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The seismic monitoring network of Mt. Vesuvius

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ABSTRACT

Mt. Vesuvius (southern Italy) is one of the most hazardous volcanoes in the world. Its activity is currently characterized by moderate seismicity, with hypocenters located beneath the crater zone with depth rarely exceeding 5 km and magnitudes generally less than 3. The current configuration of the seismic monitoring network of Mt. Vesuvius consists of 18 seismic stations and 7 infrasound microphones. During the period 2006-2010 a seismic array with 48 channels was also operative. The station distribution provides appropriate coverage of the area around the volcanic edifice. The current development of the network and its geometry, under conditions of low seismic noise, allows locating seismic events with M<1. Remote instruments continuously transmit data to the main acquisition center in Naples. Data transmission is realized using different technological solutions based on UHF, Wi-Fi radio links, and TCP/IP client-server applications. Data are collected in the monitoring center of the Osservatorio Vesuviano (Italian National Institute of Geophysics and Volcanology, Naples section), which is equipped with systems for displaying and analyzing signals, using both real-time automatic and manual procedures. 24-hour surveillance allows to immediately communicate any significant anomaly to the Civil Protection authorities.

1. Introduction

Vesuvius is one of the most dangerous volcanoes as a consequence of the high urbanization of the surrounding areas [De Natale et al. 2011].

In the 19th century an increasing interest in the Earth studies leaded to the foundation of the Osservatorio Vesuviano, the first volcanological observatory in the world [Owens 2013]. Luigi Palmieri, who was appointed director of the Osservatorio in 1854, started the first seismological observations on a volcano using a seismometer designed and built by himself [Giudicepietro et al. 2010]. The first seismometers were installed on Mt. Vesuvius since the second half of the century, at the Osservatorio Vesuviano. Since then, at least 12 eruptions occurred alternated by near persistent Strombolian activity. The detection of seismicity associated with this eruptive activity represents the first recording of seismo-volcanic signals in the world.

The intense volcanic activity of that period allowed Palmieri to understand the usefulness of the seismic observations to forecast an approaching eruption. At the beginning, only one seismometer, the Palmieri's seismometer, was used to monitor the volcano. The network improved during time till the actual one that counts up to 18 seismic stations equipped with several kinds of sensors.

Currently, it is known [De Natale et al. 2011] that an eruption of Vesuvius could represent a significant threat for the population living in this area. To mitigate this risk the Italian Civil Protection authorities developed an emergency plan based on updated scientific information concerning the dynamics of Vesuvius. The plan requires a modern and efficient monitoring network able to record several kind of scientific data and to make them available for real time and near immediate analysis (http://www.protezionecivile.gov.it/jcms/it/view_pde.wp?contentId=PDE12771) [Convertito and Zollo 2011].

In the monitoring center, automatic systems, based on real time analysis of seismological data, provide a useful support for a quick analysis of all the acquired data. Moreover all seismic events are manually classified, picked and, if possible, located. Finally all event waveforms and parameters are stored in a relational database [Giudicepietro et al. 2008, Scarpato 2011].

The Osservatorio Vesuviano (now part of the INGV, Italian National Institute of Geophysics and Volcanology, as Naples section) is the reporting authority for event locations and magnitudes and maintains the authoritative event catalog.

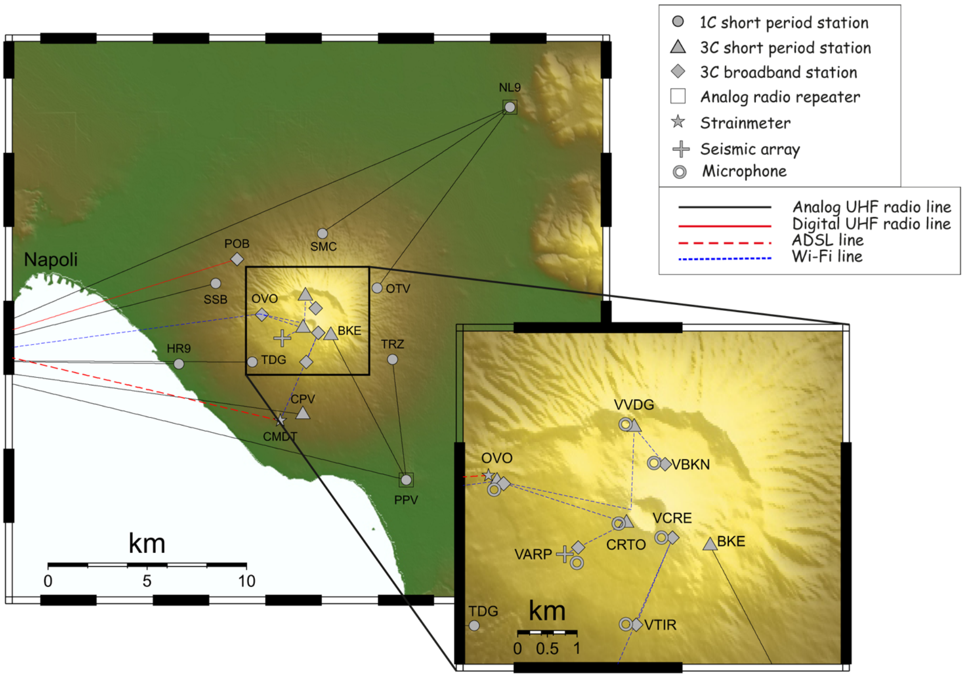


Figure 1. Map of Vesuvius permanent seismic monitoring network. Circles: short-period 1C stations; triangles: short-period 3C stations; diamonds: broadband stations; stars: strainmeters; cross: seismic array (ARV1). The radio data transmission infrastructure is also shown. Black lines: analog radio UHF lines; red lines: digital UHF lines; blue dotted lines: Wi-Fi lines; red dashed lines: ADSL digital connection; black dashed lines: analog CDA data line.

2. The permanent seismic network

The main goal of the seismic monitoring network of Mt. Vesuvius is to record and store seismic data of the Vesuvius volcanic area. These data contribute to the compilation of a seismic catalog which is a benchmark for the scientific community that needs to study this volcano [D'Auria et al. 2013]. At the same time the Osservatorio Vesuviano communicates scientific information to the Italian Civil Protection Department (DPC) regarding the state of the volcano.

The seismicity of Mt. Vesuvius is mainly localized within a radius of 3 km from the center of volcano with depth ranging from 8 km b.s.l. to 1 km a.s.l. [D'Auria et al. 2013]. For this reason the seismic stations are mainly located around the volcanic edifice with a higher density in the Gran Cono crater area (Figure 1).

As reported in Table 1, the current monitoring seismic network of Vesuvius consists of 7 short-period single-component sensors, 3 short-period 3-components sensors and 9 digital broadband sensors. The OVO site hosts both a digital broadband and a 3C electromagnetic analog sensors. The seismic network (Figure 1) has been integrated by infrasound sensors and, in the period 2006-2010, by a 48 channels seismic array.

The 8 stations closer to the Vesuvius crater are located far from the electricity grid and are then powered by solar panels and batteries. A typical station power consumption is usually lower than 500 mA supplied by 160 W solar modules and 160 Ah lead-acid gel batteries. The other 10 stations are located close to towns and are connected to the electricity grid, with batteries providing an energy storage.

Until 2006, the highest and closest stations to the volcano edifice were BKE, on the east side of the Gran Cono, and OVO, in the historical building of the Osservatorio Vesuviano. The instrumental observations collected until then suggested a small magnitude local seismicity concentrated in the volume of the Gran Cono [Giudicepietro et al. 2010, D'Auria et al. 2013]. Consequently, in order to locate these events, it was decided to increase the number of stations in this area by installing modern digital broadband stations. To achieve this goal, the first step was the realization of a modern Wi-Fi radio infrastructure located on the top area of the volcano which assures a real time communication link toward the Osservatorio Vesuviano monitoring center (lines in Figure 1). New stations in the summit area of Mt. Vesuvius were installed using a low-power digital acquisition system, named GILDA [Orazi et al. 2006, 2008], designed and developed at the Osservatorio Vesuviano to fit requirements of remote installation places. Thanks to these new installations it was possible to better delineate a seismogenetic volume close to the crater area which was, previously, poorly known [Giudicepietro et al. 2010, D'Auria et al. 2013].

All the broadband stations deployed on Vesuvius run Guralp CMG-40T (60 sec – 50 Hz) sensors except for the OVO station where a VBB sensor Nanometrics Trillium (response flat in the band 240s – 35 Hz) is used. This last sensor was installed in collaboration with Centro

Station site	Station code	Number of channels	Typology	Data transmission type	Acquisitor type	Installed sensors	Year of installation
Osservatorio Vesuviano historical headquarter	**OVO**	3	Analog	Analog UHF radio	Analog modulator	3 orthogonal geotech instr. S13	1971
		3 + 1	Digital	Wi-Fi radio	GILDA	Trillium 240 + Chaparral 25V	2011
Ercolano	**HR9**	1	Analog	Analog UHF radio	Analog modulator	Mark L4-C	1987
Cappella Vecchia	**CPV**	3	Analog	Analog UHF radio	Analog modulator	Mark L4-3D	1992
Bunker Est	**BKE**	3	Analog	Analog UHF radio	Analog modulator	3 orth. geoth. S13	1992
San Sebastiano	**SSB**	1	Analog	Analog UHF radio	Analog modulator	Mark L4-C	1993
Terzigno	**TRZ**	1	Analog	Analog UHF radio	Analog modulator	Mark L4-C	1994
S. Maria a Castello	**SMC**	1	Analog	Analog UHF radio	Analog modulator	Mark L4-C	1995
Torre del Greco	**TDG**	1	Analog	Analog UHF radio	Analog modulator	Mark L4-C	1995
Ottaviano	**OTV**	1	Analog	Analog UHF radio	Analog modulator	Mark L4-C	1996
Pollena	**POB**	3	Digital	Digital UHF radio	GILDA	CMG-40T	2000
Pompei	**PPV**	1	Analog	Analog UHF radio	Analog modulator	Mark L4-C	2004
Camaldoli della Torre	**CMDT**	3	Digital	Cabled ADSL	Q330	Guralp CMG-40T	2004
Cratere Ovest	**CRTO**	3 + 1	Digital	Wi-Fi radio	GILDA	Guralp CMG-40T + Infracyrus	2006
Vesuvio Cratere Est	**VCRE**	3 + 1	Digital	Wi-Fi radio	GILDA	Guralp CMG-40T + Infracyrus	2008
Vesuvio Bunker Nord	**VBKN**	3 + 1	Digital	Wi-Fi radio	GILDA	Guralp CMG-40T + Infracyrus	2009
Zona Baracche Forestale	**VARP**	3 + 1	Digital	Wi-Fi radio	GILDA	Guralp CMG-40T + Infracyrus	2009
Zona Baracche Forestale	**ARV1**	16×3C	Seismic array	Wi-Fi radio	Array	16 Lennartz 3D-Lite	2006
Vesuvio Tirone	**VTIR**	3 + 1	Digital	Wi-Fi radio	GILDA	Guralp CMG-40T + Infracyrus	2009
Vesuvio Valle del Gigante	**VVDG**	3 + 1	Digital	Wi-Fi radio	GILDA	Guralp CMG-40T + Infracyrus	2009

Table 1. Station summary table of permanent seismic network of Mt. Vesuvius.

Nazionale Terremoti (INGV, National Earthquake Center) in an underground vault close to the historical building of the Osservatorio Vesuviano at a depth of 35 m.

In order to discriminate earthquakes from other events (thunders, artificial explosions) and to carry out scientific studies on the propagation of infrasounds at local and regional scale most of the broadband digital stations have been equipped with infrasonic sensors too. Two kind of infrasonic sensors are employed, the commercial Chaparral model 25V with flat response between 10s – 200 Hz and an homemade sensor completely designed and realized at the Osservatorio Vesuviano [Buonocunto et al. 2011].

As for the short period stations, the sampling rate of all the broadband seismic stations and of infrasound sensors is fixed at 100 sps.

In 2006, a permanent seismic array based on 16 three-component short period sensors, was installed in the west side area of the Gran Cono. The acquired data were transmitted in real time using the Osservatorio Vesuviano Wi-Fi infrastructure [Scarpato et al. 2007]. The array was removed in 2010 because of the obsolescence of its acquisition system. Currently we are planning the installation of a new seismic array, with a 3D configuration.

The short period stations use analog FM modulators transmitting via UHF radio band to the Data Acquisition Center in Posillipo (Naples). There a multichannel data acquisition board performs the analog to digital conversion with a sampling rate of 100 sps and 16 bit of digital resolution. All these stations are equipped with 1 Hz short period electromagnetic sensors as reported in Table 1.

Digital data transmission uses three preferred carriers: UHF digital lines, Wi-Fi infrastructures and commercial ADSL providers. The path from the station to the acquisition center is sometimes composed of multiple segments, each one with a different carrier (e.g. Wi-Fi+ADSL).

Since the UHF radio frequency band cannot carry a large amount of data, in 2004 the Osservatorio Vesuviano began the deployment of a modern broadband digital radio infrastructure aimed to cover remote areas and the crater area of Vesuvius [Scarpato et al. 2007]. After the first experience in Stromboli, in 2006 we began the first installation in Vesuvius area with professional radio systems. These systems provide both radio access and local Ethernet port respectively for remote and local clients allowing complex LAN (Local Area Network) and WAN (Wide Area Network) connections. The used systems employ the free frequencies band of 2.4 GHz, and 5 GHz, as described in the IEEE802.11 protocol. The maximum transmission power for the two bands is respectively 100mW and 1W according to European legal standards.

Several radio repeaters, working as access point for seismic stations, compose the broadband digital radio infrastructure. They are located close to stations or in their line of sight. Repeaters and seismic stations are often co-located in order to save installation costs by sharing solar energy production systems. This is the case of VCRE and VVDG seismic stations. Nowadays the broadband digital radio infrastructure is composed by 5 repeaters located in the crater area (Figure 1).

All the data produced by the remote sensors are sent to the data acquisition center in Posillipo (Naples) or directly toward the Osservatorio Vesuviano in Naples. The near-immediate communication and analysis for monitoring purposes require a network with real time seismic data transmission. The monitoring center of the Osservatorio Vesuviano collects all these real time data and employes automatic software analysis systems running on Earthworm (http://www.earthwormcetral.org). The Earthworm software suite was developed in the early '90s by the USGS and now is carried on by ISTI. It is composed by a group of software modules specialized for a single task and designed to closely work together. It also provides an API to develop homemade modules in order to easily add new functionalities to the software suite.

We realized many Earthworm modules in order to perform the acquisition of our digital stations, to save the data in legacy formats and to perform automatic analyses. Moreover we also modified some existing modules in order to adapt them to our specific needs. The system for the automatic detection and location of events is based on Earthworm and has been complemented by a web interface [Scarpato 2011].

Using the Earthworm suite we also realized a geographically distributed acquisition network. Earthworm network functionality allowed us to build several peripheral acquisition centers equipped with an ADSL connection. Earthworm allows an efficient way to integrate seismic data coming from different and heterogeneous sources. In the Vesuvius area there are two local acquisition centers co-located with stations OVO and CMDT. Data coming from these peripheral centers are then collected at the Osservatorio Vesuviano where they are automatically analyzed. Peripheral centers also act as first level of storage in order to increase the redundancy of the whole system. In case of major connection losses, data are always stored locally and can be subsequently recovered.

Since their importance, the hardware and software architecture of these peripheral acquisition systems has

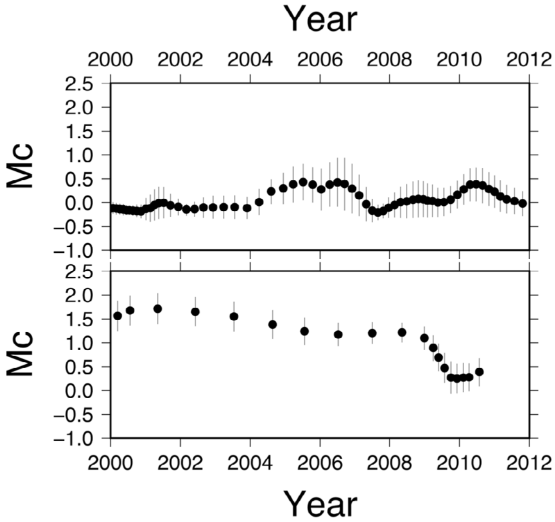


Figure 2. Temporal variation of the magnitude of completeness (Mc) for events detected at BKE station (top) and the Mc for located events (bottom).

been designed to be as more reliable as possible [Peluso et al. 2009]. At the present more than three days of data recordings are guaranteed also without any main electricity power.

Real time data arriving at the Osservatorio Vesuviano monitoring center are stored in a multi-tier structure. The peripheral acquisition centers give the first level of the tier. Once arrived at the main acquisition center the data are stored in two small NAS (Network Attached Storage) for few months. The geographical redundancy is needed to avoid any data loss due to hardware failures. The data are daily copied from these two small machines to a NAS with a higher capacity, allowing years of storage. Finally, data are also daily backed up on tapes for the final storage.

3. Network performances on VT earthquakes detection and location

In the last 13 years the seismic network of Mt. Vesuvius has recorded about 21,000 transients of local origin (i.e. recorded only by this network): 54% of them being local earthquakes, 30% artificial explosions in local quarries, 5% small local landslides and 11% thunders and other events [Esposito et al. 2013].

The seismicity of Mt. Vesuvius is currently characterized by low magnitude (Md<3) volcano-tectonic (VT) earthquakes mainly distributed below the volcanic edifice above 5 km b.s.l. [D'Auria et al. 2013]. Earthquakes are concentrated in two clusters: one between 1 and 5 km depth and another between 0.5 and 1 km a.s.l. The current network configuration is designed to detect and locate this seismicity and to be able to track possible future changes in the seismicity pattern. Figure 2 shows the variation with time of completeness magnitude (Mc) for events detected by the BKE stations (upper panel) and for located events (bottom panel). They have been computed, using ZMAP software, on groups of 200 events (with an overlap of 100 events among adjacent groups) using the maximum curvature of the experimental Gutenberg-Richter distribution as estimator [Wiemer 2001, D'Auria et al. 2013]. As evidenced in Figure 2, the location performance of the network highly improved starting from 2008 when several stations were installed on the crater area. During 2009 the Mc dropped from a value of about 1.5 to the current value of 0.5. This result was achieved thanks to the installation of 6 stations (CRTO, VCRE, VBKN, VARP, VTIR, VVDG in Table 1) close to the Vesuvius crater area. The current Mc value agrees with the theoretical analysis performed to map the location and detection performances of the network reported in Figure 3. The left panels of Figure 3 show the theoretical detection performances of the network for earthquakes located at different depths (500 m a.s.l. for panel A; 1500 m b.s.l. for panel B and 5000 m b.s.l. for panel C).

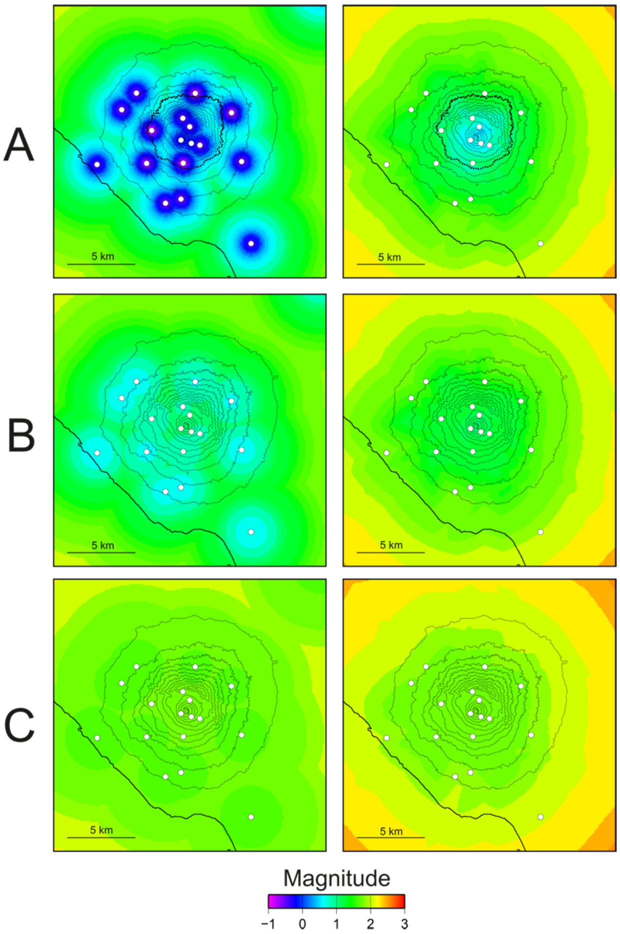


Figure 3. Left: plot of the theoretical magnitude detection threshold for the seismic stations of the Vesuvius network at 3 different depths: 500 m a.s.l. (A); 1500 m b.s.l. (B) and 5000 m b.s.l. (C). Right: theoretical magnitude of completeness calculated at the 3 different depths as in the left panels.

The detection magnitude was calculated comparing the average noise level of the whole network with the seismic signal amplitude determined by simulating the direct wave propagation. The wave amplitude at each station is calculated simulating a source in terms of a single corner frequency spectral model [Boatwright et al. 1991]. According to Brune [1970], the source is approximated by a triangular shaped function with an area proportional to the seismic moment and a base length proportional to the stress drop [Tramelli et al. 2013]. The amplitude is then attenuated taking into account the geometrical spreading and the anelastic attenuation along the ray trajectory. For simplicity, the elastic medium for pulse propagation is assumed homogeneous, with a homogeneous velocity representing the average velocity of the 3D model calculated by D'Auria et al. [2008]. The average quality factor for P waves has been assumed Qp = 40 [Bianco et al. 1999]. The use of simulated signals for the calculation of the detection and location capability of a network allows defining its performances also in areas without recorded seismicity.

Results show that within the whole Gran Cono area the magnitude detection threshold is close or lower than 0.0 for shallow earthquakes. At depth of 1500 m the detection threshold rise to about 1.0, reaching a value of about 1.5 at 5000 m depth. Furthermore this plot shows that the network is able to detect earthquakes with magnitude 1.5 occurring within a radius of 5 km from the crater and at depth up to 5 km.

In the right panels of Figure 3 the location performance of the seismic network is shown. This analysis is performed assuming that an earthquake is located when more than 4 stations are able to detect it. The detection capability is calculated as described above.

Results show that the current network configuration is able to locate events having magnitude higher than 2 within the whole Vesuvius area. Furthermore, close to the crater axis the theoretical Mc ranges from 0.5 at shallow depth to 1.5 at depths of 5 km.

We have also tested the change of the network performances in case of occurrence of strong volcanic tremor. We have simulated this situation by multiplying the background noise by a factor of 10. In this case the detection threshold at shallow depths rises to 0.8, and to about 2.5 at 5000 m depth. For the located events, at shallow depth the threshold increases to 2.0, and to about 3. at 5000 m depth.

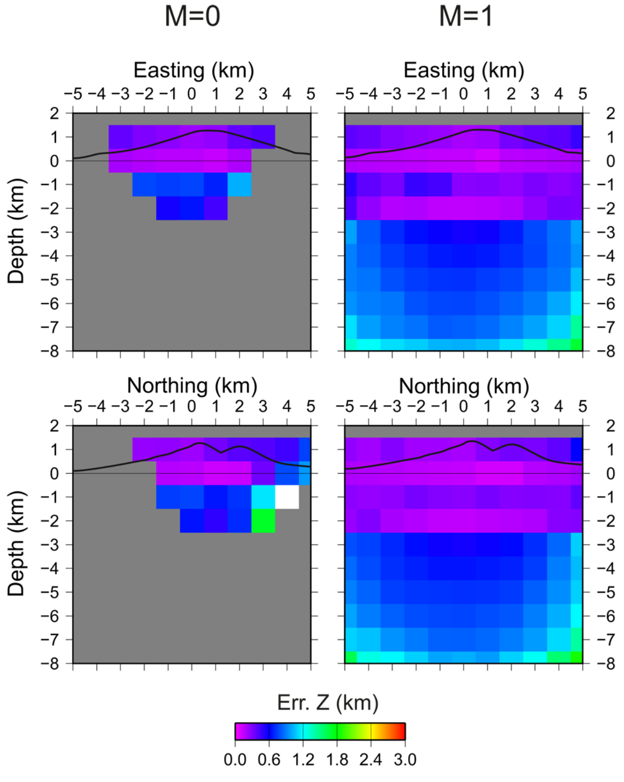


Figure 4. Results of the analysis of the location uncertainty of the seismic network for two earthquake magnitudes: M = 0 and M = 1. The color scale indicates the vertical error on the hypocenter location.

These results show the capability of the network of tracking the seismicity located mostly along the crater axis. A possible change of the seismicity pattern (e.g. seismicity associated to the opening of lateral vents) has been taken into account as well. The current network configuration is able to detect events located on the volcano edifice (that means roughly less 5 km from the crater axis) up to magnitude 1.5 (Figure 3). It should also be considered that the Italian National Seismic Network has a good location performance in the Vesuvius area starting from magnitude 2 [D'Alessandro et al. 2011]. This should allow the detection of any significant change in the seismicity pattern, prompting the deployment of dense temporary networks to track the possible evolution of the seismicity.

To better assess the performance of the network we also performed the resolution analysis of it by determining its location uncertainty. The method, described in Tramelli et al. [2013], consists in locating synthetic earthquakes using the network under test. Synthetic earthquakes with a chosen magnitude are generated on a grid spanning the whole analyzed volume and the arrival times at each station are estimated. We used stations where the SNR is greater than 2 to locate the synthetic earthquakes. When at least 4 stations detect the event, the location is performed using a linearized approach and the location error is estimated through the covariance matrix. In Figure 4 we show the vertical location errors estimated for M = 0 (left) and M = 1 (right) earthquakes. The actual network allows to locate M = 0 earthquakes below the central area of the volcanic edifice till a depth of 2-3 km b.s.l. Otherwise, M = 1 earthquakes can be located till a depth of 8 km b.s.l. The vertical location errors are generally lower than 500 m for depth lower than 2 km. Below they are generally within the range 500-1000 m. The decrease of the performances with depth is justified by both the lowering of the SNR and by the increase in the seismic wave velocity.

A further improvement of the network performances could be obtained by deploying borehole seismic stations. This would increase the SNR by lowering the cultural noise level.

4. Array analysis

A seismic array was deployed at the Southwest flank of Mt. Vesuvius in 2006 (cross in Figure 1). It was designed to investigate the presence of correlated signals, possibly related to volcanic tremor sources. It was composed of 16 three-component short period sensors (Lennartz 3D-Lite) organized on 3 branches geometry as shown in Figure 5 (top left). The distance between each sensor was 50 m. The array acquisition system was

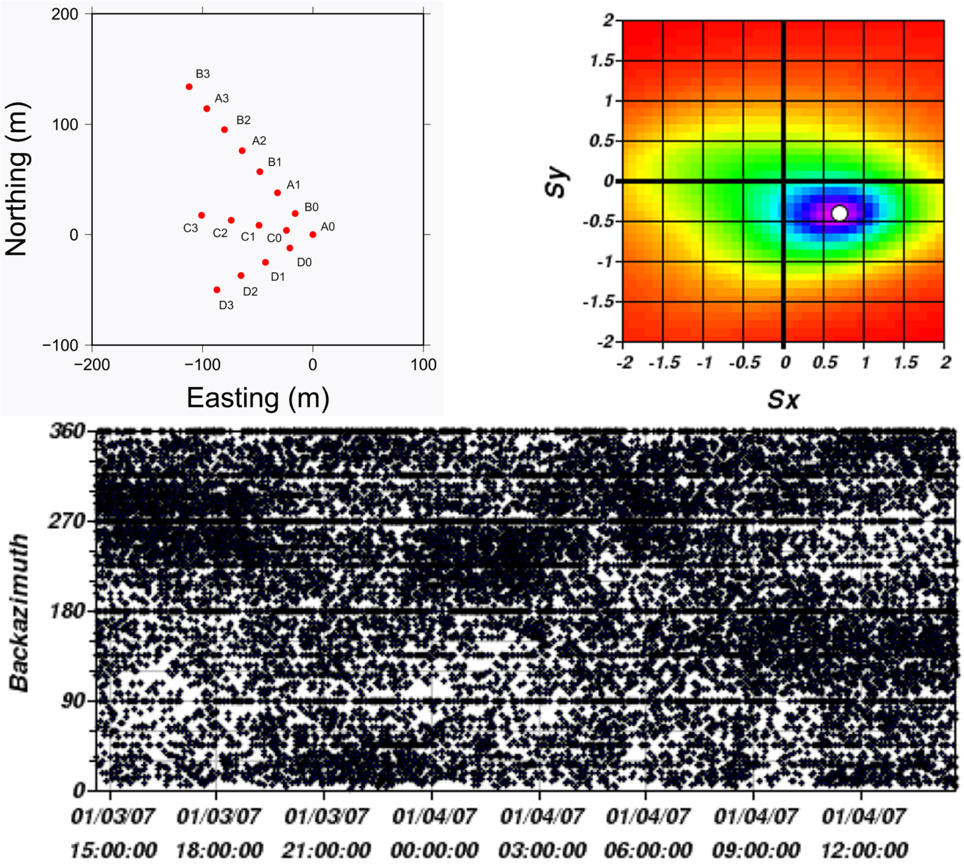


Figure 5. Top left: geometry of the permanent seismic array located in position indicated by the cross in Figure 1. Horizontal and vertical units are meters; labels indicate the array element names. Top right: slowness spectrum of 5 second of signal. Units are in s/km. Bottom: backazimuth analysis for a time window representing a typical day.

based on a central unit acquiring data from 16 ADC boards. Data were both locally stored and radio-transmitted to the Osservatorio Vesuviano monitoring center where they were real-time analyzed by a parallel cluster computing system. It furnished the propagation back-azimuth and the apparent velocity of the wavefronts crossing the array calculated with the CSS-MUSIC method [Chiou and Bolt 1993].

In Figure 5 (top right) an example of the slowness spectrum of a 5 second signal window is shown. Figure 5 (bottom) shows a typical 24 hours time series of back-azimuth values for waves having frequencies around 1.18 Hz, starting on March 1st, 2007, at 15:00 UTC. From this figure we identify different wave arrival directions related to different time periods during the day. In particular, during the night, the presence of noise coming from about 225 degrees may be related to marine noise as evidenced by Saccorotti et al. [2001]. During daytime the noise is more complex and it is possible to identify some different directions probably associated to cultural noise. Array analysis confirmed the lack of volcanic tremor, in the considered time interval. This was also previously shown by Saccorotti et al. [2001] for a different time interval.

This array allowed studying the seismic wavefield also for very low magnitude earthquakes. For example the $M = -1$ earthquake recorded by the seismic array at 03:42 UTC on March 4, 2008 (Figure 6). For stronger earthquakes it also allowed to identify seismic phases and their propagation direction. In Figure 7 an $M = 1$ earthquake recorded by the array on September 11, 2009, at 21:06 UTC, is shown. The P phase, the S phase and the coda of the signal are well distinguishable both in backazimuth and in apparent velocity.

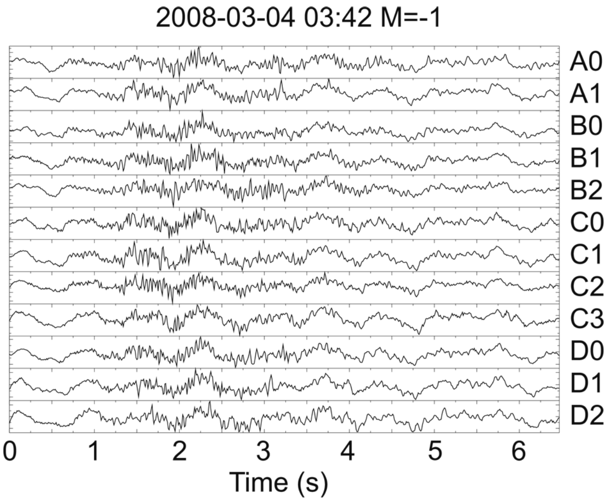
5. Other events

Even if the main seismicity that is currently recorded at Mt. Vesuvius consists of VT earthquakes, the network records a variety of different signals as artificial explosions and thunders [Esposito et al. 2013]. In the following we illustrate two cases of peculiar signals of natural origin.

Landslides

Among the signals recorded by the Vesuvius network, landslides are very common. They are usually related to small rockfalls occurring within the Vesuvius crater [Esposito et al. 2013]. Thanks to the stations deployed at the top of the volcano crater it is possible to detect and identify them.

An important landslide sequence occurred on June 4-5, 2009, when the seismic network recorded at least



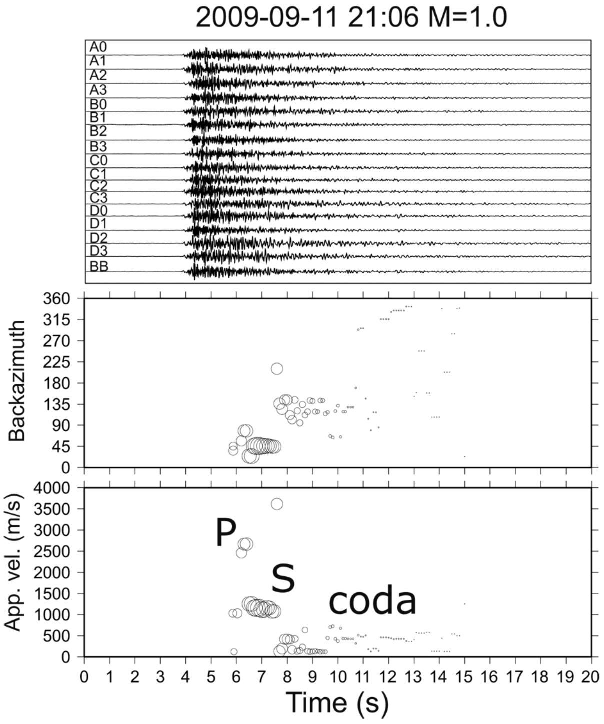


Figure 6 (above). Traces of a M = −1 earthquakes recorded by the seismic array on March 4, 2008, at 03:42 UTC. Amplitudes are normalized. Label on the right indicate the array elements (see Figure 5). **Figure 7** (right). Backazimuth and apparent velocity analysis of an M = 1 earthquake recorded by the seismic array on September 11, 2009, at 21:06 UTC. The size of circles in the two lower panels is proportional to the beam energy.

15 signals associated to landslides. The major of them was recorded at 04:41 UTC on June 5, 2009, and its source was located on the inner wall of the Gran Cono crater. A following on-site inspection associated this event to a collapse affecting an area of 50×170 m^2 inside the Gran Cono. In Figure 8 (left) we show the June 5 main landslide recorded by the broadband station VCRE. In the Figure 8 (right) the low-pass 1 Hz filtered signal is shown. In the vertical component signal a marked downward pulse is visible. We postulate it to be related to the downward single force component associated with the impact of the landslide mass with the ground [Deparis et al. 2008]. The availability of broadband recordings for these events could allow their quantification through seismological techniques.

Low-frequency earthquake

On May 11, 2012, at 01:09 UTC, the seismic network of Mt.Vesuvius recorded two low amplitude signals having peculiar features (Figure 9). In the past, long-period events, have been already identified at Vesuvius [Bianco et al. 2005]. However the aforementioned signals, have waveforms and spectra differing from those of typical LP events [Chouet 1996]. The first

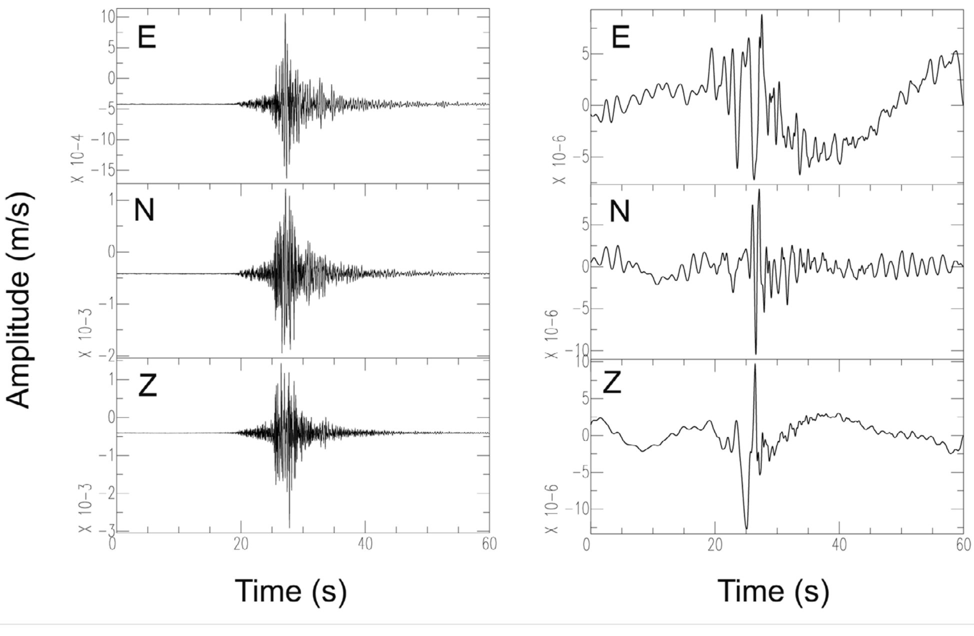


Figure 8. Waveforms of the major landslide recorded by the VCRE station on June 5, 2009, at 04:04 UTC. In the right panels the 1 Hz low pass filtered signals are shown.

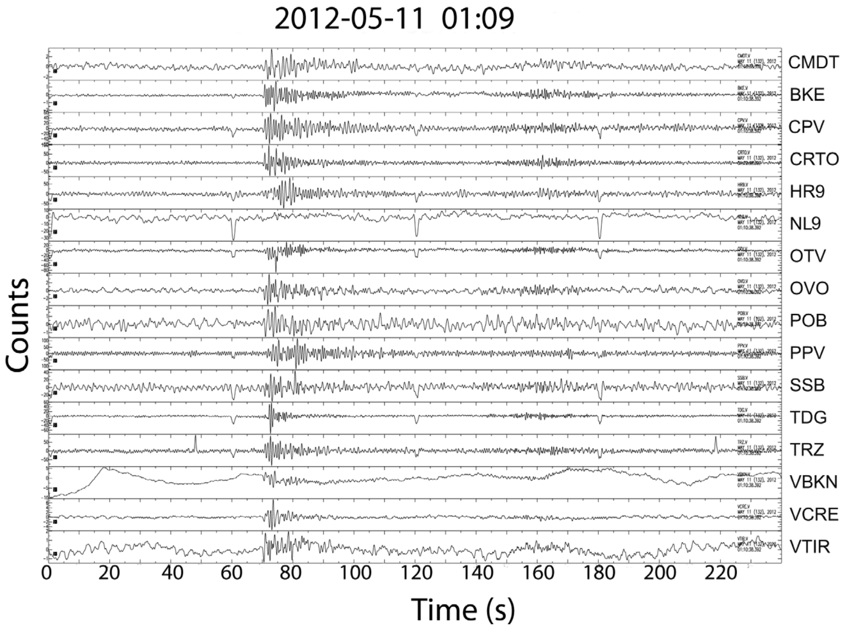


Figure 9. Traces of the very-low-frequency earthquake recorded by the seismic network of Mt. Vesuvius on May 11, 2012, at 01:09 UTC. The figure shows only the vertical components.

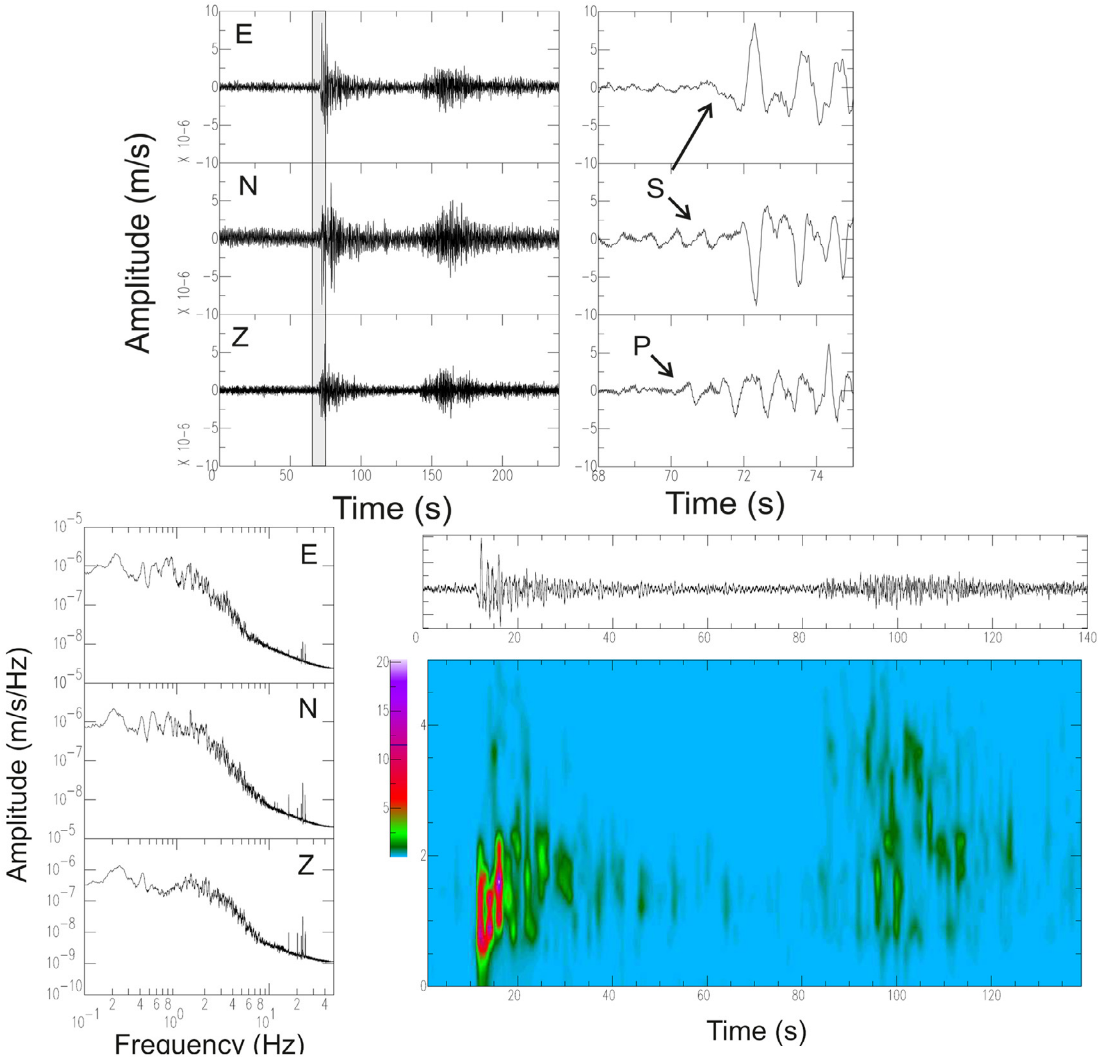


Figure 10. Top left: the three-components waveforms of the very-low-frequency earthquake recorded at OVO broadband sensor. On the top-right we show a zoom on the P and S-wave arrivals. Bottom left: displacement spectrum of the 3 waveforms shown above. Bottom right: spectrogram of the vertical component of the same event recorded at OVO.

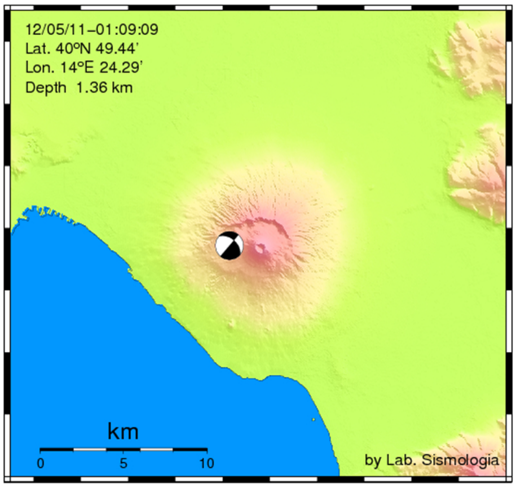


Figure 11. Focal mechanism and epicenter location of the low-frequency event.

event has clear P and S seismic phases (Figure 10). This allowed the determination of the event hypocenter which was below the volcanic edifice, West of the cone, at a depth of about 1.36 km b.s.l. (Figure 11). In particular, the station OVO, equipped with a Trillium 240 s, furnished the clearest waveform (top in Figure 10). The P wave polarities were compatible with a double couple mechanism (Figure 11). The main signal was followed, about 70 s later, by another signal having a more complex waveform but a similar spectrum (bottom right in Figure 10). This second signals seems to consist in the superposition of many small events, having the same waveform of the first one.

The displacement spectra of the S phase of the first event (bottom left in Figure 10) allowed the computation of the seismic moment which is about 6×10^{11} Nm. The corner frequency has a value of about 2 Hz. Assuming a seismic rupture speed of 0.9*Vs, the computed stress drop has a significantly low value (less than 0.1 bar), suggesting a source mechanism different from typical VT earthquakes. Another possibility is a slower rupture speed compared to VT earthquakes.

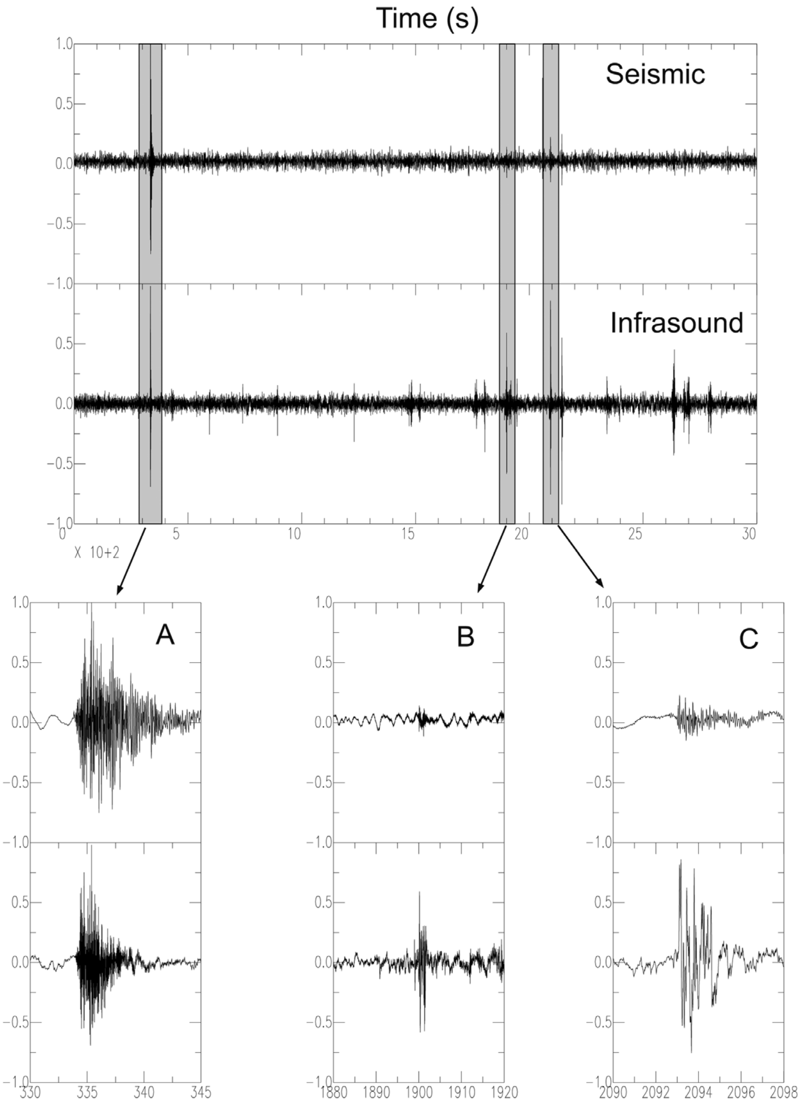


Figure 12. 3000 s time window starting at 21:30 UTC on November 8, 2009, of the seismic and infrasonic signal recorded by the VARP station. The zooms show seismic (top) and infrasound (bottom) waveforms of an earthquake (A) and two thunders (B and C).

This kinematics is similar to that of slow earthquakes, which are usually recorded along convergent plate boundaries [Ide at al. 2007]. It is interesting to note that in this case such events have been observed in a completely different geotectonic framework (a volcano within an extensional tectonic environment).

6. Infrasound

The seismic network is integrated, since 2006, with several infrasound sensors, as reported in Table 1. For volcanic monitoring purpose, infrasound signals are useful to quantify volcanic activity. Moreover these sensors are particularly useful for the event discrimination task. Their signals, compared with the seismic ones, allow a quick and reliable discrimination between earthquakes and other signals, for example thunders [Arrowsmith et al. 2010]. The Vesuvius infrasound network has recorded various transients related to thunders, explosions, supersonic jets and bolides [D'Auria et al. 2006].

For instance, on November 8, 2009, a seismic swarm was recorded simultaneously to a sequence of thunders. In Figure 12 we show a 3000 s time window starting at 21:30 UTC on November 8. The zooms show both seismic (top) and infrasound (bottom) waveforms of an earthquake (A) and two thunders (B and C). The infrasonic earthquake waveform resembles the envelope of the seismic component. The infrasonic thunder waveforms are, instead, completely different from the seismic traces.

Infrasound networks, as the Vesuvius one, have also a peculiar scientific interest in various fields [Le Pichon et al. 2010]. The study of infrasound could potentially lead to new discoveries [Le Pichon et al. 2010]. For example, Figure 13 shows the infrasonic (top 5 traces) and seismic (bottom) signals of an event of unknown origin, recorded at Vesuvius at 13:01 UTC on October 6, 2009. The sonic waveform consists of two distinct phases. Only the first one has also a seismic signature. Delays between arrival times suggest a source located in the SW direction. Future efforts will be devoted to the development of automated procedures aimed at detecting and characterizing such signals.

7. Discussion and conclusions

The seismic network of Mt. Vesuvius is the first known monitoring network on a volcano. It started working in 1856 with the installation of the first electromagnetic seismometer designed by Luigi Palmieri. Since then, seismological measurement systems have continuously monitored the volcano. The Osservatorio Vesuviano continuously improves the network by applying state of the art technologies and research tools and methods.

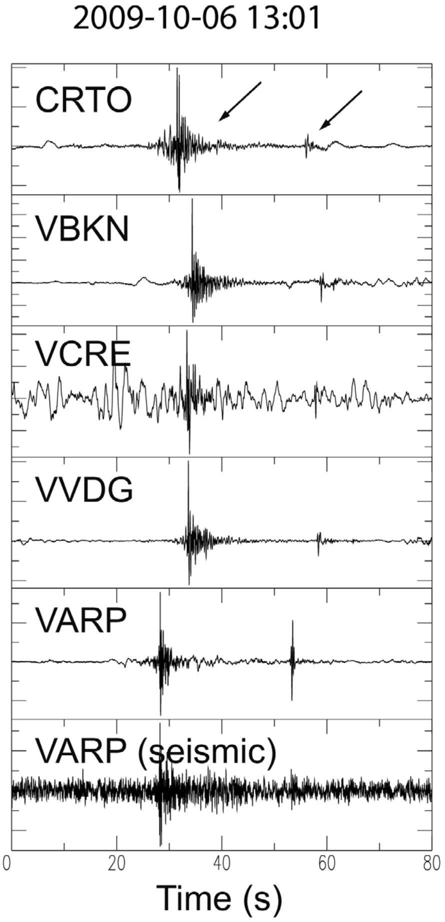


Figure 13. Infrasonic (top 5 traces) and seismic (bottom) signals of an event of unknown origin recorded on Vesuvius at 13:01 UTC on October 6, 2009. The arrows indicate two distinct phases in the infrasonic waveforms.

The most modern part is constituted by digital stations developed at the Osservatorio Vesuviano, GILDA data logger [Orazi et al. 2006, 2008]. This station was designed for low consumption, high dynamic range specifically devoted for remote installations. The use of this data logger allowed the installation of several stations close to the summit area. This led to important results for the volcano monitoring purposes. For instance, it allowed a better delineation of two seismogenetic volumes within the volcanic structure [Giudicepietro et al. 2010, D'Auria et al. 2013]. In addition, the completeness magnitude of the network was lowered down to 0 in the area below the cone at a shallow depth (500 m a.s.l.) as shown in Figure 3 (top right panel). Future deployment of borehole stations will further decrease the completeness magnitude of the seismic catalogue. The installation of the summit stations allowed also the identification and the characterization of several landslides that affected the crater walls.

The current seismic stations distribution allows to detect M = 2 earthquakes also in the area surrounding the volcano. Consequently the absence of a significant seismicity around Mt. Vesuvius can be stated. We have shown that the current network configuration would be able to detect changes in seismicity pattern, allowing an eventual reconfiguration of the monitoring system as a temporary network.

All the new installed stations are equipped with broadband sensors and GILDA data-logger. Consequently, not only the geometry of the network got improved, but also its frequency range sensibility. This allowed the first identification of a low-frequency earthquake. Such sensors can be potentially able to record seismo-volcanic signals like long-period events, which are known to be reliable precursors of volcanic eruptions [Chouet 1996]. The forthcoming installation of a 3D seismic array will provide also a valuable tool for the detection and location of possible sources of volcanic tremor.

The data transmission infrastructure is organized to be largely redundant by using different transmission systems (Wi-Fi, ADSL, UHF analog lines and UHF digital lines). To avoid as much as possible data loss, local acquisition nodes collect data of subsets of network stations. The current efforts are toward the improvement of the infrastructure robustness in order to allows its operation even in case of failure of one or more of its components. This is a critical aspect for a network designed to operate during a possible volcanic emergency. The development of a heterogeneous data transmission infrastructure has shown to be the best solution.

The development of the network and its infrastructure, has been accompanied by the parallel improvement of the automatic analysis system. All the data are collected and analyzed in real time by the Monitoring Centre of the Osservatorio Vesuviano. The expert staff which is constantly in contact with the Italian Civil Defense Authorities supervises the outputs of the automated systems. All the output parameters are available to the public at http://sismolab.ov.ingv.it/sismo/index.php.

The future development of the network will be supported by quantitative numerical tools devoted to the realistic simulation of a wide range of seismo-volcanic signals. These simulations will be used to check the improvement of the seismic network performances.

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