Tremor source location based on amplitude decay

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Abstract: A 3D grid search method for the location of the volcanic tremor source was applied to data recorded at Mt. Etna in 2004 [Di Grazia et al., 2006]. The aim of that application was to highlight changes in time and space of the location of the tremor source, heralding the onset of a lava emission on 7 September, 2004. The time span investigated ranged from January to November 2004. The method exploits the amplitude decay of the seismic signal recorded at permanent stations used for monitoring purposes. Consequently, it does not require any additional set up of temporary, mobile stations. We present here the results of that application, which was followed in the autumn of 2006 by the successful implementation of the method we named TREMLOC, as an automated and continuous near real time analysis for the location of volcanic tremor at the *Istituto Nazionale di Geofisica e Vulcanologia* (INGV) – Sezione di Catania.

Introduction

Volcanic tremor is commonly addressed to as the root-mean-square (RMS) amplitude of the seismic signal measured over a time span within a defined frequency band [e.g., Falsaperla et al., 1998]. On basaltic volcanoes with persistent activity, such as Mt. Etna [Patanè et al., 2004], Kilawea [Ferrazzini et al., 1991], and Kliuchevskoi [Gordeev et al., 1990], volcanic tremor is recorded as a persistent signal with no clearly identifiable seismic phases. Consequently, traditional event location methods fail in the attempt to locate its source. Studies dealing with this problem attribute a key role to the amplitude distribution [e.g., Hofstetter and Malone, 1986; Métaxian et al., 1997; Gottschämmer and Surono, 2000; Aki and Ferrazzini, 2000; Battaglia and Aki, 2003, Battaglia et al., 2003].
In agreement with the aforementioned studies, Di Grazia et al. [2006] tackled the problem using the spatial tremor amplitude distribution at Mt. Etna, and estimated the source location using a simplified attenuation law. In this study, we present the results Di Grazia et al. [2006] obtained from the first application of TREMLOC, a robust method to monitor the migration of tremor sources.

Data

The time span considered by Di Grazia et al. [2006] ranged from January to November 2004. It covered eight months of the pre-effusive and three months of the effusive phase, which started at Mt. Etna on 7 September, 2004 and ended on 8 March, 2005. Throughout the eruption, the lava flows stemmed from an eruptive fracture opened in the upper part of the Valle del Bove, far away from inhabited areas (Figure 1). The volcano unrest was characterized by a small effusion rate (2.3-4.1 m^3/s) and a slow progression of the lava flows reported by volcanologists [Burton et al., 2005].

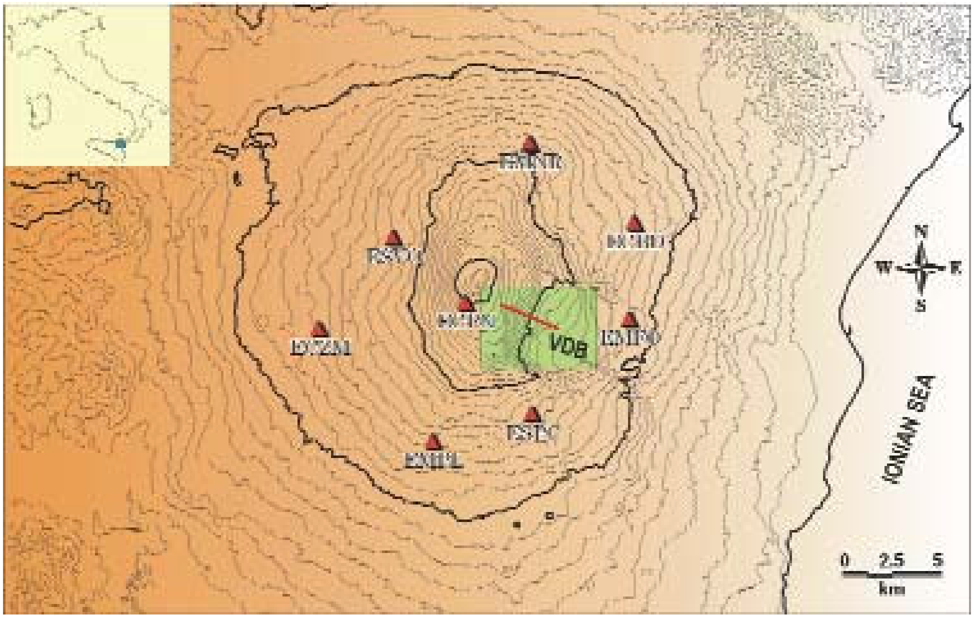

Fig. 1. Configuration of the seismic stations (solid red triangles) and eruptive fracture (red line). VDB stands for Valle del Bove. The green rectangle highlights the zone affected by lava flows.

Unlike other recent eruptions (1989, 1991-1993, 1999, 2001, 2002-2003, 2006), the volcano unrest in 2004 was neither heralded nor accompanied by earthquake seismicity (Figure 2). Volcanic tremor held the same lack of changes, even though it was affected by temporary changes in amplitude and frequency content starting from a couple of weeks after the onset of the effusive phase (Figures 3, 4).
To analyze volcanic tremor and provide the source location of this signal, the amplitude decay at eight stations of the permanent seismic network of Mt.

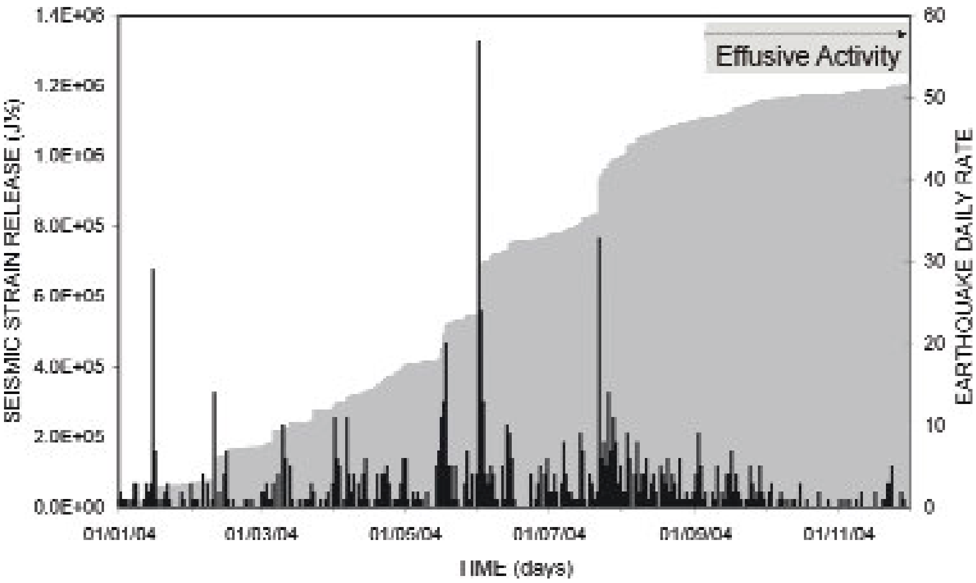

Fig. 2. Earthquake daily rate and seismic strain release from 1 January to 30 November, 2004.

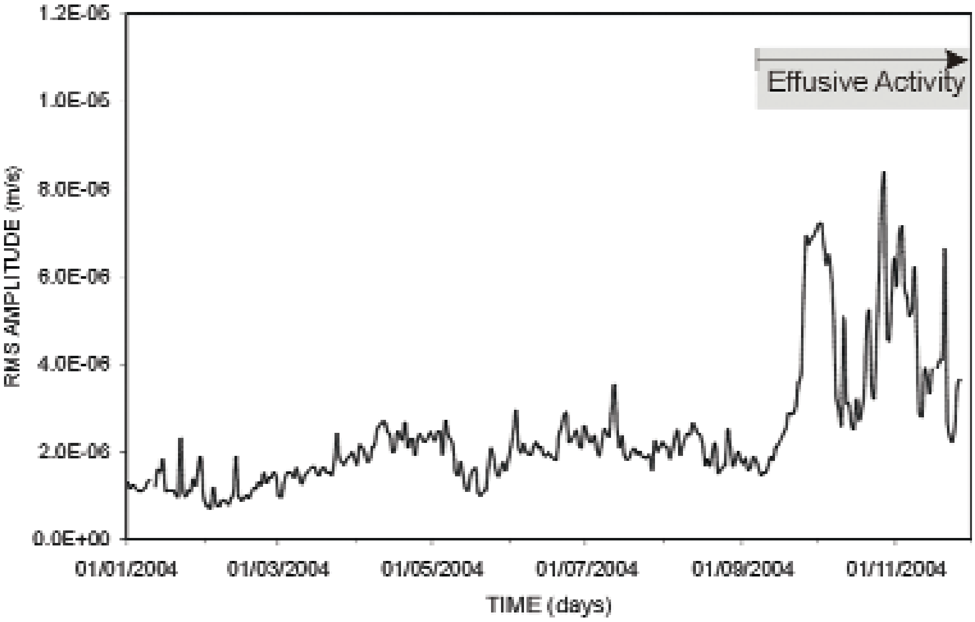

Fig. 3. RMS amplitudes of the 25th percentile of the signal at the vertical component of ECPN from 1 January to 30 November, 2004.

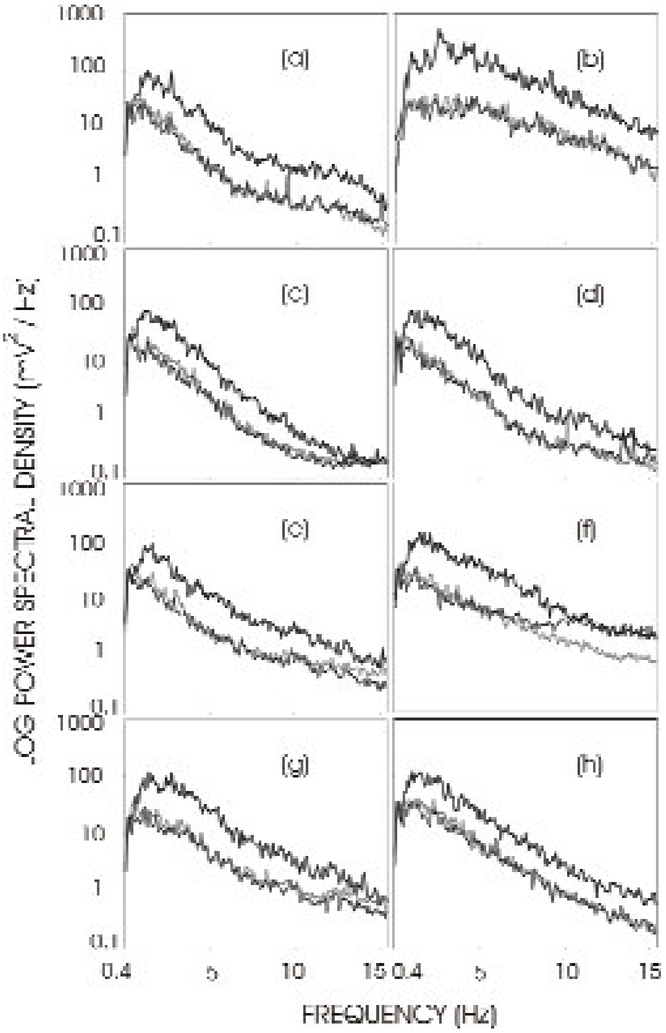

Fig. 4. Power spectral density of the signal at the vertical component of the stations considered in this study: (a) ECBD, (b) ECPN, (c) ECZM, (d) EMFO, (e) EMNR, (f) EMPL, (g) ESPC, (h) ESVO. For the station location see Figure 1. The stack of consecutive spectra calculated for each station is depicted in three time spans: on 6 (gray line) and 7 September (light black line) and 2 October, 2004 (thick black line). This spectral analysis highlighted that changes in shape and energy of the signal occurred well after the beginning of the effusive phase. Modified from Di Grazia et al. [2006].

Etna was taken into account. The stations used were all equipped with three components, broadband seismometers (Trillium 40 s cut off period sensors, Nanometrics™), and were located within 8 km distance from the summit craters (Figure 1). The choice of these stations was optimal for: their proximity to the summit craters and the zone affected by the eruptive fractures (Figure

1), the excellent signal-to-noise ratio, and the homogeneity of the instrumental chain, which allowed a fast comparison of the signals. Seismic data were acquired with a dynamic range of 24 bit; they were sampled at a frequency of 100 Hz, and transmitted to the data center in Catania via 4 Cygnus VSAT units deployed around Mt. Etna.

Method and results

Similar to Hofstetter and Malone [1986], Di Grazia et al. [2006] tackled the problem of locating the source of volcanic tremor on the basis of the distance-dependent amplitude decay. Accordingly, the source location was estimated using the seismic amplitude distributions, assuming a seismic amplitude decay with the distance based on the general law

$$\ln A_i + \alpha\, s_i = a - b \ln s_i$$

where A_i is the RMS amplitude measured at the i-th station, a and b are constants, α is the frequency-dependent absorption coefficient, and s_i is the corresponding source-to-receiver distance. A key aspect in this assumption concerned the role of absorption, a factor expressing the loss of energy as seismic waves propagates. It was verified that the frequency-dependent absorption causes only a small deviation from a linear relationship between $\ln A_i$ and $\ln s_i$. Indeed, Di Grazia et al. [2006] found out that even assuming a constant Q-factor as low as 30 [De Gori et al., 2005] and typical frequencies of between 1 and 3 Hz, the linear fit theoretically yields a degree of explained variance over 99% with respect to the total variance. Site correction factors were also taken into account, calculating station corrections based on the residuals of measured amplitudes with respect to the ones predicted by the fit. No a-priori assumption about the characteristics of the radiated waves (i.e., body or surface waves) was made, due to the different wavefield characteristics at each station, the long time window analyzed, and the possibility of concurrent activity of different sources each with its peculiar shape and extension.

The daily amplitude distribution was calculated in the night-time to minimize the effects of external noise. In addition, the 25th percentile was preferred to the mean amplitude of the signal, as the corresponding value gets rid of undesired transient events (e.g., earthquakes, explosion quakes, etc.). The tremor source location was identified on the basis of the goodness of the regression fit (hereafter R^2) obtained for each point of a 3D grid with center underneath the craters. The grid had an extension of 6 km in horizontal and 3 km in vertical direction, with spacing of 500 m. In Figure 5 we depict the results obtained from this application. The results matched two conditions, that is R^2 greater than/equal to 0.95, and at least seven stations available for the calculation. The source locations in Figure 5 are marked with two different colors, distinguishing between the pre-effusive phase (yellow) and effusive phase (red). A jackknifing procedure [e.g., Efron, 1982] was applied to assess the stability of the centroid locations. In doing so, first the location was repeated several times using 7 out of 8 stations and changing the left out station each time. Second, the deviations of these locations with respect to the original ones were calculated. Based on this jackknifing procedure, the median values of the deviations were equal to 447 m for latitude, 412 m for longitude, and 747 m for depth.

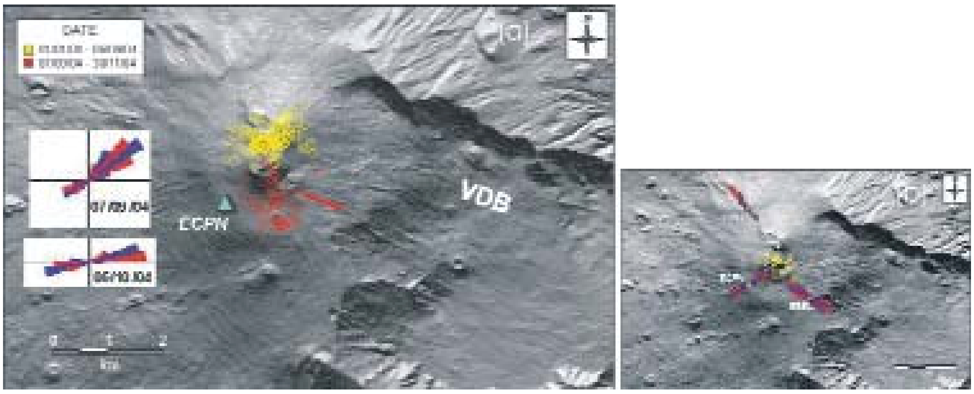

Fig. 5. (a) Map of Mt. Etna and location of the centroid of the tremor source. Colored open circles mark the centroid in two different time spans: pre-eruptive (yellow) and eruptive (red). The red line sketches the fracture system from which the lava emission stemmed. The results of polarization analysis at ECPN (blue triangle) on 7 September and 6 October are depicted on the left. VDB stands for Valle del Bove. (b) Results of polarization analysis for three stations of the permanent seismic network on 30 August, 2005. Yellow open circles mark the centroid located using the amplitude decay method. Modified from Di Grazia et al. [2006].

The results depicted in Figure 5a show that with the beginning of the lava effusion, the source locations neatly prevailed south of the summit craters, reaching a maximum distance from them of ca. 2 km. The depths of the source locations were all superficial and within the volcano edifice, i.e., between 1698 m and 2387 m a.s.l. Depths close to the maximum values (1698 m a.s.l.) were found only in the first months of 2004. The source locations had distances of 2 km both from the summit craters as well as the theatre of the volcano unrest (Figures 1, 5a). Independent evidence of this southward migration came from the principal directions of the polarization analysis of the seismic signal (Figures 5a, 5b). Additionally, in the effusive phase, the source locations laid within a region with low Qp anomalies revealed by 3D seismic attenuation tomographic images based on earthquakes recorded from 1994 to April 2001 [De Gori et al., 2005]. Based on these overall results and in agreement with volcanological data [e.g., Burton et al., 2005], Di Grazia et al. [2006]

interpreted the volcano unrest as due to a superficial phenomenon, with weak or no links to the deep internal dynamics of the magma feeder.

Discussion and conclusions

In the application of the 3D grid search method we present here and described in more detail in Di Grazia et al. [2006], we followed a heuristic approach for assessing the location of the tremor sources. Given the well known complex structure of volcanic zones and shallow source depth of tremor at Mt. Etna, we voluntarily refrained from defining physical attenuation and seismic wave propagation models, as whatever assumption would be questionable. In this light, we made no a-priori assumptions either about the source or the properties of the medium. Notwithstanding the simplicity of our method, we found that – for the range of distances of interest in our location problem – the theoretical relation for the amplitude-distance decay could be fitted fairly well by a straight line. Indeed, in our locations we encountered pretty high scores for the goodness of R^2 fit, being on the order of 0.97-0.98 in most cases.

Our location method refers to the position of the centroid of the tremor sources, without separating the single contributions. Consequently, multiple sources (e.g., central conduit, dykes) – concurrently acting within the volcano feeder – might affect the result of the calculation. Even so, however, the solution is an average result which does not necessarily coincide with fixed points in the 3D grid.

The results obtained from the processing of the seismic data recorded in 2004 pointed out that even at the beginning of such a *silent* eruption there were changes in the tremor source location, despite the absence of other geophysical and/or geochemical signals heralding the impending eruptive activity. The use of permanent stations of the seismic network for the calculation of the amplitude decay provided additional value to the method, as it did not require any additional logistic effort.

After the application described in Di Grazia et al. [2006], the 3D grid search method was implemented as a routine procedure in the automated and continuous monitoring system of INGV-Sezione Catania. TREMLOC, as we named it, has been processing seismic data recorded at Mt. Etna in near real time from the autumn of 2006. Ever since, it has proved to be an efficient monitoring tool for volcanic surveillance, and contributes in answering the compelling question of how internal volcanic dynamics at Mt. Etna affects changes of the tremor source in time and space.

Improved versions of the method are in progress to couple with enlarged, variable geometries of the seismic network, and look promising for implementations on different volcanoes where information on the tremor source can positively contribute in volcanic hazard evaluation and risk assessment.

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