

# ELF Wave Propagation Simulation using FDTD Method and Satellite Constellation Concept for Early Warning System

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**Abstract**— Earthquake is a hazardous event resulted in physical loss including fatalities. Early warning system is one of the important factors to reduce the risk of this disaster. However, in some areas (mostly remote areas) and countries, early warning system is still not working properly. Recent studies of ULF/ELF shows the electromagnetic profile disturbance prior to earthquake. This paper presents the simulation of ULF/ELF propagation along 3D cylindrical waveguide. Three key parameters are used to simulate the seismic propagation wave: radius ( $r$ ), angle ( $\phi$ ) and depth ( $z$ ). While simulation was done to see the wave propagation, the alert system concept is proposed using satellite constellation. Ground based sensor records the electromagnetic waves which are then processed by the station using FDTD method. Finally, to overcome remote area problems, the station will send the processed received data to the satellite, which relay the information to the main ground station.

**Keywords**— FDTD, Earthquake Precursor, ULF/ELF, Satellite, Constellation

## I. INTRODUCTION

Recently many researchers observed on the anomalies of ULF (Ultra Low Frequency, 0 – 3 Hz) and ELF (Extremely Low Frequency, 3 – 3000 Hz) [1] during and after earthquake. The anomalies show the disturbance in the electromagnetic waves, including the increase of background noise [2]. In some events, the disturbance was also reported prior to the large earthquake, which excited by seismo-electromagnetic emission in the ULF-ELF band [3]. The causes of earthquake so far can be categorized into three: 1) Tectonic activity which caused by sudden faults movement. This sudden release of energy causes the wave in the ground; 2) Ground shaking movement along with volcanic eruptions. For areas located in the “ring of fire”, which surrounded by the volcanoes, earthquake happens quite frequent. The activities under the volcanoes is one of the reasons for that to happen; 3) Human activity such as dynamite, bomb, ground drilling, and so on can cause ground shaking as well.

Over the years, seismograph has been used as a reliable tool to detect and record the seismic waves. However, referring to the recent observation, prior detection of earthquake is becoming more possible to mitigate the disaster. In [4], from around the site of the forthcoming earthquake, ULF

lithospheric magnetic emission was originated. Though the intensities of the lithospheric disturbance are very weak, the emission extends up to 100 Km or more from the epicentre before strong earthquakes [5]. Ground based instrument will be needed to detect, captured, and record this signal.

In this paper, simulation of ELF wave propagation is presented to show the electromagnetic characteristic over the lithosphere. Simulation was done using FDTD (Finite Difference Time Domain) method in 3D cylindrical waveguide model. FDTD is a method proposed by Kane S. Yee in 1966 [6] to solve the electromagnetic problems based on Maxwell equation. In section 2, the FDTD basic model used in the simulation will be described. It will simulate the ELF band in frequency of 3000 Hz with Mur's ABC as the boundary condition. The size of the waveguide in the simulation is  $r = 50$  m,  $z = 100$  m. The implementation concept for ground based instrument and space based application are presented in section 3. The ground based instrument is suggested as the instrument to detect the ELF signal in lithosphere. The signal will be recorded and processed in the local ground processing station. In the case of remote area, satellite constellation to relay the signal is suggested. It will continuously cover one area in the earth. The relayed signal will then be transmitted to the central ground station. Finally, conclusion is presented in section 4.

## II. ELF WAVE PROPAGATION SIMULATION

### A. FDTD Basic Model

In 3D FDTD cylindrical model, the lithosphere is modelled after the unit cell using cylindrical coordinates as shown in Figure 1.

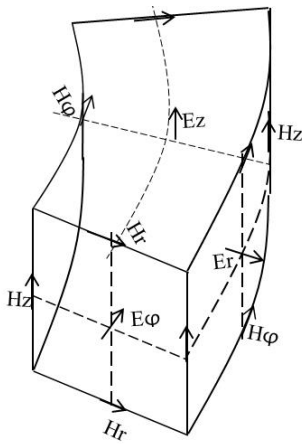


Figure 1. Cell unit in 3D cylindrical coordinate model

The basic equation for simulation is presented in [6] with Transverse Mode (TM) as the wave mode. For the simulation, it is necessary to apply the boundary condition such as ABC into FDTD algorithm. There are 6 boundaries for this model. The frequency used in the simulation will be 3000 Hz (ELF band range).

To simulate the lithosphere, the characteristic of the ground is determined. There are two electrical parameters for FDTD simulation in any medium which are also used here: relative permittivity ( $\epsilon_r$ ) and relative permeability ( $\mu_r$ ). ITU Radio communication Assembly considered that the permeability of the ground was the same as free space, or in the simulation was set to  $\mu_r = \mu$  [7]. While for the relative permittivity, it depends on the composition of the ground. Materials composed in the ground are varies, i.e. water, dry soil, moist soil, sandstone, and sand. Table 1 shows the dielectric constant for ground soil composition [8].

Table 1. List of dielectric permittivity for several substances

| Substance    | Permittivity ( $\epsilon_r$ ) relative to vacuum (F/m) |
|--------------|--------------------------------------------------------|
| Soil (dry)   | 3                                                      |
| Soil (moist) | 10                                                     |
| Water        | 88 (at 32° F)<br>80.4 (at 68° F)                       |
| Sandstone    | 20                                                     |
| Sand (dry)   | 2.5                                                    |

The present paper will consider the ground as dry soil with relative permittivity  $\epsilon_r = 3$ .

### B. Simulation Result

The simulation was done with harmonic wave source located in  $r = 2$ ,  $z = 3$ . The propagation wave is plotted in different location varies on radius ( $r$ ) and depth ( $z$ ). Location parameter which is used here is  $(r, \phi, z)$ . Simulation results presented in Figure 2 to Figure 4.

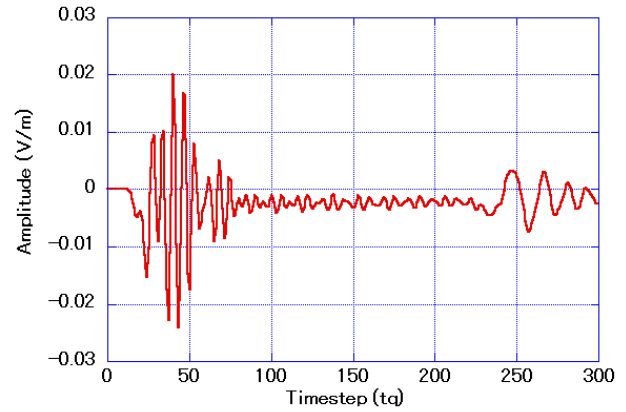


Figure 2. Simulation of harmonic wave at coordinate (3, 45°, 10)

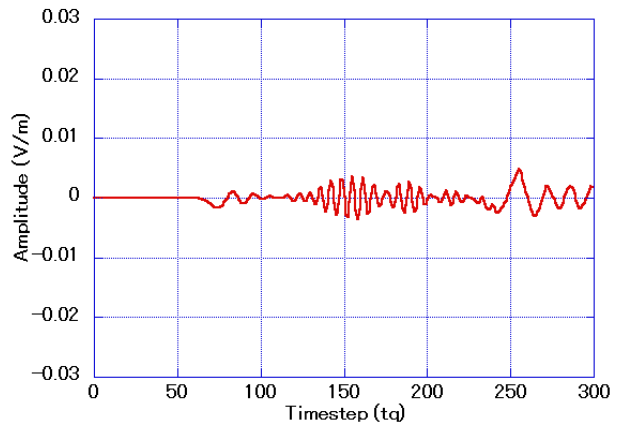


Figure 3. Simulation of harmonic wave at coordinate (4, 45°, 30)

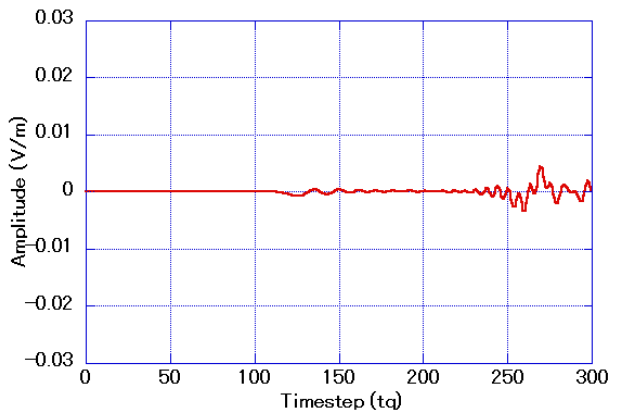


Figure 4. Simulation of harmonic wave at coordinate (5, 45°, 50)

The simulation results show the attenuation of the wave along the plane. In the same angle, the wave propagates towards the outer boundary of the medium. From the figures, there is a clearly visible ELF characteristic. The waveform starts with the first peak, propagates shortly from the source, and followed by another peak with opposite polarity. This characteristic often referred as Q-burst [9].

### III. EARTHQUAKE EARLY WARNING SYSTEM

Simulation for the ELF wave can determine the earthquake precursor by the arrival of the first peak. In this section, the system model of the earthquake early warning system based on ground instrument and space application will be described.

#### A. System Model

There are two important segments in this early warning system: Ground based instrument and space based application. Ground based instruments consist of ELF detector module, transmitter, ground processing, and main ground station. The space based application will utilize the function of satellite constellation to relay the signal to the main ground station. Overall system model is shown in Figure 5.

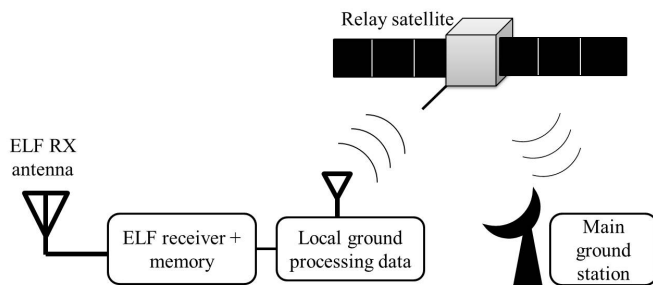


Figure 5. Early warning system model

From the main ground station, the processed data will be sent to the public, giving information about the probability of the upcoming earthquake.

#### B. Ground Based Instrument

Ground based instruments must consist of the necessary communication system to detect the ELF wave. Basic communication instruments are antenna, local ground processing data station, transmitter, receiver, and memory.

1. **ELF Antenna.** The design for the antenna should cover the ELF band range from 3 – 3000 Hz. However, to design an antenna which works on this wavelength is quite a challenge. One of the proposed ELF antenna design was described in [10]. Another design was described in [4], an inductive type antenna using PVC with more than 4000 turns of copper conductor. The PVC has outer diameter of 50 mm and length of 870 mm.
2. **ELF receiver.** One module ELF receiver should consist of an amplifier as well to apply amplification to the detected signal. ELF receiver should store the detected ELF wave to the system memory.
3. **Local ground processing data.** This unit can be considered as the main unit of ground based instrument. This unit takes the detected signal stored in the memory, and applies the processing into the signal. Because this local station should process the data, one module of data acquisition is needed. Figure 6 shows the indoor system of the local station.

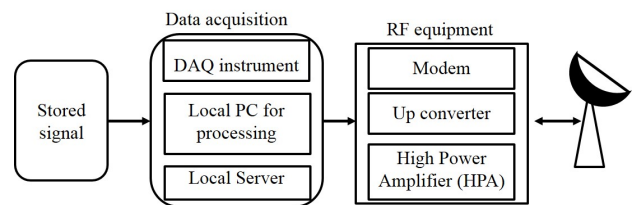


Figure 6. Local ground processing data

#### C. Satellite Constellation

Remote area mainly has difficulties in communication. For detected precursor signal in the remote area, one alternative is using satellite communication to send the signal. For one region or country, GEO satellite communication has advantage of constant area coverage. However, the challenge related to power transmission between space and ground is high. With altitude around 36,000 Km from the earth, and operating frequency between 1 to 4 GHz, the free path loss will be 183.57 dB to 195.61 dB. Antenna with good transmission from the local ground processing data is also necessary, which will be difficult for remote area.

Instead of using GEO satellite, constellation of several satellites can be an alternative. The altitude of the satellite is in LEO (altitude is around 500 Km from the earth), which resulted in non-continuous coverage of the area. For one satellite orbiting in this altitude, the period is about 94 minutes, leaves 10 – 15 minutes per one pass of one area. However, the loss from this distance will be much smaller, from 146.42 dB to 158.47 dB. Recently small satellite is used for this purpose. The idea of satellite constellation in the space is to aim the continuous coverage of the earth.

##### 1. The Total Number of the Satellite

To determine the total number of the satellite in the constellation, a rough calculation is used. One satellite can cover one area per 10 to 15 minutes. It means, at least 6 satellite is needed for complete coverage. Figure 7 shows the first simulation from constellation of 6 satellite using STK software. It has inclination angle of  $25^\circ$ , and field of view of payload  $\pm 45^\circ$ . This constellation will be advantageous for covering several remote areas in several regions. For example, it can cover two remote areas at the same time. In this simulation, two areas in Banda Aceh and Yogyakarta, Indonesia, were simulated. However, the coverage per one area is not continuous all the time, there is at least 15 to 18 minutes without satellite coverage.

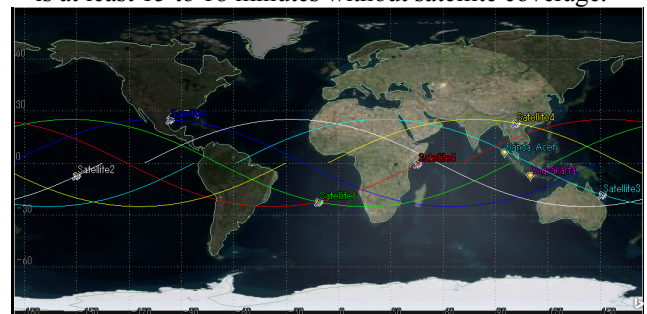


Figure 7. Six satellites constellation simulation by STK for  $25^\circ$  inclination

The second simulation is constellation with 0 degree inclination (equatorial constellation). The number of satellite are 6, with field of view of payload  $\pm 45^\circ$ . The simulation result is shown in Figure 8. The advantage in this constellation is continuous coverage almost all the time for one area. The result shows the simulation for Banda Aceh, Indonesia.

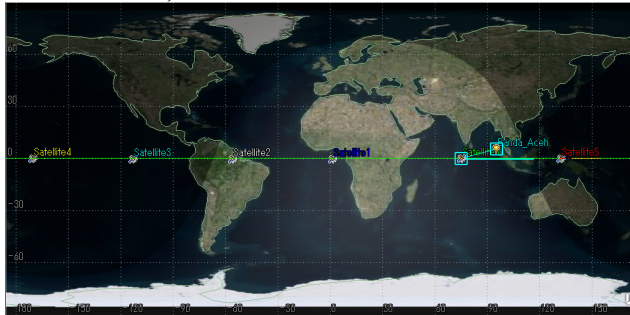


Figure 8. Six satellites constellation simulation by STK for 0 degree inclination

## 2. Communication Relay Concept

The early warning system will be an effective way to mitigate disaster if the communication can work properly. The following descriptions are the concept of communication relay in this early warning system.

- 1) Local station uplink the processed data of ELF wave into the passing satellite. Local station will keep sending the data until all the data are completely received by the satellite (Figure 9. (a)).
- 2) The receiving satellite will relay the signal to other satellite in the same constellation. The intercommunication satellite will be determined by satellite ID. The satellite will keep relaying the signal until detect the location of main ground station by sending continuous beacon signal (Figure 9. (b)).
- 3) When the satellite carrying information detects the location of main ground station, the data will be transmitted to the main ground station (Figure 9. (c)).

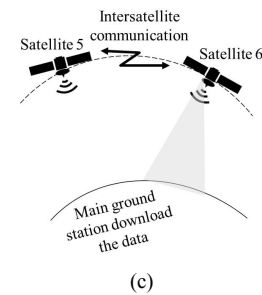
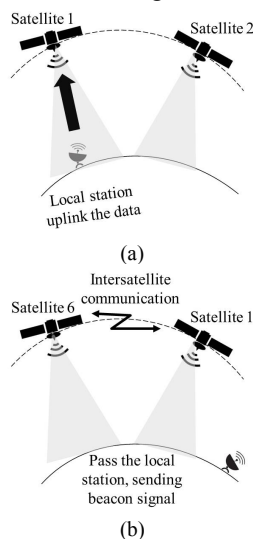


Figure 9. Communication relay concept using satellite constellation

## IV. CONCLUSIONS

ELF propagation wave using FDTD method is presented in this paper. The simulation was done with harmonic source using 3D cylindrical as the medium. The ground is simulated using relative dielectric constant for dry soil. The result from the simulation shows the wave that propagates towards the outer boundaries is attenuated. From the snapshot of the wave, the characteristic of ELF wave, Q-burst, is visible. The wave started with the first spike, shortly propagates towards the outer boundary, and followed by the next spike with opposite polarity.

This ELF wave processing can be used to determine the precursor of the upcoming earthquake. The study of sudden anomaly in ELF characteristic prior to earthquake gives possibilities of early warning system to the public. The early warning system consists of ground based instrument and space based satellite application. Instead of using GEO satellite for continuous coverage, a constellation of satellites in Low Earth Orbit is proposed. The purpose of the constellation is to relay the processed ELF data from the local station to the main ground station.

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