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Analysis of ULF Emissions in Solar Winds as A Short-Term Earthquake Precursor

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The physical destruction and fatalities caused by earthquake events compelled scientists to develop Earthquake predictions. Due to limited seismometer sensitivity, it was impossible to detect earthquake events; therefore, non-seismological is established, which in Ultra Low Frequency (ULF). The study of electromagnetic waves (EM) in the Ultra-Low Frequency (ULF) range is a promising tool for investigating seismomagnetic effects that act as an earthquake precursor. This study analysed the ULF frequency range as a short-term earthquake precursor at a depth < 100 km and an epicentral distance < 100 km (distance from Cebu magnetometer station) measured using a ground magnetometer installed in Cebu (10.36°N, 123.91°E), in the Philippines. This study also intended to determine the emission of magnetic pulsation (Pc4 and Pc5), solar wind parameters and near equatorial geomagnetic storms (SYM/H) in low latitude regions prior to an earthquake event. Findings show that the most evident ULF that acts as a potential earthquake precursor was at a frequency range of Pc5 (1.7 - 6.7 mHz) compared to Pc4 (6.7 - 22 mHz). It also shows that high solar wind changes and geomagnetic storms respond to the emission of ULF magnetic pulsations (Pc4 and Pc5) prior to earthquake events at low latitudes. Thus, it can be concluded that magnetic pulsations are signatures that indicate the probability of short-term earthquakes precursor.

Keywords: magnetic pulsation; solar winds; geomagnetic storm; earthquake precursor

I. INTRODUCTION

Earthquake events cause the release of energy in the crustal layer, which causes devastation, and in some cases, extensive damage. Thus, due to limitations in detecting seismic events, researchers have turned to non-seismological approaches to detect seismic events. The ULF emissions is the most candidate for earthquake precursor signature (Yusof *et. al.*, 2019; Piriyev *et al.,* 2021). Ultra-Low Frequency (ULF) is the best frequency range for detecting crustal activity in earthquake preparation due to its large skin depth and the ability to propagate through earth's lithospheric layer with small attenuations (Afandi *et. al.,* 2020; Kushwah & Singh, 2004; Umar *et al.,* 2019). According to Smith *et al.* (1990), community researchers have been investigating earthquake precursors in the ULF frequency range of 0.001-10Hz (Smith *et al.,* 1990). Previous studies have found ULF emissions in Pc3 magnetic pulsation at frequencies ranging from 22 to 100 mHz that have been linked to earthquakes (Mahsuri *et. al.*, 2018; Takla *et al.,* 2018). Yumoto *et al.* (2009) discovered an increase in the Pc3 power spectrum a few weeks before the Kushiro earthquake (Yumoto *et al.,* 2009). Masci (2011)

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reported that global geomagnetic activity is closely related to pre-earthquake anomalies in Pc3 (22 -100 mHz) and Pc4 (6.7 – 22 mHz) (Masci, 2011). According to Novikov *et al.* (2020), seismic responses might occur after a strong electromagnetic impact caused by a geomagnetic storm. ULF geomagnetic pulsations measured on the ground are caused by solar winds in various regions of the magnetosphere via a variety of physical processes (McPherron, 2005; Afandi *et al.,* 2018). It was revealed that the Pc3 - Pc5 wave range is a range that witnesses magnetised plasma wave propagation (Alfvén waves) in the magnetosphere and ionosphere (Han *et al.,* 2014). Takashi *et al.* (2012) discovered that a variation in Pc5 geomagnetic pulsation is related to solar wind bulk and dynamic pressure. The Pc5 mechanism is produced by high solar wind flows and can form the Kelvin–Helmholtz instability (KHI) at the magnetopause (Southwood, 1968). Likewise, Kozyreva *et al.* (2015) discovered bursts in the Pc5 geomagnetic pulsation plot with changes in solar wind pressure at high, mid, and low latitudes. This study aims to analyse reliable ULF frequency ranges that act as a possible earthquake precursor for earthquakes with depth (d < 100km) and epicentral distance (r < 100 km) from the magnetometer station using a ground magnetometer installed in Cebu (10.36° N, 123.91°E), in the Philippines. The ULF pulsation (Pc4 and Pc5) emissions in solar winds and geomagnetic storms prior to an earthquake event were also examined.

II. MATERIALS AND METHOD

ULF's Pc4 (6.7 – 22 mHz) and Pc5 (6.7 - 1.7 mHz) pulsations were investigated in this study along with solar wind parameters (solar wind speed (V), IMF-Bz, solar wind dynamic pressure (P), solar wind input energy (IE)) in geomagnetic storms near the equator region (SYM/H) for earthquake precursors at low latitude areas. Information pertaining to ULF pulsations was found in the supermag website (http://supermag.jhuapl.edu/) acquired from the Cebu (CEB) magnetometer station (10.36°N, 123.91°E) located in the Philippines (Gjerloev, 2012; Zafar *et al.,* 2021). This magnetometer station is located in the equatorial region's low latitude area. These data have a sample interval of 1s. The solar wind parameters and the symmetric part of the magnetospheric ring's current activity at the equator, which is (SYM/H), were recorded in the OMNIWeb online database (https://omniweb.gsfc.nasa.gov/form/omni_min.html) as per minute data.

The MATLAB software was used for processing data related to ULF pulsations (Pc4 - Pc5) in solar winds and SYM/H index for earthquake precursor research. The observation was analysed within two months after the data were collected, prior to the occurrence of earthquake events and was within an epicentral distance of 100 km, r (distance from Cebu magnetometer station) (Takla *et al.,* 2018) and depth of earthquake, d < 100 km. This earthquake parameter was considered because it is comparable to the skin depth of Pc4 (106.76km) and Pc5 (194.92km) pulsations when the lithosphere conductivity ($\sigma = 10^{-3}$) is assumed. This means that the propagation of Pc4 and Pc5 pulsations in the lithosphere can penetrate deeper than the depth of the earthquake, allowing for the investigation of earthquake precursors via Pc4 and Pc5 pulsations. Figure 1 depicts the location of the Cebu magnetometer station against selected nearby earthquakes, and Table 1 shows a list of earthquake events near the Cebu magnetometer station.

Figure 1. Location of Cebu (CEB) Magnetometer and the studied of earthquake events

Table 1. Details on earthquakes that occurred near the CEB Station (https://www.emsc-csem.org)

Magnetometer station	**Earthquake, EQ**	**Coordinates**	**Date & Time**	**EQ magnitude**	**EQ depth**	**EQ epicentral distance**
CEBU (CEB) (10.36^{O}N, 123.91^{O}E)	Negros-Cebu Reg, Philippines	10.06° N, 123.27° E	6th Feb 2012 03:49	6.7	40	60
	Negros-Philippines	9.93° N 123.11°E	16th Feb 2012 10:10	6.3	50	89
	Negros-Cebu Reg. Philippines	10.22° N 123.40° E	7th Feb 2012 21:59	5.0	3	81
	Negros-Cebu Reg. Philippines	10.24°N 123.40° E	7th Feb 2012 20:37	5.3	30	92
	Negros-Cebu Reg. Philippines	9.90° N 123.13° E	6th Feb 2012 11:40	5.2	40	84
	Negros-Cebu Reg. Philippines	9.90° N 123.11° E	6th Feb 2012 11:33	5.9	30	80

III. RESULTS AND DISCUSSION

Results of the analysis on ULF's Pc4 and Pc5 pulsations for a period of two months prior to the occurrence of earthquake events, including earthquake parameters (depth of earthquake, d <100km, distance from magnetometer station and earthquake events, r <100km), shows the enhancement of Pc4 and Pc5 plot trends from 23rd January 2012, as shown in Figure 2. The Pc4 pulsation increased from (-1.8 - 0.5 nT) to (-1.8 - 2.5 nT), while the Pc5 pulsation increased from (3 - 3.2 nT) to (3 - 4.5 nT). The increasing trend began approximately 16 days before the earthquake event on 6th and 7th February 2012. This corresponds to the findings of Yakawa *et al.* (2000) and Yumoto *et al.* (2009). Meanwhile, variations in solar wind parameters, such as V (kms^{-1}), P (nPa), IMF-Bz, IE (ergs), and geomagnetic storm, SYM/H (nT), as shown in Figure 3, correspond to the enhancement of the Pc4 and Pc5 pulsation plots prior to earthquake events.

Two Bz reconnections were observed ranging from (0 to -20 nT) to (0 to -10 nT) within a period of 16 days before earthquake events in response to the disturbance at near equatorial regions, SYM/H, which varied from (0 to -30 nT) to (30 to -100 nT). Simultaneously, high variations in solar wind speed, V (400 to 450 kms^{-1}) and (400 to 650 kms^{-1}), associated with dynamic pressure, P (2 to 25 nPa and 0 to 15 nPa), resulted in high ejection of plasma into the magnetosphere coupled with high energy levels, IE (0 to 3 ergs) and (0 to 15 nPa) (0.5 to 4 ergs).

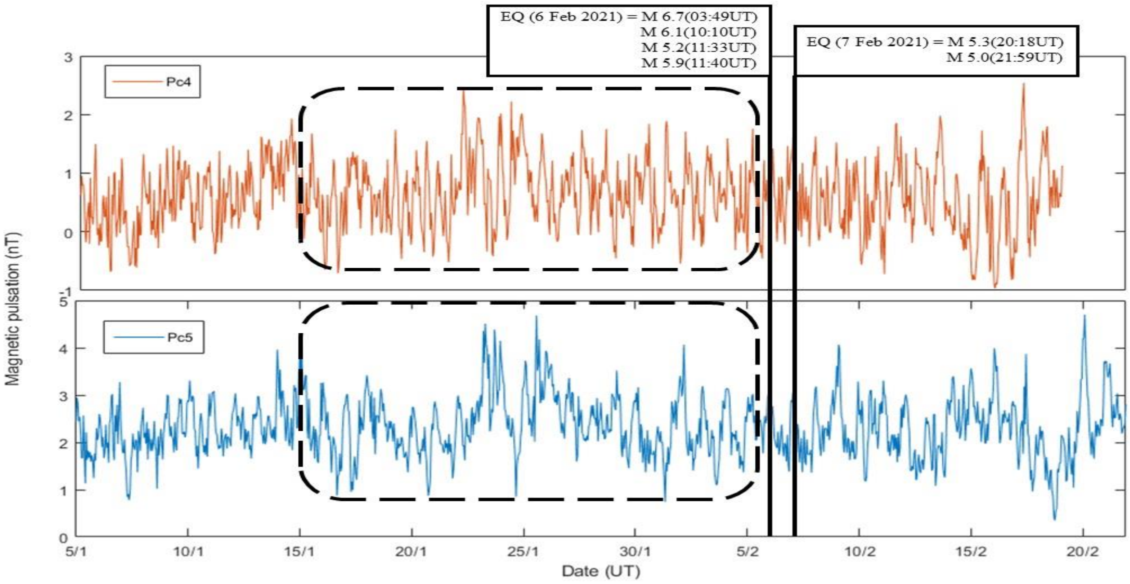

Figure 2. Variations in magnetic pulsation (Pc4 and Pc5) at the CEBU station during a period of 2 months from January 2012 associated with EQ events on 6th February and 7th February 2012 (In the dotted line, enhancement of Pc4 and Pc5 for a period of 16 days before earthquake events)

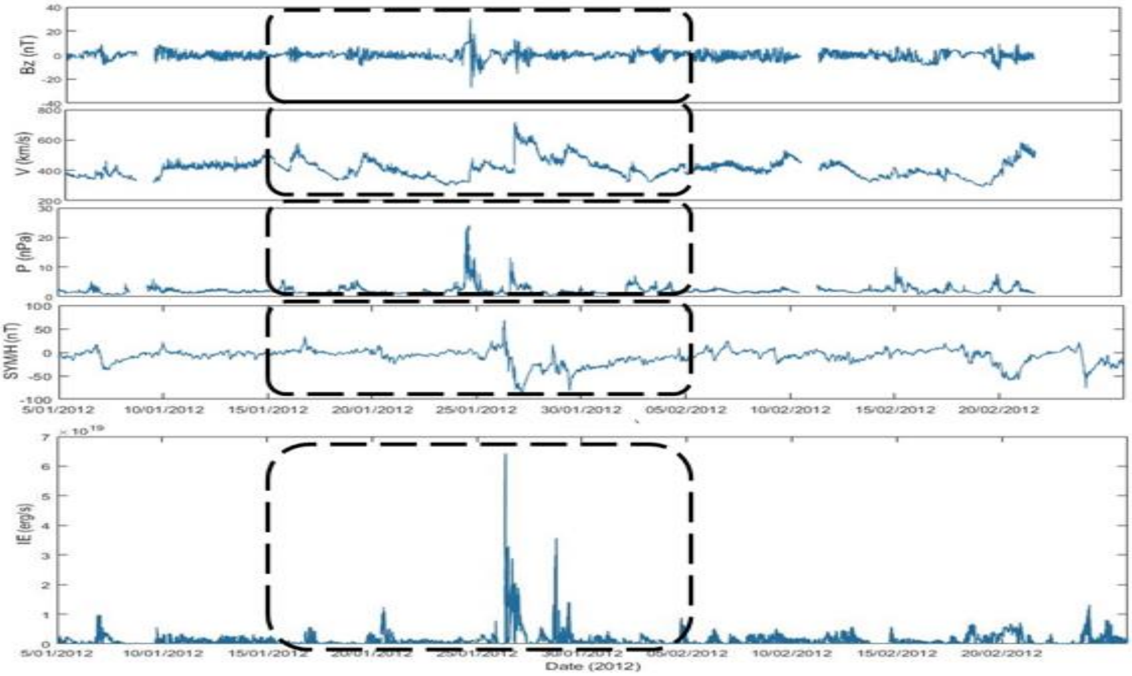

Figure 3. Variations in IMF-Bz, solar wind parameters (*V, P, IE*) and geomagnetic index, (*SYM/H*) for 2 months beginning from January 2012. (In the dotted line, high solar wind changes and geomagnetic storm (*SYM/H*) for a period of 16 days before earthquake events)

According to the plotted graph, the ULF Pc5 pulsation is a more effective frequency range for earthquake precursory study than the ULF Pc4 pulsation. This finding supports that of Rae *et al.* (2005). It clearly shows that the amplitude of the Pc5 plot trend is greater than that of the Pc4 plot trend. This indicates that the ULF Pc5 pulsation has a long wave period that allows deeper penetration under the ground; thus, responding to changes in crust resistivity in EQ structured regions (Sim˜oes *et al.*, 2000). The study's finding also shows that Pc5 is more influenced by solar wind changes and SYM/H at low latitudes compared to Pc4. This is demonstrated by the increasing value of Pc5 compared to solar wind parameters (solar wind speed, solar dynamic pressure, IMF-Bz, input energy) and near equatorial geomagnetic storms (weak storm-SYM/H =-30 nT and moderate storm-SYM/H = -100 nT). David *et al.* (2014) discovered that solar wind parameters (solar wind velocity and solar dynamic pressure) have the greatest influence on the distribution of Pc5 pulsation (Berube *et. al.,* 2014; Zong, 2022).

The injection of plasma into the magnetosphere by high dynamic pressure, combined with high solar wind speed and high input energy in the strong southward Bz component, resulted in an increase in magnetospheric current. The increased magnetosphere current than raises the ionospheric current and produces induced current under the ground that could result in an abrupt increase in Pc4 fluctuations (-1.8 - 0.5 nT) to (-1.8 - 2.5 nT) with a peak at 2.5 nT, while Pc5 fluctuations from (3 - 3.2 nT) to (3 - 4.5 nT). with a peak at 5nT. This might increase stress in the rock, triggering an earthquake event (d <100km) (Athanasiou *et al.,* 2014). This research is in comparison to Yusof *et al.* (2019), who studied the same earthquake event (6th February 2012), but with different ULF ranges and analysis methods. Yusof *et al.* (2019) investigated the period 60 days before and 60 days after the earthquake in the ULF range of (10 - 100 mHz) which in Pc3 ULF waves acquired from MAGDAS magnetometers at CEBU and Legazpi stations in the Philippines. The polarisation ($P_{Z/G}$) analysis method revealed that there were ULF anomalies 14 days before the earthquake. Yusof *et al. (*2019) studies are compared to this study because this study determines the relationship of solar wind with ULF wave pulsation for earthquake precursor. This is because the solar wind, magnetosphere, and ionosphere are the primary causes of ULF wave pulsation anomalies associated with earthquakes, which supported the Lithosphere-Atmosphere-Ionosphere coupling (LAI) theory model (Yumoto *et al.*, 2009). In contrast to Yusof *et al.* (2019), studied the earthquake precursor by analysing ULF anomalies caused by the earthquake event without taking into account the physical mechanism of the solar-terrestrial effect.

IV. CONCLUSION

This study concluded that ULF's Pc5 pulsation increased in response to solar wind changes and near-equatorial geomagnetic disturbances (weak storm-SYM/H = -30 nT and moderate storm-SYM/H = -100 nT) for a period of 16 days before the earthquake event of d < 100 km and r < 100 km in low latitude regions. It was found that high solar wind changes caused a high magnetospheric current, which then influenced the ionospheric current and thus, transferred the high induced current underground. It is said that this mechanism can cause an earthquake to occur. The ionospheric current is produced by the ULF waves in the magnetosphere, resulting in the magnetic field on the ground. The induced current underground was caused by the incident of a magnetic field. The underground induced current is affected by the wave period of ULF waves. The longer the ULF wave period, the deeper the propagation of inducing magnetic field underground. Furthermore, the Pc5 pulsation has a more effective frequency range than the Pc4 pulsation for studying short-term earthquake 'precursors associated with solar wind changes and geomagnetic storms because the waves have a longer time to penetrate deeper beneath the ground and affect the crust structurally. In future, the correlation between ULF's Pc4 and Pc5 pulsations and solar wind parameters and geomagnetic storm (SYM/H) prior to earthquake events should be investigated. Therefore, a model based on Pc4 and Pc5 pulsations, solar wind changes, and geomagnetic storms should be developed for short-term earthquake precursor prediction in low-latitude regions.

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VI. REFERENCES

Afandi, NZM, Hazmin, SN, Umar, R & Ishak, AN 2018, 'Solar radio burst detection on radio spectrum: a review of techniques in image processing', Journal of Fundamental and Applied Sciences, vol. 10, no. 1s, pp. 249–267. doi: 10.4314/jfas.v10i1s.16

Afandi, NZM, Sabri, NH, Umar, R & Monstein, C 2020, 'Burst-finder: burst recognition for e-callisto spectra', Indian Journal of Physics, vol. 94, no. 7, pp. 947–957. doi: 10.1007/s12648-019-01551-2

Athanasiou, MA, Anagnostopoulos, GC, David, CN, & Machairides, GG 2014, 'The ultralow frequency electromagnetic radiation observed in the topside ionosphere above boundaries of tectonic plates', Research in Geophysics, vol. 4, no. 1, pp. 31-39. doi: 10.4081/rg.2014.5001

Berube, D, Sanny, J, Taus, R & Garoutte A 2014, 'Dayside distribution of pc5 wave power in the quiet magnetosphere and its response to the solar wind', Planetary and Space Science, vol. 97, pp. 1–8. doi: 10.1016/j.pss.2014.04.012

Fraser-Smith, AC, Bernardi, A, McGill, PR, Ladd, M, Helliwell, RA & Villard JrOG 1990, 'Low-frequency magnetic field measurements near the epicenter of the ms 7.1 loma prieta earthquake', Geophysical Research Letters, vol. 17, no. 9, pp. 1465–1468. doi: 10.1029/GL017i009p01465

Gjerloev, JW 2012, 'The supermag data processingTechnique', Journal of Geophysical Research: Space Physics, vol. 117, no. A9, pp. 1-19. doi: 10.1029/2012JA017683

Han, P, Hattori, K, Hirokawa, M, Zhuang, J, Chen, CH, Febriani, F & Yoshida, S 2014, 'Statistical analysis of ULF seismomagnetic phenomena at Kakioka, Japan, during 2001–2010', Journal of Geophysical Research: Space Physics, vol. 119, no. 6, pp. 64998–5011. doi: 10.1002/2014JA019789

Hayakawa, M, Itoh, T, Hattori, K & Yumoto, K 2000, 'ULF electromagnetic precursors for an earthquake at Biak, Indonesia on February 17, 1996', Geophysical Research Letters, vol. 27, no. 10, pp. 1531–1534. doi: 10.1029/1999GL005432

Huzaimy, JM & Yumoto, K 2011, 'Possible correlation between solar activity and global seismicity', in Proceeding of the 2011 IEEE International Conference on Space Science and Communication (IconSpace), pp. 138–141. doi: 10.1109/IConSpace.2011.6015869

Kozyreva, OV, Kleimenova, NG & Vatermann, J 2005, 'Pc5 geomagnetic pulsations under a high dynamic pressure of the solar wind during the initial phase of the magnetic storm (april 16, 1999)', Geomagnetism and Aeronomy, vol. 45, no. 5, pp. 577.

Kushwah, VK & Singh, B 2004, 'Initial results of ultra-low frequency magnetic field observations at agra and their relation with seismic activities', Current Science, vol. 87 pp. 332–339. https://www.jstor.org/stable/24108937

Masci, F 2011, 'On the seismogenic increase of the ratio of the ULF geomagnetic field components', Physics of the Earth And Planetary Interiors, vol. 187, no. 1-2, pp. 19–32. doi: 10.1016/j.pepi.2011.05.001

Masruri, MFI, Priadi, R, Nanda, BMTF & Ahadi, S 2018, 'Analysis of preseismic event using seismo-electromagnetics data', in 2018 2nd International Conference on Applied Electromagnetic Technology (AEMT), pp. 1–7. doi: 10.1109/AEMT.2018.8572332

McPherron, RL 2005, 'Magnetic pulsations: their sources and relation to solar wind and geomagnetic activity', Surveys in Geophysics, vol. 26 no. 5, pp. 545–592. doi: 10.1007/s10712-005-1758-7

Novikov, V, Ruzhin, Y, Sorokin, V & Yaschenko, A 2020, 'Space weather and earthquakes: possible triggering of seismic activity by strong solar flares', Annals of Geophysics, vol. 63, no. 5, pp. 554. doi: 10.4401/ag-7975

Piriyev, RH 2021, 'Effectiveness of electromagnetic monitoring in studying earthquakes', Geofizicheskiy Zhurnal, vol. 43, no. 2, pp. 166-177. doi: 10.24028/gzh.v43i2.230195

Rae, IJ, Donovan, EF, Mann, IR, Fenrich, FR, Watt, CEJ, Milling, DK & Balogh, A 2005, 'Evolution and characteristics of global Pc5 ULF waves during a high solar wind speed interval', Journal of Geophysical Research: Space Physics', vol. 110, no. A12, pp. 1-16. doi: 10.1029/2005JA011007

Simões, F, Pfaff, R, Berthelier, JJ & Klenzing, J 2012, 'A review of low frequency electromagnetic wave phenomena related to tropospheric-ionospheric coupling mechanisms', Space Science Reviews, vol. 168, no. 1-4, pp. 551–593. doi: 10.1007/s11214-011-9854-0

Southwood, DJ 1968, 'The hydromagnetic stability of the magnetospheric boundary', Planetary and Space Science, vol. 16, no. 5, pp. 587–605. doi: 10.1016/0032-0633(68)90100-1

Syed Zafar, SNA, Umar, R, Sabri, NH, Jusoh, MH, Dagang, AN & Yoshikawa, A 2021, 'Effects of solar flares and coronal mass ejections on earths horizontal magnetic field and solar wind parameters during the minimum solar cycle 24', Monthly Notices of the Royal Astronomical Society, vol. 504, no. 3, pp. 3812–3822. doi: 10.1093/mnras/stab1161

Takahashi, K, Yumoto, K, Claudepierre, SG, Sanchez, ER, Troshichev, OA & Janzhura, AS 2012, 'Dependence of the amplitude of Pc5-band magnetic field variations on the solar wind and solar activity', Journal of Geophysical Research: Space Physics, vol. 117, no. A4, pp. 1-18. doi: 10.1029/2011JA017120

Takla, EM, Khashaba, A, Zaher, MA, Yoshikawa, A & Uozumi, T 2018, 'Anomalous ultra low frequency signals possibly linked with seismic activities in Sumatra, Indonesia', NRIAG Journal of Astronomy and Geophysics, vol. 7, no. 2, pp. 247–252. doi: 10.1016/j.nrjag.2018.04.004

Umar, R, Natasha, SF, Aminah, SSN, Juhari, KN, Jusoh, MH, Hamid, NSA & MAGDAS/CPMN Group 2019, 'Magnetic data acquisition system (MAGDAS) Malaysia: installation and preliminary data analysis at Eseri, Unisza,' Indian Journal of Physics, vol. 93, no. 5, pp. 553– 564. doi: 10.1007/s12648-018-1318-x

Yusof, KA, Abdullah, M, Hamid, NSA & Ahadi, S 2019, 'On effective ULF frequency ranges for geomagnetic earthquake precursor,' Journal of Physics: Conference Series, vol. 1152, no. 1, pp. 012033. doi: 10.1088/1742-6596/1152/1/012033

Yumoto, K, Ikemoto, S, Cardinal, MG, Hayakawa, M, Hattori, K, Liu, JY & Servando, N 2009, 'A new ULF wave analysis for seismo-electromagnetics using CPMN/MAGDAS data', Physics and Chemistry of the Earth, vol. 34, no. 6-7, pp. 360–366. doi: 10.1016/j.pce.2008.04.005

Yusof, KA, Abdul Hamid, NS, Abdullah, M, Ahadi, S & Yoshikawa, A 2019, 'Assessment of signal processing method for geomagnetic precursor of the 2012 M6.9 Visayas, Philippines earthquake', Acta Geophysica, vol. 67, no. 5, pp. 1297-1306. doi: 10.1007/s11600-019-00319-w

Syed Zafar, SNA, Hazmin, SN, Jusoh, MH, Dagang, AN, Adzni, MAM & Umar, R 2021, 'Behaviour of geomagnetic storm, horizontal geomagnetic field and solar wind parameters during solar flare and cmes event', Journal of Physics: Conference Series, IOP Publishing, vol. 1768, pp. 012003. doi: 10.1088/1742-6596/1768/1/012003

Zong, Q 2022, 'Magnetospheric response to solar wind forcing: ultra-low-frequency wave–particle interaction perspective', Annales Geophysicae, vol. 40, no. 1, pp. 121-150. doi: 10.5194/angeo-40-121-2022