2/v \), where \( \omega_0 \) is the angular plasma frequency and \( v \) the collision frequency of electrons. This parameter is given due importance for the propagation of VLF and LF signal. In Fig. 6 is shown the variation of attenuation of signal level with conductivity parameter for first mode. The curve has been drawn by extrapolating the result of Yamashita up to 40 kHz. The curve shows that attenuation is minimum at \( \omega_r = 1.5 \times 10^3 \) s\(^{-1} \). After that attenuation the signal again increases with further increase of \( \omega_r \), Crouchley and Rahmani and Wait considered \( \omega_r = 2 \times 10^3 \) s\(^{-1} \). On the other hand Yamashita showed that sudden enhancement of signal strength (SES) in the VLF range is well explained if \( \omega_r \) at 70 km height be considered as \( 2 \times 5 \times 10^4 \) s\(^{-1} \). Again the plasma frequency given by Budden is \( 8.98 N_e^{1/2} \) (\( N_e \) being the number density of electrons), and \( v = 10^7 \) s\(^{-1} \). Using \( N_e = 10^8 \) m\(^{-3} \) the value of conductivity parameter becomes \( 3.2 \times 10^4 \) s\(^{-1} \). The electron density in D-region of the middle of propagation path may go up to \( 10^9 \) m\(^{-3} \) during large solar flux at midday. In this case \( \omega_r \) becomes to be \( 3.2 \times 10^5 \) s\(^{-1} \). After sunrise the solar zenith angle decreases gradually. This causes appearance of more and more solar ionizing radiation both at 70 km (the reflection height) and at the absorption region below 70 km. Hence, during this period electron density of these two regions increases. The rate \( q_\lambda(x,h) \) of electron production per unit volume at a height \( h \) and zenith angle, \( x \), may be written as

\[
q_\lambda(x,h) = q_{10} \exp \{1 + \ln \tau_1 - \tau_2 \sec x\} \quad \ldots \quad (1)
\]

where, \( \tau_1 \) is the optical depth of the atmosphere down to height \( h \) corresponding to wavelength \( \lambda \), and \( q_{10} \) the rate of production of electrons at a height corresponding to unit optical depth for overhead sun. Again at quasi-equilibrium, the rate of electron production is equal to the rate of disappearance due to recombination and attachment processes. In this case

\[
q_\lambda = a_{eff} N_{e\lambda}^2 \quad \ldots \quad (2)
\]

where, \( a_{eff} \) is the effective recombination coefficient and \( N_{e\lambda} \) the contribution to electron density by the radiation of wavelength \( \lambda \).

From Eqs (1) and (2) one gets

\[
N_{e\lambda} = \left[ q_{10}/a_{eff} \right]^{1/2} \exp \left\{ \frac{1}{2} \left[ 1 + \ln \tau_1 - \tau_2 \sec x \right] \right\} \quad \ldots \quad (3)
\]

Introducing the parameter \( z \) defined by \( \tau_1 = \exp (-z) \)
we get

\[
N_{e\lambda} = \left[ q_{10}/a_{eff} \right]^{1/2} \exp \left\{ \frac{1}{2} \left[ 1 - z - \sec x \exp(-z) \right] \right\} \quad \ldots \quad (4)
\]

Since \( \omega_0^2 \) is proportional to \( N_e \), so if we neglect the variation of collision frequency the conductiv-
ity parameter becomes proportional to $N_e$. Therefore, based on Eq. (4) we show, in Fig. 7, the variation of normalized value of conductivity parameter with variation of solar zenith angle $x$ for various values of parameter $z$. Considering all curves of Fig. 7 we can say that the variation of conductivity parameter is negligible below $x = 60^\circ$ for $z = 1, 2$ and 3. For $z = 0$ and $-1$, variation of conductivity parameter is negligible below $x = 30^\circ$. Hence, on an average, maximum conductivity parameter is expected at $x = 45^\circ$. The middle point of present propagation path, zenith angle decreases to $45^\circ$ around 0745 hrs IST in pre-monsoon, around 0705 hrs IST in monsoon, and around 0815 hrs IST in post-monsoon. In winter, the lowest value of $x$ at midday at the middle of propagation path is $50^\circ$ and it occurs at around 1025 hrs IST. After the sunrise at the ionosphere over the propagation path, signal level goes on increasing for small period during which rapid increase of $\omega$ up to $1.5 \times 10^5$ s$^{-1}$ occurs. After this, the level is more attenuated due to two factors—(i) increase of attenuation with further increase of $\omega$ beyond $1.5 \times 10^5$ s$^{-1}$ and (ii) increase of electron density in the absorption region below 70 km. During midday at the middle of the propagation path both attenuations are dominant and DM is obtained. Hence DMs in respective seasons must occur at or after the above mentioned times. This is in good agreement with that presented in Fig. 3.

It is worth mentioning that Thomson observed a maxima around noon, and it is apparent that our observations contradict the result of Thomson. This apparent dissimilarity is due to the fact that VLF and LF propagations are highly path and frequency dependent due to their large wavelengths. The attenuation curve shown in Fig. 6 is highly dependent on the wavelength. Thomson used experimental observations from two nearly north-south paths to determine solar zenith angle dependence of propagation parameters. The results were then used to predict the daytime variation in VLF field strength with solar angle in the case of suitably selected path only. The present 40 kHz is almost an east-west propagation. Such propagation which is transverse to the geomagnetic field always differ from north-south propagation. A comparative study is now being done in our station between east-west propagation of 40 kHz signal and south-north trans-equatorial propagation of north-west Cape signal at 22.3 kHz. The differences in propagation will be explored on the basis of geomagnetic field and path effect. General conclusions about the influence of the lower ionosphere on VLF and LF propagation must await completion of extensive and systematic calculations with consideration of asymmetry in earth-ionosphere cavity and local effect. Detailed comparison of theory and experiment are also deferred until a theory complete in all respect is available.

Regarding the magnitude of DM, we emphasize that the link of the troposphere and the ionospheric boundary of waveguide cannot be neglected. The link between D-region electron density and the meteorological parameters is now well established. The variation in concentration of nitric oxide may affect the level of DM. Lastly, it has become clear that the ionosphere cannot be studied merely as a magneto-active plasma without a consideration of the general properties of the atmosphere. The bottom side of the upper boundary of the earth-ionosphere waveguide may be influenced by meteorological parameters like temperature and humidity. The climatic condition also remains identical along the propagational path of 40 kHz signal. The average temperature difference between Sanwa and Calcutta is 10°C. The variation of temperature in the receiving station is accompanied by a similar variation of temperature along the present radio propagation path, because both are at the low latitude northern hemisphere. Regarding humidity, receiving station Calcutta resembles the transmitting station, Sanwa. Japan is surrounded by ocean, and Calcutta is in the vicinity of Bay of Bengal. In D-region of the ionosphere, daytime electron density is the result of...
of the equilibrium between production rate and the effective loss rate. The effective loss rate depends upon effective recombination coefficient $\alpha_{\text{eff}}$. Electrons in D-region are predominantly lost through the following processes.16

(i) Recombination with the primary molecular ions such as O$_2^+$ or NO$_2^+$. The process has only a weak temperature dependence as $T^{-0.5}$.

(ii) Recombination with heavier water cluster ions which are formed by ion-chemical reactions of primary ions with neutral atmospheric constituents. These ions then recombine with electrons at rate much faster than the primary ions. The clustering process is strongly dependent on temperature as $T^{-3}$ or $T^{-4}$.

(iii) Attachment of electrons to neutral molecules thus forming negative ions. This process is appreciably impeded by presence of atomic oxygen and through photo-detachment by visible sunlight.

The temperature dependence of recombination of electrons with heavier water cluster ions gives rise to variation of $\alpha_{\text{eff}}$ on which electron density and, hence, conductivity parameter is dependent. The seasonal variation of level of DM is the manifestation of variation of $\alpha_{\text{eff}}$. In this regard one also thinks of some other agents controlling the recombination coefficient. Theoretical models of ion chemistry16,37 predict a decrease of recombination coefficient with increasing ion production. At low altitude near and below D-region, this is due to shifting away from the cluster ions with large recombination coefficient towards the primary molecular ions with significantly smaller recombination coefficient. During summer monsoon since sun rays are more vertical over 40 kHz propagation path compared to those in winter, O$_3$ is dissociated in a greater way into atomic oxygen. Atomic oxygen exerts an indirect influence on the recombination, because they can break up water cluster ions into primary molecular ions. It is worth mentioning that decomposition of water cluster into molecular ions is, to some extent, dependent on the minor species like NO, O$_3$ and CO$_2$. The first theoretical study of the chemistry of D-layer led to the expectation that the D-region should be composed primarily of O$_2^+$ and NO$_2^+$. However, the first rocket-borne experiment by Narcisi and Bailey18 revealed that in addition to O$_2^+$ and NO$_2^+$, other species of mass numbers 19 and 37, corresponding to the H$_2$O$^+$ and H$_3$O$_2^+$ clusters were present in larger abundances in D-region. The presence of relatively large amounts of heavy ions (mass numbers greater than 45), was also established by these measurements. Later studies showed that the D-region composition is dominated by heavy H$^+$ (H$_2$O)$_n$ cluster ions. The hydration order $(n)$ of the ions is dependent on geophysical conditions (particularly temperature) as well as atmospheric water vapour content. The most abundant ions generally display hydration order from 2 to 4, but at cold temperature, near the mesopause, hydration orders of 8 to 9 are not uncommon. Bjorn and Arnold19 observed ions as large as H$^+$ (H$_2$O)$_{20}$ near a very cold summer mesopause at high latitude. The ion equilibrium is strongly temperature sensitive, implying that the composition of the D-region should be quite variable with season and latitude. But there is still a dearth of knowledge on seasonal variation of minor constituent concentration in ionosphere.

The close correlation between missing of DMs and principal geomagnetic storms is obvious from Table 1. Missing of DMs during principal geomagnetic storms can be understood from the knowledge of extra-ionization produced in the region below D-region. It has been reported by many workers20-26 that the ionospheric region near 60-65 km suffers from extra-ionization during the period of occurrence of geomagnetic storms. Peak enhancement of electron density occurs at height 62-65 km with electron density up to $3 \times 10^8$ to $4 \times 10^8$ m$^{-3}$. This value is of the order of or, sometimes, greater than the normal D-region electron density of $10^8$ m$^{-3}$. Now, it is obvious that in such a case electron density near 60-65 km will be hardly controlled by the solar radiation. As a result DM must be absent. It is worth mentioning that enhancement of electron density at low latitude may not be the direct consequence of precipitation of energetic particles. Enhancement of electron density at low latitude may be the indirect consequence of transportation of nitric oxide from higher latitude to lower latitude during the period of geomagnetic storms.

The effect of geomagnetic storms on DM observed surprisingly in low latitude path is also supported by the observation of Hayakawa et al.27, where they have reported that the occurrence rate of whistler increased during geomagnetic storms. Subionospheric LF propagation and whistler effect are related through the precipitation of energetic electrons following cyclotron resonance with the waves and also by the part of propagation path through the ionosphere which is affected by the level of ionization in the D-region. Friedel and Hughes29 discussed the gyro-resonance interaction between the energetic electrons and the whistler mode wave, and showed that, in
general, the condition of electron precipitation were much worse at low latitude. But the precipitation of relativistic electrons can affect the low latitude D-region. The results were used to explain the Trimpi events. Transient enhancements of ionization in the D-region of ionosphere, as a result of wave induced precipitation of energetic electrons, have been observed to cause perturbations in the phase and/or amplitude of ionospheric VLF signals. This is known as Trimpi effect. Trimpi events on low latitude VLF propagation paths have also been reported by Friedel et al. Occurrence of Trimpis on low latitude can be interpreted as the precipitation of very high energy electrons which are capable of producing events during daytime. All these are relevant to our explanation of increased ionization in D-region giving rise to absence of DM during storms.

4 Conclusions
From the present analyses following conclusions may be drawn:
(i) The DMs are delayed in winter compared to their occurrence in other seasons.
(ii) Level of DM is lowest in monsoon and it exhibits good inverse correlation with meteorological parameters like temperature and relative humidity.
(iii) During the days of missing of DMs, postmorning signal level exhibits appreciable correlation with geomagnetic activity.

Acknowledgements
The authors are grateful to the Head of the Department of Physics, Calcutta University, Calcutta, for providing laboratory facilities. Thanks are also due to the Department of Physics, Tripura University, Tripura, for providing computer facilities in analyzing the observations.

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