Analysis of VLF Signals Perturbations on the Equatorial \textit{D}-region Ionosphere Induced by Solar Flares

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Abstract—An analysis of \textit{D}-region electron density profile variations during solar flare events for the period of January 2010 to April 2013 is presented. We measured the amplitude and phase perturbations of three fixed VLF (Very Low Frequency) signals, \( f = 19.8 \) kHz, (NWC, Australia), \( f = 22.2 \) kHz, (JJI, Japan) and \( f = 21.4 \) kHz (NPM, Hawaii) propagate along the Earth-ionosphere waveguide (EIWG). All flare effects chosen for the analysis were recorded by Stanford AWESOME VLF receiver on the single trace narrowband signal propagating through Transmitter Receiver Great Circle Path (TRGCP) with the distances of 2700 km, 3300 km, and 11000 km respectively. All selected examples showed that the amplitude and/or phase of VLF signals were perturbed by solar X-ray flares occurrence. Solar flare data from NOAA GOES15 satellite five-minute listings were used for flare event verification. In total, 145 flare events have been observed and we found that the enhancement of amplitude and/or phase of VLF signals were due to the increased ionization rate in the \textit{D}-region electron density associated with solar flare occurrences. The flare events affected the VLF wave profile in the EIWG in a different way, for different X-ray flux intensities and different characteristics of examined VLF waves.

Index Term—Electron density, Earth-ionosphere waveguide, solar X-ray, VLF wave

I. INTRODUCTION

In recent times, the severe impact to space weather conditions caused by Coronal Mass Ejections (CMEs) which modify the earth’s magnetic field has attract serious attention among astronomers and space scientists. Magnetic storms manifested by unpredicted solar terrestrial activities can easily destroy the state-of-the-art technology embedded in the satellite based communication systems as well as ground base electrical and electronics equipments. The ionosphere, which is part of atmosphere, contains ionized gases originated from the sun. The content of electrons in the EIWG (Earth-ionosphere waveguide) which is located at an altitude of between 50 km to 90 km above the earth surface is very much dependant on the photo ionization processes, UV (Ultra Violet) Lyman-\( \alpha \) radiation 121.6 nm, EUV (Extreme Ultra Violet spectral lines ranging from 102.7 nm to 118.8 nm and galactic cosmic rays. Several other dynamic phenomena that occurs in the \textit{D}-region (the lowest layer of the ionosphere) such as the diurnal effect (day/night), seasonal effect (summer/winter), solar activities (sunspot level and solar flares), effect of lightning induced electron precipitation and sprites are some of the events that cause changes in electron density of the lower ionosphere.

During normal conditions, the solar X-ray flux is insufficient to be a significant source for ionizing the \textit{D}-region; however during solar flare events, the X-ray flux from the sun increases rapidly. Thus, markedly increased the ionization rate of neutral constituents in particular nitrogen and oxygen hence increases the \textit{D}-region electron density. As a result the VLF (3 – 30 kHz) and LF (30 – 300 kHz) radio signals propagate inside the waveguide formed by the lower ionosphere and Earth’s surface [1], [2] will exhibit significant perturbations in the received amplitude and/or phase of the recorded signals.

In previous work, [3] has done a quantitative study on VLF phase anomalies during solar flare events. The results showed that there is a relationship between enhanced ionization rates in the ionosphere due to solar flare and the VLF phase deviation on the received signal recorded at Nishinomiya, Japan. Another paper by [4] reported the dimension of the daytime factor of electron density profile height (\( H' \) in km) and sharpness (\( \beta \) in km\(^{-1}\)). The observations were made from two north-south paths to study the solar zenith angle effect on both \( H' \) and \( \beta \). In another effort, [5] conducted a study mainly focus on monitoring the behavioral of the 16 kHz VLF narrowband signal propagating over England. Last but not least, [6] conducted a study to find the correlation of a moderate flare X-ray flux with the disturbance of amplitude and/or phase in the VLF wave transmission. The measurements were made at Budapest, Hungary and Gyergyóújfalu, Romania.

II. EXPERIMENTAL SETUP

The behavioral of electron density in the ionosphere can be determined using many different methods including radar measurements, balloons, rocket probes and the technique
using radio wave signals [7], [8], [9], [10] [11] and [12]. We used Atmospheric Weather Electromagnetic System for Observation Modeling and Education (AWESOME) VLF receivers to record the data in the period of January 2010 - April 2013. The receiver was developed by VLF Group, Stanford University and it was granted by NASA as part of the International Heliophysical Year (IHY) program in conjunction with United States Basic Space Science Initiative (UNBSSSI). All the data were recorded at the UKM station, Selangor, Malaysia (2.55° N, 101.46° E). There are two modes of VLF data recording; broadband and narrowband. Broadband data records full range VLF amplitude data time series, which can be later transformed into the frequency domain. Broadband data usually recorded in synthetic mode. Narrowband data (the one presented in this paper) records phase and amplitude in a specific frequency, which corresponds to the frequency of a VLF transmitter, located scattered around the globe. These data are digitized and saved in two different resolutions – high resolution (50 Hz) and low resolution (1 Hz). As pointed out by [13] the narrowband data can be recorded continuously and capable to monitor up to fifteen transmitters simultaneously.

In our case, one of the best defined signals recorded by UKM receiver originates at the NWC transmitter from North West Cape, Australia propagating at 19.8 kHz. This is possibly due to the high transmitting power (1000 kW) generated by this transmitter. Other VLF signals recorded at UKM station includes: VTX (18.2 kHz) Katabomman, India, 3SB (20.6 kHz) Datong, China, HWU (21.75 kHz) Le Blanc, France, DHO (23.4 kHz) Raudherfehn, Germany and NLK (24.8 kHz) Jim Creek, Washington USA. The Transmitter Receiver Great Circle Paths (TRGCPs) distances for these signals are between 2700km to 14000km.

In this paper we present the results of three VLF transmitters, namely JJI (at 22.2 kHz) located in Ebino, Japan, NWC (19.8 kHz) North West Cape, Australia and NPM (21.4 kHz) Lualualei, Hawaii. The propagation distances for these VLF signals are 2700km, 3300km and 11000 km respectively. The location of the transmitters and the receiving station of the subionospherically propagating VLF signals presented in Fig. 1. The JJI and NPM VLF signals propagate almost totally over the sea whereas NWC signal propagates over the sea and slightly over the Sumatran Island before reaching the receiving station which implies roughly similar conductivity characteristics of the waveguide terrains.

To ensure the validity of the flare data presented, we removed all unstable signals during dusk and dawn transition period. From January 2010 – April 2013, there were about 145 solar flare events have been studied. We analyzed the effects of electron density changes on the propagating VLF amplitude and/or phase signals and the GOES-15 satellite data available from USA National Oceanic and Atmospheric Administration (NOAA) via the website: www.swpc.noaa/ftpmenu/lists/html were used to verify the exact time and date of the occurrences of flare.

The GOES-15 satellite records the X-ray flux radiation erupted by the solar flare in two wavelength bands; 0.1 to 0.8 nm, referred to as “long” or “XL”, and 0.05 to 0.4 nm, referred to as “short” or “XS”. In the present study, we used “XL” wavelength band. Solar flares are classified into five categories A, B, C, M, and X based on the X-ray flux intensities. Class A flares representing the weakest, whereas class X is the strongest. Each class can be further divided from 1.0 to 9.9.

III. RESULT AND DISCUSSION

A. VLF Data Measurement

Since the VLF waves are reflected by D-region ionosphere and propagate through large distances, these transmitted signals from VLF transmitters around the globe can be used to study the D-region ionospheric disturbances caused by various geophysical phenomena. Fig. 2 shows the diurnal variations of amplitude (upper panel) and phase (lower panel) on NWC and NPM signals against the universal time (UT). The red line represents the diurnal variations recorded on 16 February 2011 illustrating a series of perturbed VLF signals due to several flare events. As a comparison, the blue line represents a smooth signal (no flare condition) recorded on 5 February 2011. The local noon and the sunset for the UKM receiver are labeled by two vertical red lines.

Solar flare induced perturbations in amplitude (ΔA) and phase (Δφ) of VLF transmission were determined using the method as illustrated in Fig. 3. We estimated the value as the difference between maximum values of the perturbed amplitude induced by flare (A_{Max}) and amplitude value during no flare condition (A_{Min}): ΔA = A_{Max} - A_{Min}. In the same way the perturbation of phase was estimated as: Δφ = φ_{Max} - φ_{Min}. The calculation of amplitude and phase perturbation by means of this method is similar to the one used by [14] and [15]. During the period of data analysis (January 2010 – April 2013) continuous phase data was not fully available due to unstable phase data recorded at UKM station especially for the VLF signals from JJI and NPM transmitter. Several power and...
systems failure which occurred during significant flare events have also affected the results obtained at UKM station.

Among 145 events of amplitude and/or phase perturbations on all signals recorded at UKM station, there was one induced by a minor B2.6 class flare and one induced by an extreme large X2.2 class solar flare. All other examined flare events of amplitude and/or phase perturbations on studied signals were induced by small (C-class) and moderate (M-class) solar flares. The extreme flare of X2.2 ($2.2 \times 10^4$ W/m$^2$) X-ray flux in the band 0.1-0.8nm) event that occurred on 15 Feb 2011 originated from the sun’s Active Region (AR) 1158. The flare started at 01:44 and reached to the maximum at 01:56 UT (local time = UT + 8), as recorded by GOES. Fig. 4a shows the time variation of measured amplitude perturbations on NWC/19.8 kHz, JJI/22.2kHz, and NPM/21.4 kHz signals captured at UKM station. The X2.2 flare caused an increase of $\Delta A = 4.5$ dB, 1.5 dB and 4.3 dB on NWC, JJI and NPM VLF propagation signals respectively. However, for phase signals, only NWC/19.8 kHz signal shows $\Delta \Phi = \sim 90^\circ$. There were no evidence of phase perturbation on both JJI/22.2 kHz and NPM/21.4 kHz signals as illustrated in Fig. 5a.

In the X2.2 flare event, we observed that the VLF amplitude started to increase a few minutes after the time recorded by the GOES (due to sluggishness in the ionosphere) and reached a maximum level of amplitude perturbation at 01:58 UT. The disturbed signal then started to recover back to its ambient level within two hours. At around 04:27 UT another flare event with the strength of C4.8 ($4.8 \times 10^5$ W/m$^2$) erupted again which caused the changed of the underlying ionosphere. The flare originated from the same sunspot region AR 1158. Detectable amplitude of this flare were only recorded on NWC/19.8 kHz signal in both amplitude and phase VLF signals with $\Delta A = 1.3$ dB and $\Delta \Phi = \sim 9^\circ$. There was no evidence of VLF amplitude and phase perturbations in the JJI/22.2 kHz and NPM/21.4 kHz signals for the C4.8 Class flare event (see Fig. 4a and Fig. 5a – blue and red lines). This could be due to the convolution of the peak irradiance X-ray flux which was in its mode to return to its pre-flare level before a new lower-intensity flare apparently occurs, cannot be detected by low powered VLF transmitter signals.

In Fig. 4b we presented another interesting perturbations event of amplitude on NWC/19.8 kHz, JJI/22.2 kHz, and NPM/21.4 kHz signals during a moderate M6.5 Class ($6.5 \times 10^5$ W/m$^2$) flare event occurred on 11 April 2013 which peaked at 07:16 UT and ended at 07:29 UT. The overall time taken for the perturbed signal to return to its base level is around 35 minutes. This ten times weaker than extreme X-Class flare event caused additional ionization in the $D$-region producing waveguide during geophysical phenomena such as solar flares, lightning induced electron precipitations, cosmic gamma ray flares, terrestrial gamma ray flares, geomagnetic storms, etc, have led to significant contributions in the development of plasma physics and space physics. In Fig. 4 we presented the results of simultaneous observation of amplitude perturbations on three different VLF signals, NWC/19.8 kHz, JJI/22.2kHz, and NPM/21.4 kHz during solar flare events for the period of data analysis.

**B. VLF Signals Perturbations Induced by Solar Flare**

Continuous monitoring of VLF waves provides a powerful remote sensing tool for understanding the processes incurred in the $D$-region ionosphere. Furthermore, simultaneous observation of electron content in the Earth-ionosphere...
amplitude perturbations detectable on all NWC/19.8 kHz, JJI/22.2 kHz, and NPM/21.4 kHz signals with amplitude signals disturbances of 4.3 dB, 5.0 dB, and 2.0 dB respectively. The shapes of all three VLF recorded signals are almost identical to each other as can be seen in Fig 4b. Measured phase perturbations for this event only detectable on NWC/19.8 kHz signal with $\Delta A = -9^\circ$, while no evidence of phase disturbance on JJI/22.2 kHz and NPM/21.4 kHz signals as can be clearly seen in Fig. 5b.

On 15 November 2012, a C6.3 Class ($6.3 \times 10^{-6}$ W/m$^2$) flare erupted at 04:22 UT and peaked at 04:37 UT which acquired around half an hour to settle down to its pre-flare condition. The flare originated from sunspot region AR 1610. The magnitude of the flare effect can be clearly seen from Fig. 4c. As usual, NWC/19.8 kHz signal successfully detected almost every flare event as proven in previous discussions. The increase in VLF amplitude caused by this flare on NWC/19.8 kHz, JJI/22.2 kHz, and NPM/21.4 kHz signals are 2.2 dB, 4.0 dB, and 2.0 dB respectively. However, phase perturbations recorded 15° phase shift on NWC/19.8 kHz and 130° phase shift on NPM/21.4 kHz signals (see Fig. 5c – red line). While typical JJI/22.2 kHz as usual, shows no evidence of phase disturbance as can be clearly seen in Fig. 5c (blue line). In Fig. 4d we presented the weakest flare detected during the four years period of data analysis. It can be clearly visible that the NPM/21.4 kHz signal recorded a tremendous fluctuation of amplitude perturbation during the weakest flare among all studied samples, standing at 8.0 dB compared to the ambient level before the beginning of the minor B2.6 Class ($2.6 \times 10^{-7}$ W/m$^2$) solar flare. The flare occurred on 26 September 2010, started at 07:00 UT, peaked at 07:04 UT and back to its quiet condition in less than 15 minutes. The increase in amplitude of NWC/19.8 kHz and JJI/22.2 kHz signals were 1.0 dB and 4.0 dB respectively. However this minor B2.6 flare fail to trigger any phase shift on all NWC/19.8 kHz, JJI/22.2 kHz, and NPM/21.4 kHz signals as can be plainly seen in Fig. 5d.

![Fig. 5. Perturbations of VLF phase on NWC/19.8 kHz, JJI/22.2 kHz, and NPM/21.4 kHz signals recorded at UKM station during a large X2.2 class flare, medium M6.5 class, small C6.3 class and minor B2.6 class flare, as shown in panels a), b), c) and d), respectively.](image)

### TABLE I

<table>
<thead>
<tr>
<th>Solar Flare Class</th>
<th>Amplitude Perturbation</th>
<th>Phase Perturbation</th>
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<tbody>
<tr>
<td>Minor flare</td>
<td>$A_t = 2.6 \times 10^{-7}$ [W/m$^2$]</td>
<td>$\Delta A = 1.0$ [dB] $\Delta \Phi = -2.2$ [deg]</td>
</tr>
<tr>
<td>Small flare</td>
<td>$A_t = 6.3 \times 10^{-6}$ [W/m$^2$]</td>
<td>$\Delta A = 4.0$ [dB] $\Delta \Phi = 4.0$ [deg]</td>
</tr>
<tr>
<td>Moderate flare</td>
<td>$A_t = 6.5 \times 10^{-5}$ [W/m$^2$]</td>
<td>$\Delta A = 8.0$ [dB] $\Delta \Phi = 2.0$ [deg]</td>
</tr>
<tr>
<td>Large flare</td>
<td>$A_t = 2.2 \times 10^{-4}$ [W/m$^2$]</td>
<td>$\Delta A = 8.0$ [dB] $\Delta \Phi = 2.0$ [deg]</td>
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</table>

In Table I, we provide measured values of perturbations of amplitude and phase on NWC/19.8 kHz, JJI/22.2 kHz, and NPM/21.4 kHz signals received at UKM station triggered by various types of solar flare during the period of data analysis. Based on the studied flare events, we observed that the NWC/19.8 kHz VLF signal originated from North West Cape, Australia is the best define signal received by the UKM AWESOME receiver in both amplitude and phase VLF signal.

In Fig. 6, we provide measured excesses of VLF amplitude signals perturbations induced by small, moderate and extreme...
class solar X-ray flares with the value of $0.2 \leq \Delta A \leq 12$. In all examined events, the NWC/19.8 kHz signal is the most stable results obtained during the whole analysis period. Fig 6a shows that the flare $\Delta A$ for NWC/19.8 kHz signal is nearly proportional to the logarithm value of the X-ray irradiance with positive correlation coefficients equal to 0.81. As for comparison, Sulic and Srecevovic (2014) obtained correlation coefficients value equal to 0.83 for ICV/20.27 kHz VLF signal transmitted from Isola di Tavolara, Italy to Belgrade, Serbia. The result is published in [13]. As shown in Fig 6b and 6c, the correlation coefficients for both JJI/22.2 kHz and NPM 21.4 kHz signals data points are 0.52 and 0.68 respectively. The higher correlation coefficients value of NPM as compared to JJI data point could be due to the higher power transmitted by NPM transmitter which is 424 kW whereas JJI transmit only 200 kW.

However, the abrupt changes of X-ray radiation in the Earth’s ionosphere waveguide during solar flare event causes not only the enhancement of the maximum electron density, but it also revolutionize the distribution of ionization from an upper layer to a lower layer of the D-region ionosphere. Thus, it is inequitable to justify that the magnitude of amplitude and phase perturbation ($\Delta A$ and $\Delta \Phi$) totally depends only on the strength of the transmitted VLF signals by the transmitter and the X-ray flux intensities.

The explanation for this argument can be clearly seen in Fig. 4d and Table I that shows a minor B2.6 flare occurred on 26 September 2010 generated $\Delta A = 8.0$ dB on NPM/21.4 kHz signal whereas an extreme large X2.2 solar flare only produced $\Delta A = 4.3$ dB on the same VLF signal and great circle path. A details and more comprehensive study with more sets of data has to be done in order to determine the exact parameters resulting in the numerical values of $\Delta A$ and $\Delta \Phi$.

**IV. SUMMARY**

The purpose of this work is to simultaneously examine the effect of solar flare events on three VLF radio waves propagating along the EIWG namely NWC/19.8 kHz, JJI/22.2 kHz, and NPM/21.4 kHz. The results revealed that the magnitudes of the VLF amplitude and/or phase changes increase with the X-ray flux intensity of solar flares. We also found that all observed solar flare-associated VLF measured excesses of perturbations were followed by positive polarity amplitude and/or phase signals. This is illustrated in Figs. 2 to 5. Due to unstable phase signal recorded on almost half of the studied events (except several NWC/19.8 kHz signals), further analysis cannot be carried out on phase data for comparison.

We also found an interesting data fact that the NPM/21.4 kHz VLF signals have more sensitivity in probing minor (B Class) flare event. In order to confirm this probing potentiality, further analysis should be carried out to monitor consistencies of NPM/21.4 kHz VLF path in detecting minor flare events. Furthermore, overall results exhibited good agreement with previous work. Thus, demonstrate that the results obtained by UKM AWESOME will provide additional data for the study of lower ionosphere and magnetosphere response to various solar terrestrial phenomena.

**Acknowledgment**

M. M. A. Rashid is very grateful to colleagues from the Optical Fiber lab; especially to Ali and Rahman for a very
fruitful discussion. M. M. A. Rashid also would like to thank Majlis Amanah Rakyat (MARA) for their financial support throughout the research.

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