Characterization of lower ionosphere disturbance associated with classes of solar flare using VLF Monitoring System

A. Taat, M. H. Jusoh, S. A. Enche Abdul Rahim, M. Abdullah

Abstract—The response of the D-region low-latitude ionosphere has been studies for difference classes of Solar flares on October 2013 using VLF Signal from Northwest Cape, Australia (NWC, 19.8kHz) transmitter monitored at National University of Malaysia (UKM, 2.55°N, 101.46°E). Attention is restricted to diurnal variation and the solar X-ray effects on propagation of VLF Signal. The changes and the enhancement of amplitude signal (VLF) are related to the X-ray fluxes that measured by GOES satellite. The two main parameters of lower ionosphere which are reference height ($H'$) and sharpness factor ($\beta$) was estimated by using the Long Wave Propagation Capability (LWPC) Code. Statistical results show both parameters is strongly depend on the flare classes and local time of flare’s occurrence. This research are also presents the trend of the amplitude perturbations correlated with the intensity of the X-ray flux by difference classes of solar X-ray flares during second peak of solar cycle 24.

Index Terms—VLF Signal; Solar flares; D-region; Ionosphere

I. INTRODUCTION

D-region of the ionosphere has drawn serious attention as most of the ionization due to X-rays, entering the Earth’s atmosphere from these sources occur in the region between 60-90km. The Vey Low Frequency (VLF, 3-30kHz) waves are reflected from this part of the ionosphere and the perturbations is well corresponding to Solar X-ray Flux. The measurement of VLF signals, generated by navigation transmitters has emerged as one of the reliable tools for remote sensing of the D-region electron density perturbations associated with solar flares [1]-[2]. The ionospheric respond to prompt changes in solar flares connected with burst in EUV, X-ray and particles [3] and geomagnetic storm conditions with time scale from several hours to 1-3days [4]-[5].The ionosphere also show seasonal variations [6] and diurnal variation; daytime and nighttime that affected the VLF wave [7]. The diurnal variation on NWC (21.82°N,114.20°E) and JJI (32.04°N,130.81°E) transmitters signals received at UKM through EIWG path length are shown in Figure 1.

A. Sudden ionospheric disturbance detector

The condition of the ionosphere is highly significant to electromagnetic wave propagation and an idea tools for real-time monitoring observation for ionospheric study. The amplitude and phase of the VLF wave are sensitive to changes in electrical conductivity due to propagate through lower ionosphere (D-region in daytime and E-region during nighttime) [3][7]-[8] and effective in the space weather studies. The VLF wave also propagate in long distance with less attenuation within the EIWG and acts the lower ionosphere and earth surface as a good conductor for signal propagation. The signal is then received at various receiver over the world. Several researchers have been study the VLF perturbation with ionospheric disturbance due to solar X-ray flux and geomagnetic events [9]-[12]. Others method to studies the ionospheric disturbance are include observational and experimental techniques tools such incoherent scatter radar, Global Navigation Satellite System (GNSS), Ionosonde, Magnetometers, etc. [3][13]-[15].

Figure 1: Diurnal Variation from JJI and NWC Transmitters.

B. The ionospheric effects due to space weather variations

Geomagnetic storms, is one of disturbance in the Earth’s magnetosphere caused by solar wind shock wave and cloud of...
magnetic field which interacts with the Earth’s magnetic field. Besides the solar flares, magnetic storms are accompanied by ionospheric disturbance which can occur up to D and E regions. However, more attention on the geomagnetic storms impact on the ionosphere has been at high latitude [9]. In 1974,[10] was found that the phase (VLF signal received at Uji, Japan from NWC transmitter) decreased in the nighttime in association with the main phase of two large geomagnetic storms during 1968 to 1969. In additional,[16] also found distinct anomalies in the amplitude and phase based on signal received at Kamchatka (low-mid latitude path) from NWC transmitter. Based on the results, negative phase and amplitude variations of the VLF signal both during day and nighttime during the main storm phase days, but the nighttime variations were more pronounced. There have not been other studies on solar flares and geomagnetic storms associated subionospheric changes at low latitude paths. However, there have been several studies on VLF perturbations due to storm induced energetic electron precipitation at mid and high latitude [17]-[18].

II. DATA METHOD AND ANALYSIS

The Automatic weather Electromagnetic system for Observation Modeling and Education (AWESOME) VLF Receiver located at UKM (National University of Malaysia, 2.55°N, 101.46°E) is used to record the VLF signal by NWC transmitter (f:19.8kHz, 21.80°S, 114.20°E), Australia. The VLF signal propagate along the Earth-Ionosphere waveguide (EIWG) from NWC transmitter to UKM Station is shown in Figure 2. EIWG path length is about ~3040 km for NWC-UKM propagation path, which classified under medium path length under the path classification given by [8]. The month of October 2013 that occurred during solar cycle 24 are selected for analysis depending the availability of VLF data at UKM Station. The X-ray flux data recorded by the Geostationary Operational Environment Satellite (GOES) satellites is obtained from the USA National Oceanic and Atmospheric Administration. The flux intensities corresponding to different classes of the flares are given in Table 1. In this research the solar flux with 0.1 to 0.8 nm are used.

<table>
<thead>
<tr>
<th>Class</th>
<th>Peak Flux Intensities (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$1 \times 10^7$</td>
</tr>
<tr>
<td>B</td>
<td>$10^5 \leq I \leq 10^7$</td>
</tr>
<tr>
<td>C</td>
<td>$10^4 \leq I &lt; 10^5$</td>
</tr>
<tr>
<td>M</td>
<td>$10^3 \leq I &lt; 10^4$</td>
</tr>
<tr>
<td>X</td>
<td>$10^2 \leq I$</td>
</tr>
</tbody>
</table>

Table 1. X-ray flux intensities for different classes of flares

In the present study we have estimated the change in amplitude $\Delta A$ as, $\Delta A = A_{\text{perturbation}} - A_{\text{min}}$, where $A_{\text{perturbation}}$ is the maximum VLF amplitude observed during the given solar flare event and $A_{\text{min}}$ is the amplitude pre-flare. The perturbations in phase is not determine as it unstable during most of the flares.

III. VLF WAVE OBSERVATION

A. VLF variation during daytime and nighttime (diurnal variation)

Diurnal behaviors have been monitored at UKM station that propagate through EIWG from NWC transmitter (21.80°N, 114.20°E). In this study, a month of amplitude data of 2010, 2013 and 2014 were selected. The characteristic variations of the amplitude perturbations that occurred before sunrise, between mid-day and after sunset have been calculated. For comparison, the calculation of amplitude monthly average of every May 2010, 2013 and 2014 of NWC VLF wave against local time (LT) over daylight has shown in Figure 4.
Figure 4 shows monthly averaged amplitude values of NWC/19.8 kHz radio signal over daylight (daylight is treated because considered the solar flare events) [19] by order of succession three years. The shapes of the curves is similar to each other. Monthly average of May 2010 is greater compared to May 2013 and 2014, and assumed that changes in solar activity as illustrated in Figure 5.

![Figure 5](image)

**Figure 5**. The illustration of solar activities from 2009 until May 2017.

### B. Solar Flare effect on VLF wave at low latitude station: UKM-Malaysia

In this studies October 2013 have been selected due to high solar flare events nearly 227 solar flares (190 C-class, 33 M-class and 4 X-class). The data of VLF wave have been analyzed to examine the changes of the VLF amplitude, Wait’s parameters, electron density and local time dependence of flares effect. Figure 6 shows an example the amplitude perturbations in the NWC/VLF wave received at UKM-Malaysia corresponding to the X-ray flux (GOES data) for 25th October 2013. The amplitude enhancements are observed for two C-class, one M-class and one X-class flares that occurred on 25th October 2013. These enhancement due to extra ionization sharpens in D-region or upper boundary of EIWG and lowers it up to several kilometers depending the intensity of solar flare flux [8][20]. When very low frequency (VLF) wave propagate through the region of enhanced electron concentration, it is finds a sharper boundary which gives a mirror type of reflection [20], as a results the amplitude of the VLF waves is increased.

![Figure 6](image)

**Figure 6**. An example of variation of X-ray Flux detected by GOES and NWC VLF wave amplitude at UKM-Malaysia station on 25th October 2013.

Table 3 gives the details of all the solar flares events considered in this present study. The change in the VLF signal amplitude (ΔA) depends on the flares strength (solar x-ray flux) which can be effectively utilized to estimate the electron density change due to solar flares [21]. Figure 7 (a and b) shows variation in the ΔA of NWC waves for October 2013.

![Figure 7](image)

**Figure 7**. Variation of change in the VLF amplitude with the X-Ray flux intensity for October 2013 (a) C-Class (b) M and X-class.

It can be seen the ΔA varies between 0.1 to 2.48 dB for C-class solar flares and between 1.3 to 4.0 dB for M-Class. The lowest flares which produced the perturbations in the signal amplitude is a C 1.2 class flare (0.1dB). There are only 1 X-class flare occurred during October 2013, therefore the data of top solar flares during solar cycle 24 have been analyzed. Table 2 shows the details of the solar flares range between M and X-class.

<table>
<thead>
<tr>
<th>Date</th>
<th>Year</th>
<th>Flares-Class</th>
<th>X-ray Intensity (Watt m-2)</th>
<th>ΔA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb-25</td>
<td>2014</td>
<td>X 4.9</td>
<td>0.43</td>
<td>5.075</td>
</tr>
<tr>
<td>May-14</td>
<td>2013</td>
<td>X3.2</td>
<td>0.22</td>
<td>4.578</td>
</tr>
<tr>
<td>Feb-15</td>
<td>2011</td>
<td>X2.2</td>
<td>0.16</td>
<td>4.071</td>
</tr>
<tr>
<td>Oct-25</td>
<td>2013</td>
<td>X1.7</td>
<td>0.09</td>
<td>4.169</td>
</tr>
<tr>
<td>Apr-25</td>
<td>2014</td>
<td>X1.3</td>
<td>0.11</td>
<td>5.551</td>
</tr>
<tr>
<td>May-15</td>
<td>2013</td>
<td>X1.2</td>
<td>0.12</td>
<td>4.493</td>
</tr>
<tr>
<td>Nov-10</td>
<td>2013</td>
<td>X1.1</td>
<td>0.035</td>
<td>3.607</td>
</tr>
<tr>
<td>Nov-08</td>
<td>2013</td>
<td>X1.1</td>
<td>0.028</td>
<td>3.988</td>
</tr>
<tr>
<td>Oct-24</td>
<td>2013</td>
<td>M9.3</td>
<td>0.048</td>
<td>2.182</td>
</tr>
<tr>
<td>Jan-07</td>
<td>2014</td>
<td>M7.2</td>
<td>0.092</td>
<td>4.878</td>
</tr>
<tr>
<td>Apr-11</td>
<td>2013</td>
<td>M6.5</td>
<td>0.074</td>
<td>4.326</td>
</tr>
</tbody>
</table>
The VLF wave amplitude (dB) is varies from 3.6 to 5.6 dB for M-class to X-class as shown in Figure 8. In general, as the intensity of the flares increase, the ΔA also increase but not linearly. For example, the ΔA for three X-class flares, X4.9, X3.2 and X2.2 were estimated change to 5.1dB, 4.6dB and 4.1dB respectively. However some inconsistency in ΔA values is occurred. For example, the X1.3 flare on 25th April 2014 produced ΔA ~ 5.6dB which is more compared to X4.9 on 25th February 2014. The nonlinearity comes from the fact that
ΔA also depends upon pre-flare condition and local time [22]-[23].

Figure 9 shows the time delay (ΔT) varies from 1-3min with difference classes of solar flares. The approximately ~1min of ΔT is occurred for X-class and M-class of solar flare. The ΔT have been discussed from previous researchers [7][24] with difference term such as sluggishness and relaxation time. The changes or delay of time is caused by recombination-ionization process to recover balance due to the increasing of x-ray irradiance. In addition, the ionospheric is also fast respond when electron density become to high. Hence, the minimum time delay for M to X-Class. In 1972, [25] showed the time delay is decrease when solar induced ionization increase by using the x-ray data from Inter-Cosmos 1 Satellite. The results presented here for Malaysia (Low-Latitude) is show the significant variation in time delay due to time occurrence and difference classes of solar flare.

C. Variation in Wait’s D-region parameters due to solar flares

LWPC Code was developed by US Navy [26]. This code is used to calculate the changes in the Wait’s ionosphere parameters [19], ionospheric reflection edge height, denoted by $H'$ (km) and exponential sharpness factor, denoted by $\beta$ (km$^{-1}$) due to solar flares by using Eq.(1):

$$N_e(h, \beta, H') = 1.43 \times 10^7 e^{0.15 h} e^{(\beta-0.15)(h-H')/H'}$$  

Figure 9. Time Delay versus Classes of Solar flare.

This model has been used to simulate the VLF propagation through the Earth-ionospheric waveguide (EIWG) at regular conditions [27], as well as for the conditions corresponding to the flare peak irradiance [28].The change in the VLF signal propagates through the region of enhanced electron concentration and the sharper boundary which gives a mirror type of reflection [20]. The changes in the VLF signal amplitude (ΔA) depends on the flares strength which can be effectively utilized to estimate the electron density change to the solar flares [20]-[21]. Figure 10 shows the comparison of electron density profile at altitude 60-90km for normal day on 3rd October 2010 and for solar flares M-Class and X-Class on 11th August 2013 and 25th February 2014 respectively.

The electron density profile during perturbed day (flares) show the 10% increase in electron density as compared to the normal values. During the flare events the ionizations in the lower ionosphere, induced by electromagnetic radiation from the solar X-ray range (0.1-0.8nm), significantly exceeds the ionization of all the regular ionization factors (such as Lyman-α 121.6nm and cosmic rays) and causes photoionization of neutral constituents in the lower ionosphere, becoming a major source of ionization in this region. Electron density increase as a result of additional ionization of the lower ionosphere constituents and thus changes the lower ionosphere electron density heights profile, affecting the Earth ionosphere waveguide characteristics. Table 2 shows the $H'$ and $\beta$ values estimated using LWPC model for all solar flares considered in the present study. The variation of $H'$ and $\beta$ with local time for C, M and X classes of flares is shown in Figure 11a and b. In Figure 11a, it is seen the $H'$ is minimum for M-class and X-class flare and maximum for C-class flares. The $H'$ value is also seen that had maximum value in the morning and evening periods and minimum in noon period. The $H'$ varies from 65.4 to 74km and 60.4 to 72.7km for C-class, M and X-Class respectively. Figure 11b shows the $\beta$ follows an opposite trend as compared to $H'$. In this results, the maximum value of $\beta$ is 0.45km$^{-1}$ for X-Class and followed by C-Class with 0.43km$^{-1}$. There are also show 3 values of C-Class with high $\beta$ value which are 0.43km$^{-1}$, 0.40km$^{-1}$ and 0.39km$^{-1}$ for C5.3, C4.0 and C4.5 respectively All these flares are ≥ 4.0 of C-Class and occurred in the noon period of local time. Several researchers [27][29] have been discussed the variation changes of $\beta$ is due to energetic of electron precipitation and highly correlated with solar zenith angle. The maximum and minimum changes in $H'$ and $\beta$ are estimated to be 10km, 0.14km$^{-1}$ for X1.7 flare and 0.2km,0.01km$^{-1}$ for C1.2 respectively as referred to unperturbed (normal) condition by [21]. Good agreement defined for Wait’s parameters ($H'$ and $\beta$) as compared with previous studies as per discussed.
IV. CONCLUSION

In this research studies we have analyzed the effect of C, M, and X-class of solar flares on NWC transmitter on period of second peak Solar cycle 24 which is October 2013. The one month data was filtered according to available data at UKM receiver station. The details of parameters and flares was shown in Table 3. The results shows that ΔA varies from 0.1-5.6dB for C to X-Class. The ΔT varies from 1-3minutes and is approximately minimum for M and X-Class due to fast respond of ionosphere when electron density become high. The maximum increase of signal amplitude is 4dB for X1.7 that occurred during daytime,16:02LT. The intensity of X-ray flux are also change the D-region parameters when the variation of reflection height (H') and sharpness factor (β) are show opposite trend respectively for each classes of solar flare. This research will provide further opportunity to investigate the correlation of D-region parameters and geomagnetic response with larger data set in Malaysia.

ACKNOWLEDGMENT

We acknowledge Universiti Kebangsaan Malaysia (UKM), for providing the data of VLF Signal This work is financially supported by Fundamental Research Grant Projects, FRGS (Code No.600-RMI/FRGS 5/3(140/2014).We also would like to thank Universiti Teknologi MARA for the management support and consideration throughout the project.

REFERENCES


Figure 11. a) Variation of reflection (H’) with respect to C, M, and X classes of flares. b) Variation of sharpness factor (β) for C, and X classes of flares.


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