International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:2, No:6, 2008

Temporal Change of Fractal Dimension of Explosion Earthquakes and Harmonic Tremors at Semeru Volcano, East Java, Indonesia, using Critical Exponent Method

Sukir Maryanto and Iyan Mulyana

Abstract**—**Fractal analyses of successive event of explosion earthquake and harmonic tremor recorded at Semeru volcano were carried out to investigate the dynamical system regarding to their generating mechanism. The explosive eruptions accompanied by explosion earthquakes and following volcanic tremor which are generated by continuous emission of volcanic ash. The fractal dimension of successive event of explosion and harmonic tremor was estimated by Critical Exponent Method (CEM). It was found that the method yield a higher fractal dimension of explosion earthquakes and gradually decrease during the occurrence of harmonic tremor, and can be considerably as correlated complexity of the source mechanism from the variance of fractal dimension.

Keywords**—**Fractal dimension, Semeru volcano, explosion earthquake, harmonic tremor, Critical Exponent Method

I. Introduction

SEMERU volcano an andesitic stratovolcano, is one of the most actives volcanoes in Indonesia located in East Java, Indonesia. The summit, called Mahameru, rises 3676 m above sea level and it is the highest, active volcano on the island of Java. Semeru volcano has been continuously active since 1967 [3, 4]. In the recent period, its activity characterized by small to moderate strombolian type explosion at time interval of 15 to 45 minutes, producing explosion plumes rising 400–1000 m above the summit. Sometimes, the explosive eruption accompanied with explosion earthquakes and followed by volcanic tremor. During active periods, lava flow, lava dome extrusion and pyroclastic flows have also been observed. In 2005 the frequency of the explosions averaged 3453 times per month and 115 per day, respectively [5, 6].

Many researchers have studied the generating mechanism of separately event of volcanic signals between volcanic tremors and non-tremors. A few volcanoes exhibit explosive earthquakes followed by harmonic tremor such as Sakurajima volcano, Karymsky volcano and Arenal volcano [7, 8, 9]. These impulsive signals, theirs appearance of harmonic spectra and their source characteristics have become the subject of controversy. In general, based on their spectra characteristics, they have been interpreted as emanating from the resonance of a conduit containing a mixed two-phase fluid body in the upper parts of volcanic conduit [8, 13].

Most of the previous study mentioned above are mainly based on the characteristics of spectra which mostly triggered by linear process, however little intent has been given on nonlinear process. In contrary, theoretically volcanic tremors can be generated by some kind of nonlinear processes [15]. Methods based on the discipline of nonlinear dynamics have been rarely applied to the volcanic tremor and explosion earthquake recorded at some volcanoes. The first investigation of fractal properties of volcanic signals have been conducted for volcanic tremor for the tremor and gas piston events recorded at Kilauea volcano, Hawaii [16]. The results revealed a fractal dimension of the tremor attractor in the range of 3.1-4.1 with the average value of 3.75. This was interpreted that the source of tremor is not controlled by a stochastic process (where fractal dimension should be infinite), therefore it can be described by only a few degrees of freedom. Some studies of tremor and low-frequency events reported similar estimates of the fractal dimensions confirming the low-dimensional nature of the phenomena.[15-19)] Furthermore, the time interval between two successive explosions can be considered as a dynamical variable.

In the present paper, another approach of fractal analyses of the volcanic earthquakes and tremor analysis has been applied based CEM. We applied the method to successive event of explosion earthquakes and harmonic tremors recorded at Semeru volcano, East Java, Indonesia. First, we briefly describe the data obtained from Center for Volcanology and Geological Hazard Mitigation, Indonesia. We then present a method to estimate the fractal dimension of the explosion earthquakes and harmonic tremor. We follow with an application of the method to our data and terminate with a discussion of the implications of these results for driving mechanism of harmonic tremor..

S. M. is with the Physics Department of Brawijaya University, Malang, East Java, Indonesia (corresponding author to provide phone: +62-34-575833; fax: +62-341-554403; e-mail: sukir@brawijaya.ac.id).
I. M. is with Center for Volcanology and Geological Hazard Mitigation (CVGHM), Jl. Diponegoro, Bandung 40002, West Java,. Indonesia. (iyan@vsi.esdm.go.id).

II. Observation

Semeru volcano has been monitored by Center for Volcanology and Geological Hazard Mitigation using 2 permanent seismic stations, LEK and BES, and 3 temporary seismic stations, PCK, KPL and TRS. They are distributed at 0.76 – 8.9 km apart from the active crater. Seismic sensor installed at the summit and northwest-south slope. Station PCK is near the summit and station KPL is 2.5 Km north of the summit. Station LEK, TRS and BES are located at east to south flank of the volcano (Fig.1). The 5 stations are equipped with short-period (1 Hz) vertical seismometers. The recorded seismic signals transmitted to the G. Sawur Volcano Observatory by FM radio telemetry. Locations of the stations are summarized in Table I.

TABLE I Location of permanent seismic stations at Semeru volcano

NO	STATION	Geographic position		
		Latitude (S)	Longitude (E)	Altitude (m)
1	PCK	8°6'26.3"	112°55'26.7"	3657
2	KPL	8°5'02.7"	112°55'13.0"	2764
3	TRS	8°8'54.5"	112°57'50.3"	1208
4	LEK*)	8°8'14.8"	112°59'09.4"	1060
5	BES*)	8°10'50.0"	112°57'09.2"	917

**) Permanent stations used in this study*

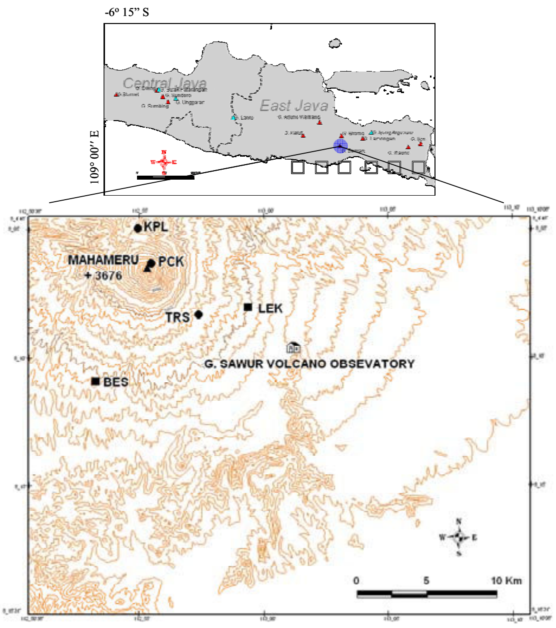

Fig. 1. Map of Semeru volcano and locations of seismic stations at this volcano operated by Center of Volcanology and Geological Hazard Mitigation. Triangle, circles and squares represent summit crater, temporary and permanent stations, respectively. The temporary stations installed during September – December 2005.

The seismic signals are recorded by analog drum recorders; Kinemetrics PS-2 and digitally sampled 100 Hz by data loggers (Datamark LS-7000) with GPS time calibration. Characteristic signals such as volcanic earthquakes, tectonic earthquakes, and eruption earthquakes also harmonic tremor are recognized on the seismograms. The selected successive events of explosion earthquakes and harmonic tremor are represented in Table II. Fig. 2 shows the typical seismogram of these events. The harmonic tremor occurred about 2-3 minutes after explosion.

TABLE II Explosion earthquake and harmonic tremor events

Time of eruption	Estimated time interval between eruption and harmonic tremor (min)	Estimated duration (min)
2005:03:12 23:36	2	6
2005:03:13 00:39	2	10
2005:03:14 05:34	3	21
2005:03:15 00:05	3	23

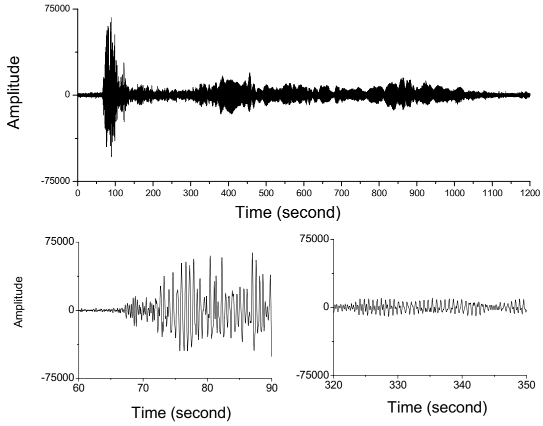

Fig. 2. An example seismogram (vertical component) of small eruption followed by volcanic tremor (upper part). Left bottom shown a typical of the explosion earthquake and right bottom is harmonic tremor.

III. Critical Exponent Method

The fractal concept has been widely used to describe the objects in space since it has been found to be useful for analysis of volcanological signals. The time series with fractal nature to be describable by the functions of fractional Brownian motion *(fBm)*, for which the fractal dimensions can easily be set. This paper proposed the fractal dimension evaluation based on the critical exponent method. The power spectral density (PSD), $PH(\nu)$, of observed signals in the frequency domain is determined as:

$$P_H(\nu) \approx \nu^{2H+1} = \nu^{-\beta} \qquad (1)$$

In the CEM, $I\alpha$ of the Power Spectral Density (PSD) is determined as:

$$I_\alpha = \int P_H(\nu)\ \nu^\alpha d\nu, \ \ (-\infty < \alpha < \infty) \qquad (2)$$

Considering the limited bands of frequency and subs. (1) in (2)

$$I_\alpha \approx \int \nu^{\alpha-\beta} d\nu = \frac{1}{\alpha-\beta+1}(\Omega^{\alpha-\beta+1} - 1) \qquad (3)$$

$$= \frac{2}{U} \exp\left(\frac{U \log \Omega}{2} \right) \quad (4)$$

where α is the moment exponent, is the frequency variable which was normalized to the lower bound of the integration region as 1, and let $U = \alpha + \beta + 1$. In the CEM, the condition of $U = 0$ is satisfied for the moment of critical exponent as $\alpha = \alpha_c$ at which the value of the third order derivative of log $I\alpha$ with respect to is zero as the following equation:

$$\frac{d^3 \log I_\alpha}{d\alpha^3} = \frac{I'''_\alpha I^2_\alpha - 3I''_\alpha I'_\alpha + 2(I'_\alpha)^3}{I^3_\alpha} \quad (5)$$

Finally, from this value of α_c, $\beta = \alpha_c$ - 1 and the estimated fractal dimension is given as:

$$D = 2 - \frac{\alpha_c}{2} \quad (6)$$

where α_c is the critical exponent value. Fig. 3 shows the determination of the critical exponent value of the traditional fBm signal with $H = 0.07$ and the sample length is 1,024 points. The CEM can evaluate its fractal dimension was $D = 1.93$.

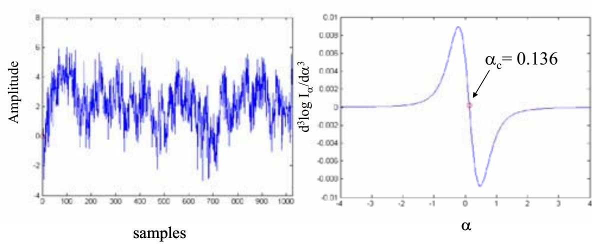

Fig. 3. Determination method of the critical exponent value. (a) Traditional fBm signal with H = 0.07. (b) Third order derivative of the logarithmic function and the zero crossing point.

The volcanic seismic signal contains the fluctuations concerned with frequency, amplitude, self-affine property, chaotic behavior, etc. Therefore, if we divide the whole time-sequential data into several short time intervals and measure the degrees of freedom of the fluctuations inside these time-intervals, we can observe the change in the degree of fluctuations with respect to time. These fluctuations are effectively characterized by the fractal dimensions. In this paper, we will approach the CEM in order to evaluate the fraction dimensions and called the time-dependent fractal dimension (TDFD).

In practice, we divided the seismogram data into short time intervals by a windowing with a window function. We then evaluate the fractal dimensions of the points inside this windowing. Next, we move this window by n points (Δt) and again evaluate the fractal dimension of moved window. By repeating this process throughout the whole data, we can observe the change in the fractal dimension with respect to time. In the case of TDFD, the horizontal axis is the window index and vertical axis is the fractal dimension value. Fig. 4 shows typical successive events of explosion earthquakes and harmonic tremor occurred on March 15, 2005 and its temporal change of fractal dimension determined by CEM with TDFD.

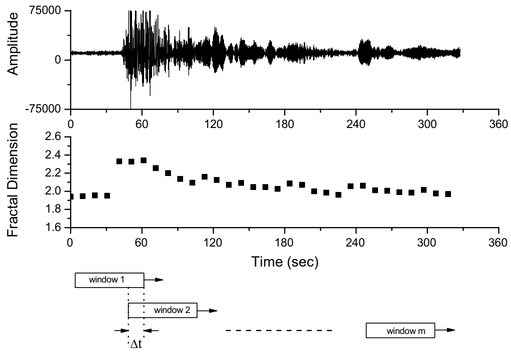

Fig. 4. Typical of successive event of explosion earthquakes and harmonic tremor and its temporal change of fractal dimension. The fractal dimension was estimated based on CEM with TDFD.

IV. Results and Discussions

In our study of the temporal change of fractal dimension of successive event between explosion earthquakes and harmonic tremor have been calculated based on CEM with moving windows of 1024 points and 50% overlap. The temporal pattern shows that fractal dimension gradually decreased from explosion earthquakes to volcanic tremor and fluctuates in a certain range during the occurrence of harmonic tremor as shown in Figs. 5 and 6. The fractal dimension of explosion earthquakes has higher value than harmonic tremor at all events.

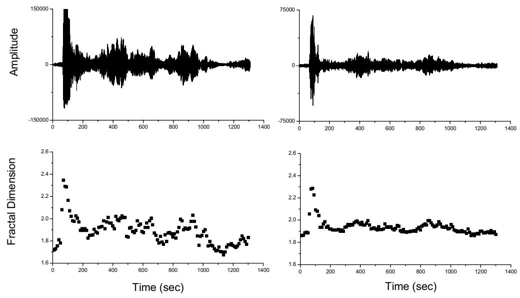

Fig. 5. Example event occurred on 2005:03:15 00:38 recorded at station BES (top left) and station LEK (top right). Bottom graphs are their temporal change of fractal dimension at station BES (left) and LEK (right).

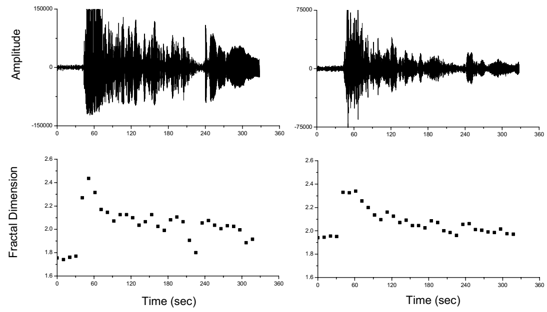

Fig. 6. Similar with Fig. 5 for event occurred on 2005:03:15 00:05.

The variation of fractal dimension along the seismogram can be explained in terms of stationary or non-stationary behavior of source. The results suggest that explosion earthquakes show non-stationary behavior indicated by higher fractal dimension, ≈ 2.2-2.5, while harmonic tremors present stationary behavior characterized by lower fractal dimension ≈ 1.6-1.9. These indicate that explosion earthquakes have more complicated structure of signals or the quantity information embodied in a pattern.

Several source models may be employed to explain the source of these successive events, including the non-linear excitation due to unsteady flow and resonance of fluid-filled cavity model with various geometries [8 ,9, 14].Furthermore, Maryanto et al [7, 8]. and Tameguri et al [20, 21], suggest that based on the spectra analysis, moment tensor analysis, visual observations, and ground deformation associated with successive event of explosion and harmonic tremors of Sakurajima volcano, Japan, the following facts should be considered as constraints for modeling of their generation mechanism; spectrum peaks appear at the frequencies of multiple integers of the fundamental frequencies, peak frequencies of harmonic tremor are rather stable, source depths coincide with the gas pocket at uppermost part the conduit. Because of successive events contain of two different types of volcanic seismic signals, we estimated that the source of these events should be changed from non-stationary to stationary source as detected by temporal change of fractal dimension. In this case, when an explosion earthquake occurred a resonance may occur immediately at the upper part of the conduit. In order to discuss the detailed source mechanism, we would have to perform an analysis of spectra and waveform inversion of these events. We have not yet attempted the analysis for this data set.

However, the temporal change of the fractal dimension measured on seismograms may vary depending on the signal-to-noise ratio, on the amplification of the signal, and on the sampling frequency. Also, determination of an optimum window length is important, as fractal analysis is sensitive to window length. The effect of non-stationary sampling of the signals composed of segments of differing spectral characteristics may also contribute to the observed change.

The suggestion that volcanic tremor is the result of non-linear source processes involving one or several different kinds of magmatic activity is not only supported by theoretical considerations[10,14], but also by certain characteristics observed in volcanic seismic signals, which are believed to be common among systems exhibiting aperiodic, chaotic behavior.

Qualitatively, this fact can be considered as constraint in source modeling of explosion earthquakes following by harmonic tremor. Similar low values of fractal dimension of these events have been reported at Sakurajima volcano[19]. The similarities between the properties of the Semeru and Sakurajima tremor point to the possibility of similar characteristics of the source processes.

A comparison of pattern of temporal change between BES and LEK stations (Fig. 7) shown a similar pattern between them due to the sources effect. This effect as well as presented by the similarities of spectra between two stations as shown in Fig. 8. The relationship between the spectral amplitudes in different frequencies allows, for the fractal detector, a complete analysis in a broad frequency range of seismic waves. The results of this analysis can be applied to a set of phenomena related with differentiation of similar signals of different nature. This study demonstrates that the relevant information on fractal dimension of the system contained in the volcano seismic signals.”

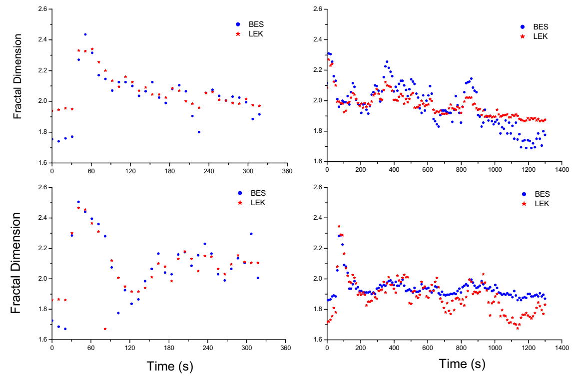

Fig. 7. Time dependent of fractal dimension of four events. Data are from vertical component of ground velocity recorded at station BES (blue dots) and LEK (red stars).

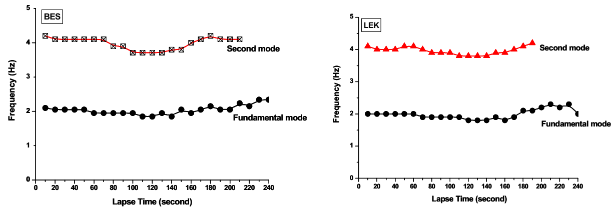

Fig. 8. Example of temporal change of fundamental frequencies and second mode of similar event at Fig. 6.

V. Conclusions

Using Critical Exponent Method, fractal analysis of explosion earthquakes followed by harmonic tremor at Semeru volcano has been carried out. The fractal dimension evaluated based on CEM with TDFD. The critical exponent value, which is determined by CEM, characterizes the self-affine property of explosion earthquakes and harmonic tremor. It was found that the method yield a higher fractal dimension of explosion earthquakes and gradually decrease during the occurrence of harmonic tremor, and can be considerably as correlated complexity of the source mechanism from the variance of fractal dimension. Therefore, the fractal dimensions were effective for investigating the volcano seismic event. Moreover, the method described in this paper can be considerably utilized the volcanic earthquakes characterization.

ACKNOWLEDGMENT

We wish to expressing thank to Hery Kuswandarto, Suparno, Liswanto of G. Sawur Volcano Observatory at Semeru for their collecting data.

.

REFERENCES

[1] M Nakagawa, "Chaos and Fractal in Engineering," Singapore: World Scientific, 1999, ch. 3.
[2] M Phothisonothai, M Nakagawa, "EEG-Based Fractal Analysis of Different Motor Imagery Tasks using Critical Exponent Method," Intl. Journal of Biomedical Sciences, vol. 1; pp175-180, 2006
[3] K Kusumadinata, "Catalogue of References on Indonesian Volcanoes with Eruptions in Historical Time", Volcanological Survey of Indonesia, pp 304, 1979
[4] S Siswowidjoyo, U Sudarsono, A D Wirakusumah, "The threat of hazards in the Semeru volcano region in East Java, Indonesia," Journal of Asian Earth Sciences, vol 15; pp. 185-194, 1997
[5] I Mulyana, "Characteristics of harmonic tremor at Semeru volcano, East Java, Indonesia," JICA Final Report of Volcanology and Comprehensive Sediment-related Disaster Prevention Measures J05-00876, 2006)
[6] K Nishi, M Hendrasto, I Mulyana, U Rosadi, M A Purbawinata, "Micro-tilt changes prior to the summit explosions at Semeru volcano, Indonesia" Earth, Planets and Space, vol. 59; pp. 151-159, (2007
[7] S Maryanto, M Iguchi, and T Tameguri, "Spatio-Temporal Characteristics on Spectra and Particle Motion of Harmonic Tremors at Sakurajima Volcano, Japan," Ann. Disast. Prev. Res. Inst., Kyoto University, vol. 48B, pp. 329-339, Apr. 2005
[8] S Maryanto, M Iguchi, and T Tameguri, "Constraints on the sources mechanism of harmonic tremors based on seismological, ground deformation, and visual observations at Sakurajima Volcano, Japan," Journal of Volcanology and Geothermal Research, vol. 170, pp. 198-217, 2008
[9] J Benoit and SR McNutt, "New constraints on source processes of volcanic tremor at Arenal volcano, Costa Rica, using broadband seismic data" Geophys. Res. Lett., vol. 24, no. 4, pp. 449–452, Feb. 1997
[10] B Chouet, "Excitation of a buried magmatic pipe: a seismic source model for volcanic tremor," J. Geophys. Res., vol. 90, no. B2, pp 1881-1893, Feb. 1985.
[11] V Schlindwein, J Wassermann and F Scherbaum. Spectral analysis of harmonic tremor signals at Mt. Semeru volcano, Indonesia. Geophys. Res. Lett., vol. 22, no. 13, pp 1685-1688, Jul. 1995.
[12] M Hellweg, "Physical model for the source of Lascar`s harmonic tremor," J. Volcanol. Geotherm. Res., vol 101, no. 1-2, pp. 183-198, Aug. 2000.
[13] S Kedar, S Bradford, and H Kanamori, "The origin of harmonic tremor at Old Faithful geyser," Nature, vol. 379, no. 22, pp. 708-711, Feb. 1996.
[14] BR Julian, "Volcanic tremor: non-linear excitation by fluid flow," J. Geophys. Res., vol. 99, no. B6, pp 11859-11877, Jun. 1994.
[15] B Chouet and HR Shaw, "Fractal Properties of Tremor and Gas-piston Events Observed at Kilauea Volcano, Hawaii," Journal of Geophysics Research, vol. 96, no B6, pp. 10177-10189, Jun. 1991.
[16] C Godano, C Cardaci, and E Privitera, "Intermittent Behaviour of Volcanic Tremor at Mt. Etna," Pure Appl. Geophysics, vol. 147, no. 4, pp. 729–744, Oct. 1996.
[17] C Godano and P Capuano, "Source Characterisation of Low Frequency Events at Stromboli and Vulcano Islands (Isole Eolie Italy)," Journal of Seismology, vol. 3, no. 4, pp. 393-408, Oct. 1999.
[18] KI Konstantinou, "Deterministic Nonlinear Source Processes of Volcanic Tremor Signals Accompanying the 1996 Vatnajökull Eruption, Central Iceland," Geophys. J. Int., vol. 148, no. 3, pp 663-675, March 2002.
[19] KI Konstantinou and Lin CH, "Nonlinear Time Series Analysis of Volcanic Tremor Events Recorded at Sangay Volcano, Ecuador. Pure Appl. Geophysics, vol. 161, no. 1, pp. 145–163, Jan. 2004.
[20] T Tameguri, S Maryanto, and M Iguchi, "Moment tensor analysis of harmonic tremors at Sakurajima Volcano," Ann. Disast. Prev. Res. Inst. Kyoto University, vol. 48B, pp. 323-328, Apr. 2005.
[21] T Tameguri, S Maryanto, and M Iguchi, "Source Mechanism of Harmonic Tremor at Sakurajima Volcano," Bull. Volcanol. Soc. Japan, vol. 52, pp 273-279, 2007.