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Unraveling the Seismic Signal Anomaly at Mount Rinjani Station: In-Depth Exploration with the Detrended Fluctuation (DFA) Analysis Method in Connection with the 2018 Big Earthquake on Lombok Island, West Nusa Tenggara

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Abstract: We analyzed the seismic signals of the Mount Rinjani station to identify possible seismic anomalies before a series of major earthquakes on Lombok Island in 2018. We observe anomalies before earthquake events Mw >= 5.90. This research applies the detrended fluctuation analysis (DFA) method to investigate possible earthquake precursors associated with the analyzed earthquake. The results showed a relationship between scaling seismic signals (α) that exceeds the threshold of α values during the analysis period, and there is a deviation of the root mean square fluctuations in the corresponding scaling that should be rising but constant. The value of α with constant root mean square fluctuations occurs one to three days before the preliminary earthquake Mw 6.40 (28/07/2018) UTC and eight to 10 days before the main earthquake Mw 6.90 (05/08/2018). The Mw 6.90 earthquake had the most magnitude and could significantly contribute to the appearance of seismic anomalies.

Keywords: Anomaly; Detrended fluctuation analysis; Earthquake; Precursor; Seismic signal

Introduction

An earthquake is a sudden release of seismic wave energy. This release of energy is caused by the deformation of tectonic plates that occur in the Earth's crust. Lombok Island is one of the earthquake-prone areas in Indonesia. Tectonically, Lombok Island is an active seismic zone that has the potential to experience earthquakes because of its proximity to two earthquake-prone areas in the south and north. The Indo-Australian plate subducts under Lombok Island to the south, and Flores Back Arc Thrusting is a geological formation in the north (Fajar et al., 2023; Ridwan et al., 2021). The series of major earthquake events that occurred in 2018 are likely related to a thrust fault nested above the Flores main fault (Wang et al., 2020).

Lombok is a seismically active location due to its tectonic activity. Due to its location between two earthquake-producing zones in the south and north, Lombok is highly prone to earthquakes. Below Lombok Island, to the south, the Indo-Australian plate undergoes subduction, while to the north, there is a geological formation known as Flores Back Arc Thrusting. Look at the Lombok Island earthquake activity map. We can see that the entire island has many scattered epicenter points, which implies that there is a lot of seismic activity in the region. Therefore, it is reasonable to say that Lombok Island is an earthquake-prone area (Ridwan et al., 2021). Earthquakes are strong shocks caused by

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disturbances in the lithosphere (Earth's crust) that propagate to the surface. This disturbance results from the accumulation of energy in the Earth's crust, which is about 100 km thick, due to the movement of the Earth's crust. At this time, earthquakes occur, releasing their energy in different directions. Earthquakes usually occur at tectonic plate boundaries. However, the most powerful earthquakes generally occur at compressional and translational plate boundaries (Timor et al., 2016).

The movement of two plates bordering each other and moving relative to each other creates friction along the plate boundary. The elastic properties of these two plates can produce elastic energy. If plate movement continues over a long period, energy will accumulate at plate boundaries. Under certain conditions where rocks can no longer withstand the force generated by relative plate motion, the accumulated elastic energy will suddenly be released as elastic waves that propagate in all directions. These waves reach the Earth's surface as ground vibrations that can be felt. Furthermore, the elastic waves emitted by these earthquakes are called seismic waves (Fulki, 2011).

Based on information from BMKG (Indonesia's Meteorology, Climatology, and Geophysical Agency), a series of earthquakes occurred on Lombok Island 2018 from July to August. The foreshock happened on July 28, 2018, at 22:47:39 UTC with magnitude Mw 6.40 coordinates 8.24°S 116.508°E with a depth of 14 km. Then, the main earthquake (mainshock) occurred on August 5 at 10:46:38 UTC with a magnitude of Mw 6.90 at coordinates 8.258°S 116.438°E, at a depth of 34 km. The aftershock occurred on August 9, 2018, at 04:25:32 UTC with magnitude Mw 5.90 at coordinates 8.307°S 116.23°E, depth of 15 km. Another aftershock occurred on August 19, 2018, with a magnitude of Mw 6.30 occurred at 04:10:22 UTC, location coordinates 8.3337°S 116.599°E depth of 16 km, and magnitude Mw 6.90 occurred at 14:56:27 UTC at coordinates 8.319°S 116.627°E, depth 21 km. According to data from BNPB (Indonesian National Disaster Management Agency), this series of earthquakes on Lombok Island in 2018 damaged 71962 houses, 671 educational facilities, 52 health facilities, 128 places of worship, and infrastructure. The casualty data included 460 fatalities, 7733 injuries, and 417529 displacements.

Research on tectonics carried out on the island of Lombok includes (Zubaidah et al., 2010). Finding adjacent negative-positive geomagnetic anomalies suggests a possible relationship with geological and tectonic features in this area. According to Yang et al. (2020), seismic interpretation and structural mapping state that off the north coasts of *Lombok* and Bali, Flores's tremendous thrust is fundamentally blind, damaging the seafloor with folds, not faults.

Earthquakes and efforts to reduce their risk have been the center of attention of many scientists. Initiatives to deal with risks and potential hazards are crucial, especially for decision-makers committed to designing optimal earthquake mitigation strategies (Scholz, 2010). Furthermore, some researchers have investigated early signs before an earthquake known as precursors (Bolton et al., 2019; Ghamry et al., 2021; Marchetti et al., 2020; Sahoo et al., 2020; Sekertekin et al., 2020; Tariq et al., 2019; Toulkeridis et al., 2019; Xiong et al., 2021). In reducing the impact of major earthquakes, it is important to observe the early signs (precursors) and the time they occur before the earthquake occurs. One method widely used by researchers to observe early signs before an earthquake occurs is the detrended fluctuation analysis method (DFA). According to (Nenovski et al., 2013; Telesca & Hattori, 2007; Telesca & Lovallo, 2009), DFA is a powerful method for determining scaling behavior in nonstationary time series. DFA has an exponent similar to the Root Mean Square (RMS). Kamişlioğlu et al. (2019) Says that detrended fluctuation analysis was very useful in stochastic processes to uncover long-term correlations. Some studies on the application of DFA include the analysis of geomagnetic signal anomalies in earthquakes in Lebak Regency, Banten Province (Fazriyanti et al., 2020). A GPS time series study of land surface displacement recorded in various parts of the world shows different degrees of seismic activity. This analysis demonstrates how DFA methods are used to calculate quantitative metrics of chaoticity (Filatov et al., 2020). (Mariani et al., 2020) implemented DFA that effectively classifies volcanic eruption data. Fan et al. (2019) states that the application of DFA can significantly improve the level of short-term forecasting for the catalog of actual earthquakes (Italy).

To determine anomalies in scaling behavior that can be considered early signs before a major earthquake on the island of Lombok in 2018, we applied the DFA method to the seismic signal of the Rinjani station in 2018. The DFA approach can establish Data scaling behavior (Febriani et al., 2022). DFA can help avoid scaling errors and detect correlations that can lead to errors in trends and nonstationary data (Peng et al., 1995). Li et al. (2020) has used the DFA scaling exponent to determine modes relevant to constructing filtered signals.

The DFA method will generate a scaling relationship value (α) that can be used to identify anomalies before the 2018 major earthquake on Lombok Island. The data processing results using the DFA method will be associated with large earthquakes Mw>=5.90 on Lombok Island in 2018, West Nusa Tenggara.

Method

In this study, we apply Detrended Fluctuation Analysis (DFA), which can be used to examine complex phenomena. This method generates an α parameter that can detect relationships or correlations in variations in data values as a function of time, denoted as y(k), defined in Equation (1) below.

$$y(k) = \sum_{i=1}^{N} [s(i) - s_{ave}] \tag{1}$$

Where k = 1, 2, 3, ..., N, and N is the total length of the data, s(i) represents seismic signal data (m/s) at time-i, and s_{ave} the average value of the seismic signal obtained using Equation (2).

$$S_{ave} = \frac{\sum s(i)}{n} \tag{2}$$

Where n is the number of seismic signals, after obtaining the value y(k), $y_n(k)$ is determined to represent the local linear trend in each observation box. Then, we count the average fluctuations of the square root $F(n)$ as shown in Equation (3) below.

$$F(n) = \sqrt{\frac{1}{N}\sum_{k=1}^{N}[y(k) - y_n(k)]^2} \tag{3}$$

Where n is the number of observation boxes, and F (n) is the average fluctuation of the smallest square root in each observation box. Then, we calculate Equation (4) for all box sizes to give the relationship between F (n) and n by applying the resulting linear line by plotting. $log_{10}F(n)$ towards $log_{10}n$. The graph indicates the presence of a scaling or correlation relationship, denoted as α. The resulting α represents the slope of the line corresponding to $log_{10}F(n)$ towards $log_{10}n$.

$$\mathrm{F(n)} \propto \mathrm{n}^{\alpha} \tag{4}$$

If α > 0.5, the data shows persistent or non-random data. Non-random data has the potential to be predictable (Simanjuntak et al., 2013). If α = 0.5, the data does not correlate (Skordas et al., 2020).

The next step identifies outlier α values, a statistical technique that identifies suspicious events or items that deviate from the normal shape of the data set (Alghushairy et al., 2021). Outliers have a low probability derived from the same statistical distribution as other observations in the data set. On the other hand, data with extreme values are observations that may have a low probability of occurrence but cannot be displayed because they come from a different distribution than other data (Walfish, 2006). Checking outlier data can also be done by checking the standard score (z-score) dari data. Data is considered an outlier if the z-score is less than -3 or greater than 3 (Sihombing et al., 2023). We use the following Equation (5) to determine outliers.

$$Z\ score = \frac{x - \mu}{\sigma} \tag{5}$$

Where Z-score represents a standard score, x is the value of the data examined (α), μ represents the average value of the data, and σ represents the standard deviation value, which is shown in Equation (6) (Mulyana et al., 2020).

$$\sigma = \sqrt{\frac{\sum(x - \mu)^2}{n - 1}} \tag{6}$$

Where σ represents the standard deviation value, x is the value of the data being processed, μ represents the average value, and n represents the number of data points. From equation (5), the value of the anomalous α can be determined using Equation (7).

$$\alpha > 3\sigma + \mu \text{ or } \alpha < -3\sigma + \mu \tag{7}$$

Result and Discussion

The Results of Seismic Signal Data Processing Using the DFA Method

Figure 1 shows the results of processing seismic signal data recorded by the Mount Rinjani station on January 1, 2018, using the DFA method. The horizontal axis represents the value. $log_{10}n$, While the vertical axis represents the average fluctuation value of the square root, namely: $log_{10}F(n)$. Blue dot showing a variation of value $log_{10}F(n)$ plotted against $log_{10}n$. The purple line indicates linear regression y=0.57x + 1.02, with slope α (scaling exponent) of 0.57.

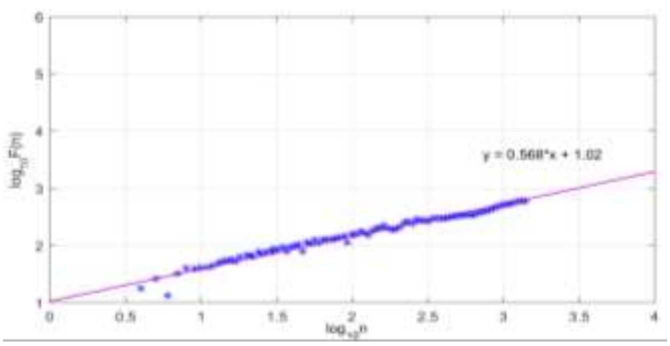

Figure 1. Results of seismic signal processing using the DFA method for data dated January 1, 2018

Seismic signal data at the Mount Rinjani station is recorded every minute so that every day, there is as much as 1440 data. The total data from January to December amounted to 522720 data points. Of the 1440 daily data points, the data is divided into 96 squares (per 15 minutes), producing one value α, 96 votes from $log_{10}F(n)$ towards $log_{10}\,n$ for each box.

Anomaly of the Seismic Signal Data Using DFA Method

Figure 2 presents the characteristics of α values for all periods of analyzed data. We calculate the upper and lower threshold values of the outliers of the α shown in red, which are 0.87 and 0.36, respectively. The black arrow line symbolizes the time of the 2018 great earthquake on Lombok Island. Arrow line A is an earthquake that occurred on July 28, 2018, with a magnitude of Mw 6.40 SR. Line B earthquake on August 5, 2018, with a magnitude of Mw 6.90; Line C earthquake on August 9, 2018, with a magnitude of Mw 5.90; and on August 19, 2018, a line D earthquake of magnitudes Mw 6.90 and Mw 6.30 occurred. The magnitude and timing of significant earthquake events during 2018 can see in Table 1. The α values are all above the lower threshold value, and the average is above the 0.50 value, as shown in Figure 2. It indicates the presence of persistent or non-random correlations, which have predictive potential for the period of the data analyzed. Previous studies have shown similar α value characteristics (Febriani et al., 2022; Nenovski et al., 2013; Peng et al., 1995; Simanjuntak et al., 2013; Skordas et al., 2020). In addition, nine anomalies were found with a range of α values that qualify as outlier data, namely α ≤ 0.36 or α ≥ 0.87, as shown in Figure 3 - Figure 11. The anomaly was detected on January 6, 2018, but the preliminary earthquake on Lombok Island occurred in July. Therefore, it is likely that the anomalies found in January are related to earthquakes in other locations, such as the one that occurred in Lebak Regency, Banten Province, on January 23, 2018, with a magnitude of Mw 6.1. Graphic $log_{10}F(n)$ towards $log_{10}n$ for all nine α values that are considered anomalies are shown in Table 2. From the table it can be seen $log_{10}F(n)$ towards $log_{10}n$, namely numbers 5, 6, and 7 that occurred on July 26-28, 2018, has a constant value for the last 6 hours where the value F (n) does not increase. According to Peng et al. (1995) value F(n) It should usually increase as the number of observation boxes (N) increases. Based on the values of α and F(n) the constant is considered an anomaly seen 1-3 days before the preliminary earthquake Mw 6.40 (28/07/2018) UTC and 10 days before the main Mw 6.90 earthquake (05/08/2018). The time span of these anomalous events is also seen in research conducted by (Akhoondzadeh et al., 2019; Fu et al., 2020; Kanata et al., 2014; Senturk et al., 2019; Shah et al., 2019, 2021; Song et al., 2020). According to research Supendi et al. (2020), an Mw 6.40 event most likely preceded the entire series of Lombok earthquakes in 2018 as an initial event or foreshock. The same phenomenon is found in our paper, which has been presented at the International Joint Seminar on Education, Social Science and Applied Science (IJESAS 2023) about "Detrend Analysis of Temperature Fluctuations to Identify Anomalies Related to the 2018 Major Earthquake on Lombok Island," which focuses on processing temperature data at the Lombok Geomagnetic Observatory (LOK) in 2018 sourced from NASA satellites using DFA. Obtained value of

Table 1. Major Earthquake Events in 2018

Date of Earthquake	DOY	Depth (km)	Mag. (Mw)	Position
July 28, 2018	210	14	6.40	8.240°S 116.508°E
August 5, 2018	217	34	6.90	8.258°S 116.438°E
August 9, 2018	221	15	5.90	8.307°S 116.230°E
August 19, 2018	231	21	6.90	8.319°S 116.627°E
August 19, 2018	231	16	6.30	8.337°S 116.599°E

Table 2. Seismic Signal Data Anomaly Using DFA Method

No.	Date of anomaly occurrence	DOY	α
1	January 6, 2018	6	0.915
2	January 7, 2018	7	0.965
3	January 22, 2018	22	0.893
4	January 29, 2018	29	0.877
5	July 26, 2018	207	0.911
6	July 27, 2018	208	1.035
7	July 28, 2018	209	0.982
8	August 5, 2018	217	1.028
9	August 19, 2018	231	0.932

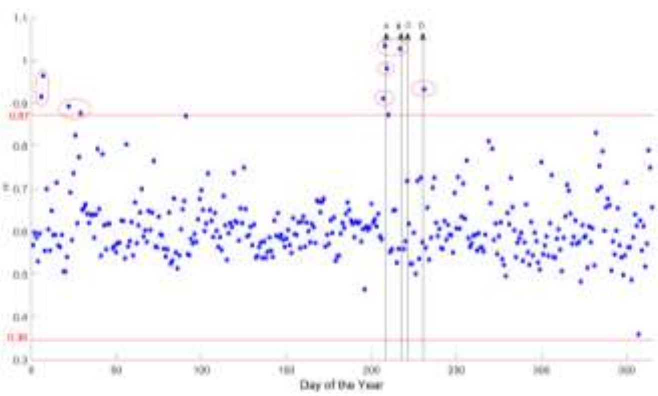

Figure 2. Plot α values during 2018

$log_{10}F(n)$ towards $log_{10}n$, which has a value of constant at the beginning and end, occurred about a month before the earthquake on July 28, 2018. It reinforces that, in addition to the α value being an outlier, the value F (n) Constant can also be considered an anomaly.

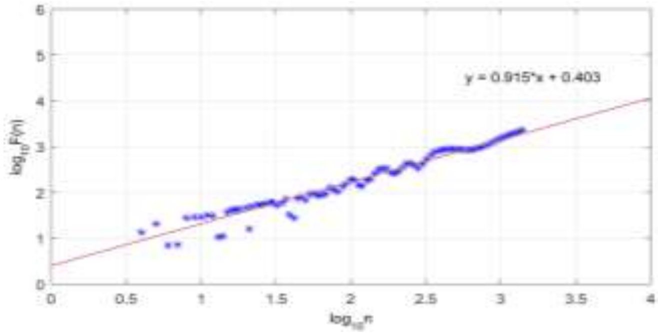

Figure 3. Graph of $log_{10}F(n)$ towards $log_{10}n$ (Blue Star) and the trend (purple line) for the anomaly value α= 0.92 on January 6, 2018

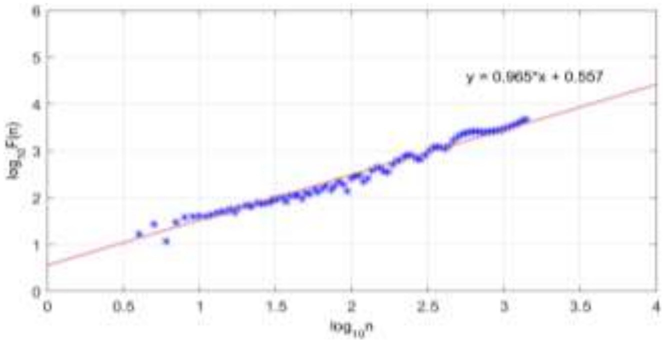

Figure 4. Graph of $log_{10}F(n)$ towards $log_{10}n$ (Blue Star) and the trend (purple line) for the anomaly value α= 0.97 on January 7, 2018

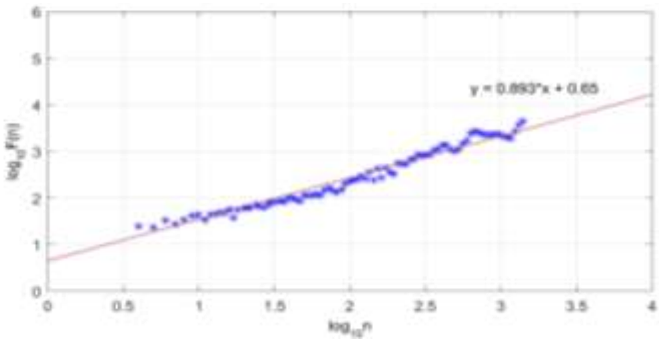

Figure 5. Graph of $log_{10}F(n)$ towards $log_{10}n$ (Blue Star) and the trend (purple line) for the anomaly value α= 0.89 on January 22, 2018

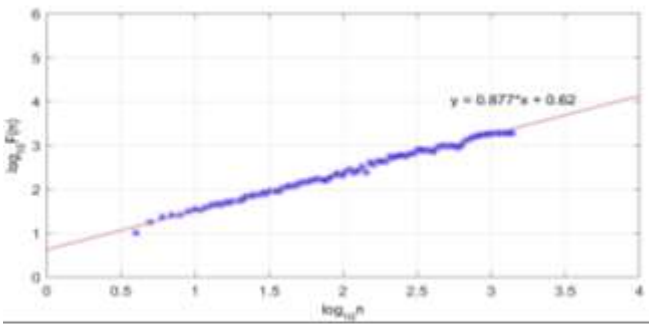

Figure 6. Graph of $log_{10}F(n)$ towards $log_{10}n$ (Blue Star) and the trend (purple line) for the anomaly value α= 0.88 on January 29, 2018

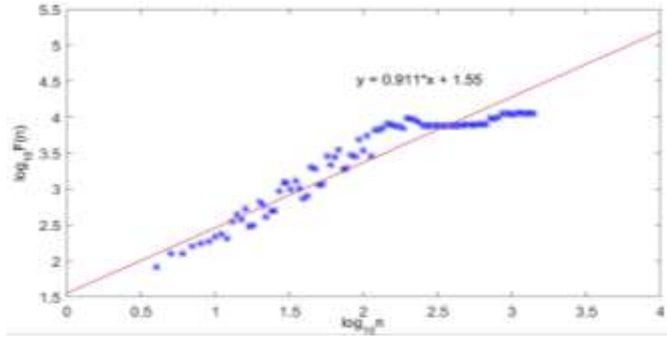

Figure 7. Graph of $log_{10}F(n)$ towards $log_{10}n$ (Blue Star) and the trend (purple line) for the anomaly value α = 0.91 on July 26, 2018

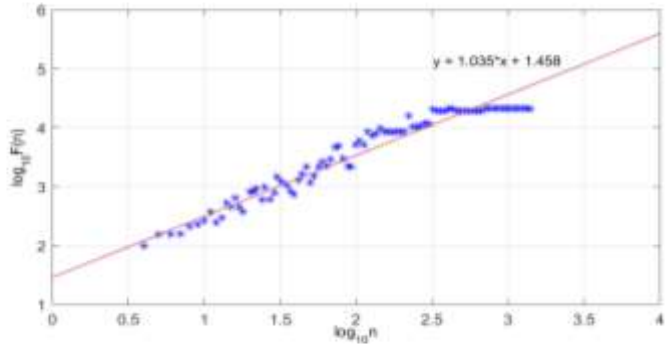

Figure 8. Graph of $log_{10}F(n)$ towards $log_{10}n$ (Blue Star) and the trend (purple line) for the anomaly value α= 1.04 on July 27, 2018

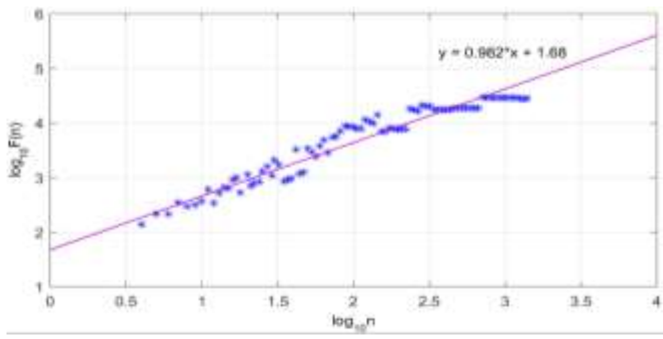

Figure 9. Graph of $log_{10}F(n)$ towards $log_{10}n$ (Blue Star) and the trend (purple line) for the anomaly value α= 0.98 on July 28, 2018

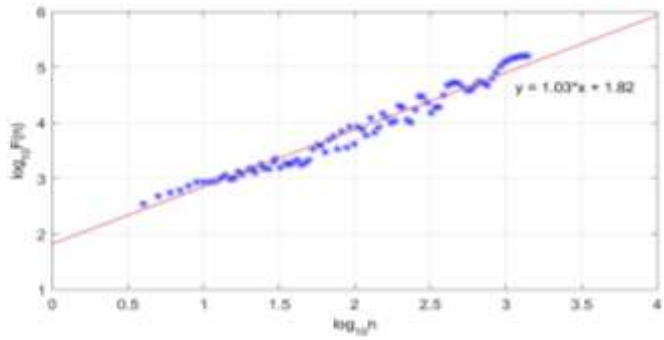

Figure 10. Graph of $log_{10}F(n)$ towards $log_{10}n$ (Blue Star) and the trend (purple line) for the anomaly value α= 1.03 on August 5, 2018

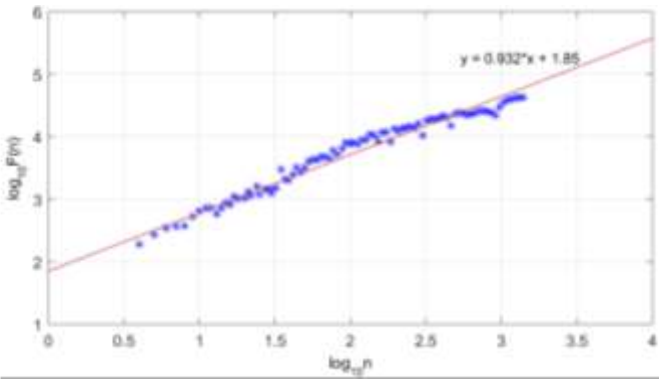

Figure 11. Graph of $\boldsymbol{log_{10}F(n)}$ towards $\boldsymbol{log_{10}n}$ (Blue Star) and the trend (purple line) for the anomaly value α = 0.93 on August 19, 2018

Conclusion

We applied detrended fluctuation analysis (DFA) on seismic signal data recorded at the Mount Rinjani station to analyze the precursors of seismic signals related to large earthquakes Mw>5.90 in July-August 2018. The DFA analysis results showed that there were nine scaling relations (α) that crossed the scaling threshold limit, three of which had constant F(n) root mean square fluctuations that occurred one to three days before the preliminary earthquake of Mw 6.40 (07/28/2018) UTC and eight to 10 days before the main Mw 6.90 earthquake (05/08/2018).

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Author Contributions
Conceptualization, B. K, T. Z, R., and N. F.; methodology, B. K, T. Z, and N. F.; formal analysis, B. K, T. Z, R., and N. F.; data acquisition, M. F.; writing—original draft preparation, B. K and N. F.; writing—review and editing, T. Z, A. Z, M. S. Y, and D. R.; All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest
No conflict of interest.

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