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Variations of ULF and VLF During Moderate Geomagnetic Storm At Equatorial Region

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***Abstract*—This paper presents variations of Ultra Low Frequency (ULF) and Very Low Frequency (VLF) during moderate geomagnetic storm using ground based observatories, Magnetic Data Acquisition System (MAGDAS)/Circum-Pan Magnetic Network (CPMN) magnetometer and Atmospheric Weather Electromagnetic System for Observation Modeling and Education (AWESOME) VLF receiver. In this analysis, the recorded ULF horizontal (H)-component are extracted from MAGDAS magnetometer at Yap Island (YAP), Federated States of Micronesia, Davao (DAV), Philippines, and Tirunelveli (TIR), India stations. VLF amplitude data were observed from VLF receiver at UKM while the transmitters are located at Katabomman (VTX), India, North West Cape (NWC), Australia and Lualualei, Hawaii (NPM), USA. The observations of the space weather conditions in this study are divided into two categories: quiet day (10 April 2010) and moderate geomagnetic storm (6 April 2010). The results show that the ULF and VLF variations are significantly affected during geomagnetic storm which geomagnetic activities are closely related with the solar parameters.**

Keywords*—*ULF; VLF; geomagnetic storm; equatorial region

I. INTRODUCTION

Space weather has its cycle with solar activity rising and falling over ~11 years solar cycle [1]. Space weather and geomagnetic storm at certain conditions will penetrate into the Earth's ionosphere through polar region and cause higher variations in the Earth's magnetic field [2]. The Earth's magnetic field is constantly affected by the solar wind, a stream of charged particles continuously emitted by the sun. When the solar wind interacts with the earth's magnetic field, it forms a cavity called the magnetosphere. The interaction process between space weather conditions and Earth's magnetic field is one of the factors that lead to the variations effect of both ULF and VLF waves which can be observed in space and on the ground. These waves propagate along or across the magnetic field and are converted to electromagnetic waves in the ionosphere. ULF and VLF variations are recorded in the frequency range of 1.7 - 500 MHz and 3-30 kHz respectively. Recent observations have shown that pulsations especially in the range 6.7-100 MHz are influenced by solar wind (SW) parameters; predominantly controlled by solar wind speed (Vsw), solar wind dynamic pressure (Pdyn) and solar wind input energy (ε) [3]-[5]. In addition, the correlation between solar flare (space weather parameter) and VLF variations was analyzed by [6] and [7]. Therefore, the aim of this study is to present the characteristics of both ULF and VLF influenced by space weather conditions, based on the data extracted from installed monitoring systems within the region using MAGDAS/CPMN magnetometer and AWESOME VLF receiver.

II. METHODOLGY

In this part, analysis of data is arranged in three sections which include classification of space weather conditions, ULF data and VLF data. For ULF data are extracted from MAGDAS magnetometer at Yap Island (YAP), Federated States of Micronesia (9.5 8°N, 138.08°E), Davao (DAV), Philippines (7°N, 125.4°E), and Tirunelveli (TIR), India (8.70°N, 77.80°E) stations as shown in Fig.1. The raw data from MAGDAS/CPMN stations was digitally bandpass-filtered in period range 150-600 sec before plot the dynamic power spectra density to identify the occurrences of Pc5 ULF pulsations.

VLF amplitude data were observed from VLF receiver at Universiti Kebangsaan Malaysia (UKM), Malaysia (2.55°N, 101.46°E) while the transmitters are located at Katabomman (VTX), India (8.47°N, 77.4°E), North West Cape (NWC), China (21.8°S, 114.2°E) and Lualualei, Hawaii (NPM), USA (20.4°E, 158.2°W) as shown in Fig. 2. Summarize of analysis data are listed in Table I.

TABLE I. ANALYSIS OF DATA

Space Weather Conditions	Dst Index (nT)	Date	ULF Stations	VLF Stations
Quiet	-30< Dst <0	10 April 2010	YAP DAV	VTX NWC

Space Weather Conditions	Dst Index (nT)	Date	ULF Stations	VLF Stations
Moderate	-50< Dst <-100	6 April 2010	TIR	NPM

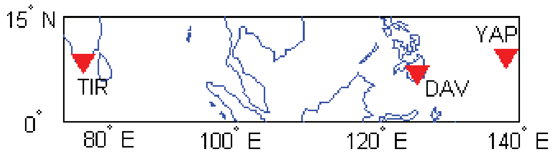

Fig. 1. Map of MAGDAS magnetometer for YAP, DAV and TIR stations

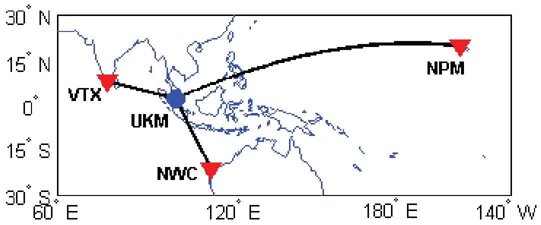

Fig. 2. Location of AWESOME VLF for UKM receiver, VTX, NWC and NPM transmiters with great cirle path

A. Classification of Space Weather Conditions

To characterize the space weather conditions, three (3) parameters have been considered which are; solar wind input energy, z-direction of Interplanetary Magnetic Field (IMF), Bz and Dst index. IMF Bz (nT) were obtained from the Space Physics Data Facility (SPDF) based at NASA's Goddard Space Flight Center. Dst indices are provided by the World Data Center for Geomagnetism, Kyoto, Japan. Solar wind input energy can be calculated using Akasofu epsilon, ε [3] as equation (1):

$$\varepsilon = Vsw\, B^2\, F(\theta)\, I_o^2 \qquad \text{(Watt or ergs)} \qquad (1)$$

where Vsw is solar wind speed [km/s], B is total magnetic field [nT], Io is Earth's radius [km] and F(θ) is a function of the angle, θ (By/Bz).

B. Quiet Period

Fig. 3 shows space weather parameters that considered in this study, a) Dst index and b) solar wind input energy and IMF Bz on 10 April 2010. Fig. 3 a) shows that the minimum Dst index is -25 nT at 0000 UT which is in range -30 nT <Dst index> 0 nT and classified as quiet day. For Fig.3 b), the IMF Bz is turned northwards (positive) from 0000 UT to 2100 UT and turned southwards (negative) from 2200 UT to 2300 UT. The minimum and maximum of solar wind input energy are$1.56\text{x}10^{11}$ erg/s and $1.11\text{x}10^{17}$ erg/s, respectively. Thus, 10 April 2010 is classified as quiet day based on the space weather parameters.

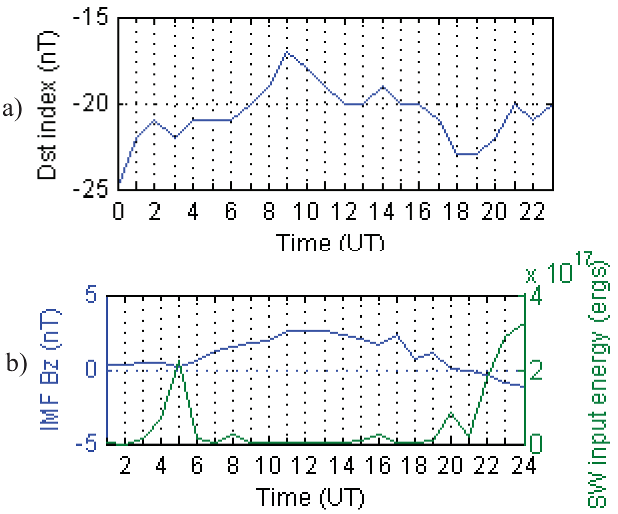

Fig. 3. Space weather parameters a) solar wind input energy (green) and IMF Bz (blue), and b) Dst index on 10 April 2010

C. Moderate Geomagnetic Storm

Fig. 4 shows space weather parameters a) Dst index and b) solar wind input energy and IMF Bz on 6 April 2010. Moderate geomagnetic storm is occurred during high solar wind input energy and on the same time Dst index is at minimum value with -81 nT as shown in Fig.4 a). The IMF Bz turned decreased on 6 April 2010 meanwhile solar wind input energy is increasing from 0000 UT to 1200 UT. However, the solar wind input energy is decreased when the IMF Bz increasing from 1300 UT to 2300 UT as shown in Fig. 4 b). The minimum and maximum of solar wind input energy are $1.78\text{x}10^{15}$ erg/s and $1.11\text{x}10^{17}$ erg/s respectively. Thus, 6 April 2010 is classified as a main phase of moderate geomagnetic storm based on the space weather parameters. This fact has been confirmed with World Data Center for Geomagnetism, Kyoto, Japan in list of quiet and most disturbed day.

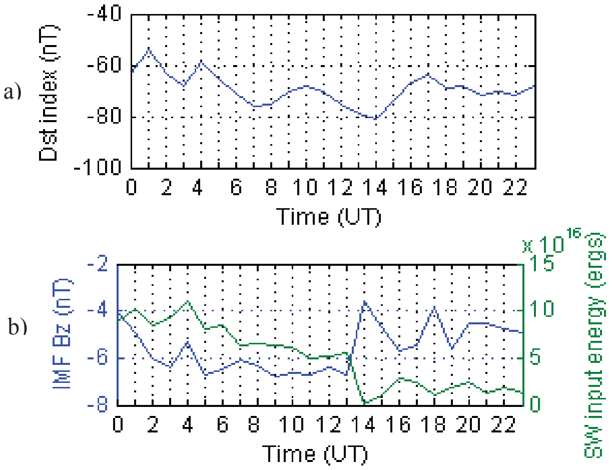

Fig. 4. Space weather parameters a) solar wind input energy (green) and IMF Bz (blue), and b) Dst index on 6 April 2010.

III. RESULTS AND ANALYSIS

A. *Earth's Geomagnetic H-component*

Figure 5 shows ULF H-components observed during quiet day (blue) on 10 April2010 and moderate geomagnetic storm (red) on 6 April 2010 at a) YAP, b) DAV and c) TIR station. The results indicate that H-components are smooth during quiet day. However on 6 April 2010, H-components are more fluctuated and less during moderate geomagnetic storm at these three stations compared to the H-component during quiet day as shown in Fig.5 a), b) and c). Both variations on quiet day and moderate geomagnetic storm at YAP and DAV stations show that H component recorded higher amplitude at time 0000 to 0700 UT (Universal Time). While for TIR station, the amplitude of H component is higher start from 0300 UT to 1000UT as shown in Fig. 5c). The H components afterwards maintained during night time at three stations and start increased only at YAP and DAV stations from 2200 UT to 2300 UT.

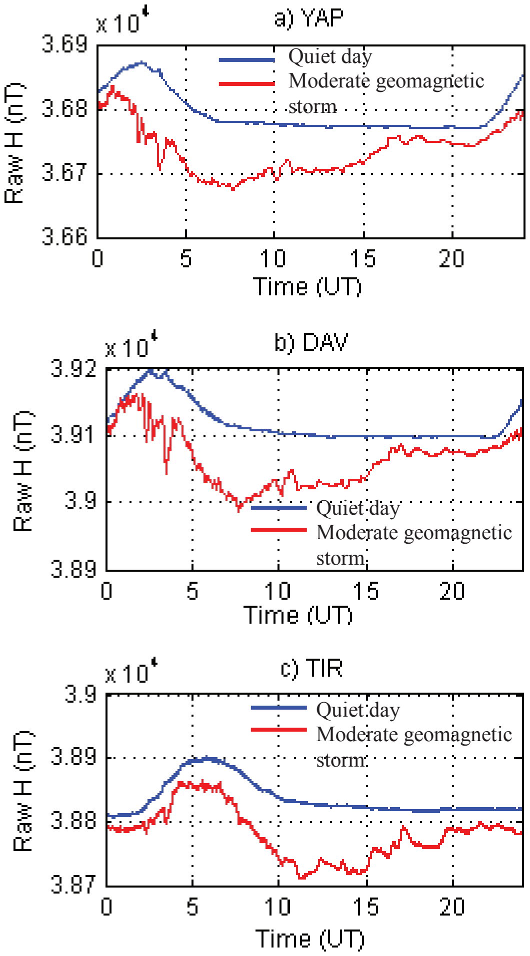

Fig. 5. ULF H-component during quiet day (blue) on 10 April 2010 and moderate geomagnetic storm (red) on 6 April 2010 at a) YAP, b) DAV and c) TIR stations

B. *ULF Variations*

1) *Quiet Day*

Fig. 6 shows a Pc5 pulsation and power spectral density at a) TIR, b) DAV and c) YAP stations. Based on result, the Pc5 ULF pulsations observed during quiet day are occurred from 0000 UT to 0800 UT at three magnetometer stations. However, higher fluctuation of Pc5 during nighttime was detected from 2200 UT to 2300 UT at YAP and DAV stations. Power spectra density (PSD) as shown in Fig. 6 produce confirms the existence of Pc5 geomagnetic pulsation. The darkest color show high intensity color resembles the occurrence of geomagnetic pulsation variations. Most Pc5 events are occurred from 0000 UT to 0800 UT at YAP, TIR and DAV stations as shown in power spectral density.

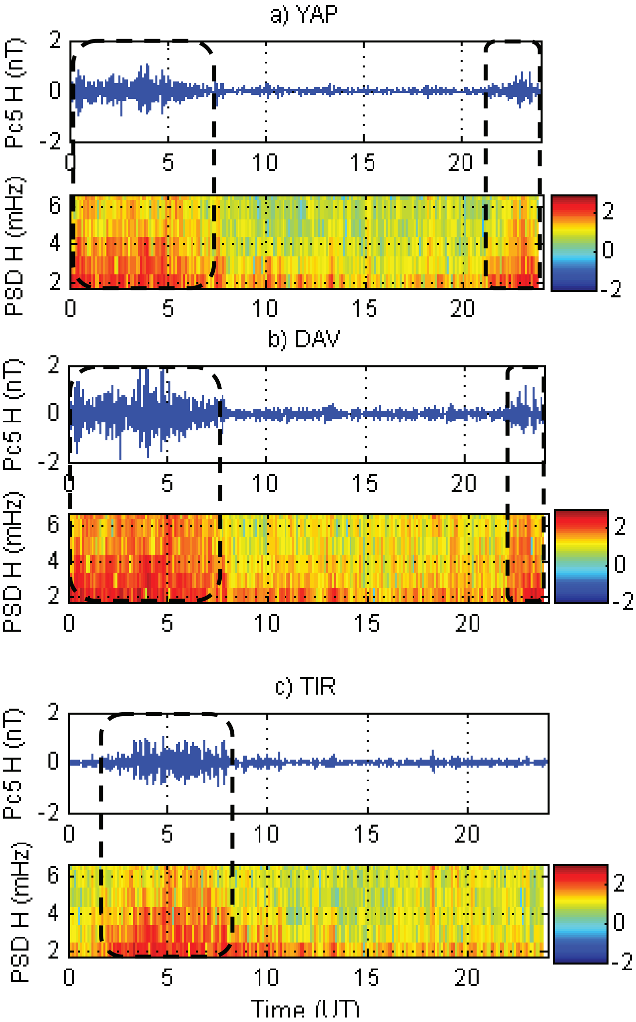

Fig. 6. ULF Pc5 pulsation (nT) and Power Spectral Density (mHz) at a) YAP, b) DAV and c) TIR stations on 10 April 2010

2) *Moderate Geomagnetic Storm*

Fig. 7 shows a Pc5 pulsation and power spectral density at a) TIR, b) DAV and c) YAP stations. It was found that Pc5 pulsations observed during moderate geomagnetic storm show higher fluctuation as compared to the Pc5 during quiet day at these three magnetometer stations. The occurrence of Pc5 event at TIR, DAV and YAP stations is clearly observed in PSD, which occurred from 0000 UT to 1000 UT on 6 April 2010 at range between 1.7-6.7 MHz. However, Pc5 was detected during nighttime from 2200 UT to 2300 UT at YAP and DAV stations. Pc5 more occurred and reached almost 6.7 MHz during moderate geomagnetic storm compared to the quiet day at these three stations.

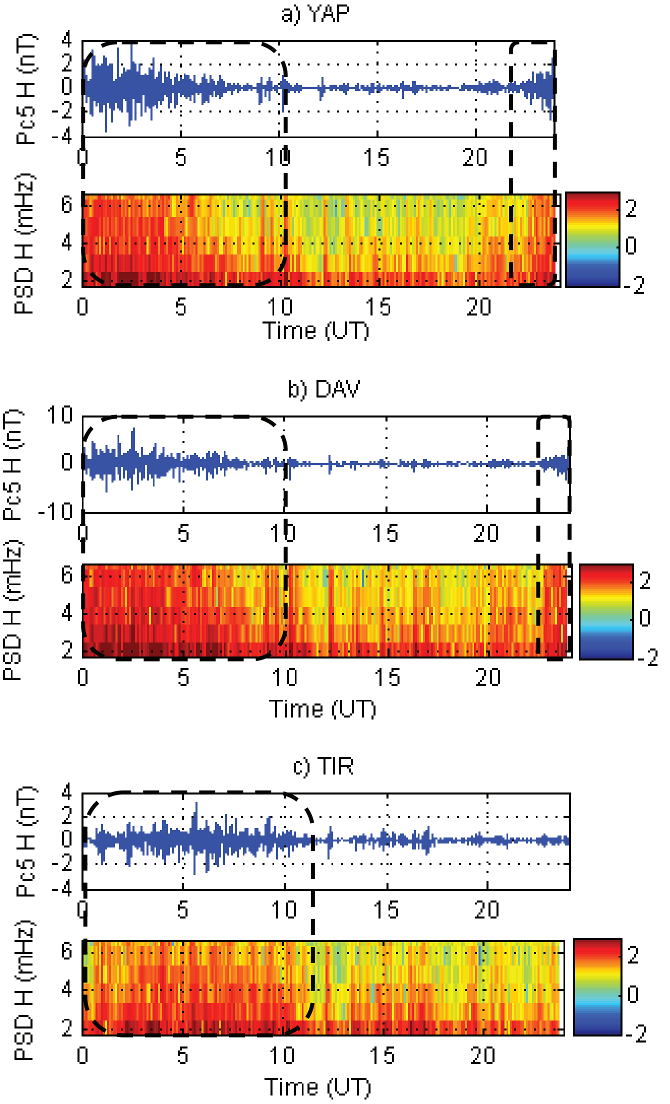

Fig. 7. ULF Pc5 pulsation (nT) and Power Spectral Density (mHz) at a) YAP, b) DAV and c) TIR stations on 6 April 2010

C. VLF Amplitude Variations

Fig. 8 a) and b) show that VLF variations for quiet day (blue) and moderate geomagnetic storm (red) on 10 April 2010 and 6 April 2010 respectively from VTX, NWC and NPM signals. Based on Dst index on 6 April 2010, moderate geomagnetic storm is occurred at 1400 UT with minimum peak Dst -81 nT. Then, the VLF variations are only focused between 1200 UT to 1600 UT as shown in figure below. The results indicate that the VLF variations are significantly affected and vary during moderate geomagnetic storm by comparing with the VLF variations in quiet day. The VLF variations during geomagnetic storm have a bigger difference amplitude signal comparing with VLF signal on quiet day on 1400 UT. However, the VLF signal from 0800 UT to 1000 UT and from 1800 UT to 2300 UT also might be affected by moderate geomagnetic storm because 6 April 2010 is a main phase of geomagnetic storm.

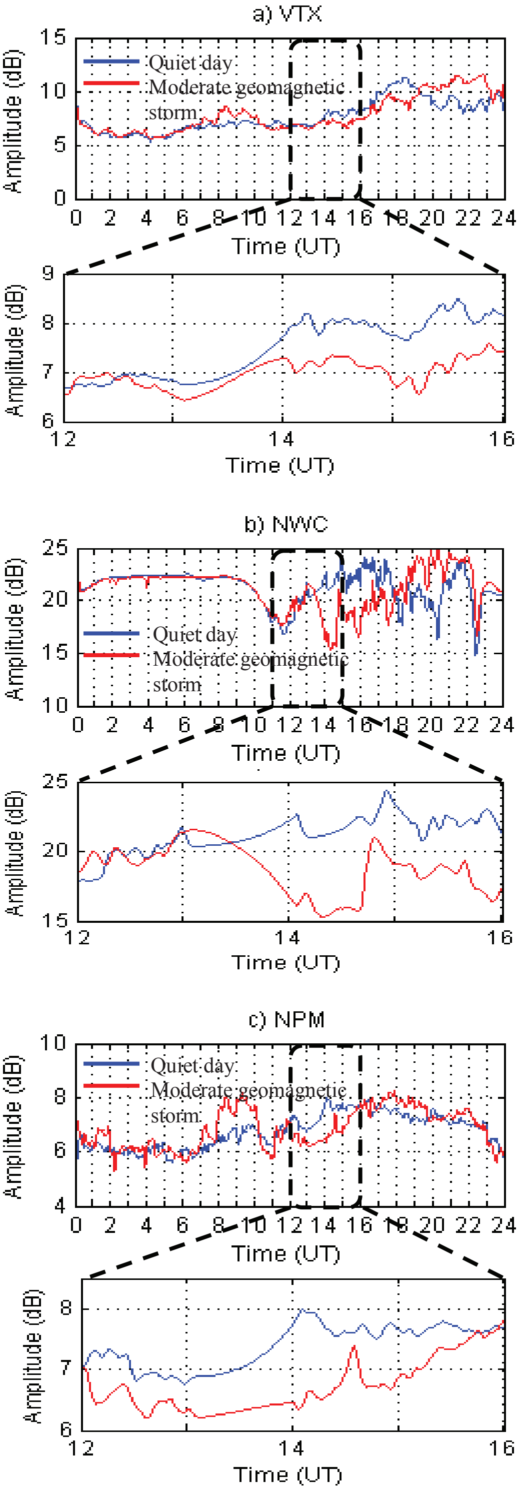

Fig. 8. VLF variations during quiet day (blue) on 10 April2010 and moderate geomagnetic storm (red) on 6 April 2010 from a) NPM, b) VTX and c) NWC transmitters

IV. DISCUSSION

In this paper, the characteristic of both ULF and VLF variations during moderate geomagnetic storm at equatorial region was examined. Anomalous conditions in the interplanetary magnetic field (IMF) and solar wind plasma might influence the occurrence of geomagnetic storms by various solar parameters include solar wind speed, solar input energy and solar wind dynamic pressure. The input energy transferred from the solar wind into the magnetosphere depends on the orientation of the interplanetary magnetic field (IMF). When these parameters penetrate to the earth, the ionosphere occasionally becomes disturbed due to the recombination process between charged particles (mostly proton and electron) of solar wind and Earth's magnetic field. However, geomagnetic storm at certain conditions with IMF strength and high speed solar wind can be observed from the Ultra-Low Frequency (ULF) and Very Low Frequency (VLF) variations.

Fig. 9 shows amplitude ratio of H-component between quiet day and moderate geomagnetic storm event at YAP, TIR and DAV stations. The results indicate that the amplitude ratio of H are increased during daytime compared to the nighttime of its local time at these three stations as shown in Fig. 9 a), b) and c). The peak amplitude ratio of H at YAP and DAV stations recorded at 0330 UT. While for DAV station, the peak amplitude ratio occurred at 1100 UT. It shows that most significant effects on H are occurred during daytime (local time) and it decreased during nighttime (local time).

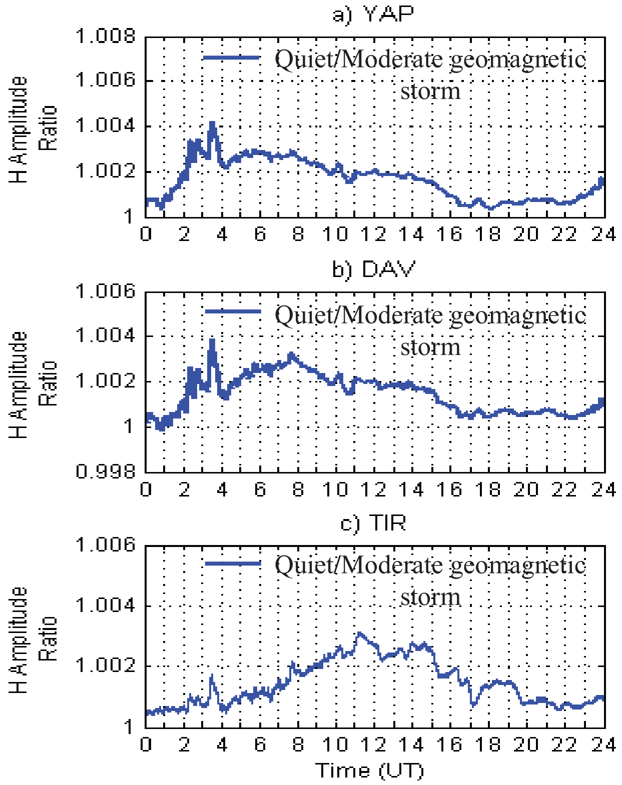

Fig. 9. ULF H component (nT) amplitude ratio between quiet day and moderate geomagnetic storm at a) YAP, b) DAV and c) TIR stations

This observation agrees with the result of previous study e.g. [8] and [9]. The higher variation on H component during daytime was attributed to the influence of equatorial electroject (EEJ) current system and dynamo action at equatorial regions. The results was supported by [10], that the EEJ is characterized by zonal ionospheric conductivity, which is very high during the daytime and the ionospheric conductivity is relatively reduced in the nightime. The night amplitudes are seen to remain relatively constant since there are no solar radiations during night and the variations observed is from sources other than ionosphere [11].

Based on [12], the ULF pulsations are driven by energy transfer from compressional modes, magnetospheric waveguide modes, cavity modes and Kelvin-Helmholtz instabilities at the magnetopause boundary. In addition, according to [10], based on their observation of Pc5 magnetic storm time at equatorial region, it is due to manifestation of gyrotropic MHD waves generated in the E-region of the EEJ.

VLF signal also have significant effects during moderate geomagnetic storm. The amplitude ratio of VLF signal between quiet day and moderate geomagnetic storm event from VTX, NWC and NPM signals are shown in Fig.10. Fig.10 a) shows that amplitude ratio slowly increased from 1200 UT to 1400 UT and varies until 1900 UT due to moderate geomagnetic storm The VLF signal from VTX transmitter produce longer recovery more than five hours. Fig.10 b) and c) show the VLF variations correspond well with the moderate geomagnetic storm event and reach high peak at 1400 UT. The VLF amplitude ratio from NWC transmitter continue fluctuated and take more than four hours to recover the signal as shown in Fig.10 b). However, the VLF amplitude ratio from NPM transmitter slowly decreased and produce short recovery signal that takes only two hours after moderate geomagnetic storm occurred (see Fig.10 c)).

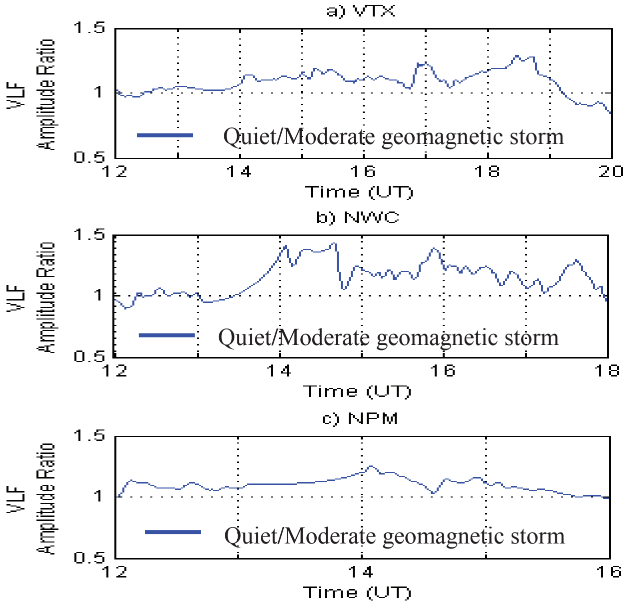

Fig. 10. Ampliutde changes of VLF (dB) for hourly between quiet day and moderate geomagnetic storm at a) NPM, b) VTX and c) NWC transmitters

Based on Fig. 10, the amplitude of VLF signal from NPM, NWC and VTX transmitters correspond to the storm main phase occurred at 1400 UT. This is due to the slow recombination of atoms and molecules diffusion at D-region during geomagnetic storms [13] and might be due to the VLF signal propagation mode through surface wave and sky wave with small penetration and absorption at the ionosphere.

VLF signal propagation is traveling in zigzag pattern and reflected at D-region (60-90 km) of ionosphere through Earth-ionosphere waveguide (EIWG) in which strongly depends on the ionospheric ionization condition [9]. VLF signal can be disrupted during propagation process by extraterrestrial events. During high speed solar wind event, the solar wind input energy gives rise to large ionospheric current vortices above the sun-lit northern and southern hemispheres. This ionospheric current may affect the variations of VLF at D-layer. However, the concrete explanation for this condition is still under investigation.

V. CONCLUSION

The analysis of ULF and VLF variations during moderate geomagnetic storm from the selected ground based stations has been discussed. From the results obtained, it can be conclude that the ULF and VLF variations at equatorial region correspond well with the main phase of geomagnetic storm event. Communication using ULF and VLF should be carefully analyzed during space weather perturbations. This shows that any activities on the Sun plays significant role in affecting the data observed from the ground based stations. It is important to study solar terrestrial environment in order to understand the effects of solar activities to the communication systems on Earth.

Acknowledgments

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