Observation of the effects of solar flares on the NWC signal using the new VLF receiver at Tay Nguyen University

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Abstract. Observing the responses of the Very Low Frequency (VLF) signal (19.8 kHz) due to solar flares using the new VLF receiver at Tay Nguyen university, Vietnam (12.65o N, 108.02o E) during October and November 2013, results reveal that the enhancement of VLF signal which is reflected at the D layer of the ionosphere is nearly proportional to the logarithm of the peaks of X-ray flux. We also found that most peaks of VLF signal occurred about 1 - 6 min after the peaks of X-ray flux. The increases of VLF signals during solar flares are due to the ionizing of X ray radiated by solar flares. The ionization of X-ray radiation becomes more predominating than that of the cosmic rays and Lyman-α emissions, which causes the increase of the electron density hence the ionospheric boundary becomes sharp. The observation of the effects of solar flares on the VLF signals helps us to understand the behavior of ionospheric D-region during solar flares.

Keywords: VLF signal, solar flares; X-ray flux, ionospheric D-region.

Introduction

The formation of ionosphere of the Earth is due to the solar emissions such as X-ray, Ultra Violet (UV) and cosmic rays. The ionosphere is separated into the D, E and F regions. The D-region (70 – 90 km) is ionized by X-ray with the wave-length from 0.1 nm to 1 nm. The E-region (100 – 120 km) is ionized by UV (80 – 103 nm) and X-ray (1-20 nm). The F-region (above 120 km) including two layers F_1 and F_2 during daytime is ionized by UV (20 – 80 nm) (More et al., 2010). The height of D layer is too high for the balloons and too low for satellites. In addition, the electron density of the D-region is too low to be measured by ionosondes with the frequency of 1 – 30 MHz (Ohya, Shiokawa and Miyoshi, 2008). The satellites can observe the ionosphere above 200 km, the techniques of ionospheric sounding can observe in the range of 90 – 500 km and the balloons only reach to the height of 50 km. The sounding rockets also directly measure the electron density profile of this region, but they are launched from limited locations (Maeda, 1971). Therefore, D-region's electron density profile remains, until now, difficult to ascertain accurately. This is a problem still in search of a solution. In recent decades, however, the VLF (Very Low Frequency, 3 kHz – 30 kHz) technique is gaining worldwide attention due to its potential ability to record electron density variations and the reflection height of the D-region, both of which relate to D-Region's absorption characteristics. Therefore the monitoring of VLF signals provides a window for observing and analyzing the complex physics processes of the ionospheric D-region.

It is well known that the D-region comprise complex chemical mechanisms and absorbable environment for radio signals. There are many ionic sources which contribute to produce the ions. The Lyman-α emission with the wavelength of 121.5 nm penetrates below 95 km and ionizes the nitric oxide (NO). The EUV (Extremely Ultra Violet) (102.7 nm – 111.8 nm) ionizes the excited oxygen in the state $O_2(^1\Delta_g)$. This emission also ionizes the O_2 and N_2. The hard X-ray (0.2 – 0.8 nm) ionizes all of constituents, and strongly affects on the major species O_2 and N_2. The cosmic rays are the mainly ionic sources of D-region (Hargreaves, 1992). The ionospheric D-region is also the absorbable region. The absorption per unit height is dependent on the electron density and the collision frequency between electrons and neutral particles (Hunsucker and Hargreaves, 2003).

In 1937, J. H. Dellinger discovered that there was the fade-out of the high frequency signals which propagated through the ionosphere and was significantly absorbed during the solar flares. This fade-out performed about 10 min. These rapid effects are called by the sudden ionospheric disturbance (SID) (Hargreaves, 1992). The effects of solar flares on the ionosphere indicate that there is the enhancement of the emissions of the Sun. During the solar flares, the radiations strongly ionize the D-region, which leads to a sudden increase in the electron density of this region with 1 – 2 orders of magnitude (Grubor et al., 2008). The VLF receivers can record the sudden variation of the amplitude and phase of VLF signals.

The solar flares accompany the coronal mass ejection (CME). CME flows from the Sun at speeds of the 2 million kilometers per hour towards the Earth.

CME creates the shock wave which compresses the field lines of Earth's magnetic field, impacts on the magnetosphere and causes the magnetic storms (Hargreaves, 1992; Scherrer et al., 2009). They endanger the astronauts on spacecraft, the satellites, the power system, communication system on the ground, etc…

The intensity of solar flares is recorded by the GOES (Geostationary Operational Environmental Satellite). Basing on the intensity, the solar flares are separated the classes which include B, C, M, X classes (Table 1). Each class is also partitioned the different levels from 1.0 to 9.9 (Gustafsson, 2011; Rashid et al., 2013). The X-ray data can be downloaded from website of the US National Geophysical Data Center (http://www.swpc.noaa.gov/ftpmenu/lists/xray.html).

Table 1. The classes of solar flares

Flare classes	Intensity I_X (W/m^2)
B	$I_X < 10^{-6}$
C	$10^{-6} \leq I_X < 10^{-5}$
M	$10^{-5} \leq I_X < 10^{-4}$
X	$I_X \geq 10^{-4}$

The equatorial ionosphere is the object of considerable scientific study and Vietnam has begun to investigate the effects of solar flares on the behavior of ionospheric D-region at low latitude. In this paper, we used the new VLF receiver at Tay Nguyen university, Vietnam (12.56° N; 108.02° E) to observe the perturbations of the amplitude of NWC/19.8 kHz signal due to solar flares from October to November 2013. This aims to find the relationship between the X-ray intensity and the temporal variation of amplitude of VLF signal to understand the behavior of ionospheric D-region during the solar flares.

Experimental setup and analysis method

We installed the VLF receiver which includes orthogonal loop antennas, a pre-amplifier, a soundcard, a GPS receiver, a PC and UltraMSK software. Figure 1 shows the block diagram of this new receiver. The VLF antennas capturing the field component of VLF wave include two right triangle loops which have the base of 1.2 m, the resistor of 1.2 Ω and the inductance of 0.748 mH. Two loops are orthogonally set by the direction of East/West (E/W) and North/South (N/S). The pre-amplifier has two channels which filter the noise and amplify the weak signals. The VLF signals are transferred by the long coaxial cables. These cables are connected to the isolating transformer of the winding ratio 1:1 before connecting to the PC. The soundcard, Delta Audio M 44, has the sample rate of 96 kS/s, the analog to digital converter with the solution of 24 bit, and four analog inputs. The HP Z3816A GPS Frequency Standard Receiver has 1PPS output with the width of pulses of 20 microseconds. These pulses are converted to the pulses with the width of 10 microseconds which make the clock of VLF receiver to record the VLF signals every second. The PC is connected to internet and its clock is set to within +/- 500 milliseconds of UTC by using the Network Time Protocol. The PC and UltraMSK software run under the Linux operating system (Brundell, 2013).

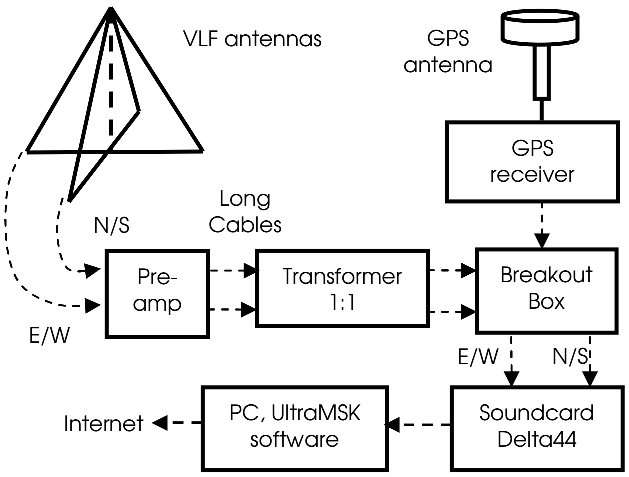

Figure 1: The VLF receiver block diagram.

We recorded the NWC signal which propagates from Australia to Tay Nguyen University (TNU). Figure 2 shows the great path which transects over both the sea and land.

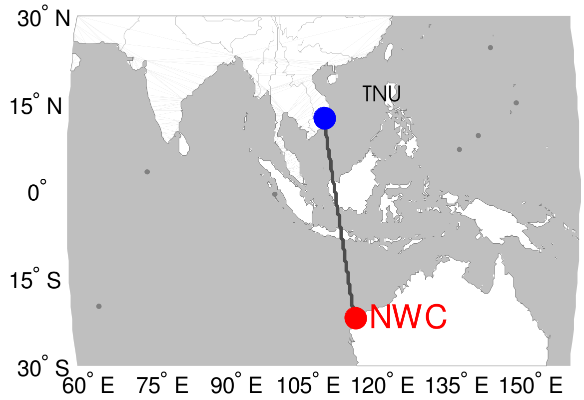

Figure 2: The map of the locations of NWC transmitter and the VLF receiver.

The NWC signal can be clearly captured by N/S loop antenna. The amplitude of NWC signal was recorded during October and November 2013. The observation of the perturbations of the VLF signal during the solar flare near the sunrise and sunset is not analyzed to remove the effects of these phenomena. The amplitude perturbations are calculated as $\Delta A = A - A_o$, where A is the values of the peaks of the amplitude perturbations and A_o is the unperturbed values of amplitudes (Figure 3).

The output data is the files with the extension "txt". These VLF data files are analyzed by Matlab code to export the pictures. Subsequently, we use the GetData Graph Digitizer to capture the enhancement of the amplitude signal and time lag between the peaks of amplitude signal and the peaks of X-ray flux.

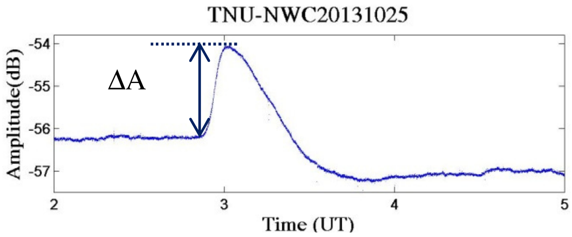

Figure 3: Capturing the enhancement of VLF signal.

Results

Figure 4 presents the VLF signals in the quiet days of October and November 2013. It is shown that the first modal minimum occurred around 11:30 UT (local time = UT + 7) after sunset and the second modal minimum occurred around 21:30 UT before sunrise. In the daytime, the VLF signals vary about 8 dB.

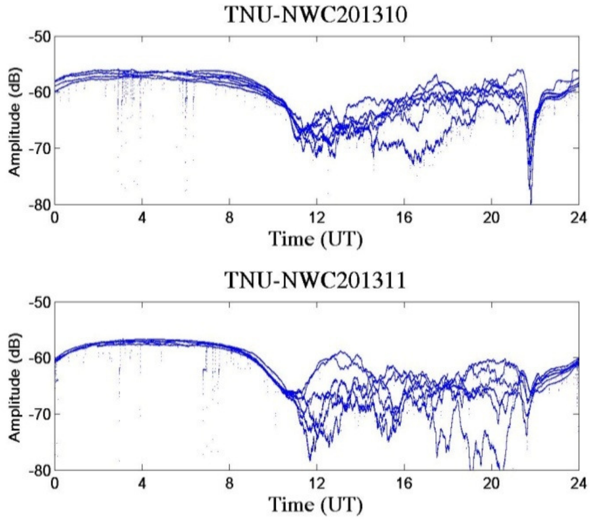

Figure 4: The variation of NWC amplitudes in the quiet condition of the ionosphere in October and November 2013.

A total of 40 VLF perturbations in associated with solar flare events were recorded by VLF receiver (Table 2). The flare classes C, M, and X are obtained by 65 %, 27.5 % and 7.5 %, respectively. The VLF receiver clearly responds to the lowest class C1.5 with the VLF enhancement of 0.25 dB and the highest class X1.7 with the VLF enhancement of 2.89 dB.

Examples of the recorded disturbances are displayed in Figures 5 – 6. The dash lines on these figures mark the occurred solar flare events and the arrows indicate the detected perturbations. The solar flare event with M2.3 at 6:06 UT, 26 October 2013 caused the increase of VLF signal with 2.03 dB and the peak of VLF amplitude occurred about 2 minutes after the peak of X-ray flux (Figure 5). The solar flare events continuously occurred on 16 November 2013 caused the complex fluctuation of VLF signal. However, the series of flare classes C2.6, C2.0, C5.2, M1.2, C2.8, C8.6 and M1.6 are clearly identified by VLF receiver (Figure 6). Table 2 shows that the time lag between the peaks of X –ray flux of these solar flares and the peaks of VLF amplitude is from 2 – 5 min.

Table 2: The type of solar flares, the enhancement of VLF amplitude, and occurred event time during observable period.

Date	Flare class	ΔA (dB)	Flare peak time (UT)	VLF peak time (UT)	Time lag
15.10	C9.5	0.88	5:07	5:09	02
20.10	C2.9	0.16	8:40	8:42	02
22.10	M1.0	1.79	0:21	0:23	02
22.10	C4.3	0.87	3:37	3:40	03
22.10	C4.0	0.35	4:21	4:23	02
24.10	M9.3	2.68	0:29	0:30	01
24.10	C3.1	0.20	3:43	3:45	02
24.10	C2.1	0.12	4:15	4:21	06
24.10	C3.6	0.22	5:06	5:09	03
24.10	C3.0	0.18	5:27	5:30	03
24.10	C9.3	0.71	5:59	6:01	02
25.10	M2.9	2.09	3:02	3:01	01
25.10	X1.7	2.89	8:01	8:00	01
26.10	M2.3	2.03	6:06	6:08	02
28.10	C5.2	0.94	9:22	9:23	01
3.11	M5.0	2.38	5:21	5:22	01
5.11	M2.5	1.65	8:18	8:20	02
6.11	C8.6	1.51	8:51	8:53	02
7.11	C4.3	0.80	1:52	1:56	04
7.11	M2.3	1.71	3:40	3:41	01
7.11	C4.3	0.67	8:23	8:25	02
8.11	X1.1	2.27	4:26	4:25	01
10.11	C1.5	0.25	1:52	1:53	01
10.11	C3.0	0.35	3:39	3:40	01
10.11	X1.1	2.29	5:14	5:13	01
10.11	C3.2	0.68	9:27	9:28	01
13.11	C1.8	0.09	3:09	3:13	04
13.11	C6.5	0.32	3:58	4:01	03
13.11	C2.6	0.31	4:42	4:46	04
14.11	C3.5	0.53	6:46	6:50	04
14.11	C4.9	1.03	8:00	8:06	06
15.11	M1.1	1.24	2:29	2:31	02
16.11	C2.6	0.29	2:08	2:13	05
16.11	C2.0	0.12	2:27	2:29	02
16.11	C5.2	0.41	2:49	2:51	02
16.11	M1.2	1.28	4:53	4:55	02
16.11	C2.8	0.39	5:37	5:40	03
16.11	C8.6	0.74	6:21	6:23	02
16.11	M1.6	1.38	7:49	7:52	03
23.11	M1.1	1.36	2:32	2:35	03

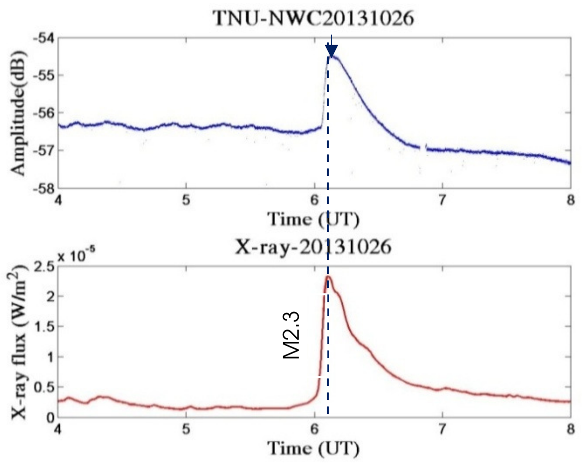

Figure 5: The detected perturbation of NWC signal with M2.3 flare class on 26 October 2013.

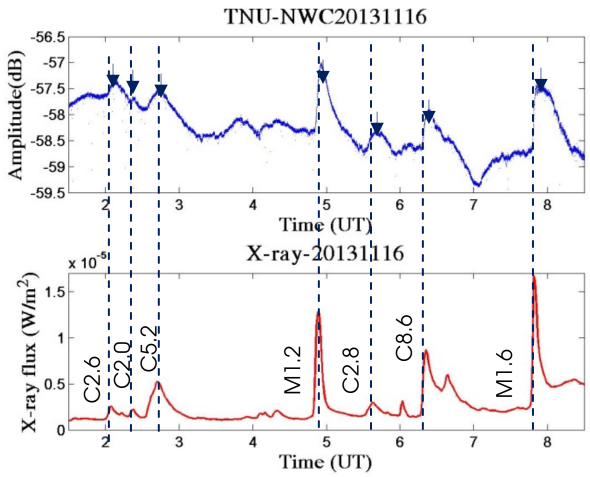

Figure 6: The detected perturbations of NWC signal with the series of flare classes on 16 November 2013.

The statistical results on the table 2 indicates that the time lag between the peaks of VLF amplitude and the peaks of X-ray flux is from 1 – 6 minutes. With respect to the solar flare events M2.9 on 25 October, and X1.7 on 8 and 11 November, the peaks of VLF amplitudes appeared about 01 minute before the peaks of flare flux.

In addition, Figure 7 shows that the enhancement of amplitude perturbations (ΔA) is nearly proportional to the logarithm of the peaks of X-ray flux (I_X) with the high coefficient of determination (R^2) of 0.8971.

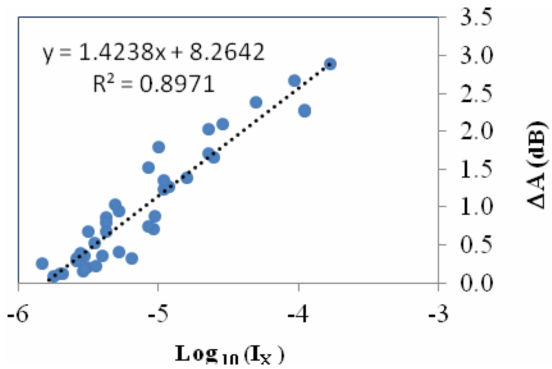

Figure 7: Amplitude perturbations of NWC signal as a function of X-ray flux recorded at TNU. The dotted line is the fitted straight line for those data points.

Discussion

In the daytime, the VLF signals are smooth (Fig. 4). This can be explained that the ionospheric D-region is formed by Lyman-α emission which ionizes the NO. The ionization of X-ray flare is more significant than that of the cosmic rays and Lyman-α emission. This leads to enhance the electron density profile which increases more smoothly with height in the disturbance condition than that in the normal condition (Thomson and Clilverd, 2001) . The ionospheric boundary becomes more conductive, hence the VLF signals reflect better at D-region.

From May to July 2011, observing the responses of TFK, NPM and NAA which are paths to Michigan (USA) and Mannheim (Germany) during the solar flares, authors saw that time delay is about 1 – 5 min (Tan and Tuyen, 2013). Our observation is nearly similar to this result. However, in some special cases, it is noted that the amplitude peaks occurred before the flare flux peaks. The mechanism of this phenomenon has not been clearly understood. According to the work (Žigman, Grubor and Šulíc, 2007), the time delay is needed for the D-region recombination – ionization processes to recover balance under the enhancement of X-ray flare. This time is also a important key to solve the continuity equation of electrons, and identify the responses of ionospheric D-region to solar flares.

Figure 7 shows that result is in accordance with the result of Kumar who observed the responses of VLF signal to solar flares in six months of 2007 at Suva, Fiji (18.08° S; 178.3° E). This author found that the variation of both amplitude and phase of VLF signal related to the X-ray intensity with the logarithmic function (Kumar, 2007). If we know this relationship, we can predict the strong solar events by detecting the VLF perturbations when the GOES detectors are saturate to lead to uncertainly obtain the correct values of the peak X-ray flux (Clilverd et al, 2009). Therefore, it can be concluded that the VLF technique is useful to detect the SID and understand the physics processes and chemical mechanism of ionospheric D-region.

Conclusion

Recording the perturbations of the great path NWC (19.8 kHz) from Australia to Tay Nguyen University, Vietnam due to the solar flares during October and November 2013, it is seen that our VLF receiver is sensitive to identify the flare classes C1.5 - X1.7. The C flare classes often occurred with 65 % of the total of detected solar flare events. We also found that the almost peaks of the amplitude perturbations of VLF signal occurred after the peaks of X-ray flux radiated by solar flares with the time delay of 1-6 min, and the enhancement of VLF amplitude relates to the logarithmic function of the peaks of X-ray intensity. These results investigate that the effects of X-ray radiation on the D-region of ionosphere become more significant than that of the cosmic rays and Lyman-α emission during the solar flares. This causes the enhancement of the electron density, which leads to increase the magnitudes of VLF signals. In the future, we will continue to record the perturbations of both amplitude and phase of VLF signals to deeply study the behavior of ionospheric D-region at low latitude.

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