Detrended Fluctuation Analysis Associated with the M5.1 Earthquake Precursor in Banten, Indonesia

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***Abstract*—We studied the behavior of scaling components associated with the M5.1 earthquake that occurred in Banten on 7 July 2020 by using the Detrended Fluctuation Analysis (DFA). DFA is a powerful technique to assess the self-similarity of fractals in time series data. The time series data were obtained from Sukabumi (SKB) geomagnetic observatory station during April - August 2020. We only used the nighttime data (16.00-21.00 UTC) for our analysis to reduce the artificial noise due to human activities. The results revealed long-term correlations during the whole observation period. Moreover, we also used the results of our previous study using the Fast Fourier Transform (FFT) for further analysis in this paper. The combined analysis of the spectral density ratio (SDR) value obtained from FFT and the scaling exponent value obtained from DFA showed the presence of EQ precursors from the end of April until early June 2020.**

Keywords*—*ULF geomagnetic, fractal analysis, scaling exponent, earthquake forecast

I. Introduction

The western part of Java Island consists of large cities which are densely populated because they become the center of the economy and industry. Geologically, this area is located at the confluence of the Eurasian and Australian plates [1]. As a result, in this area earthquakes (EQs) often occur which have the potential to cause casualties and material losses. It was recorded that 3,243 EQs occurred in West Java from 2009 - 2019. The number of EQs was the highest compared to other provinces in Java [2]. Based on United States Geological Survey (USGS) data, there were 3 EQs in western Java with magnitude (M) more than 5 occurred in 2020. These data reveal that western Java is a seismically active area. Therefore, it is necessary to reduce the risk of EQ disasters, such as by studying the characteristics of EQ precursors in the western part of Java Island using geomagnetic data.

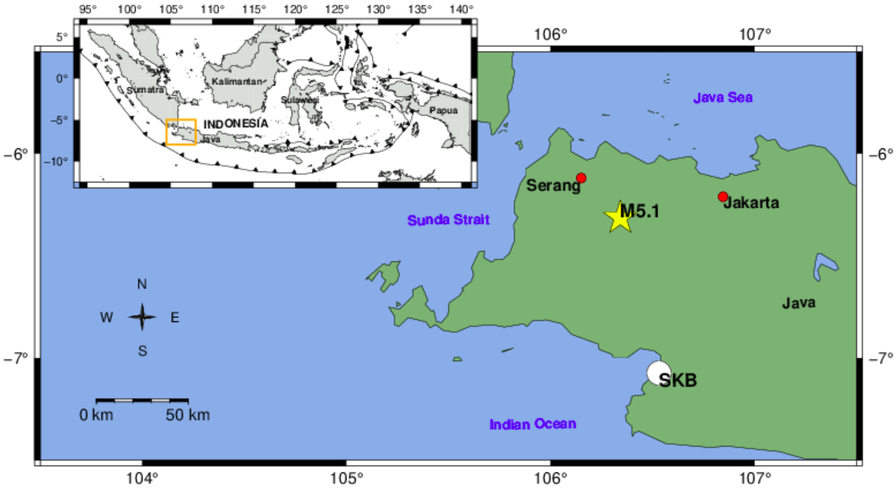

Fig. 1. The locations of the M5.1 EQ and SKB station

Analysis of Ultra Low Frequency (ULF) geomagnetic data can be applied as an approach to determine short-term EQ precursor [1]-[9]. Since ULF (<1 Hz) has low attenuation and can penetrate deep areas, it may contain information about the EQ preparation process in the lithosphere, such as micro fractures near the hypocenter, or nonlinearity lithospheric dynamics concerning EQ [10], [11]. In our previous study, EQ precursors from three EQs with M>5 that occurred in 2020 were analyzed using the Fast Fourier Transform (FFT) analysis. We get the results that the M5.1 EQ that occurred on 7 July 2020 showed the most significant ULF anomaly compared to other EQs [12]. However, a multidisciplinary analysis is still needed to confirm that the ULF geomagnetic anomaly is related to the M5.1 EQ because EQ preparation is a complex process.

This study was conducted to confirm the results of the EQ precursor found in previous studies with the FFT analysis for the M5.1 EQ based on Sukabumi geomagnetic observatory (SKB) data. The location of the EQ and SKB shown in Fig.1. The ULF geomagnetic anomalies related to seismogenic processes should contain fracture process information that occurs in the lithosphere. Considering that fracture processes have fractal behavior, it is necessary to analyze the disturbances in ULF fractal characteristics [10], [13], [14]. A powerful technique that can be used to identify the degree of self-similarity of fractals in a non-stationary time series is the detrended fluctuation analysis (DFA) [15]. DFA analysis is advantageous for analyzing time series to find long-range correlations of the data [16], [17]. It has been extensively applied to ULF geomagnetic data to reveal that scaling disturbances in ULF geomagnetic data before the EQ are related to the EQ event itself [16]-[22]. Therefore, we applied the DFA method over the same timeframe as in the case of FFT analysis to obtain a comprehensive analysis in the evaluation of the M5.1 EQ precursors.

II. METHODS

We analyzed the M5.1 EQ that took place in Rangkasbitung on 7 July 2020 at 04:44:13 UTC. The EQ epicenter is located at 6.31°S 106.34°E with a depth of 96.85 km. The magnetometer located SKB belonging to the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG) with an epicenter distance less than 100 km. The recorded time series data is represented in horizontal and vertical components (X, Y, and Z) with a sampling frequency of 1 Hz.

We take 5 months of daily geomagnetic data from April to August 2020 from SKB. Then, we selected only the nighttime (16.00-21.00 UTC) data for analysis to reduce the artificial noise due to human activities. An example of three components of geomagnetic nighttime data on 20 June 2020 can be seen in Fig. 2. We used DFA analysis to find the exact scaling behavior of non-stationary data because DFA is capable to detect the dynamic features and prevent non-stationary artifacts [20], [23]-[25].

DFA is applied in a time series data x(i) with N length and the profile is determined by integrating the time series (1):

$$y(k) = \sum_{k=1}^{i} [x_i - x_{ave}] \qquad (i = 1, \ldots, N) \qquad (1)$$

where x_{ave} is the average of the time series data. Then, the profile y(k) is divided into non-overlapping segments with equal length n. We performed the least square polynomial to each segment to represent the trend of the segment. The integrated time series y(k) is detrended by subtracting the local trend yn(k) in each segment. The root mean square fluctuation of the integrated and detrended time series is calculated by (2):

$$F(n) = \sqrt{\frac{1}{N} \sum_{k=1}^{N} [y(k) - y_n(k)]^2} \qquad (2)$$

To find the relationship between F(n) and n, we calculate (2) over all segments. Generally, F(n) will increase according to the increase of n. The power-law scaling defines the relationship between F(n) and n will obey (3):

$$F(n) \propto n^{\alpha} \qquad (3)$$

The scaling exponent α is the slope of the line fitting log F(n) and log n that represent its correlation in the time series data. The α value shows the presence of long-range correlation or not. An α > 0.5 means the presence of persistent long-range correlations, and α < 0.5 means the presence of anti-persistent long-range correlations [20], [23], [24].

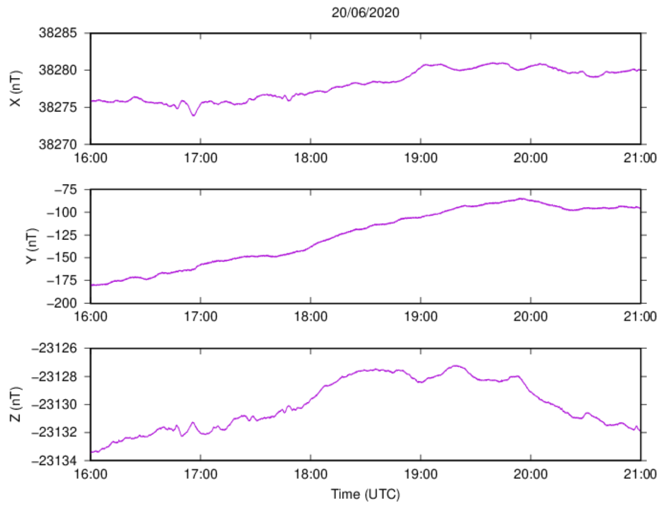

Fig. 2. Time series observed in X, Y, and Z components at nighttime (16.00-21.00 UTC) from SKB on 20 June 2020.

III. RESULT AND DISCUSSION

We analyzed the ULF geomagnetic data observed at SKB from 1 April 2020 until 31 August 2020. Fig. 3 exhibits an example of the fluctuation function computed with the DFA method of the X, Y, and Z components. Generally, it informs about the relation of F(n) and n which is in the form of a straight line and almost uniform with a single scaling exponent for all timescales.

Fig. 4 illustrates the time variation of the scaling exponents α of the X, Y, and Z components during the observation times. The red vertical line on 7 July 2020 denotes the EQ day and the orange horizontal lines denote the threshold of the data (mean ± 2σ, σ is the standard deviation). The scaling exponents are given from the top for X, Y, and Z components. The bottom panel is the Dst index that represents the global geomagnetic activity obtained from the World Data Center for Geomagnetism, Kyoto University. The high geomagnetic activity (Dst ≤ -50 nT or Dst ≥ 50 nT) may disturb the geomagnetic data. From the Dst data analysis, it can be seen that almost the whole observation period is quiet days so the global geomagnetic disturbances can be minimized. We observed that the average α value is greater than 0.5 that indicating a long-range correlation. These fractal properties are associated with transient electrical signal emission due to stress variations in the focal area before an EQ [21].

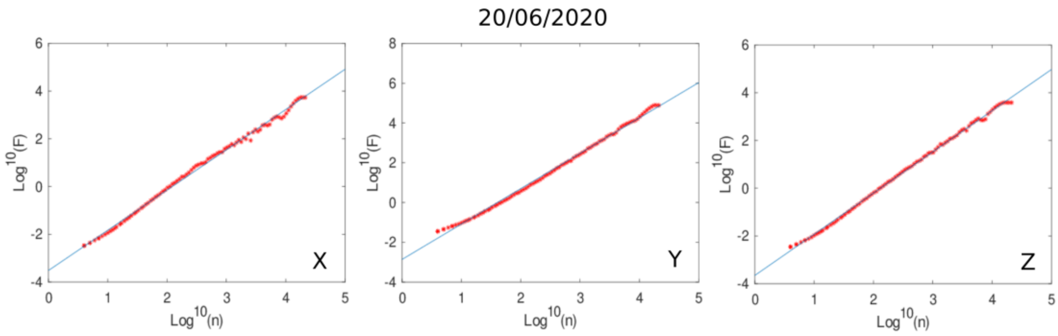

Fig. 3. An example of log F(n) versus log n plots of the X, Y, and Z components for the observed data on 20 June 2020

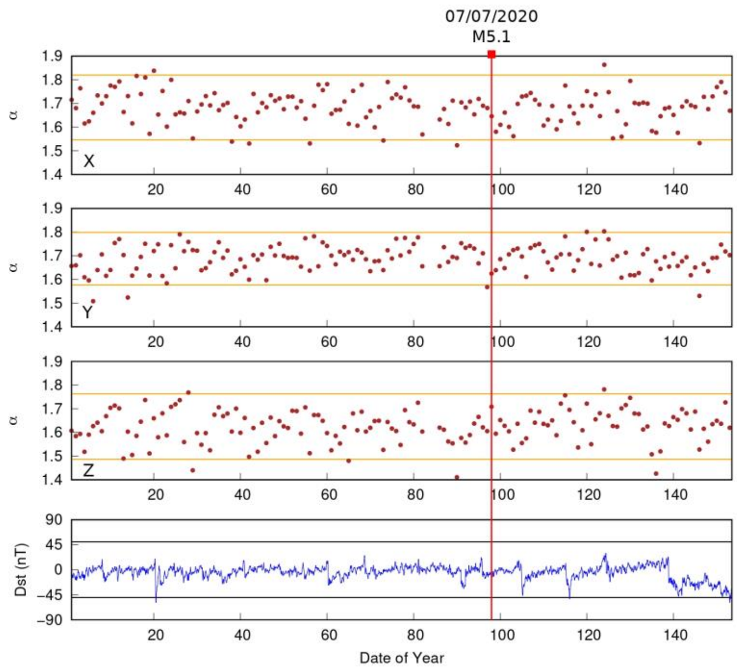

Fig. 4. Time variation of the α values in X, Y, and Z components from 1 April 2020 until 31 August 2020. The red vertical line shows the occurrence of M5.1 EQ and the orange horizontal lines show the threshold of the data

We sampled the results of our previous study for this EQ using the FFT analysis in the same period to compare with the results of the DFA analysis. Our previous study calculated the spectral density ratio (SDR) of the S_Z/S_G over 0.01 - 0.06 Hz to find the optimum frequency for precursor detection [12]. We have compared the S_Z/S_G values of all frequencies (0.01 Hz - 0.06 Hz) with the scaling exponents of the Z component as shown in Fig. 5.

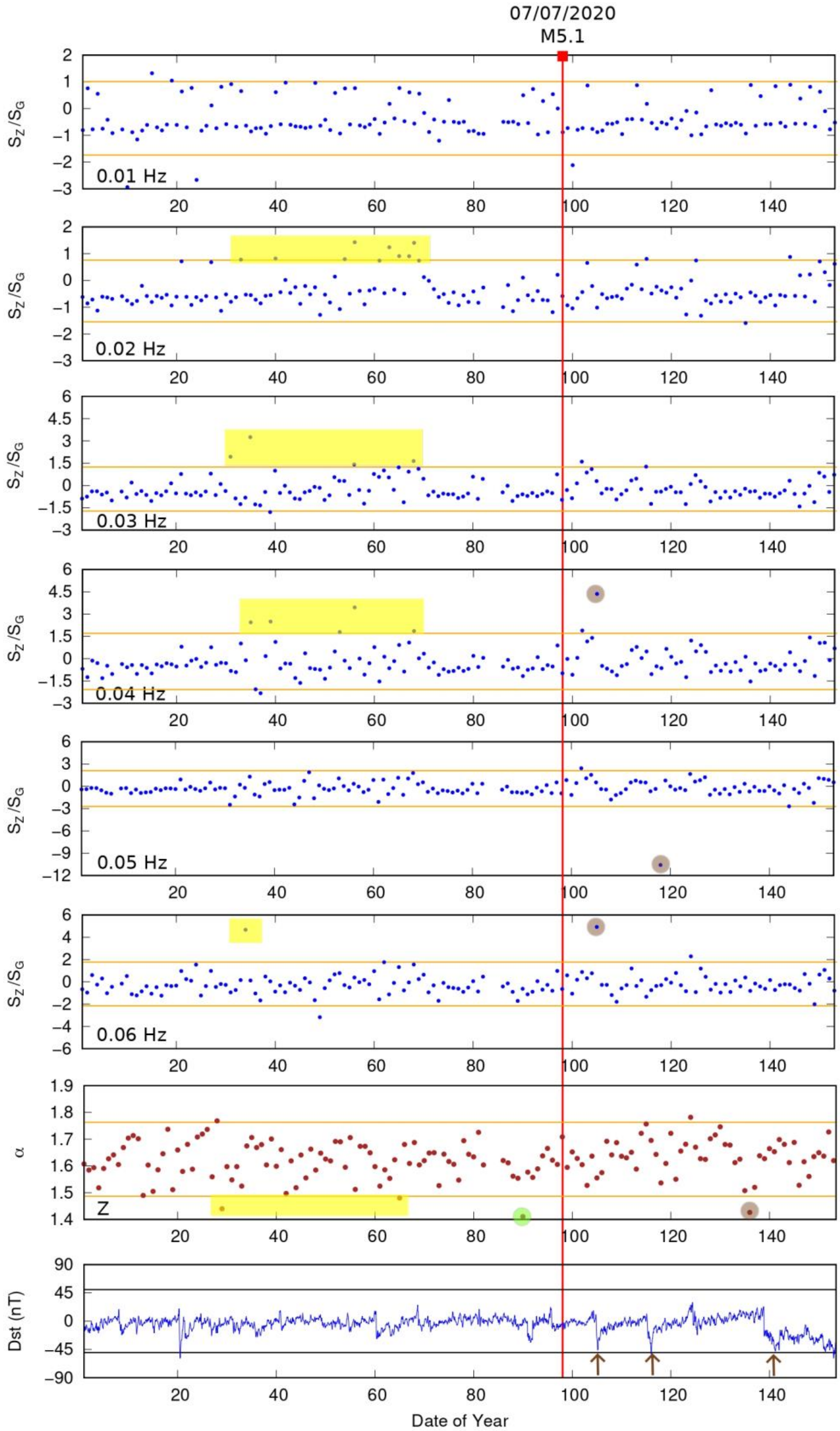

Fig. 5. Time variation of the S_Z/S_G values over 0.01 - 0.06 Hz compared with the α values of the Z components from 1 April 2020 until 31 August 2020. The red vertical line shows the occurrence of M5.1 EQ and the orange horizontal lines show the threshold of the data. The α and S_Z/S_G anomalies that occur simultaneously and related to the EQ precursor are marked as yellow area, while the α anomaly occurring before EQ without S_Z/S_G anomaly is marked with a green circle. Meanwhile, the α and S_Z/S_G anomalies related to the high global geomagnetic activity (brown arrows) are marked with brown circles

The anomalies from S_Z/S_G and α values were found at almost the same period marked with the yellow areas at frequencies of 0.02, 0.03, 0.04, and 0.06 Hz which may indicate a relationship in predicting EQ precursors. In general, the above-mentioned frequencies indicate that if there is an increase in S_Z/S_G exceeding the threshold, there will be a decrease in the α value which is smaller than the threshold at almost the same time. These characteristics occur from the end of April (2.5 months before EQ) to early June 2020 (1 month before EQ) during the quiet days of global geomagnetic activity. The anomalies in the S_Z/S_G and α values described above are thought to be related to the EQ preparation process. We also found an anomaly in the α value smaller than the threshold (marked with a green circle) without an increase in the S_Z/S_G value at 8 days before the EQ when the Dst value showed normal global geomagnetic activity. Meanwhile, there are also some significant anomalies in the S_Z/S_G and α values after the EQ event (marked with the brown circles) which occurs when the Dst value drops significantly to the threshold (marked with the brown arrows) which means there is a high global geomagnetic activity, so it is not related to EQ activity.

Our result is similar to previous research which found the decrease of the α values at the same time as an increase in SDR values around 20 days before the M7.5 EQ (2009) near the Pelabuhan Ratu station, West Java, Indonesia [22]. Another case study for the M6.1 EQ (2018) which occurred about 100 km from the Banten geomagnetic observatory showed the geomagnetic anomalies were found about 2 weeks before EQ [26], [27]. Moreover, long duration of lead times also have been found 5 months before the M7.4 Guerrero-Oaxaca EQ [21] and 2 months before the M6.6 EQ in Japan [28]. The presence of anomalies that exceed the threshold when there is no high global geomagnetic activity is the characteristic of the EQ precursors detection from ULF geomagnetic data. However, this research is still preliminary and suggestive, it requires a comprehensive statistical analysis and approaches from other methods to reveal the precursors before the EQ.

IV. CONCLUSION

We have analyzed the nighttime ULF geomagnetic data recorded from SKB during April - August 2020 by using the DFA analysis. We tried to find the characteristics of the α values before the M5.1 EQ took place in Rangkasbitung on 7 July 2020. The results of the DFA analysis revealed that during the whole observation period, the α values indicate a long-range correlation. Moreover, the combination of the SDR value from our previous study and the α value obtained from this study found the presence of the EQ precursor starting from 2.5 - 1 month before the EQ. This is indicated by an increase in the SDR value exceeding the threshold that occurred in the same period with a decrease in the α value smaller than the threshold. Nevertheless, our research is still preliminary and needs other perspectives analysis of precursor detection.

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REFERENCES

[1] S. Widiyantoro, P. Supendi, A. Ardianto, A.W. Baskara, C.A. Bacon, R. Damanik, N. Rawlinson, E. Gunawan, D.P. Sahara, Z. Zulfakriza and Y.M. Husni. Implications for fault locking south of Jakarta from an investigation of seismic activity along the Baribis fault, northwestern Java, Indonesia. Scientific reports, 12(1), pp.1-10 (2022).

[2] Sabtaji. Buletin Meteorologi, Klimatologi, dan Geofisika, 7, pp. 31-46 (2020).

[3] M. Hayakawa, A. Schekotov, J. Izutsu and A.P. Nickolaenko. Seismogenic effects in ULF/ELF/VLF electromagnetic waves. Int. J. Electron. Appl. Res, 6(2), pp.1-86 (2019).

[4] S.M. Potirakis, A. Schekotov, Y. Contoyiannis, G. Balasis, G.E. Koulouras, N.S. Melis, A.Z Boutsi, M. Hayakawa, K. Eftaxias and C. Nomicos. On possible electromagnetic precursors to a significant earthquake (Mw= 6.3) occurred in Lesvos (Greece) on 12 June 2017. Entropy, 21(3), p.241 (2019).

[5] P. Han, J. Zhuang, K. Hattori, C.H. Chen, F. Febriani, H. Chen, C. Yoshino and S. Yoshida. Assessing the potential earthquake precursory information in ULF magnetic data recorded in Kanto, Japan during 2000–2010: Distance and magnitude dependences. Entropy, 22(8), p.859 (2020).

[6] S. Warden, L. MacLean, J. Lemon and D. Schneider. Statistical analysis of pre-earthquake electromagnetic Anomalies in the ULF Range. Journal of Geophysical Research: Space Physics, 125(10), p.e2020JA027955 (2020).

[7] Singh, and Y. Hobara. Simultaneous study of VLF/ULF anomalies associated with earthquakes in Japan. Open Journal of Earthquake Research, 9(2), pp.201-215 (2020).

[8] K.A. Yusof, M. Abdullah, N.S.A. Hamid, S. Ahadi, and A. Yoshikawa. Correlations between earthquake properties and characteristics of possible ULF geomagnetic precursor over multiple earthquakes. Universe, 7(1), p.20 (2021).

[9] X. Yao, W. Wang and Y. Teng. Detection of Geomagnetic Signals as Precursors to Some Earthquakes in China. Applied Sciences, 12(3), p.1680 (2022).

[10] S.M. Potirakis, M. Hayakawa and A. Schekotov. Fractal analysis of the ground-recorded ULF magnetic fields prior to the 11 March 2011 Tohoku earthquake (MW= 9): discriminating possible earthquake precursors from space-sourced disturbances. Natural Hazards, 85(1), pp.59-86 (2017).

[11] M. Hayakawa M and Y. Ida. Fractal (mono- and multi-) analysis for the ULF data during the 1993 Guam earthquake for the study of prefreacture criticality. Curr Dev Theory Appl Wavelets 2(2), pp.159–174 (2008).

[12] C.N. Dewi, F. Febriani, T. Anggono, Syuhada, M. Hasib, A.D. Prasetio, A. Sulaiman, H.S. Suprihatin, S. Ahadi, M. Syirojudin, Hasanudin and I. Marsyam. The optimum frequency for detecting earthquake precursors based on Ultra-Low Frequency (ULF) geomagnetic data from Sukabumi (SKB) station. AIP Conference Proceedings, in press.

[13] M. Hayakawa, T. Ito and N. Smirnova N. Fractal analysis of ULF geomagnetic data associated with the Guam earthquake on August 8, 1993. Geophys Res Lett, 26(18), pp. 2797–2800 (1999).

[14] NA. Smirnova and M. Hayakawa. Fractal characteristics of the ground-observed ULF emissions in relation to geomagnetic and seismic activities. J Atmos Sol Terr Phys, 69, pp. 1833–1841 (2007).

[15] C-K. Peng, S. Havlin, H.E. Stanley and A.L. Goldberger AL. Quantification of scaling exponents and crossover phenomena in nonstationary heartbeat time series. Chaos, 5, pp. 82–87 (1995).

[16] L. Guzmán-Vargas, C. Carrizales-Velazquez, I. Reyes-Ramírez, J. Fonseca-Campos, A.D.L. Rosa-Galindo, V.O. Quintana-Moreno, J.A. Peralta and F. Angulo-Brown. A comparative study of geoelectric signals possibly associated with the occurrence of two Ms> 7 EQs in the South Pacific Coast of Mexico. Entropy, 21(12), p.1225 (2019).

[17] T. Kataoka, T. Miyaguchi and T. Akimoto. Detrended fluctuation analysis of earthquake data. Physical Review Research, 3(3), p.033081 (2021).

[18] L. Flores-Márquez, J. Márquez-Cruz, A. Ramírez-Rojas, G. Galvez-Coyt and F. Angulo-Brown. A statistical analysis of electric self-potential time series associated to two 1993 earthquakes in Mexico. Natural Hazards and Earth System Sciences, 7(5), pp.549-556, (2007).

[19] L. Guzman-Vargas, A. Ramírez-Rojas, R. Hernández-Pérez and F. Angulo-Brown. Correlations and variability in electrical signals related to earthquake activity. Physica A: Statistical Mechanics and its Applications, 388(19), pp.4218-4228 (2009).

[20] L. Telesca, V. Lapenna, M. Macchiato and K. Hattori. Investigating non-uniform scaling behavior in Ultra Low Frequency (ULF) earthquake-related geomagnetic signals. Earth and Planetary Science Letters, 268(1-2), pp.219-224 (2008).

[21] Ramírez-Rojas, E.L. Flores-Márquez, L. Guzman-Vargas, G. Gálvez-Coyt, L. Telesca and F. Angulo-Brown. Statistical features of seismoelectric signals prior to M7. 4 Guerrero-Oaxaca earthquake (México). Natural Hazards and Earth System Sciences, 8(5), pp.1001-1007 (2008).

[22] F. Febriani, P. Han, C. Yoshino, K. Hattori, B. Nurdiyanto, N. Effendi, I. Maulana, Suhardjono and E. Gaffar, Nat. Hazards Earth Syst. Sci, 14, pp. 789–798 (2014).

[23] C.-K. Peng, S. V. Buldyrev, S. Havlin, M. Simons, H. E.Stanley and A. L. Goldberger, Mosaic organization of DNA nucleotides, Phys. Rev. E, 49, 1685 (1994).

[24] Y.I. Ida, M. Hayakawa and K. Gotoh. Multifractal analysis for the ULF geomagnetic data during the Guam earthquake. IEEJ Transactions on Fundamentals and Materials, 126(4), pp.215-219 (2006).

[25] K. Gotoh, N. Smirnova and M. Hayakawa. Fractal analysis of seismogenic ULF emissions. Physics and Chemistry of the Earth, Parts A/B/C, 29(4-9), pp.419-424 (2004).

[26] F. Febriani, T. Anggono, Syuhada, A. D. Prasetio, C. N. Dewi, A. S. Hak and S. Ahadi, "Investigation of the ultra low frequency (ULF) geomagnetic anomalies prior to the Lebak, Banten earthquake (M=6.1; January 23, 2018)," AIP Conference Proceedings, vol. 2256, no. 1, p. 090002 [AIP Publishing, Melville, NY, 2020]

[27] F. Febriani, S. Ahadi, T. Anggono, Syuhada, C. N. Dewi and A. D. Prasetio, "Applying Wavelet Analysis to Assess the Ultra Low Frequency (ULF) geomagnetic anomalies prior to the M6. 1 Banten Earthquake (2018)," IOP Conference Series: Earth and Environmental Science, vol. 789, no. 1, p. 012064 [IOP Publishing, Bristol, UK, 2021].

[28] S.T. Uyeda, Y. Nagao, T. Orihara, Yamaguchi and I. Takahashi. Geoelectric potential changes: Possible precursors to earthquakes in Japan. Proc. Nat. Ac. Sc. (PNAS), 97–9, pp.4561–4566 (2000).