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Locating Tremor Source with Polarization and Semblance Methods During the 2014 Crisis Period of Raung Volcano

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Abstract - Raung is a basaltic-andesitic volcano with strombolian-type eruptive activity located in East Java Province, Indonesia. The seismic activity of this volcano increased on 11th November 2014 which was dominated by tremors. Due to the difficulty to distinguish the onset of body waves of tremor waveform, polarization and semblance methods were proposed and applied to locate the tremor source. The tremors recorded during November to December 2014 were analyzed. The results showed that the back-azimuth values obtained by the polarization method were around N 288° - 324° E in accordance with the direction of Raung summit, while the incidence angle ranged around N 81° - 89.3° E. The semblance method was performed on 2 x 2 km area around the summit. The result of the tremor source showed the distribution of epicentre extending N52° E to the northeast direction about ±2.1 km away from the Raung summit.

Keywords: Raung, back-azimuth, incidence angle, volcanic earthquake

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Introduction

Raung, a basaltic-andesitic volcano, is located in East Java Province. It is one of the most active volcanoes in Indonesia. The characteristic eruption of this volcano is explosive of which most have been categorized as moderate explosions (Volcanic Explosivity Index/VEI = 2), while in 1593 the explosion was categorized as very large (VEI=5). Raung has erupted at least fifty-seven times since 1593, and one notorious eruption occurred in 1638. The eruption generated and poured lahar into the surrounding rivers, Stail and Klatak Rivers. At that time, more than 1,000 people were killed by the flood and lahar. Another calamity eruptions occurred in 1597, 1730, and 1817.

On the late October 2012, the status of Raung Volcano raised to level 2 alert after volcanic tremors were recorded. The exclusion zone was then placed with radius 3 km around the crater. Then, a large eruption occurred on 8th November 2012 where ash emission reached a height of ± 9 km. Strombolian eruptions were observed with 200 m in height above the crater.

In 2014, a crisis period of Raung Volcano started from November 2014, which then the eruption took place on 29th June 2015. The seismic activity of the volcano was fluctuated from November 2014 to June 2015. Volcanic tremors had been recorded since the initial crisis period of this volcano on 11th November 2014, after which the seismic activity was dominated by tremors. Some tremors occurring on 12th November 2014 had been recognized as quasi-harmonic tremors (Ipmawan *et al.*, 2018a). By the end of November 2014, tremors became continuous where the dominant frequency of this volcano had the range of 0.95 ± 0.15 Hz (Ipmawan, 2018b).

Raung Volcano is monitored by the Centre for Volcanology and Geological Hazard Mitigation (CVGHM) using four seismic stations, namely: RAUN, MLTN, KBUR, and MLLR. All the stations were equipped with L-4C 1 Hz 1-component seismometers, except MLLR station that was equipped with a L-22D 2 Hz 3-channel seismometer. The distribution of seismic stations in Raung is shown in Figure 1. Tremor is a volcanic earthquake that occurs in a long period, lasting from several minutes to several days, preceding and/or accompanying most volcanic eruptions (Konstantinou and Schlindwein, 2002). Physical processes generating volcanic tremor involve complex interactions of magmatic fluids with the surrounding rocks (Zobin, 2017). Tremor is a powerful tool for better understanding the physical processes controlling explosive eruptions. There are good agreements between tremor and eruption activities. In particular, a shift of dominant frequencies towards lower values was noted which corresponds to increasing explosive activity (Cannata *et al.*, 2007).

Generally, an epicentre of earthquake can be obtained using P-wave and S-wave arrival time. In contrast, both P-and S waves of tremor interfere each other, which makes their arrival time be difficult to distinguish (Hofstetter and Malone, 1986). Polarization is a method to obtain the epicentre of tremor that was introduced by Jurkevics (1988). This method does not require identification onset

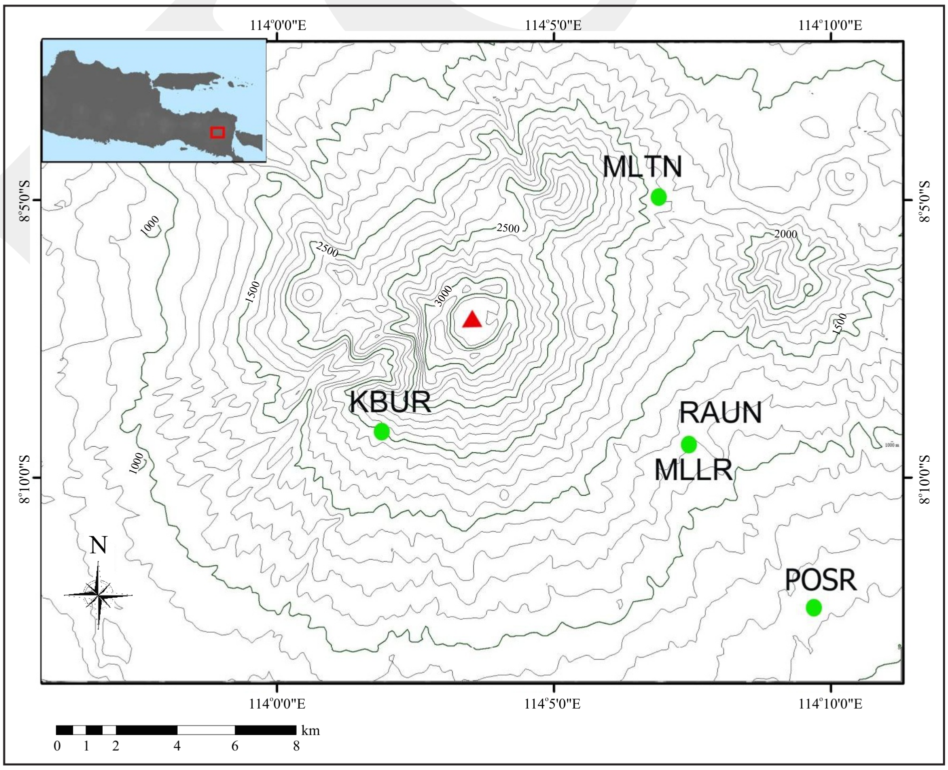

Figure 1. Distribution of seismic stations at Raung Volcano.Green solid circles and red solid triangle denote seismic stations and the peak of Raung, respectively.

of body wave arrival time. Sugianto (2014) applied this method to analyze the seismic source location of Bledug Kuwu mud volcano in Central Java, Indonesia. The method requires at least three 3-components seismometers which are located in different quadrants. The parameters obtained through this method are the back azimuth and the incidence angle of the source.

The semblance method can also locate source locations of tremor without any information of the onset of body waves. This method is used for locating the epicentre and hypocentre of tremor (Kawakatsu *et al*., 2000; Andinisari *et al*., 2013) and the migration of tremor source (Takagi *et al*., 2006).

This study located tremors originating at Raung Volcano using polarization and semblance methods. The result is compared with another seismic activity during the crisis period of the volcano. There are many studies that discuss about Raung activity, but not many discussing the position of the source of volcanic tremors in detail.

Methods and Materials

Some stages were applied to tremors for obtaining the tremor source location. First, tremor data were analyzed with spectral coherence method to know the bandpass filter range for the polarization method. The results are important to understand whether the signal at this frequency originating from the same source, assumed by Raung activity, or not. Second, the polarization method was applied to tremor data to obtain back azimuth and incidence angle. These suggest the estimation of epicentre and hypocentre of Raung tremor, respectively. Third, the semblance method was performed of which the output was the distribution of semblance location with 2 x 2 km area based on semblance coefficient. This method was chosen due to most tremor waveforms had an emergent onset to the extent that the picking of the first arrival was almost impossible and the travel-time location method used for earthquakes could not be applied. The polarization and semblance methods were combined for determining a better tremor location.

Spectral Coherence

Spectral coherence is a statistic method used for testing the degree of linearity between two random signals (Koopmans, 1995; Priestley, 1981). This method can also be used to identify the similarity of signal content in frequency domain.

By considering two random signals *V(t)* and *W (t)*, then *Y (t)* is defined as:

$$Y(t) = [\mathrm{V}(t)\ W(t)]^{\mathrm{T}} \quad \text{.................................} (1)$$

The Discrete Fourier Transform of $X(t)$ is:

$$T(\omega) = \sum_{t=1}^{N} Y(t)\mathrm{e}^{i\omega t} \quad \text{....................................} (2)$$

Then function φ(ω) is defined as:

$$\phi(\omega) = \frac{1}{N} Y(\omega) Y^{T}(\omega) \text{...............................} (3)$$

$$\phi(\omega) = \begin{bmatrix} \phi_{WW}(\omega) & \phi_{WV}(\omega) \\ \phi^{*}_{VW}(\omega) & \phi_{VV}(\omega) \end{bmatrix} \text{.....................} (4)$$

Thus, complex coherence can be written as (Stoicaand Moses, 1997):

$$C_{WV} = \frac{\phi_{WV}(\omega)}{\left[\phi_{WW}(\omega)\phi_{VV}(\omega)\right]^{1/2}}\ . \text{.........................} (5)$$

C_{wv} is complex coherence and $|C_{wv}|$ is spectral coherence.
The value of spectral coherence is between $0 \leq |C_{wv}| \leq 1$.

The minimum value means that both signals have no similarity. The maximum value means that both signals are perfectly similar.

Polarization

Matrix **X**= $|x_{ij}|$ is defined as a set of sample data from 3-component seismometer with $i = 1, 2, 3$ and $j = 1, 2, \dots, M$. The *i* index refers to the component of seismometer, for i=1=Z, i=2=N, and i=3=E.

A polarization can be analyzed from the covariance matrix **S** of data (Jurkevics, 1988):

$$S_{ik} = \frac{XX^T}{M} = \left\lfloor \frac{1}{M}\sum_{j=1}^{N} x_{ij}x_{jk} \right\rfloor \text{ .... (6)}$$

T means tranpose from a matrix. The covariance matrix **S** is 3x3, real and symmetric.

$$S = \begin{bmatrix} S_{ZZ} & S_{ZN} & S_{ZE} \\ S_{ZN} & S_{NN} & S_{NE} \\ S_{ZE} & S_{NE} & S_{EE} \end{bmatrix} \text{ .... (7)}$$

Explicitly, the terms of **S** are the auto- and cross-variances of the three components of motion.

The eigen value and the eigen vector of matrix **S** can be obtained by:

$(\mathbf{S}-\lambda^2\mathbf{I})\mathbf{u} = 0$ .... (8)

Where:
I is 3x3 identity matrix and
0 is a column vector of zeros.
The eigen vectors $\mathbf{u}_1$,$\mathbf{u}_2$, and $\mathbf{u}_3$ are orthogonal. The length of eigen vector $\mathbf{u}_i = u_{i1}\hat{z} + u_{i2}\hat{n} + u_{i3}\hat{e}$ is arbitrary, but it can be normalized to be unit vector. The eigen vector components u_{ij} are the length of eigen vector projection in *Z, N,* and *E* axes.

Geometrically, the eigen value λ_i and the eigen vector $\mathbf{u}_i$ shape an ellipsoid. Once the principal axes of the polarization ellipsoid are estimated, the particle motion in the data window is determined. Information describing the characteristics of ground motion is extracted using attributes computed from the principal axes. The azimuth of P-wave propagation can be estimated as:

$$\text{P- back-azimut } \mathrm{P} = \tan^{-1}\left(\frac{u_{31}sign(u_{11})}{u_{21}sign(u_{11})}\right) \text{ .. (9)}$$

The *sign* function is introduced to resolve the 180° ambiguity by taking the positive vertical component of $\mathbf{u}_1$. Similarly, the apparent incidence angle of rectilinear motion, as measured from vertical, may be obtained from the vertical direction cosine of $\mathbf{u}_1$.

$$P - inc = \cos^{-1}\left|u_{11}\right| \text{ .... (10)}$$

Semblance Method

Semblance is the measure of the similarity of multichannel data defined as (Almendros and Chouet, 2003):

$$S_o = \frac{\sum_{j=1}^{M}\left(\sum_{i=1}^{N} U_i(\tau_i + j\Delta t)\right)^2}{N\sum_{j=1}^{M}\sum_{i=1}^{N} U_i(\tau_i + j\Delta t)} \text{ .... (11)}$$

Where:
Δt denotes the interval of sampling,
τ_i is the origin time of the window sampling of the ith channel,
$U_i(\tau_i + j\Delta t)$ is the jth time sample of the signal U recorded on the ith channel, and
M and N represent the number of samples in the window and number of channels, respectively.
S_o is a number measuring the similarity of either waveform and amplitude.

In this research, only the similarity of waveform is interesting, so equation (1) can be modified as (Almendros and Chouet, 2003):

$$S_o^{'} = \frac{1}{MN^2}\sum_{j=1}^{M}\left(\sum_{i=1}^{N}\frac{U_i(\tau_i + j\Delta t)}{\sigma_i}\right)^2 \text{ .... (12)}$$

where: $\sigma_i = \sqrt{\frac{1}{M}\sum_{j=1}^{M} U_i(\tau_i + j\Delta t)^2}$ is the rms (root-mean-square) velocity of the signal within the selected time window sampling the ith channel.

The value of semblance coefficient that is higher than 90% of all semblance coefficient value produced can be considered as the epicentre of tremor (Almendros and Chouet, 2003).

Seismic Waveform

Seismic data used in this study were obtained from seismic stations at the Raung Volcano operated by the Centre for Volcanology and Geological Hazard Mitigation (CVGHM). There are five seismometers at Raung Volcano, namely: KBUR (located 4 km from the summit crater), MLLR (6 kmaway), RAUN (6 km away), MLTN (6 km away), and POSR (14 kmaway). Unfortunately, MLTN seismometer was damaged due to a technical reason. The polarization method can only be applied on waveform recorded at 3-component seismometer. Thus, the sesimic data recorded at MLLR seismic station was used to analyze using the polarization method.The spectral coherence method was applied to KBUR-RAUN and KBUR-MLLR, in order to know the band pass filter range for the polarization method. The POSR seismic station is used as the reference to distinguish between volcanic and tectonic earthquake waveforms since the station is located quite far from the summit. Furthermore, the semblance method was applied to tremors recorded at KBUR, MLLR, and RAUN.

Result and Analysis

The waveforms recorded at MLLR on 12th, 19th, 30th November 2014 and 12th, 25th December 2014 were used for the polarization analysis. These dates were chosen due to some significant activities recorded at Raung Volcano as seen in Table 1.

The tremors with approximately 3.0 to 5.5 minutes in duration were analyzed using the polarization method. The length of window is 30 seconds with 50% overlaping for the window shift. Before the polarization method was performed, bandpass filter around 1.17 Hz (1.1 to 1.24 Hz) was applied to each signal. The filter frequency range was obtained by the spectral coherence between KBUR-MLLR and KBUR-RAUN waveforms. Both spectral coherence showed the same results at 1.17 Hz with spectral coherence coefficients of 0.7 and 0.5 Hz, respectively (Figure 2).

Polarization parameters, such as back-azimuth and incidence angle, from various dates were obtained. The source location could be interpreted from these parameters.The result showed that back-azimuth had dominant of 288° to 324° in direction (Figure 3). Meanwhile, the incidence angle obtained using polarization method showed 81° to 89.3° in direction (Table 2). The consistency of incidence angle value was also showed on Raung tremor.

All those parameters were relatively constant during the various activities on November - December 2014.

The semblance method was applied to KBUR, MLLR-Z, and RAUN recordings with the duration of 30 seconds in 19th November 2014. The length is adequate to obtain information about particle motion of the tremors. Grid of 2 x 2 km was applied near Raung caldera for locating the distribution of epicentre. The area was divided into 100 m which produced 41 x 41 nodes, and assuming homogenous isotropic medium.

The result showed that the distribution of tremor epicentre was extended in the northeast

Table 1. Activities of Raung Volcano on 2014 Crisis Period

No	Date and Time	Raung Activity
1.	12th November 2014 01:00:00	Quasi-harmonic tremor occurred
2.	19th November 2014 20:00:00	White plume emmitted approximately 50 m high above the summit
3.	30th November 2014 13:40:00	White plume emmitted approximately 500 m high above the summit
4.	12th December 2014 02:10:00	Rumbling was frequently heard at the observation post
5.	25th December 2014 20:00:00	Incandescence was seen at the crater

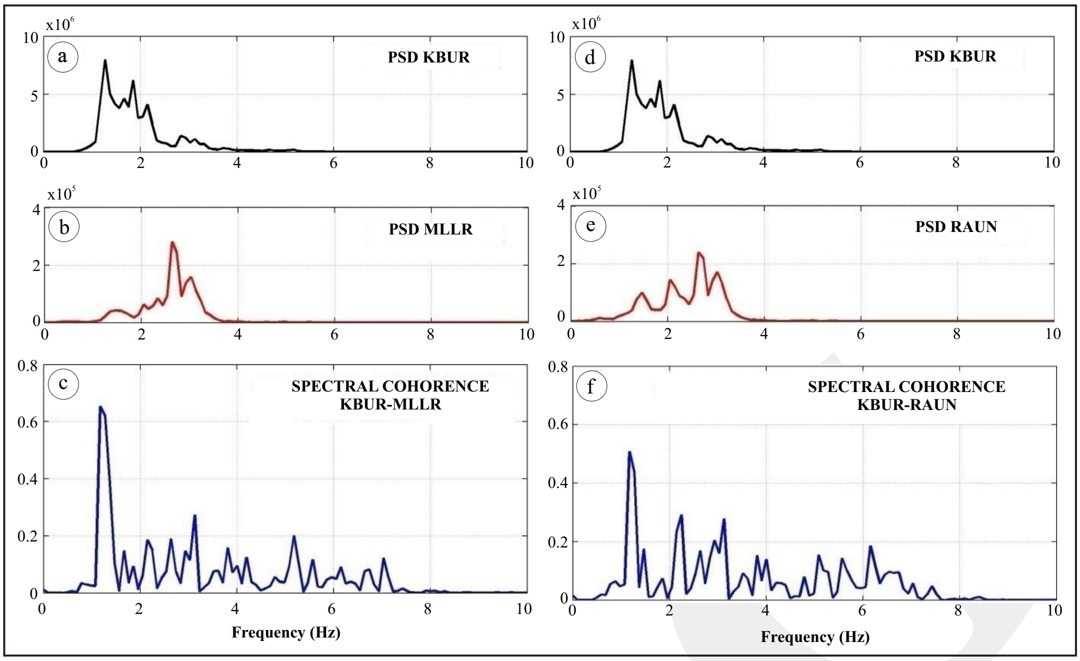

Figure 2. Spectral coherence between KBUR-MLLR and KBUR-RAUN waveforms. Both have spectral coherence frequency dominant at 1.17 Hz. (a) Power Spectral Density (PSD) of KBUR, (b) PSD of MLLR, (c) spectral coherence between KBUR-MLLR, (d) PSD of KBUR, (e) PSD of RAUN, (f) spectral coherence between KBUR-RAUN.

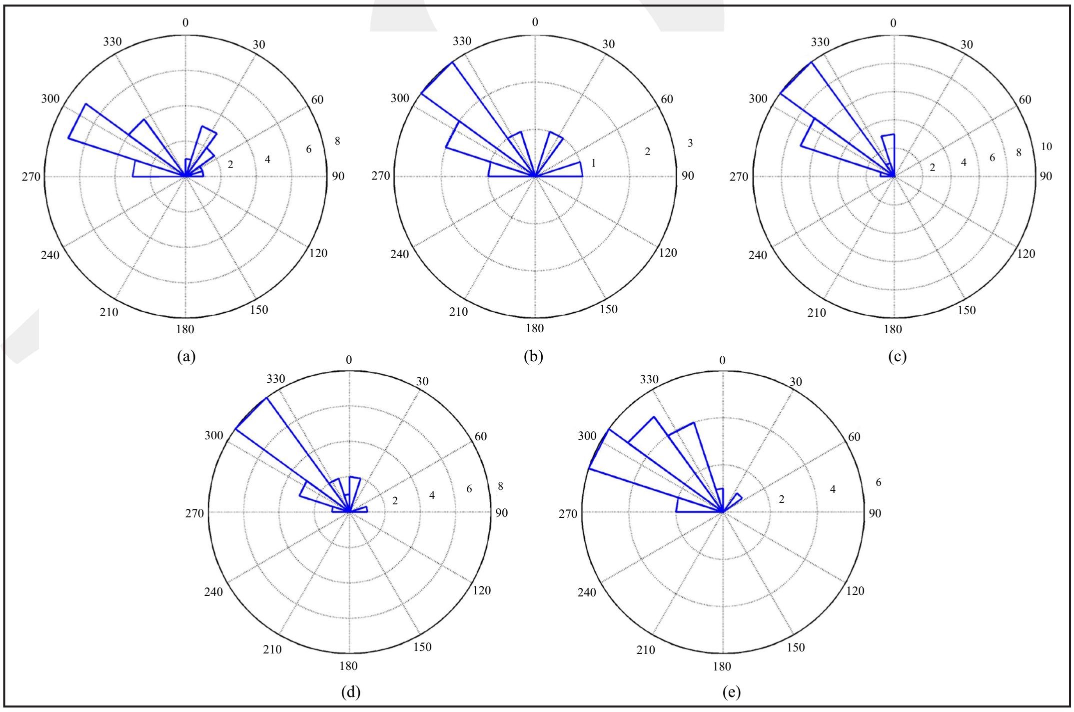

Figure 3. Back-azimuth of Raung tremors in various dates having dominant values around 288° to 324°. (a). Back-azimuth of 12th November 2014; (b). 19th November 2014; (c). 30th November 2014; (d). 12th December 2014; and (e). 25th December 2014.

direction. By assuming tremor velocity was 2,000 m/s and constant due to the wave travels in homogenous isotropic medium, the prediction of epicentre was obtained based on the highest value of semblance coefficient (S'_o) having dark-red colour in Figure 4.

Table 2. Incidence Angle of RaungTremors in Various Dates

No	Date	Incidence Angle
1.	12th November 2014	83.6° - 89.3°
2.	19th November 2014	80.3° - 88.2°
3.	30th November 2014	80.6° - 88.9°
4.	12th Desember 2014	81.0° - 89.3°
5.	25th Desember 2014	82.0° - 89.3°

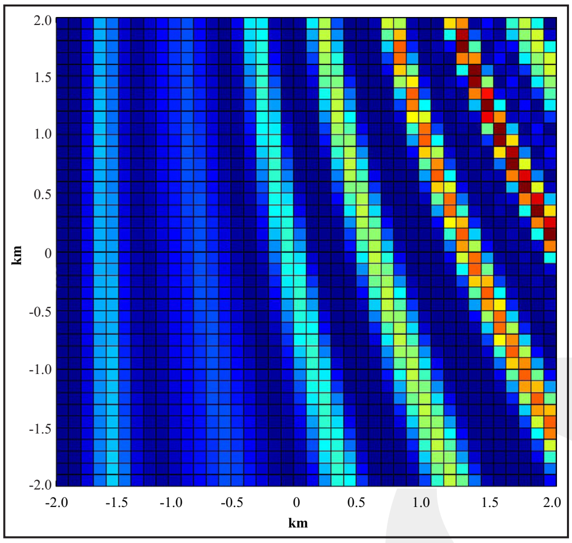

Figure 4. Result of semblance location with 2 x 2 km area. The dark-red coloured boxes are the epicentre predictions.

Discussion

Spectral coherence from two pairs of tremors shows the same frequency at 1.17 Hz. This consistency of dominant frequency at 1.17 Hz reveals that the tremors has similarities to each other at frequency 1.17 Hz (Figure 2). It can also be intrepreted that the signal at this frequency is originated from the same source, and the frequency is derived from Raung activity.

The back-azimuth has dominant values around 288° to 324° (Figure 3a and 3b) for the whole tremor waveform recorded during November - December 2014. These results are in accordance with the direction of the summit of RaungVolcano, which is located in the northwest of MLLR seismic station (Figure 1). There is no significant temporal variation of polarization parameter associated with various activities of RaungVolcano between November and December 2014.

On 12th and 19th November 2014, the back-azimuth as seen on Figure 3 directed not only to the summit of Raung Volcano, but also to around 18° to 54°. This direction may be associated with Ijen Volcano complex located close to RaungVolcano. It could be the seismic signals that came from Ijen Volcano, since sometimes Raung tremors were also recorded at Ijen seismic stations. The distance between Raung MLLR seismic station and Ijen summit is about 17 km.

The incidence angle of tremor obtained through polarization method ranges about 81° to 89.3° (Table 2). It can be interpreted that the source of tremor is relatively shallow to medium in depth. By assuming homogeneous isotropic medium, the source depth could be obtained with a simple Pythagoras formula. Based on the semblance and polarization methods, the epicentre of tremor was located at 6.2 km away from MLLR station, and the depth could be obtained at about 0.07 to 1.03 km.

The epicentre distribution of the tremor source elongated to the northeast direction (Figure 3).It could be due to the small number of seismometers and their distribution does not cover all azimuth directions. KBUR seismometer is located on the third quadrant, whereas MLLR and RAUN are on the fourth quadrant. For a good constraint, at least, five seismometers should be deployed in three different quadrants.

The polarization method obtained only the direction of back-azimuth without knowing exactly the distance of the epicentre from MLLR 3-component seismometer. The exact distance is preferably obtained by deploying at least three 3-component seismometers around the volcano. The distance was obtained by the intersection of the back-azimuth directions from the polarization method applied to three 3-component seismometers.

The assumed epicentre obtained by combining polarization and semblance methods can be seen in Figure 5. The epicentre of tremor source is ±2.1 km away and 52°NE direction from the Raung summit.

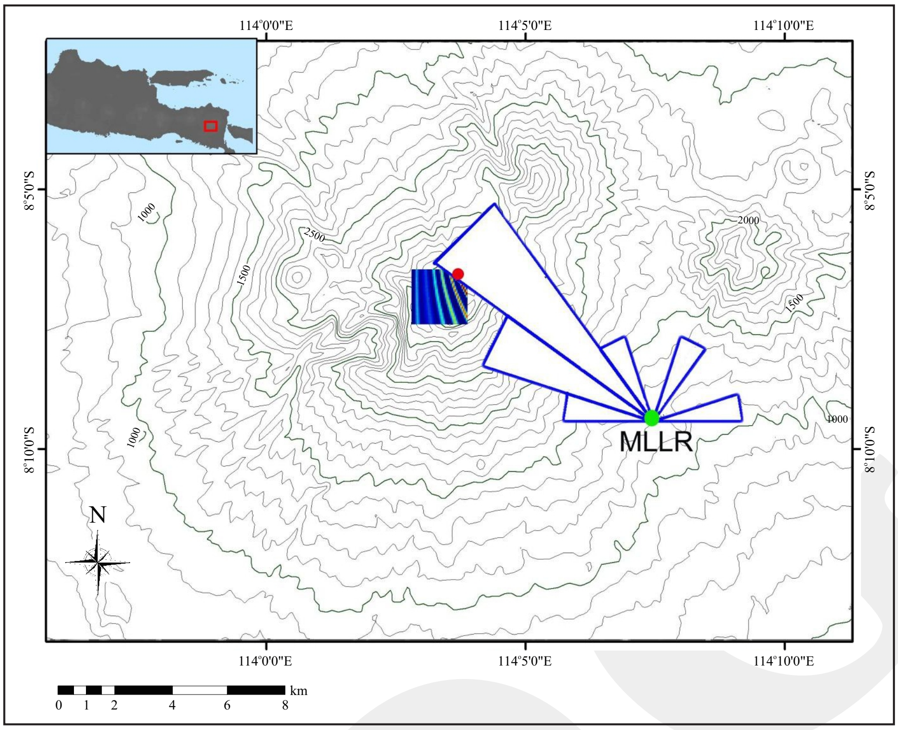

Figure 5. A combination result of semblance and polarization methods. The solid red circle is the epicentre and the solid green circle is the location of MLLR station.

Conclusions

The back-azimuth of Raung tremors are around 288^o - 324^o in accordance with the direction of Raung summit. The incidence angle of Raung tremors is relatively constant at around 81^o - 89.3^o. There is no relation between various activities on Raung and polarization parameters.

The semblance method performed on 2 x 2 km area around the Raung summit shows the extended distribution of the epicentre in the northeast direction. The epicentre of tremor source obtained through the combination of polarization and semblance methods is ±2.1 km away and is based on 52^o NE direction from the Raung summit.

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