Very low frequency/low-frequency receiver for monitoring disturbances in the ionosphere D layer

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Abstract. The Ionosphere layer can influence radio wave propagation from one place to another place with a very long distance on the Earth and between satellites to the receiver. Each ionosphere layer has different characteristics and the presence of the ionosphere changes daily according to solar activity. The D layer is the innermost ionosphere layer, starting about 60 - 95 km above the Earth’s surface. Observation of the D layer cannot be carried out by balloon, ionosonde, and satellite because it is too low so that continuous observation is very difficult. VLF/LF radio wave can be traveled hundreds to thousands of kilometers from the transmitter with multiple reflections between the earth and the ionosphere that is known as the Earth-Ionosphere WaveGuide (EIWG). VLF/LF receiver is an instrument that can be used to observe changes in the low region ionosphere layer due to solar activities.

1. Introduction

Appleton and his research group were the first to prove the presence of a reflecting layer at an altitude of about 100 km (the E ionosphere layer). He has performed a radio broadcasting experiment continuously where the radio transmitter and receiver were different places over a large distance. The results of his research can be measured by the height of the reflector layer by measuring the difference signal between the signal emitter and the signal received from the results of reflection. The ionosphere is partially ionized of the atmosphere by solar radiation and it extends from about 60 km to 1000 km [1]. The ionosphere layer contains charged particle electricity and it can be reflected in certain radio waves. Certain radio waves cannot penetrate the ionosphere layer but are partially absorbed and reflected. The ionosphere layer plays an important role in the electricity of the atmosphere and forms a boundary in the magnetosphere layer. The presence of the ionosphere layer is very useful in high frequency (HF) radio communications [2]. In the HF radio wave signal, the radio wave signal can be traveled very long distances due to refraction and reflection in the ionosphere layer. Signals that propagate through the ionosphere layer are called ionosphere ware or skywave. The ionosphere layer is very important because the ionosphere can affect propagation radio from one area to another area over long distances on the Earth and between satellites with ground stations. The main source of ionization in the ionosphere is solar radiations such as extreme ultraviolet (EUV) and X-ray radiations and high-frequency radiations and charged particles from the sun [1, 3].
In a day, the ionized process occurs by solar radiation, and at night it does not occur but due to cosmic rays. The number of electrons and free ions in the ionosphere layer is dependent on solar radiation intensity and gas density. Based on height and electron density value, the ionosphere layer can be divided into three layers, denoted by D, E, and F layers. Each layer is controlled by different physical processes and has different main ions \(^{[1]}\).

**Figure 1.** Representation of ionosphere layers \(^{[4]}\)

Figure 1 is shown the ionosphere layer in general from Earth atmosphere that located in a range of about 50 km to more 1000 km above Earth surface and contain charge electric particle. D layer is the lowest layer at altitude ~50 - 90 km above the ground, E layer is the second ionosphere layer, starting at about ~90 - 150 km. The F layer is the last of the ionosphere layer, starting at about 150 - 600 km and it can extend up to more than 1000 km that is the uppermost of the ionosphere. The differences in the formation of the ionosphere layer are influenced by solar activities, this can seen the formed ionosphere layers depends on time: D, E, F1, and F2 layers. In the night condition, the amount of electrons is decreased so that only F2 and E layers occur. The D layer is a fundamentally solar controlled layer and the transport process is not very important in this layer of the ionosphere \(^{[3,5]}\). It can reflect very low frequency 3 - 30 kHz (VLF) and low frequency 30 - 300 kHz (LF) radio wave and absorb medium frequency 300 kHz - 3 MHz (MF) and high frequency 3 - 30 MHz (HF) up to some extent \(^{[3,6]}\).

VLF/LF Radio waves can be traveled hundreds to thousands of kilometers from the transmitter with repeated reflections between the Earth and the ionosphere that is called Earth-Ionosphere Wave-Guide (EIWG). Earth surface (sea and land) becomes the lower boundary propagation and the ionosphere D layer becomes upper boundary propagation radio wave VLF/LF \(^{[7]}\). The repeated reflections between the Earth and the ionosphere can be utilized to observe changes in the ionosphere layer by using VLF/LF radio wave from natural source or VLF/LF transmitters, especially at the D layer can be disturbed due to solar flare, lightning energy, cosmic rays, earthquake etc. The D layer is the ionosphere layer that is difficult to observe. It is too high to be observed by balloon, too low to be observed by ionosonde, and too low to be observed by satellite \(^{[7, 8]}\) so the D layer is difficult to observe continuously. The D layer observation using rocket sounding has been carried out but this is very limited to certain places and uses certain frequencies, Besides that, It has been used medium frequency radar (MF Radar) but requires high cost \(^{[8]}\). About 30 VLF/LF transmitters on range frequency 10 - 77.5 kHz are operated in many countries: Australia, the United States of American, Japan, China, India, and some in European countries. By utilizing the VLF/LF transmitters, we can
observe the occurrence of solar flare by looking at the phase and amplitude changes of the signal received using the VLF/LF receiver.

2. Research Method
VLF/LF receiver located in Pontianak space and atmospheric observation (0.00°U, 109.37°T) of the facility of the National Institute of Aeronautics and Space (LAPAN). This VLF/LF receiver is joined in the Asia VLF Observation Network (AVON) that has the aims to monitoring lightning activity, Energetic particle precipitation from radiation belts, solar X-ray flare event effect on upper and middle atmospheres, the effect of the solar eclipse, atmospheric gravity waves, and sound wave on the lower ionosphere and detection of a gamma-ray burst. VLF/LF radio waves from the transmitters are reflected by the low region ionosphere layer will be received by a receiver that has undergone a change in amplitude and phase.

2.1. VLF/LF Receiver
The VLF/LF receiver was installed, operated and worked in three modes on August 26, 2010. The first mode is VLF-E that worked in the frequency of 100 Hz - 20 kHz. The second mode is VLF-B that worked at the frequency of 1 kHz - 40 kHz and the third mode is LF-STD that worked at the frequency of 10 kHz - 100 kHz. In this research, The VLF/LF receiver will be worked in the LF-STD mode and using a vertical electric monopole antenna. Figure 2 shows a diagram block of the VLF/LF receiver and It system consists of the vertical electric monopole antenna, low noise amplifier (pre-amplifier), the main amplifier included low pass filter, GPS locked oscillator, and computer included analog to digital converter (ADC) and software for signal processing and data recorder.

![Diagram block of VLF/LF receiver system](image)

The vertical monopole antenna was selected to avoid a large land use and can also receive signals from any direction. The monopole antenna constitutes a group of derivative of dipole antennas and only half of the dipole antenna needed for operation so the presence of the ground plane allows the monopole antenna to operate as electrically equivalent to a dipole antenna\(^\text{[11]}\). The input signals from the ionosphere reflector is received by the antenna and is almost in few micro-watts or less, therefore the VLF/LF receiver requires a Pre-Amplifier to amplify the signal and then amplifies again by the main amplifier to require on the minimum input of the VLF/LF receiver system. The pre-amplifier is located very close to the vertical monopole antenna to avoid the decrements of the signal transmitted through the coaxial cable. The GPS locked oscillator is an external reference oscillator needed by the main amplifier to generate a local oscillator, on the other hand, it is also used as an accurate source of timing.
2.2. Data

There are about 30 VLF/LF transmitters in the world such as Australia, the United States of America, Japan, China, India, and several in European countries. In this research, The VLF/LF receiver located in Pontianak (PTK, Geographic lat. 0.00°N, long. 109.36°E) that will record the LF signal from Fukushima-Japan (JJY40) in the frequency of 40.0 kHz, Fukuoka-Japan (JJY60) in the frequency 60.0 kHz, and Pucheng-China (BPC) in the frequency 68.5 kHz. Figure 3 shows the location of the VLF/LF receiver and transmitters that used in this research. The Transmitter Receiver Great Circle Path (TRGCP) from JJY40, JJY40, and BPC transmitter to the receiver station at PTK is about ~5262.84 km, ~4307.97 km, and ~3908.59 km, respectively. Three transmitters were selected based on data available where the results of the observation from those transmitters are the best base on empirical data.

The VLF/LF data is a form binary format with a time resolution of 0.1 seconds. In this research, data will be processed when a solar flare occurs from 2011 to 2016. The data was selected to represent every one of the incidences of solar flare events in the C, M, and X classes for analysis. Solar flare events data obtained from https://satdat.ngdc.noaa.gov/sem/goes/data/full/ in computable document format (CDF) file and solar flare event archive or real-time monitoring can be seen from https://www.spaceweatherlive.com/en/archive. Solar flare event observed is used by Geostationary Operational Environmental satellites (GOES) using X-ray sensors onboard the Space environment Monitor (SEM). The X-ray sensor provides solar X-ray fluxes for the wavelength bands of 0.5 to 4 Å and 1 to 8 Å. Solar flares are classified in A, B, C, M, and X classes according to the peak flux in Watts per square meter (W/m²). Solar flares events are selected only a few events that represent M, C, X classes that show in Table 1.

Figure 3. Location of VLF/LF receiver and transmitters
Table 1. Solar flare events starting in 2011 until 2016

| Class | Date       | Start   | Maximum | End   |
|-------|------------|---------|---------|-------|
| X2.2  | 2011/02/15 | 01:44   | 01:56   | 02:06 |
| X6.9  | 2011/08/09 | 07:48   | 08:05   | 08:08 |
| X5.4  | 2012/03/07 | 00:02   | 00:24   | 00:40 |
| X1.8  | 2012/10/23 | 03:13   | 03:17   | 03:21 |
| M8.7  | 2012/01/23 | 03:38   | 03:59   | 04:34 |
| X3.3  | 2013/11/05 | 22:07   | 22:12   | 22:15 |
| M2.9  | 2013/06/21 | 02:30   | 03:14   | 03:43 |
| M2.1  | 2015/01/29 | 11:32   | 11:42   | 11:52 |
| C7.2  | 2016/02/18 | 01:49   | 01:58   | 02:04 |

2.3. Data processing

The file name of VLF/LF data has a format RRRYYYYMMDDHH where RRR for the initial site location, ie. PTK for Pontianak, YYYY for observation year, MM for a month, DD for the day, and HH for an hour. In the file, there are 3601 blocks of data or rows, and the size of each block of data can be calculated using Eq 1.

\[
\text{size of each block} = \text{Number of frequency channel} \times 20 \times 2 \text{ Byte} + 4 \text{ Byte} \quad (1)
\]

The information contained in the VLF/LF data is divided into two parts: the header file and observation data (phase and amplitude parameters). The header file is the first of block data where it has three parts of the information: observation time (Year, Month/Day, and Hour), sampling frequency, Data length for FFT, number of the frequency channel, block size, and list of frequency channels. Table 2 shows the structure of the header file. The data observation is divided into two parts such as zero pad and information blocks. The zero pad is a block of data that values all contain zeros so this block data should be removed when data processing. Information block is the main data resulting from observations consisting of time, amplitude, phase for every on frequency channel.

Table 2. Structure of header file

| No. | Contents                  | Size   |
|-----|---------------------------|--------|
| 1   | Year (YYYY)               | 2 Byte |
| 2   | Month/Day (MMDD)          | 2 Byte |
| 3   | Hour (HH)                 | 2 Byte |
| 4   | Sampling frequency (kHz)  | 2 Byte |
| 5   | Data length for FFT (point)| 2 Byte |
Number of the frequency channel | 2 Byte
---|---
Block size (byte) | 2 Byte
Frequencies recorded | 2 Byte x Number of the frequency of channel

The information block has 3601 field data, always starting with a value of 0X7FFF in hexadecimal or 32767 in decimal, time (minute and second) in the second field data, and next field data for amplitude and phase for every frequency channel and resolution time of 0.1 second. That will be repeated as many times as the number of the frequency channel and a minute observation will be recorded in one data block so one file of VLF/LF data for one hour observation. Figure 4 shows the structure of the information block data.

Data processing includes reading, filtering, and plotting the amplitude and phase of the VLF/LF signals. The filtering is used to remove noise from the data for easier reading and analysis. The median filter is applied in data processing to remove noise, one of the reasons for using median filter, is simple and fast in the computational. The median filter visits each point in the data and places its center on it; all the intensity values within the window are sorted, and the median intensity value is then used to replace the window’s center in the filtered data \(^{(12)}\). The window is used of 900 in this data processing.

3. Results and discussion
Solar activities can affect sudden changes to the ionosphere layer, these impulse will change the amplitude and phase strength when the solar flare occurs, the amplitude and phase strengths will increase suddenly. The changes are used to detect solar flare events by observing changes on the ionosphere D layer. The sudden change in the ionosphere layer caused by the energy of solar flare reaching the Earth’s upper atmosphere, this energy will be increased by the ionization in the ionosphere \(^{(13)}\). Figure 5 shows the solar flare event detected by the VLF/LF receiver in Pontianak on February 15, 2011, and confirmed using X-ray flux data from GOES satellite observation.

The solar flare that occurred on February 15, 2011, was an X-class flare with a magnitude of X2.2. During the solar flare event, the X-ray flux is increased suddenly together with the amplitude and phase of JJY40, JJY60, and BPC transmitters as shown in figure 5. The solar flare occurred on February 15, 2011, starting at 01:44 AM (UT) until 02:06 AM (UT), the peak of the solar flare at 01:56 AM (UT). If we look further, time delays (\(\Delta t\)) between amplitude and phase peaks with the X-ray peak about of 0.5 to 5 minutes is estimated for some of the flares, with the C class of flare...
revealing the largest time delay of 5 minutes \[^{14}\]. In Figure 5c, the amplitude signal did not increase suddenly, there are several possible causes for his case, due to the VLF/LF receiver was a problem on the amplitude processing or below may not have produced any detectable VLF perturbations \[^{14}\]. The phase change represents an increase or decrease in the effective reflection height of the VLF/LF radio wave.

Figure 5 shows the phase and amplitude changed when the solar flare occurs on the X-class flare where the phase and amplitude are the results of VLF/LF observation and the X-ray flux is the result of GOES satellite observation. In figure 5, the phase value is more than 360 degrees and it has an ambiguity of 360 degrees, in this case, the magnitude of the phase change depends on the effective reflection height value. The phase value is more than 360 degrees due to change in the effective reflection height becoming larger than the wavelength of the radio wave so the phase change cloud becomes more than 360 degrees. In data processing to correct the jump, we need to add +360 or -360 degrees on the phase value when it is increasing or decreasing and crosses +180 or -180 degrees to avoid the phase suddenly changing to -180 or +180 degrees. A rapid decrease of effective reflection height by changing the ionization rate of O2 and N2 and increasing the ionosphere D layer ionization degree at lower heights \[^{15, 16}\].
Figure 5. Plotting of VLF/LF signal amplitude, phase, and X-ray flux when solar flare event in X-class flare on February 15, 2011. a). Solar flare event is detected from BPC transmitter, b). Solar flare event is detected from JJY60 transmitter, and c). Solar flare event is detected JJY40 transmitter.

The difference phase value is caused by the behavior of the ionosphere D layer as EIWG to the VLF/LF propagation through the ionosphere and the conditions corresponding to the flare peak. The X-rays from solar flare will ionize the neutral atmosphere at the ionosphere D layer which increases the electron densities, thus markedly lowering the effective VLF/LF reflection height where this lowering of the reflection height is the main cause of the increase in amplitude and phase values during the solar flare events [14]. Besides, the electron density at the lower edge of the ionosphere D layer will sharpen during solar flares in the sense that the rate of increase of electron density with height increases, and this also can be affected the amplitude and phase at the VLF/LF receiver [15, 17]. Figure 6 shows a few solar flares event on August 9, 2011, June 21, 2013, and February 18, 2016, in X-class, M-class, and C-class flares, respectively.
Figure 6. Plotting of VLF/LF signal amplitude, phase, and X-ray flux when solar flare event on August 9, 2011, a). Solar flare event is detected from the JJY40 transmitter, b). Solar flare event is detected from the JJY60 transmitter, and c). Solar flare event is detected the BPC transmitter.
Figure 7. Plotting of VLF/LF signal amplitude, phase, and X-ray flux when solar flare event on June 21, 2013, d). Solar flare event is detected from the JJY40 transmitter, e). Solar flare event is detected from the JJY60 transmitter, and f). Solar flare event is detected the BPC transmitter.
Figure 8. Plotting of VLF/LF signal amplitude, phase, and X-ray flux when solar flare event on February 18, 2016, g). Solar flare event is detected from the JJY40 transmitter, h). Solar flare event is detected from the JJY60 transmitter, and i). Solar flare event is detected the BPC transmitter.

The ionization densities in the ionosphere D layer are sufficient to support the ionospheric propagation of VLF/LF radio waves and the reflection from a weak lower layer D dominates the propagation mechanism for the longer paths [18, 19]. The perturbation of the ionosphere D layer due to the solar flares can be seen in the amplitude and phase of the VLF/LF signals that suddenly changes. Delta amplitude (\(\Delta A\)) and phase (\(\Delta P\)) values are used to find out how much perturbation of the ionosphere D layer due to the solar flares. Both values are calculated by subtracting the maximum values (A\(_{\text{peak}}\) and P\(_{\text{peak}}\)) during the solar flare events to the regular value or the normal condition value. The \(\Delta A\) values in solar flare events on Feb 15, 2011, January 23 and March 7, 2012, June 21, 2013, and February 18, 2016, are 5.0 dB, 4.66 dB, 6.49 dB, 2.17 dB, and 3.70 dB respectively and the \(\Delta P\) values are 422 deg, 344 deg, 772 deg, 264, and 249 deg respectively. The values of \(\Delta A\) and \(\Delta P\) are influenced by the magnitude of the solar flare, in that data, the largest solar flare events are X5.4 and X2.5 classes on Feb 15, 2011, and March 7, 2012.

Besides that, the magnitude of the disturbance is also influenced by the propagation of VLF/LF signals through Earth’s ionosphere waveguide due to the solar X-ray flares, significant modifications of the propagation happen due to significant changes in the lower ionosphere electron density [20,21]. The values of \(\Delta A\) and \(\Delta P\) change as there is an increase in density in the D layer in the electrical conductivity at the upper waveguide edge along the trace of the VLF/LF signals and consequently
gives rise to the change in all propagating parameters [20] so the VLF/LF radio wave does not lose energy as it reflects from the bottom of the ionosphere D layer [22].

4. Conclusion
Solar flare events will increase the density of the ionosphere D layer, as a result of that change will be increased the signal strength at the amplitude and phase of the VLF/LF receiver. Increased amplitude and phase are used as an indicator of solar flare events but only increased sudden can be used as an indicator of solar flare events. The increase in the amplitude and phase are due to electron density increasing in the D layer so that the VLF/LF radio waves does not lose energy as it reflects from the D layer. The magnitude of the amplitude and phase depend on the class of solar flares, the solar flare of X class will show a high enhancement in the amplitude and phase when compared to solar flare of the M-class and C-class. The magnitude of perturbation can be calculated by subtracting the value of the maximum (amplitude or phase) with the value of the normal condition of amplitude or phase.

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