Detailed investigation of Long-Period activity at Campi Flegrei by Convolutive Independent Component Analysis

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Abstract

This work is devoted to the analysis of seismic signals continuously recorded at Campi Flegrei Caldera (Italy) during the entire year 2006. The radiation pattern associated with the Long-Period energy release is investigated. We adopt an innovative Independent Component Analysis algorithm for convolutive seismic series adapted and improved to give automatic procedures for detecting seismic events often buried in the high-level ambient noise. The extracted waveforms characterized by an improved signal-to-noise ratio allows the recognition of Long-Period precursors, evidencing that the seismic activity accompanying the mini-uplift crisis (in 2006), which climaxed in the three days from 26 - 28 October, had already started at the beginning of the month of October and lasted until mid of November. Hence, a more complete seismic catalog is then provided which can be used to properly quantify the seismic energy release. To better ground our results, we first check the

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robustness of the method by comparing it with other blind source separation methods based on higher order statistics; secondly, we reconstruct the radiation patterns of the extracted Long-Period events in order to link the individuated signals directly to the sources. We take advantage from Convolutive Independent Component Analysis that provides basic signals along the three directions of motion so that a direct polarization analysis can be performed with no other filtering procedures. We show that the extracted signals are mainly composed of P waves with radial polarization pointing to the seismic source of the main LP swarm, i.e. a small area in the Solfatara, also in the case of the small-events, that both precede and follow the main activity. From a dynamical point of view, they can be described by two degrees of freedom, indicating a low-level of complexity associated with the vibrations from a superficial hydrothermal system. Our results allow us to move towards a full description of the complexity of the source, which can be used, by means of the small-intensity precursors, for hazard-model development and forecast-model testing, showing an illustrative example of the applicability of the CICA method to regions with low seismicity in high ambient noise.

1. Introduction

The classification of seismic signals occurring on active volcanoes is relevant in discriminating those that can be considered strictly related to the dynamics of a volcano from various other external influences. Indeed, the detection of specific signals such as Long-Period (LP) events or explosion-quakes or the prompt recognition of the resurgence of volcanic tremor is very relevant

(see, e.g., Konstantinou and Schlindwein 2002; Kawakatsu and Yamamoto, 2007) because these signals are associated with the source mechanism and often appear in the pre-syn eruptive process. In addition, an increase in the number and/or in the amplitude of such signals may reveal a variation of the dynamical state of the volcano, implying a different contribution of the seismic energy involved in the process. The latter could give new insights on the general modeling and shed light onto the nature of seismic events such as LPs often associated with the renewing activity (see, e.g., Chouet and Julian, 1985; Julian, 1994; Neuberg et al., 2000; Bean et al., 2014). Anyway, the accuracy of automatic procedures for detecting seismic events and locating their sources is influenced by many factors including errors in seismic phases picking, events that are often buried in the high-level ambient noise, network geometry, and even variability in the waveforms. So, a significant objective is the improvement of detection procedures by developing accurate algorithms for quasi-real time seismic data processing, easily manageable in observatory practice: the most important advantages are their consistency and their capability of processing large datasets such as those produced for monitoring densely-populated volcanic areas. Many efforts have been made to solve that problem both from a theoretical point of view and from developing numerical algorithms suitable for specific cases with the main aim to clearly identify the P-phase (refer to, e.g., Kao et al., 2007; Rouland et al., 2009; Küperkoch et al., 2010; Moni et al., 2013). As an alternative approach, we seek to recognize and extract all the waveforms. A detailed review of the methodologies adopted to perform decomposition and detection of relevant seismic signals can be found in Carniel (2014) and references therein. This

work is devoted to the analysis of seismic signals continuously recorded at Campi Flegrei Caldera (Italy) during the entire year 2006 which includes the main LP swarm that occurred during 26-28 October, and investigating the radiation patterns associated with the LP energy release. Specifically, the analyzed time series are the recordings of ground velocity along the three directions of motion (North-South, East-West and Vertical) for each station. We adopt an innovative technique, i.e. the Convolutive Independent Component Analysis (CICA) algorithm, adapted and improved to give automatic procedures for detecting seismic events often buried in the high-level ambient noise, as Ciaramella et al. (2011) showed investigating the limited period for the most energetic activity of the swarm. The main interests are: 1) to establish whether the occurrence of LPs is only limited to the swarm climaxed on the three days 26-28 October 2006, or a longer period is experienced; 2) to investigate the radiation patterns of all events, particularly interesting in the case of small-energy events. The latter exploits the capability of CICA to provide basic signals eventually correlated to the main seismic phases, so an immediate polarization is obtained, giving information on the source mechanism. This should solve the hard problem to identify the best filter bands corresponding to the fundamental and other interesting phases; 3) to characterize all small events in terms of dynamical system in order to link them to the main hydrothermal resonating structure.

To test the performance of the method to separate low-energy events from noise in the pre/post climax activity, we compare CICA with a number of efficient algorithms for ICA both based on second order and higher order statistics. The extracted waveforms with improved signal-to-noise ratios

(SNR) via CICA coupled with automatic phase picking will allow the compilation of a more complete seismic catalog, which could be used to better quantify the seismic energy release taking into account the overall LP activity and characterize the source from a dynamical point of view (i.e. giving the degrees of freedom of the system).

2. Geological setting of Campi Flegrei and dataset

The Campi Flegrei volcanic complex is a nested caldera, which originated from two large collapses which occurred during the eruption of the Campanian Ignimbrite (39 ka) and the Neapolitan Yellow Tuff (15 ka) eruptions, and it is located to the West of the town of Naples (Southern Italy). The caldera, characterized by a very complex structural setting (Capuano et al., 2013), is affected by the phenomenon of Bradyseisms, continuous slow subsidence, interspersed with fast ground uplifts accompanied by seismicity. The most relevant recent ground deformation episodes occurred in 1969-1972 and 1982-1984 and generated a net uplift of 3.5 m around the town of Pozzuoli (Orsi et al., 1999). Since that time, minor uplift episodes (i.e., 2000, 2005-2006, 2010, 2012-2013) occurred (Saccorotti et al., 2007). The presence of geothermal reservoirs plays an important role in determining the dynamics of the caldera and many tomographic studies (see, e.g., De Siena et al., 2010; Petrosino et al., 2012) provide evidence of fluids, whose intrusion and migration to the shallower hydrothermal system causes ground deformations (De Natale et al., 2006). The deformation episode of 2005-2006 was characterized by a large release of seismic energy and by the occurrence, in October 2006, of the most remarkable LP swarm ever recorded in the area. The documented

LP activity lasted for about 1 week and climaxed on days 26, 27 and 28, when hundreds of events were counted (Saccorotti et al., 2007; Ciaramella et al., 2011). The LP signals appear like spindle-shaped monochromatic oscillations and their spectra exhibit a main peak at a frequency around 0.8 Hz attributed to a source effect (Cusano et al., 2008). These LP events have been studied in detail and have been attributed to a fluid-rock interaction in the hydrothermal system (Cusano et al., 2008; Falanga and Petrosino, 2012; De Lauro et al., 2012).

Data used for the present analysis were collected by four broadband three-component seismic stations (ASB2, AMS2, TAGG, BGNG) belonging to the Campi Flegrei seismic monitoring network (see location on the map in Fig. 1), managed by the "Istituto Nazionale di Geofisica e Vulcanologia-Osservatorio Vesuviano (INGV-OV)" (see for details Saccorotti et al., 2007) during the 2006 ground uplift. Specifically, the analyzed time series are the recordings of ground velocity along the three directions of motion (North-South, East-West and Vertical) for each station. We study the seismic signals continuously recorded during the entire year 2006 with the main purpose to detect LP events (eventually buried in the noise), taking into account the remarkable LP swarm, which climaxed on 26-28 October. An example of continuous seismic signal recorded at four selected stations is reported in Fig. 1.

3. Detection method: Convolutive Independent Component Analysis

Independent Component Analysis (ICA) was proposed some years ago to achieve blind source separation when the source signals are mutually sta-

tistically independent and mixed instantaneously with an unknown matrix (Hyvärinen et al., 2001). The intuitive notion of maximum nongaussianity is used in ICA estimation adopting techniques which involve higher-order statistics. We remind the reader that classical measures of nongaussianity are the kurtosis, the negentropy, and the mutual information. ICA in its classical formulation can be now considered a well established method of time deconvolution for signals recorded in a variety of natural systems (Capuano et al., 2011; De Lauro et al., 2005, 2009). However, many natural phenomena are better modeled assuming convolutive mixtures rather than instantaneous ones. For example, in seismological framework, seismic signals are thought to be the convolution of a source function with path, site and the instrument response. So we apply an Independent Component Analysis based approach for the Blind Source Separation (BSS) of convolutive mixtures in the frequency domain. Briefly, in the frequency domain, the convolution leads to products so that the convolutive mixture problem is transformed into subproblems of instantaneous BSS/ICA models at each frequency. The transformation in the frequency domain is usually the Short Time Fourier Transform (STFT). Here, the observed mixtures can be broken up into frames (which usually overlap each other, to reduce artifacts at the boundaries) and each frame is Fourier transformed. The complex result is added to a matrix of frequency bins and then each point ($X_i(\omega, t)$) can be observed both in time and frequency. For each frequency bin, we have, therefore, n observations, which can be applied to the ICA models in the complex domain. To achieve separation we implement a fixed-point algorithm (FastICA) that has a convergence, which is quadratic, much faster than other approaches based on the linear

convergence obtained by gradient methods. Finally, the permutation indeterminacy is solved by using the Hungarian approach that has a complexity of O(n^3) (Ciaramella et al., 2011).

3.1. Blind Source Separation and ICA

In various real world applications, we observe that the source signals have different time delays due to the propagation in the medium. In addition, time-delayed versions of the same source exist, due to propagation paths typically caused by reverberations from some obstacles.

In the context of convolution, the data model is given by

$$x_i(t) = \sum_{j=1}^{n} \sum_{k} a_{ikj} s_j(t-k) \qquad \text{for } i = 1, \ldots, n \tag{1}$$

where $x_i(t)$ represent the convolutive mixtures, $s_j(t)$ are the source signals, whereas each a_{ikj} represents a Finite Impulsive Response (FIR) filter model. To invert the convolutive mixtures $x_i(t)$, a set of similar FIR filters is typically used:

$$y_i(t) = \sum_{j=1}^{n} \sum_{k} w_{ikj} x_j(t-k) \qquad \text{for } i = 1, \ldots, n \tag{2}$$

The output signals $y_1(t), \ldots, y_n(t)$ of the separating system are the estimates of the source signals $s_1(t), \ldots, s_n(t)$ at discrete times t. The w_{ikj}'s are the coefficients of the FIR filters of the separating system. In this work, we solve the problem cast in Eq. 1 relative to convolutive mixtures of seismic sources, by using the ICA-based approach described in (Ciaramella et al., 2011 and references therein). The main idea of that approach is moving to the frequency domain in order to transform the convolution into multiplications and to apply ICA methods, in the complex domain, for instantaneous

mixtures. In the frequency domain, the data model of Eq. 1 becomes

$$X_i(\omega) = \sum_{j=1}^{m} A_{ij}(\omega) S_j(\omega), \text{ for } i = 1, ..., n \tag{3}$$

where $X_i(\omega)$, $S_j(\omega)$ and $A_{ij}(\omega)$ are the Fourier transforms of $x_i(t)$, $s_j(t)$ and $a_{ij}(t)$, respectively. Comparing Eq. 1 with Eq. 3, we note that the convolutive mixture problem is transformed into subproblems of instantaneous BSS/ICA models at each frequency.

The transformation in the frequency domain is usually the Short Time Fourier Transform (STFT). Here, the observed mixtures can be broken up into frames (which usually overlap each other, to reduce artifacts at the boundaries) and each frame is Fourier transformed. The complex result is added to a matrix of frequency bins and then each point $(X_i(\omega, t))$ can be observed both in time and frequency. For each frequency bin, we have, therefore, n observations, to which apply the ICA models in the complex domain. For more detailed description on convolutive blind source separation method refers to Pedersen et al. (2008). A classical example for ICA model is the cocktail party problem, in which the task is to recover speech in a room of simultaneous and independent speakers recorded by a set of microphones. The idea of CICA is to transform the mixed signals (speech signals) to the time-frequency domain, obtaining relative spectrograms. After that, we perform a blind source separation having as input these spectrograms by standard ICA, obtaining the main frequencies. Finally, the separated signals in the time domain are reconstructed by inverse-FFT from the spectrograms of the separated components.

4. Analysis of seismic activity through CICA

The CICA method is applied in order to determine the presence of early onsets of LP activity and their effective duration, checking throughout the year if clusters of LP events occur. We run the method on the hourly seismic traces acquired simultaneously at the four selected stations (ASB2, AMS2, BGNG, TAGG) and, independently, for the three directions of motion. An example of separation is shown in Fig. 2 where transients are separated from noise of both meteo-marine (spectral peaks less than 1 Hz) and anthropogenic sources (spectral peaks above 1.5 Hz): extracted LPs show emergent onsets, absence of shear wave arrivals, appear to be spindle-shaped monochromatic oscillations and have a typical spectral content in the range 0.2-2 Hz with main peak at a frequency around 0.8 Hz as reported in the literature (see, e.g., Kawakatsu and Yamamoto, 2007 and references therein). By investigating the entire year 2006, CICA identifies a large number of alarms also from the week of the climax. In this way we extract about 1900 alarms. In order to avoid false alarms, the extracted waveforms are correlated with an LP master event (occurred on 26 October at 12:18:15 UT) chosen among those reported in the catalog of Saccorotti et al. (2007) (see inset of Fig. 3). We only consider those events having a correlation coefficient higher than 0.7 with the LP master. In such a way, alarms with correlations less than 0.7, which are 10% of the total alarms, are neglected. We do not exclude that the events with lower correlation can be LPs but with different waveforms from the master.

An example of extraction is reported in the lower panel of Fig. 3. Specifically, the interested period of LP occurrence spans from the beginning of

October until mid November, improving the statistics of the seismic catalog compiled both by Saccorotti et al. (2007) and Ciaramella et al. (2011). Indeed, the first LP catalog produced by Saccorotti et al. (2007) counted about 300 events applying a trigger coincidence criterion to data recorded at two seismic stations with the best signal-to-noise ratio (SNR); whereas Ciaramella et al. (2011) counted about 800 events including very small energy LP events during the three days of intense activity.

Looking at the new catalog, one realizes that a non-negligible amount of energy has been released by very small events, in agreement with Falanga and Petrosino (2012), who revealed a persistent sustained activity consisting of very low-energy volcanic signals. These lower energy signals have been unburied from background noise by CICA thus improving the statistics of picked events. The new catalog containing about 1700 events is reported in Fig. 3.

5. Comparison with other blind signal processing methods

The extraction of signals with improved SNR is crucial for obtaining precise polarization analyses and locations. In addition, the highlighting of low-energy events allows a prompt detection of volcanic signals such as LPs that often represent indicators of renewing activity. CICA seems to be very efficient in detecting relevant signals in volcano-seismology, and this section is just devoted to show the performance of the adopted method with respect to a number of other efficient algorithms used for the blind source separation. The choice to adopt ICA methods is based on the capability of ICA to extract relevant signals from noise with a very low signal-to-noise ratio. Indeed, De

Lauro et al. (2005) demonstrated that deterministic harmonic signals can be recognized by ICA in a noise with an amplitude 1000 times higher. We select two types of suitable BSS/ICA methods: ICA algorithms exploiting mutual independence based on higher order statistics (HOS) and algorithms based on second order statistics (SOS), that is, exploiting spatio-temporal decorrelation. Among the SOS, we select AMUSE (Algorithm for Multiple Unknown Source Extraction based on eigenvalue decomposition) and SOBI (Second Order Blind Identification), which are based on the eigenvalue decomposition of a single/multiple time-delayed covariance matrixes. Among HOS, we test the following algorithms:

- *Efficient variant of FastICA* is the version asymptotically more efficient than the original FastICA. Indeed, it extracts features which are robust to non-stationary noise contaminating the mixtures (i.e., seismic signature from background noise).

- *Natural Gradient Flexible ICA* is an adaptive nonlinear ICA learning algorithm. It implements a parameterized generalized Gaussian density model on a natural Reimannian gradient structure to ascertain the distribution of the source, and is able to process real-time mixed data containing sub Gaussian and super Gaussian sources. The nonlinear function of flexible ICA is controlled by a Gaussian index which is an estimate of the kurtosis of the decomposition filer output.

- *Extended Robust ICA based on cumulants* is asymptotically equivariant in the presence of Gaussian noise. This algorithm separates the signals from an m mixture of n sources (with non zero kurtosis) in the presence

of Gaussian noise. This algorithm is a quasi-Newton iteration that will converge to a saddle point with locally isotropic convergence, regardless of the distributions of the sources.

- *Simultaneous Blind signal Extraction using cumulants* performs the simultaneous blind signal extraction of an arbitrary group of sources from a rather large number of observations. Is optimizes the Maximum Likelihood criterium and solves the problem of separation whenever the explicit knowledge of the source densities is lacking.

All these techniques are implemented in an existing Matlab toolbox - ICALAB developed by Cichocki et al. (2003). The robustness of the results and the consistency of the different algorithms for the same model (and in the same mixing conditions, i.e. same seismic traces) is confirmed by a Monte Carlo analysis being executed on a large number of trials (equal to 100 runs for each technique on the same dataset). We have exploited the performance of those methods in periods both pre and post climax, when both the intensity and the occurrence of LPs are decreasing. The background noise may mask the presence of LPs and standard seismic techniques, based on the clear waveform identification, are failing. As an example, we report the results relative to the day 24 October in Figs. 4-5 just approaching the climax. No separation is clearly achieved, not by second order methods nor by higher order statistics. Looking at the spectral content of the extracted components (sources), LPs are not clearly separated from noise still displaying a broadband spectrum. We remind the reader that LPs show rather monochromatic oscillations, with spectra typically peaked at about 0.7 Hz (Saccorotti et al., 2007; Cusano et al., 2008). On the contrary, CICA application works very

well in separating LPs from noise as shown in Fig. 2, where the spectral peak below 1 Hz is generally associated with the meteo-marine component whereas the anthropogenic noise extends above 1.5 Hz.

6. Recognition of temporal pattern

The extraction of signals with improved SNR is crucial for obtaining precise polarization analysis and locations.

In addition, the highlighting of low-energy events allows a prompt detection of volcanic signals such as LPs that often represent indicators of renewing activity (Aki et al., 1977; Chouet and Julian, 1985; Kumagai and Chouet 1999; Neuberg et al., 2000; Kumagai et al., 2002; Nakano et al., 2003; Matsubara and Yomogida, 2004; Bean et al., 2014).

Indeed, the volcanic nature of the extracted signals can be checked by both looking at the seismological properties such as the polarization state or locations and at the characteristics of the dynamical systems associated with the source. In this sense, the capability of CICA to provide basic signals eventually correlated to the main seismic phases allows the performing of an immediate polarization analysis, avoiding "ad hoc" filtering procedures. In line with these thoughts, we perform a polarization analysis on all 1700 LPs of the CICA catalog. Based on the results of Falanga and Petrosino (2012), who demonstrated that the LPs are composed of P waves with very shallow incidence angles, we study the particle motion on the horizontal plane (NS-EW). As an example, Fig. 6 shows the particle motions of a representative subset of LPs at three stations with the best SNR (ASB2, AMS2, TAGG) selected during the period October-November. As can be seen, polarization

is generally linear indicating the presence of body wave, specifically the P wave, though noise can affect some results (see, e.g., TAGG which is the farthest station from the source). The polarization of the first arrivals at three stations can be used to locate the source: indeed, the polarization vectors point towards a specific area, the Solfatara volcano, in agreement with the localization of the source of LPs at about 500 m beneath (see, Saccorotti et al., 2007). The method allows a much better estimate of the seismic activity defining the duration of the phenomenon. In particular, a clear polarization also for the low-energy events occurring at the beginning of October indicates that the seismic activity had started well before the main crisis.

A further check on the LP nature of the events extracted by CICA can be performed by looking at the dynamical properties. Indeed, LPs can be described by a low-dimensional dynamical system (two degrees of freedom), while ambient noise unrelated to volcanic activity is higher dimensional process (Falanga and Petrosino, 2012). In order to extract information about the effective number of degrees of freedom of the dynamics, we explore the phase space in which presumably their asymptotic dynamics evolve. We adopt the averaged mutual information (AMI) (Fraser and Swinney, 1986) and the false nearest neighbours (FNN) techniques (Kennel et al., 1992) to estimate the time delay and the dimension of the phase space (embedding dimension), respectively. The time delay corresponds to the time lag at which the AMI attains the first minimum; the embedding dimension corresponds to the value at which the percentage of FNN approaches zero. The results are reported in Fig. 7 in which the percentage of FNN (estimated on the basis of

the time lag derived from AMI) is plotted against the embedding dimension: a two-dimension phase space is clearly solved indicating that these signals are very low-dimensional as one expects for LPs in agreement with the results of Falanga and Petrosino (2012). Similar techniques have revealed dimensions as higher as 7-8 relative to e.g. the volcanic tremor Events Recorded at Vatnajökull Volcano, central Iceland (Konstantinou, 2002).

7. Discussion and conclusions

The presence of LP seismicity in a volcano affords the opportunity for studying the plumbing system because the seismicity may be caused by pressure fluctuations in magmatic and hydrothermal systems beneath a volcano. Swarms of LP seismic events are recognized as a precursory phenomenon for the eruptive activity and are indicators of renewing activity (Chouet, 1996). LP events have been interpreted as indicators of fluid presence and migration in terms of linear resonances of fluid-filled cracks or cavities (Aki et al., 1977; Chouet and Julian, 1985; Kumagai and Chouet 1999; Neuberg et al., 2000; Kumagai et al., 2002; Nakano et al., 2003; Matsubara and Yomogida, 2004) or nonlinear flow-induced oscillations in channels transporting volcanic fluids (Julian, 1994; Rust et al., 2004). LP events with different energies may depend on the magnitude of the pressure drop in the system (Chouet, 1996) and changes in the flow regime may be related to different excitation levels of the system (Arciniega-Ceballos et al., 2003). Furthermore, recent studies conducted on three active volcanoes (Etna-Italy, Turrialba volcano-Costa Rica, Ubinas volcano-Peru) indicate that LP events may also be triggered without any fluid and connected with the deformations of poorly consoli-

dated topmost layers of volcanic edifice (Bean et al., 2014; Eyre et a., 2015; Thun et al., 2015). In the light of that scientific debate, the prompt identification of very low-energy LPs become more relevant because it adds further information on their nature, allowing a deeper understanding of the physical processes involved. This topic could be a key contribution in the eruption forecasting. At Campi Flegrei, LP events were never observed before the 2000 year ground deformation (Saccorotti et al., 2001; Bianco et al., 2004), although they are commonly detected in active volcanic/hydrothermal areas; the events detected in October 2006 currently constitute the most remarkable LP swarm ever recorded in the area. For sake of completeness, "a posteriori", D′Auria et al. (2011) recognized the occurrence of an ambiguous LP episode, which occurred in the year 1982. In this area, these deformations can be ascribed to nonlinear resonances of conduits or branches in the uppermost hydrothermal system (De Lauro et al., 2012). Indeed, the 2005-2006 deformation episode has been attributed to two hot fluid batches injected from a deeper reservoir below the Pozzuoli bay, reaching the surface at Pozzuoli and Solfatara area (D′Auria et al., 2012). On the other hand, all the activity of the shallow geothermal reservoir generates a sustained hydrothermal tremor as reported in De Lauro et al. (2013). The role of fluids is further supported by geochemical studies, which have revealed an increase of the flow rate at the fumaroles of Solfatara in connection with the main LP swarm (see, e.g., Chiodini et al., 2010).

In this work, we show an improved and more complete analysis of LP activity at Solfatara volcano, Campi Flegrei (Southern Italy), investigating continuous seismic signals spanning the entire year 2006 including the climax

26-28 October, by means of innovative techniques. We adopt an Independent Component Analysis algorithm for convolutive (CICA) seismic series adapted and improved to give automatic procedures for detecting seismic events often buried in the high-level ambient noise. Summarizing, our study shows:

1. the existence of low-energy LP precursors provide evidence that the seismic activity accompanying the mini-uplift crisis (in 2006), which climaxed in one week at the end of October, started as early as at the beginning of the month of October and lasted until mid November. Hence, a more complete seismic catalog is then provided which can be used to properly quantify the seismic energy release and eventually to connect the occurrence of the LP events to the deformative history of the caldera. Indeed, during the mini-uplift period, most energy is released in August-September together with an increased fumarolic gas emission (see, e.g., Chiodini et al., 2010), whereas the uplift ends in December;
2. that CICA extracts basic signals from recordings along the three directions of motion. This is particularly important because it allows objective identification of the polarization parameters without pre-processing the data by filtering procedures that often distort the signals, preventing blind information about the source;
3. that the extracted signals are superficial events mainly composed of P waves with radial polarization pointing to the seismic source of the main LP swarm, i.e. a small area in the Solfatara. This also applies to the small-events that both precede and follow the main activity;
4. that very-low energy LPs can be described by two degrees of freedom

dynamical system similar to those of the main swarm, indicating the same low complexity associated with the vibrations from superficial hydrothermal system.

The identification and characterization of LP precursors permits better highlighting the features of the hydrothermal system. Indeed, the presence of a long preparatory period that leads to a mini-uplift at Campi Flegrei, whose climax lasted for only a few days, and a detailed study of the low-level seismicity associated with this initial period, can shed light on the renewing of the activity. Moreover, such low-energy LP events appear to be generated by the same superficial dentritic network of branches of a hydrothermal system identified by Falanga and Petrosino (2012) and De Lauro et al. (2012), implying that this system was already acting before the climax. From this point of view, a detailed investigation of the stress-tensor could give information on the formation and propagation of fracturing cracks. It would be appropriate to re-analyze the previous time series to check retrospectively the features highlighted in the year 2006, in particular in correspondence with other periods of uplift and changes in other parameters, such as chemical trends. This analysis would allow the verification of whether the absence of LPs before year 2000 is real or due to a lack detection because of less sensitive techniques unable to extract small events buried in the noise. Finally, from a methodological point of view our technique is well-suited to detect transient events and should be extended to short duration (seconds to minutes) episodes of tremor, which also represent indicators of renewing activity. Our method holds promise for improvement of early warning procedures.

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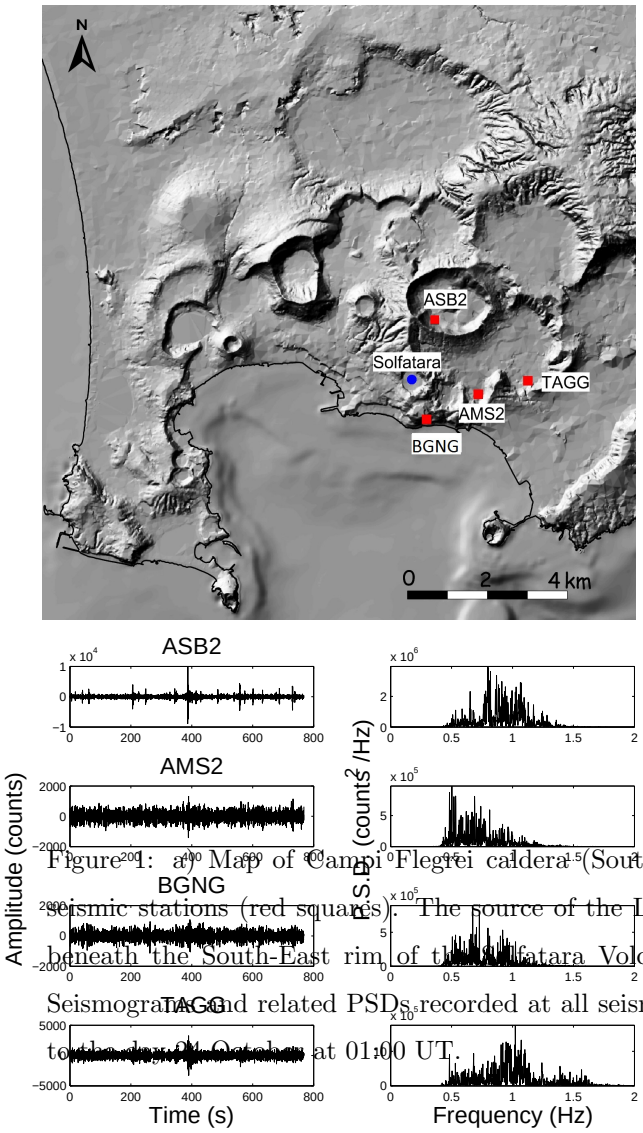

Figure 1: a) Map of Campi Flegrei caldera (Southern Italy) with the locations of the seismic stations (red squares). The source of the LP seismicity (blue circle) is clustered beneath the South-East rim of the Solfatara Volcano at a depth of about 500 m; b) Seismograms and related PSDs recorded at all seismic stations (NS component), relative to the days 24 October at 01:00 UT.

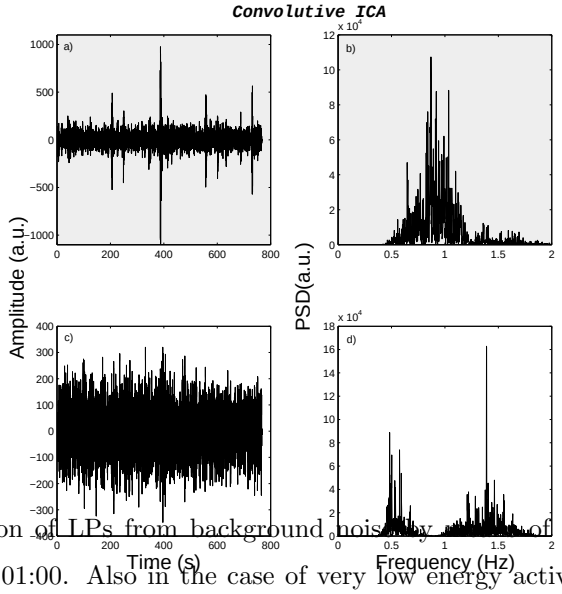

Figure 2: Separation of LPs from background noise by means of CICA relative to the day 24 October at 01:00. Also in the case of very low energy activity and hence of low signal-to-noise ratio (SNR), the CICA approach permits to obtain a better result. Indeed, from PSDs we can discriminate two fundamental frequency bands, one associated with the LP seismic signals, typically peaked around 0.8 Hz, and another with a broader spectral content associated to the ambient noise (contribution of both the meteo-marine component (peak below 1 Hz) and the anthropogenic activity (peak at 1.5 Hz).

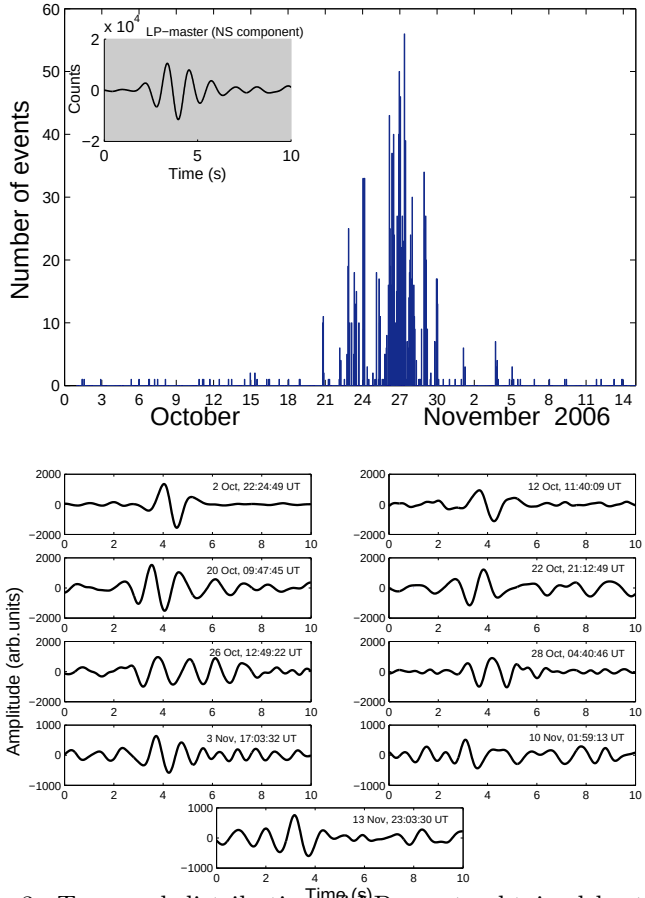

Figure 3: Temporal distribution of LP events obtained by the automatic picking of the CICA time series considering the entire period; each bar of the histogram corresponds to 1-h-long interval. About 1700 LPs with high correlation coefficients with respect to an LP master event are extracted spanning a period from the beginning to October until mid November. The inset shows the LP master event recorded at the Station ASB2, North-South component (it occurred on 26 October at 12:18:15 UT). The lower panel shows a subset of nine LP waveforms taken all along the period representative of the seismic crisis.

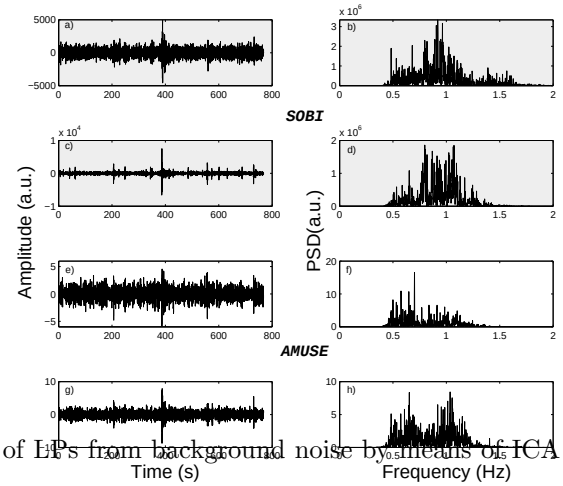

Figure 4: Separation of LPs from background noise by means of ICA algorithms relative to the day 24 October at 1 h: Source signals and relative PSD as extracted by SOBI (a-d) and AMUSE (e-h).

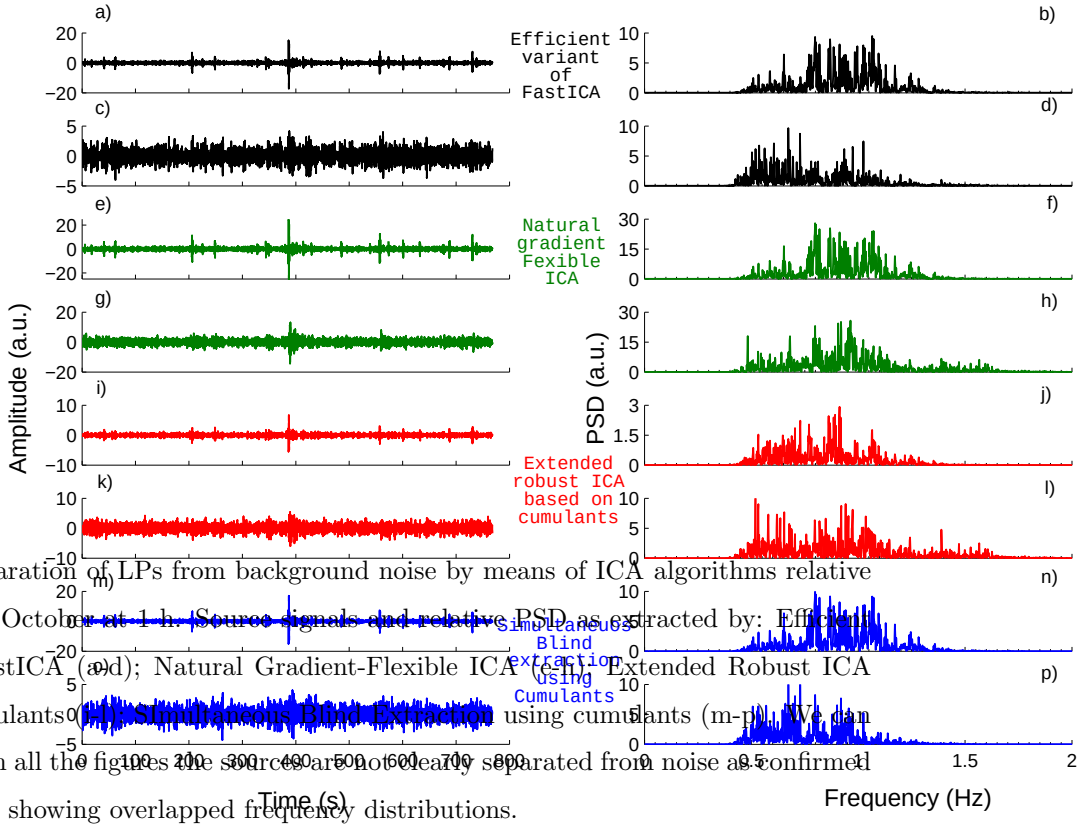

Figure 5: Separation of LPs from background noise by means of ICA algorithms relative to the day 24 October at 1 h. Source signals and relative PSD as extracted by: Efficient Variant of FastICA (a-d); Natural Gradient-Flexible ICA (e-h); Extended Robust ICA based on cumulants (i-l); Simultaneous Blind Extraction using cumulants (m-p). We can observe that in all the figures the sources are not clearly separated from noise as confirmed by their PSDs showing overlapped frequency distributions.

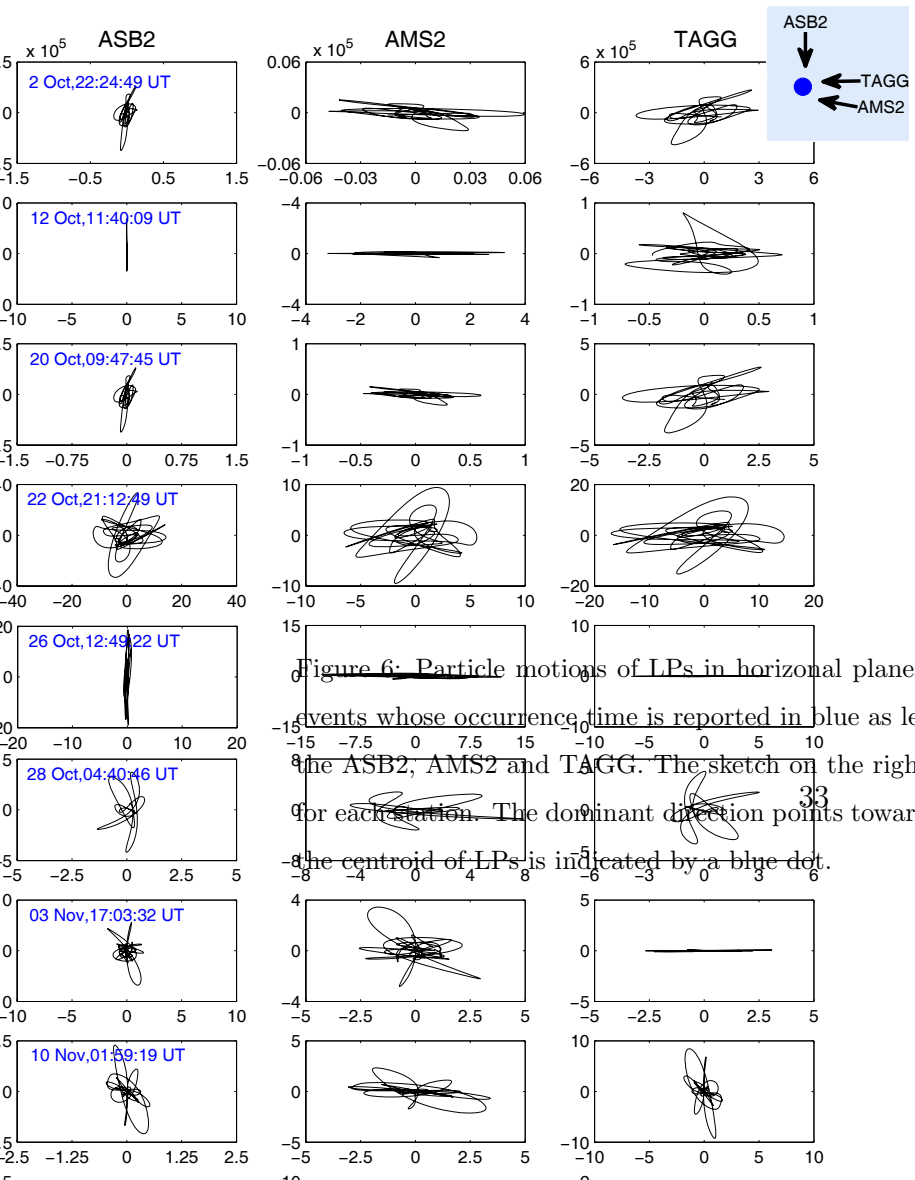

Figure 6: Particle motions of LPs in horizonal planes. The rows are relative to selected events whose occurrence time is reported in blue as legend, whereas the columns indicate the ASB2, AMS2 and TAGG. The sketch on the right shows the directions of the source for each station. The dominant direction points towards the Solfatara (see the inset where the centroid of LPs is indicated by a blue dot.

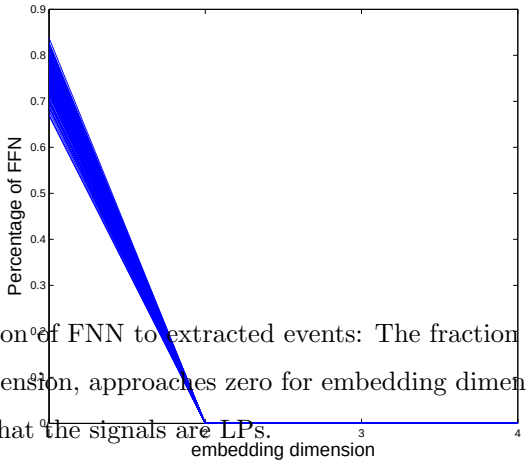

Figure 7: Application of FNN to extracted events: The fraction of FNN, as a function of the embedding dimension, approaches zero for embedding dimension equal to two: this is a clear indication that the signals are LPs.