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# Integrating ambient noise with GIS for a new perspective on volcano imaging and monitoring: The case study of Mt. Etna

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ABSTRACT

The timely estimation of short- and long-term volcanic hazard relies on the availability of detailed 3D geophysical images of volcanic structures. High-resolution seismic models of the absorbing uppermost conduit systems and highly-heterogeneous shallowest volcanic layers, while particularly challenging to obtain, provide important data to locate feasible eruptive centres and forecast flank collapses and lava ascending paths. Here, we model the volcanic structures of Mt. Etna (Sicily, Italy) and its outskirts using the Horizontal to Vertical Spectral Ratio method, generally applied to industrial and engineering settings. The integration of this technique with Web-based Geographic Information System improves precision during the acquisition phase. It also integrates geological and geophysical visualization of 3D surface and subsurface structures in a queryable environment representing their exact three-dimensional geographic position, enhancing interpretation. The results show high-resolution 3D images of the shallowest volcanic and feeding systems, which complement (1) deeper seismic tomography imaging and (2) the results of recent remote sensing imaging. The study recovers a vertical structure that divides the pre-existing volcanic complexes of Ellittico and Cuvigghiuni. This could be interpreted as a transitional phase between the two systems. A comparison with recent remote sensing and geological results, however, shows that anomalies are generally related to volcano-tectonic structures active during the last 17 years. We infer that seismic noise measurements from miniaturized instruments, when combined with remote sensing techniques, represent an important resource to monitor volcanoes in unrest, reducing the risk of loss of human lives and instrumentation.


## 1. Introduction

Mt. Etna volcano (Sicily, Italy) is the highest volcano of the Eurasian plate (3343 m a.s.l.) and one of the most active in the world. Due to its persistent eruptive activity throughout the last century and its proximity to highly urbanized areas, it is highly hazardous and thus well monitored. Understanding its dynamics and imaging its shallow subsurface structures are considered a crucial step to be taken in order to develop an effective eruption-forecasting model and devise efficient responses to unexpected changes in its volcanological behaviour (Del Negro et al., 2013). Geophysical measurements and derived tomographic models contribute to the assessment of the physical state, shape, and dimension of feeding systems in volcanoes. Seismic ray-dependent travel-time and attenuation tomography generate 3D images of the inner structures of a volcano, and are increasingly becoming a standard imaging and monitoring tool (Lees and Lindley, 1994; De Gori et al., 1999; Patanè et al., 2006a; De Siena et al., 2010; Koulakov et al., 2010; Koulakov, 2013). At Mt. Etna, the first regional-scale travel-time and high-frequency attenuation imaging dates back to 1980 (Sharp et al., 1980). This was followed by local travel-time 3D velocity studies focused on imaging depths down to 20 km under the central portion of the volcano (Hirn et al., 1991; Cardaci et al., 1993; De Luca et al., 1997). Seismic images have steadily improved resolution on structures in the shallow part of the Earth (Patanè et al., 2002, 2003; De Gori et al., 1999; Patanè et al., 2006a; Alparone et al., 2012), in an attempt to monitor magma intrusions with time-resolved models (Patanè et al., 2006a). As of today, however, imaging of the volcanic cone is limited above 1 km a.s.l, with a resolution of 1 km (Alparone et al., 2012).

It is challenging to obtain high-resolution seismic images of a volcanic edifice. Seismic methods based on coherent-wave propagation are affected by site effects, highly-reflective topography, and complex 3D propagation effects. These corrupt both seismic phases and amplitudes, which are better described by stochastic models and

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resonance (Neuberg and Pointer, 2000; Wegler, 2003; De Siena et al., 2016, 2014). A full 3D imaging of these Earth layers is hindered by the lack of a dense seismic network, with node spacing of the order of e.g. 250 m (Kiser et al., 2016); this lack is due to the elevated economic costs, installation difficulty, high level of risk for operators when installing standard seismic stations, and has been used as a valid argument for the development of alternative geophysical imaging techniques in volcanoes (Carbone et al., 2014).

In this study, we try to close the gap between deep travel-time tomography imaging, surface geomorphology information, and shallow feeding systems modelling, using the Horizontal to Vertical Spectral Ratio (HVSR) method integrated with the Geographic Information System (GIS). The HVSR technique uses seismic ambient noise data recorded at a single station and has been developed in the framework of civil engineering to study resonance frequencies of buildings (Nakamura, 1989; Parolai et al., 2002). The method has already been used in Earth subsurface imaging, with applications spanning from the characterization of thermal basins (Galgaro et al., 2014) to the study of lateral heterogeneity in small alluvial valleys (Chávez-García and Kang, 2014). Surface waves (the main constituents of ambient noise) can reveal novel information about the structure of the volcanic edifice (Neuberg and Pointer, 2000). The method may thus represent the right complement to passive tomographic imaging, providing shallow geological information. Still, in volcanoes, the HVSR is generally used to measure seismic site effects only (Mora et al., 2001). Almendros et al. (2004) improve the HVSR method and apply it at Teide volcano. The authors estimate a time-dependent HVSR and create vibration frequencies maps across the summit area of the volcano. Merging their HVSR results with different methodologies and geological constraints they achieve an adequate interpretation of the shallow subsurface volcanic structures.

Remote sensing is an important alternative to seismic imaging when investigating the shallowest volcanic crust. Using DInSAR and GPS data to study ground deformation, it was possible to locate in space and time the position of the dike that produced the 2008 eruption of Mt. Etna (Currenti et al., 2011). Using GIS in combination with the HVSR method opens a path (1) to see beyond the shape and dimensions of the structures, for an improved correlation with geomorphological information; (2) to locate anomalies in space exactly and perform query to measure relevant quantities like volume, size, and extension of the anomalies (Barreca et al., 2013); (3) to precisely overlap any kind of map (thermal, tectonic, geological, tomographic, etc.), constraining the interpretation of the seismological results (De Siena et al., 2016). Mount Etna is one of the most studied volcanoes in the world, thus the perfect laboratory to test new methods to image the uppermost part of volcanic cones, with the aim of better predicting future shallow magma ascending path. The experiment of joint seismic and GIS data acquisition as well as the feasible automation of data collection and analysis via the development of smaller instrumentation (Middlemiss et al., 2016) will then represent a feasible resource for hazard assessment solution during volcanic crises.

## 2. Geological and structural background

Mount Etna volcano is considered a relatively young volcano with a developing process that started about 500 ka ago, in the Quaternary. The volcano is divided into 4 supersynthems and 8 synthems, according to the isotopic datation of De Beni et al. (2011). The actual shape of the volcano is the result of the last synthem ("Il Piano synthem"), begun around 10.4 ka ago. It has an extension of 47 km from North to South and 38 km from East to West and an area of about 1200 km$^2$.

The volcano is located at the boundary between the Calabro-Peloritan Arc (North) and the Hyblean foreland (South) (Branca et al., 2004; Lentini, 1982; Gillot et al., 1994). On the eastern shore of Etna (and Sicily) there is the " Malta-Hyblean escarpment", an important system of faults that extends uninterrupted from Malta to the Aeolian Islands passing through the Hyblean area (Fig. 1).

The Maltese-Hyblean-Aeolian faults system is considered the main discontinuity between the African plate (West) and the Ionian oceanic microplate (East) (Gvirtzman and Nur, 1999) as well as the major contributor to the volcano feeding system through an asthenospheric window (Lanzafame and Bousquet, 1997). The western sector, named by Patanè et al. (2006b) "Domain a" (Fig. 2), is characterized by faults and fractures with a prevalent NE-SW direction. The intersection of "Domain a", comprising NE-SW-oriented structures, and "Domain b" (Fig. 2), comprising NW-SE-oriented structures, creates discontinuities that are considered the main cause of magma uprising to the main craters (Patanè et al., 2006b).

## 3. Instruments and data

In this study, we combine geophysical techniques with information and communication technologies (ICT) and remote sensing. Seismic data were recorded by a single seismic station, which was moved in space in order to apply the HVSR technique. As ICT and remote sensing, we used a GIS environment, a tablet PC, and a GPS antenna. The first phase of the study has been the creation of the workspace inside the GIS environment. In the second phase, we acquired field data. Finally, data have been elaborated in a joint geophysics and GIS environment.

### *3.1. GIS and WEBGIS*

The setup of a workspace implementing a reliable coordinate system and including all available data from literature is a fundamental step to develop an accurate field work (Barreca et al., 2013). We chose an area of 10.5 km$^2$ located between 14.98° and 15.00° longitude E and 37.71° and 37.75° latitude N, spanning altitudes between 2281 m and 3265 m a.s.l. (Fig. 3).

The area was subsequently subdivided into 22 W-E oriented lines and 9 S-N oriented lines, with nodes spaced 250 m, giving an array of 21 rows and 8 columns. The intersections of these lines form 198 points. 37 of these points were cut off, due either to their proximity to the craters or to the time restrictions during acquisition, thus performed at a total of 161 points (Fig. 4).

To allow us to be more accurate on reaching the measurement points we created, for each point, 3 buffer circles at 5, 10 and 15 m, respectively. Two basemaps were added to the workspace as final step of the setup: a digital elevation model (DEM) of Mount Etna and a topographic map with a scale 1:10000 (Bisson et al., 2016). The workspace was then uploaded to a server in order to obtain a WebGIS, which is a combination of the WEB standards with geographic information system (Fu and Sun, 2010). Hence, we were able to use this online map operating on a portable device (tablet PC) and carry it to every measurement point. Due to the risk of losing connectivity, the map was also downloaded into the tablet local storage.

### *3.2. Seismic data collection experiment*

To reach the 161 points created during the setup phase we used a tablet PC with a CPU Quad-core 1.4 GHz Cortex-A9, 2 GB of RAM, and an internal GPS. This was supported by an external GPS antenna equipped with a chipset SiRF Star III, a 20 channels receiver, able to process signals from all the visible satellites GPS and WAAS, a frequency of 1575,42 MHz and a TTFF (Time to First Fix) lower than 1 s. We were able to see in real time our position in the field thanks to the connection to the WebGIS and/or the map available on the tablet

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