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Time-dependent Fisher Information Measure of volcanic tremor before the 5 April 2003 paroxysm at Stromboli volcano, Italy

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ABSTRACT

The investigation of the time dynamics of volcanic tremor recorded at Stromboli volcano before the paroxysm occurred on April 5, 2003 was performed, on the base of a new approach, the Fisher Information Measure (FIM), which allows to detect changes in the dynamical behavior of a complex system. The particular observed pattern suggests that the signal varies between sets of disordered states (small FIM) and sets of ordered states (large FIM). Significant precursory changes in the temporal variation of the FIM were revealed at least 42 h before the paroxysm and lasting about 17 h. The timescales highlighted are compatible to those found by other authors and could qualify the FIM as a good detector of regime changes and possible precursors of anomalous volcanic activity.

1. Introduction

Stromboli is the emergent part (924 masl) of a ~3-km high volcano, located at the NE end of the Aeolian islands (southern Italy). Its subaerial cone was constructed during the last 100 ky (Gillot and Keller, 1993; Hornig-Kjarsgaard et al., 1993) and the currently active summit craters are located in the upper part of Sciara del Fuoco, a horseshoe-shaped collapse scar cut in the NW flank of the cone (Kokelaar and Romagnoli 1995; Tibaldi 2001) at about 750 masl. Stromboli is the prototype for Strombolian activity, that has been observed for the last 2000 years (Rosi et al., 2000). The normal activity of the volcano is characterized by low to moderate energy, intermittent, Strombolian explosions from the summit craters and noneruptive degassing (Polacci et al., 2009). The latter consists of continuous flow of passive, nonexplosive gases supplied to the persistent volcano plume mainly by the open, summit vents, fractures and fumaroles present on the volcano flanks, and as a stream of more vigorous, discrete, nonpassive gas puffs (Harris and Ripepe, 2007) along with infrasonic pulses (Ripepe et al., 1996) which change according to regimes that alternate on a timescale of tens of minutes (Ripepe et al., 2002). Explosions at Stromboli originate from the buoyant rise of deep-sourced gas slugs bursting at the magma free surface with an average interevent time of 10–20 min (Burton et al., 2007). Two styles of explosions mainly characterize the eruptive activity of the NE and the SW craters: ejection of coarse ballistic particles are predominant at the NE crater, while thick, ash-rich plumes accompanied by the emission of coarser ejecta characterize the SW crater (Marchetti and Ripepe, 2005; Patrick et al., 2007). Occasionally, lava effusions and paroxysmal explosions occur (Barberi et al., 1993; Jaquet and Carniel, 2003). Twenty-six lava effusions have been documented between 1888 and 2002, approximately one every 4 years on the average (Barberi et al., 1993; Landi et al., 2006). Several effusive episodes occurred during the 7-month-long flank activity of 2002–2003 (Calvari et al., 2005; Landi et al., 2006; Lodato et al., 2007), and between February and April 2007 (the eruptive daily activity is reported at www.ct.ingv.it). Paroxysms are very explosive events, ranging from relatively small-scale events (Métrich et al., 2005), characterized by showers of ash, lapilli, and bombs that blanket the upper slopes of the volcano, to large-scale, vulcanian events like the one of 1930 (Rittman, 1931), characterized by meter-sized bombs and blocks fallen up to a few kilometers away from the summit (Speranza et al., 2004). These larger events are capable of erupting the so called "golden pumice" and could be triggered by the fast ascent of either primitive magma batches from a depth of 7.5–11 km (Bertagnini et al., 2003; Métrich et al., 2005) or large CO_2-rich gas slugs formed by bubble accumulation in the sub-volcano feeders (Allard, 2009). The paroxysms are not predictable in a deterministic sense, although periods with a temporary increase in probability can be defined e.g. by using a multivariate stochastic approach (Jaquet and Carniel, 2003). The most recent paroxysms occurred on 5 April 2003 and 15 March 2007 (Polacci et al., 2009).

In this study, the 5 April 2003 paroxysmal phase at Stromboli was investigated. On 28 December 2002, an effusive eruption started (Alean et al., 2010) and ended on 21–22 July 2003 (Calvari, 2003) showing the most energetic associated explosive event at 7:12 GMT of 5 April 2003. This vulcanian explosion was extensively investigated in the literature. Significant precursory increases of CO_2, H_2 and He dissolved in thermal waters and changes in dissolved carbon isotopic

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composition revealed an increasing output of deep gases likely produced by depressurization of a rising batch of a deep gas-rich magma, whose fragments were emitted during the explosion (Carapezza et al., 2004). Brusca et al. (2004) analyzed the relationship between volcanic activity, soil temperatures, CO_2 fluxes and wind speed and direction, suggesting that soil temperature measurements at an open conduit volcano such as Stromboli could be used to monitor the level of volcanic activity. Mattia et al. (2004) using GPS measurements were able to model with geodetic data the shallow magma chambers that gave rise to Strombolian explosive activity. Anomalous sulphur degassing 2–3 days before the event, with SO_2/HCl ratios significantly larger than those typical of quiescent degassing, were documented in Aiuppa and Federico (2004) who associate these anomalies to deeply-derived magmatic gas. Métrich et al. (2005) proposed that the triggering mechanism of the paroxysm was initiated at moderate pressures (≥240 MPa) and was related to bubble-driven ascent of magma blobs. Calvari et al. (2006) recorded a significant increase in temperature inside Crater 1 accompanied by a thicker gas plume 3 min before, while 32 s before the explosion blast, reddish ash was emitted from Crater 1. Seismic signals related to the event were recorded by a permanent broadband network giving information about the eruption kinematics; in particular 1 min before the explosion a high frequency signal (period<0.1 s) was observed and was related to the vesiculation of the rising batch of gas-rich magma (D'Auria et al., 2006). The investigation of volcanic tremor continuously measured by a short period summit seismic station was performed by means of spectral and dynamical methods (Carniel et al. 2006a) and the singular spectrum analysis (Carniel et al. 2006b), revealing the presence in the volcanic tremor of possible precursory signatures at a timescale of a few hours. The relationship between Singular Spectrum Analysis and Fourier analysis was recently investigated by Bozzo et al. (2010).

Stromboli volcano represents an example of a very complex geophysical system. Such complexity can be investigated by using the Fisher Information Measure (FIM). The FIM was introduced by Fisher in 1925 in the context of statistical estimation (Fisher, 1925). In a seminal paper Frieden has shown FIM to be a versatile tool to describe the evolution laws of physical systems (Frieden, 1990). FIM permits to accurately describe the behavior of dynamic systems, and to characterize the complex signals generated by these systems (Vignat and Bercher, 2003). This approach has been used by Martin et al. to characterize the dynamics of EEG signals (Martin et al., 2001). Martin et al. have shown the informative content of FIM in detecting significant changes in the behavior of nonlinear dynamical systems, characterizing, thus, FIM as an important quantity involved in many aspects of the theoretical and observational description of natural phenomena (Martin et al., 1999). The FIM was used in studying several geophysical and environmental phenomena, revealing its ability in describing the complexity of a system (Balasco et al., 2008; Telesca et al., 2008; Telesca et al., 2009a) and suggesting its use to reveal reliable precursors of critical events (Telesca et al., 2005a; Telesca et al., 2005b; Telesca et al., 2009b).

The aim of the present paper is to reveal possible precursory changes in the FIM variability of a seismic time series measured at Stromboli volcano, before its paroxysm occurred on April 5, 2003.

2. Data description

One of the longest continuous seismic time series available at Stromboli comes from an automatic seismic station installed in 1989 by the Dipartimento di Georisorse e Territorio of the University of Udine (Carniel and Di Cecca, 1999) with the purpose of studying the long-term evolution of strombolian activity. The summit station, based on three Willmore MKIII/A seismometers (eigenfrequency $f_0 = 0.5$ Hz), is located at 800 masl and about 300 m from the craters (Beinat et al., 1994). During the flank activity of 2002–2003, the hardware and software of the receiving station were upgraded by the Consejo Superior de Investigaciones Cientificas (CSIC) for continuous acquisition and internet data transmission (Ortiz et al., 2001). Original data used in this study are sampled with 16 b (96 dB) at 50 Hz. Starting from raw seismic data, 1-minute time windows are used in a preliminary data reduction phase aimed to downsampling (Carniel and Tárraga, 2006) to obtain a RSAM (Real-time Seismic Amplitude Measurement, Endo and Murray, 1991) time series which is the object of the processing described below (Fig. 1).

3. Fisher Information Analysis

We analyzed the RSAM data using the Fisher Information Measure (FIM), which is a powerful tool to investigate complex and nonstationary signals.

Let us introduce the relevant Fisher-associated quantities (Martin et al., 2001). Let $f \equiv q^2$ be a probability density in $\Re^N$ $(N \geq 1)$. Fisher's quantity of information associated to f (or to the probability amplitude q) is defined as the (possibly infinite) non-negative number I

$$I(f) = \int_{\Re^N} d\mathbf{x} \frac{|\nabla f|^2}{f} \tag{1}$$

or in terms of the amplitudes

$$I(q) = \int_{\Re^N} d\mathbf{x} (\nabla q \cdot \nabla q). \tag{2}$$

where ∇ is the differential operator. This formula defines a convex, isotropic functional I, which was first used by Fisher (1925) for statistical purposes. It is clear that from Eq. 2 the integrand, being the scalar product of two vectors, is independent of the reference frame (Martin et al., 2001).

Let us focus the attention on one-dimensional case. Let us consider a measurement x whose probability density function is denoted as $f(x)$. Its FIM is defined as

$$I = \int \left(\frac{\partial}{\partial x} f(x) \right)^2 \frac{dx}{f(x)}. \tag{3}$$

Eq. 3 involves the calculation of the probability density function (pdf) $f(x)$.

An estimation of the pdf $f(x)$ may be obtained by means of the kernel density estimator technique (Devroye, 1987; Janicki and Weron, 1994).

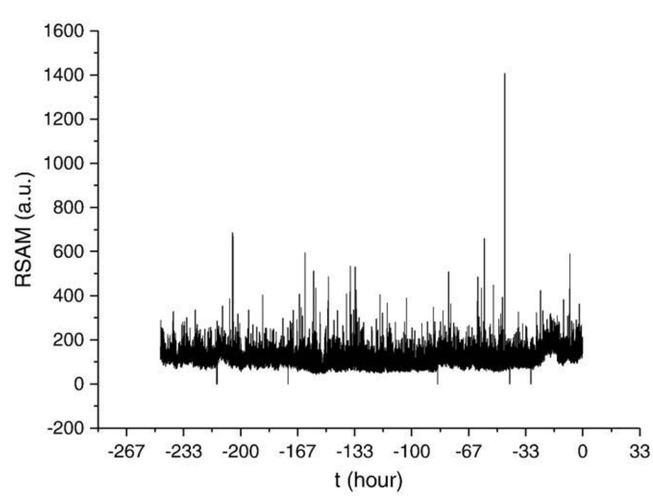

Fig. 1. Seismic time series measured at Stromboli volcano for about 10 days before the paroxysm of April 5, 2003. The time 0 indicates the time of eruption.

The kernel density estimator provides an approximate value of the density in the form

$$\hat{f}_N(x) = \frac{1}{Nb}\sum_{i=1}^{N} K\left(\frac{x-x_i}{b}\right). \tag{4}$$

$K(u)$ is the kernel function, which is a continuous non-negative and symmetric function satisfying

$$K(u)\geq 0 \text{ and } \int_{-\infty}^{+\infty} K(u)du = 1, \tag{5}$$

whereas b is the bandwidth. In our estimation procedure the kernel used is the Gaussian of zero mean and unit variance. In this case

$$\hat{f}_N(x) = \frac{1}{N\sqrt{2\pi b^2}}\sum_{i=1}^{N} e^{-\frac{(x-x_i)^2}{2b^2}}. \tag{6}$$

The Gaussian kernel allows to evaluate the kernel density estimator and the bandwidth with a low computational complexity (Raykar and Duraiswami, 2006).

4. Results and discussion

The time-dependent FIM or local FIM was analyzed. By using the concept of sliding windows commonly used for spectral and dynamical parameters (Carniel and Di Cecca, 1999) one can calculate the temporal evolution of the local FIM. In our case we considered a sliding window of 3 h, and we calculated the local FIM in each window by means of the procedure given by Eqs. 3–6. The shift between two successive windows was set to 10 min, in order to smooth the results and evaluate the variation of FIM with a high time resolution. Fig. 2 shows the results. It is evident that a variability appears in the time pattern of the FIM, which denotes that the volcanic system changes between disordered states (low FIM values) and ordered ones (high FIM values). The most striking feature of the FIM time pattern is the quasi-spike-like behavior, which indicates that the system almost suddenly changes its status with an abrupt transition. The presence of abrupt transitions between different regimes in the evolution of a volcanic system is a feature that is increasingly being recognized at a number of different volcanoes with different characteristics. At the same Stromboli volcano, abrupt transitions separate the low and high degassing regimes associated to the normal strombolian activity (Ripepe et al., 2002) on the order of tens of minutes. The same timescales and the same abrupt transitions also characterize the convection regimes of Erta Ale, Ethiopia (Jones et al., 2006) and Ambrym, Vanuatu (Carniel et al., 2003) lava lakes and the geothermal activity regimes at Dallol, Ethiopia (Carniel et al., in press).

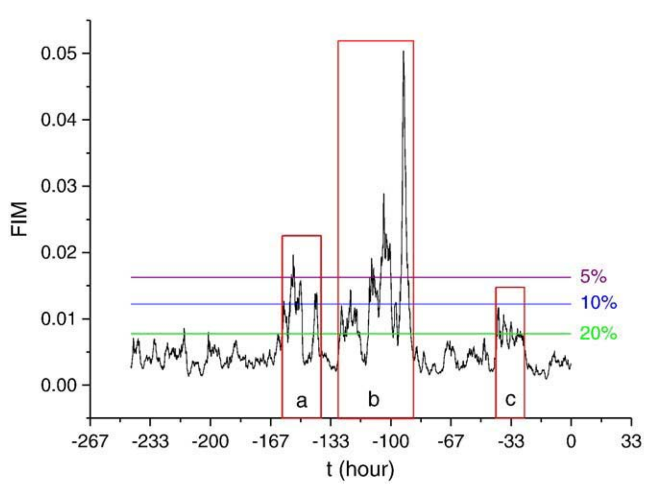

Fig. 2. Time variation of the FIM with a sliding window of 180 min and shift of 10 min. The red boxes identify the temporal phases where the FIM assumes relatively high values: a) between −160 h (~6.6 days) and −140 h (~5.8 days); b) between −128 h (~5 days) −88 h (~3.6 days), with maximum at −93 h (~3.87 days), and c) between −42 h and −25 h. The green, blue and purple horizontal lines define the thresholds for the identification of the FIM anomalous values (see text for details).

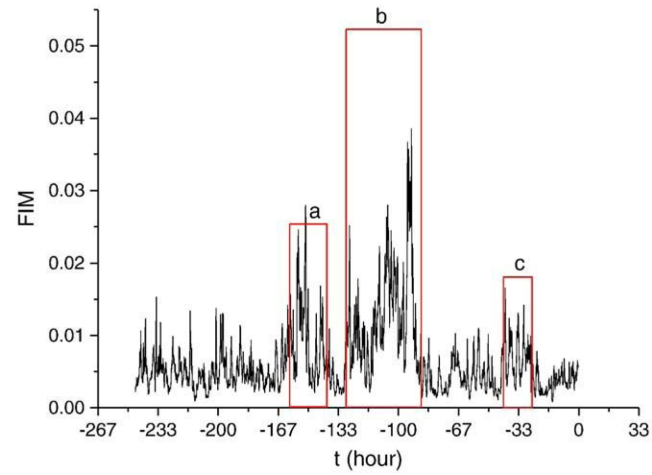

Fig. 3. Time variation of the FIM with a sliding window of 60 min and shift of 10 min. The red boxes identify the same temporal phases as in Fig. 2.

The quasi-spike-like behavior of the FIM is given by the presence of local maxima or "anomalous" FIM values (Fig. 2). A FIM value can be considered anomalous if it is above a fixed threshold. To evaluate the threshold, the distribution of the obtained FIM values can be calculated, and the $FIM_{threshold}$ can be identified as selecting a relatively small percentage of the total number of FIM values. Therefore a region $FIM \geq FIM_{threshold}$ indicates the anomalous FIM range. Fig. 2 shows that selecting the highest 20% of the FIM values, the obtained threshold (green horizontal line) allows to identify approximately three periods of anomalous FIM. These periods, indicated by the red boxes are: a) between −160 h (~6.6 days) and −140 h (~5.8 days); b) between −128 h (~5 days) −88 h (~3.6 days), with maximum at −93 h (~3.87 days), and c) between −42 h and −25 h. Increasing the threshold, thus selecting a lower percentage of higher FIM values ,10% (blue line) and 5% (purple line) the first two anomalous FIM ranges are detected as well.

In order to check the independence of the results from the choice of the length of the sliding window, Fig. 3 shows the FIM results with a sliding window of 60 min and shift of 10 min. Although a larger roughness in the FIM curve due to the shorter time window, the results are almost identical to those shown in Fig. 2; and this suggests that the FIM is robust. Although not a critical choice, the window size selection could still benefit from information about the memory of the system, as estimated e.g. via the variogram tool (Jaquet and Carniel, 2003).

Similar results were obtained in investigating satellite thermal signals recorded in the volcanic area of Etna (Italy) (Lovallo et al., 2009), in which most of the eruptive phases of the volcano were preceded by an increase of the FIM.

Although it is not a simple task to interpret these phases of high FIM, it is noteworthy that the timescales involved are comparable to the ones indicated by other parameters and analysis such as the ones of Brusca et al., 2004. In particular, the last period (c) roughly coincides with the only period of seismic tremor anomaly that Pino (2009) considers of reliable volcanic origin, and with a period of plume geochemical anomalies related by Aiuppa and Federico (2004) to sustained degassing due to the rise of magmatic gas of deep origin.

5. Conclusions

We suggested a new approach in investigating the time dynamics of seismic signals recorded at Stromboli volcano in connection with the paroxysmal event occurred on April 5, 2003. The Fisher Information Measure acts as a detector of changes in the dynamical behavior of the system generating those data. The particular observed pattern suggests that the signal varies between sets of disordered states (small FIM) and sets of ordered states (large FIM). These could be characterized by different features, e.g. a different persistence of behavior that can be estimated by the use of variogram analysis (Jaquet and Carniel, 2003) which in turn can lead to a physical interpretation and quantification (Jaquet et al., 2006). It is also worthwhile to remember that sometimes parameters, as with the Singular Spectrum Analysis, are introduced on an almost purely empiric basis (Carniel et al., 2006a; 2006b) and later be better interpreted in their relationship with known spectral quantities (Bozzo et al., 2010) which are more easily physically modeled (Jousset et al., 2003). An example of application of the FIM is the detection of changes that can be possibly linked to external triggers such as the tectonic activity (Carniel and Tárraga, 2006), where again the triggering can be first detected on an empirical basis (Carniel and Tárraga, 2006) and then investigated in order to quantify the physical mechanisms that actually govern the triggering (De la Cruz-Reyna et al., 2010). For this reason we claim that FIM is another tool that can help us reach a better understanding of the complexity of volcanic systems.

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