MONITORING THE CAMPI FLEGREI CALDERA THROUGH PASSIVE IMAGE INTERFEROMETRY

L. Zaccarelli[1], F. Bianco[2], M. La Rocca[2], D. Galluzzo[2]
[1] Istituto Nazionale di Geofisica e Vulcanologia, sezione di Bologna, Italy
[2] Istituto Nazionale di Geofisica e Vulcanologia, sezione di Napoli, Osservatorio Vesuviano, Italy

Campi Flegrei caldera. The Campi Flegrei caldera is an active volcanic complex located in the southern Italy. The caldera includes a very densely populated area, as well as the western suburbs of the city of Naples. Its formation dates back to the occurrence of two major collapses: the Campanian Ignimbrite (39 ka), and the Neapolitan Yellow Tuff (15 ka) eruptions. In the followings volcanism continued and has been distinguished into 3 epochs of activity. After the last epoch a 3.4 ky of quiescence followed, and then the last eruption took place in 1538, generating the Monte Nuovo crater. The majority of the eruptive events has been characterized by high explosivity and was accompanied by pyroclastic density currents (Orsi *et al*., 2009). This kind of eruptive activity means that it is particularly important the understanding of the Campi Flegrei volcanic processes in order to delineate a realistic volcanic hazard in this areas. What makes it even more complex than in other volcanoes is the existence of a very active hydrothermal system inside the caldera, which causes major deformations such as bradiseismic episodes. As sake of example the 1982-84 events generated 180 cm of maximum uplift and was accompanied by more than 16,000 earthquakes (with low-medium magnitudes, the more energetic events was a M = 4), centered in the Pozzuoli town (Aster *et al*., 1992). In the last decades the constant subsidence of the caldera have been interrupted by four minor uplift episodes in 1989, 1994, 2000, and 2005-2006. The general pattern is that the resurgence phases are accompanied by seismicity occurrence, while the subsidence is an aseismic phenomenon (Saccorotti *et al*., 2001). Thanks to the installation of a broadband seismic network in support of the permanent short-period monitoring stations, during the last ground uplift it has been possible to distinguish and analyse also some Long Period events among the Volcano Tectonic seismic swarms (Saccorotti *et al*., 2007).

After 2005, the ground started a new uplift phase that has been accelerating ever since, possibly indicating the early signs of a new period of volcanic unrest at Campi Flegrei (Chiodini *et al*., 2012). In the three years period between January 2010 and December 2012 (which the present study is referred to), the Campi Flegrei experienced a low velocity uplift of 6 cm and, generally a low rate of seismicity, with some low energy seismic swarms. In particular, on March 30th 2010, a 147 volcano tectonic events swarm was recorded. The entire swarm occurred in the Solfatara area in a depth range between 1 and 2 km, with a maximum magnitude 1.2. During 2011 a low rate of very low energy seismicity occurred again mainly in the Solfatara area. The rate of seismicity increased during 2012. In particular, on September 7th 2012, a seismic swarm of several thousands events (maximum magnitude = 1.7) struck the area westward to Pozzuoli and la Solfatara, affecting the first 4 Km of the crust. It is remarkable that, the higher velocity values for the uplift (in the range [1.5 - 3] cm/month) have been recorded in the period July - August 2012, just before the occurrence of the September swarm. The compositions of the fluid analysed in the area, shows a magmatic content that appears to be increased in the analysed period, as well as the spatial amount of degassing in the area aof Solfatara and Pisciarelli (just eastward of Solfatara). According to Chiodini *et al*., 2012, this phenomenology may be addressed to the occurrence of repeated magmatic fluid injections in the hydrothermal system. Moreover, recently Amoruso *et al*., 2014, modeling the 2011 - 2013 accelerated uplift with a two sources model (in agreement with the ones proposed by D'Auria *et al*., 2012), suggested a predominantly magmatic unrest in 2011 - 2013.

From a seismological point of view, the Campi Flegrei area shows a spot activity. In this picture, it is particularly difficult to distinguish between unrests of magmatic or hydrothermal origin, especially because at this stage the volcano is quiescent and few data are available during the recent unrests. It would be therefore necessary to develop a seismic investigation that is not depending on the availability of earthquake data.

Passive Image Interferometry. Passive Image Interferometry is a technique, which bases its origin in Aki studies on microtremors (Aki, 1957), but it has been mainly developed in very recent times since the availability of long continuous seismic recordings. It affords the seismic analysis from a completely new point of view: the objects of the study are the whole continuous recordings instead of their short cuts around the seismic events. This constitutes a great advantage because we dispose of data to be analyzed independently on the earthquake occurrences. The principle at the base of this technique is that cross-correlating the seismic noise recorded at two different stations we obtain a function that is related to the Green function of the medium between the two station locations (Lobkis and Weaver, 2001). To obtain the exact reconstruction of the Green function we need a homogeneous noise field in space and time (Campillo, 2006, and references therein). In Earth sciences this assumption holds, as a first approximation, if we are dealing with the noise generated by the oceanic waves. Although these noise sources are not uniformly distributed on the surface, and even if they experience very large seasonal variations (Landes *et al.*, 2010), the Green function's reconstruction may be acquired thanks to:i) multiple scattering (scatterers act as secondary sources; Derode *et al.*, 2003); ii) time-reversal (i.e. taking long time series; Stehly *et al.*, 2006); iii) reciprocity between sources and receivers (i.e. a dense network may overcome the lack of noise sources; Paul *et al.*, 2005). These properties of the ambient noise cross-correlations have been used to get the Rayleigh wave (Shapiro *et al.*, 2004), as well as the P wave arrivals (Poli *et al.*, 2012), then to acquire tomographic images of the Earth crust (Shapiro *et al.*, 2005).

Anyway, since we apply an interferometric technique, searching for temporal variations of the cross-correlation functions, it is not important the exact reconstruction of the Green function but the only requirement is the presence of quite stable noise sources (Hadziioannou *et al.*, 2009). Moreover we may overcome also the presence of non-isotropically distributed sources by cutting the central part of the cross-correlations since the source variations would affect the ballistic part of the signal, while the codas would be randomized by the effect of scattering (Froment *et al.*, 2010). Among the first studies of Passive Image Interferometry to monitor the crustal velocity variations, Brenguier *et al.* (2008a) could track the co-seismic drop of velocity and post-seismic relaxation of the crust along the San Andreas fault and during a period of time which included the occurrence of two major earthquakes (San Simenon M = 6.5, and Parkfield M = 6.0).

Applications to volcanic environments are more rare compared to faults. Sens-Schonfelder and Wegler (2006) firstly analyze the relative velocity changes occurring on Merapi volcano by finding out that the more superficial layers of crust (tens of meters in depth) were seasonally influenced by the rainfall. Brenguier *et al.* (2008b) firstly associated the relative velocity changes to the eruptive activity by studying the Piton de la Fournaise volcano. This is probably the more studied volcano thanks to its alternation of quiescence phases and eruptions in very short times and the long record of data (Duputel *et al.*, 2009; Sens-Schonefelder *et al.*, 2014). On the contrary Colima volcano, which is very active as well, showed velocity variations only weakly associated with eruptive activity, probably reflecting the open state of the volcano during the 15 year period of study, while major changes were associated to large tectonic events (Lesage *et al.*, 2014). Finally Ueno *et al.* (2012) analyzed the seismic recordings from Izu peninsula and suggested a relationship between subsurface velocity changes and magma intrusion into the crust.

All these previous works depict a great variety of results demonstrating the high potentiality of Passive Image Interferometry technique applied to the volcanic areas, and its capability to discern the crustal changes related to (hopefully future) changes in eruptive activity, large earthquake occurrences, magma injections at depth… thanks also to the nonlinear elastic behavior of the soft and not well compacted material characteristic of the volcanic edifices.

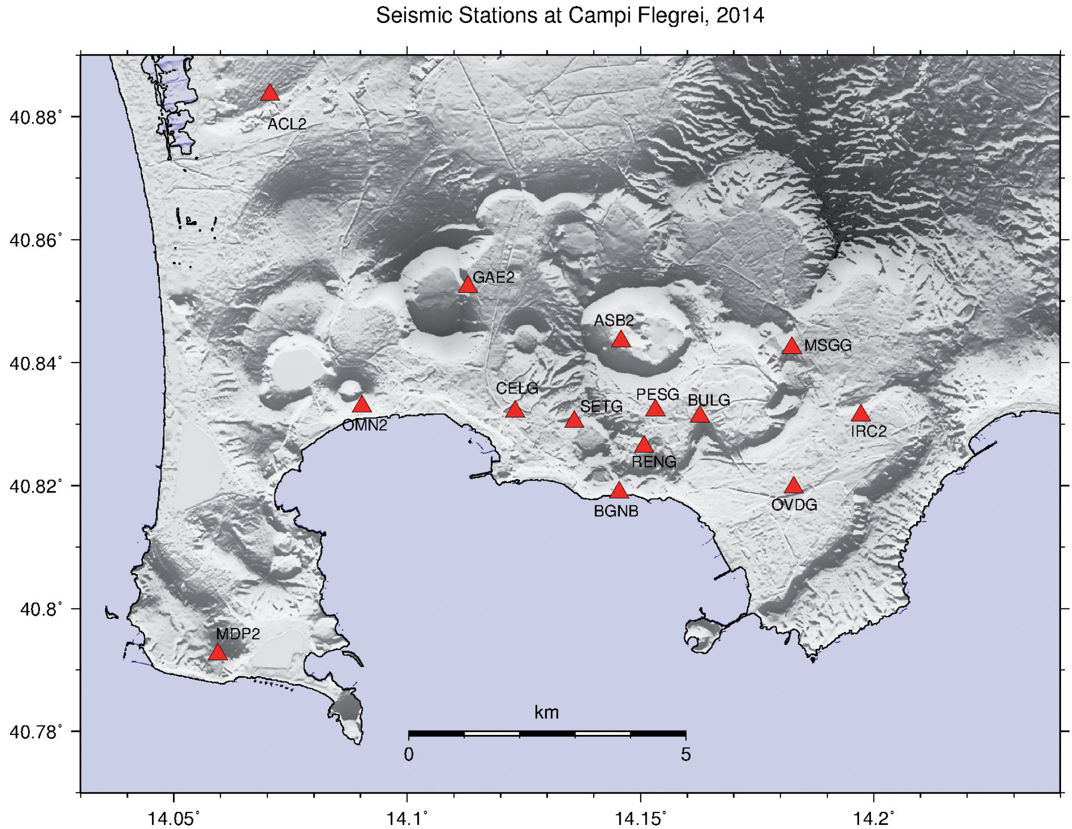

Fig. 1 – Map of the Campi Flegrei caldera. Stations used for this study are the 11 broadband velocimeters (red triangles), which were operating continuously since 2010 (see text for more details).

Campi Flegrei monitoring through Passive Image Interferometry. In Fig. 1 the broad band Campi Flegrei seismic monitoring mobile network operated during the three-year period between January 2010 and December 2012 is showed. We dispose of the continuous recordings from the following eleven broadband seismic stations: ACL2, ASB2, OMN2, BGNG, PESG, RENG, BULG, CELG, OVDG, SETG, MSGG. Sampling interval is 0.008 s for all stations, except for CELG, OVDG, SETG, stations that have a sampling interval of 0.01 s. The stations ACL2, ASB2 and OMN2 are equipped with Lennartz LE3D/20s sensors; stations BGNG, PESG and RENG are equipped with Guralp CMG 40T sensors; stations BULG, GELG, OVDG, SETG are equipped with Geotech KS200 sensors.

First of all we operate an instrument correction because the seismic stations have different acquisition systems with different responses. In fact, ACL2, ASB2, BULG, OMN2, PESG, MSGG and RENG stations are equipped with Marslite acquisition systems; BGNG and OVDG are equipped with M24 acquisition systems; CELG with a Reftek 130 and SETG with a Taurus acquisition system. The successive step is to synchronize the traces in order to avoid any delay between instruments that would be misleading. Our data manipulation includes the interpolation of gaps when these are shorter than the 20% of one hour. These is an arbitrary choice due to the fact that often seismic data recordings are affected by very short gaps in the data (on the order of some samples); in such a way we make the data as continuous as possible.

It is possible to isolate the oceanic noise source by filtering the signal in a frequency range between 0.1 and 1 Hz. Instead of a simple band pass filter we prefer to whiten the spectra of the time series in the same frequency band (Bensen *et al.*, 2006). Then it is important to cancel all high amplitudes due to transient phenomena since the object of the study is the wave phase. This may be acquired through a 1-bit normalization (Derode *et al*., 1999), which is a quite strong operation, but it has been demonstrated to allow reproducing the exact phase and amplitude information in the cross-correlation functions (Cupillard *et al*., 2010, 2011). Finally it is possible to cross-correlate all recordings grouped by couples of stations.

In order to perform an interferometric analysis it is necessary to define a reference cross-correlation function, which is indicative of the background state of the crust, and many current cross-correlation functions that have to be specific of different time periods. The easiest way is to define the reference function as the cross-correlation of the whole time series (or equivalently the sum of all 1-h cross-correlations, which is convenient in terms of computation times). After that, we find the time period, for the definition of the current functions, as a trade off between similarity and difference with the reference function. We chose this stacking period on the basis of the evolution of the correlation coefficient of the reference with respect to all current functions of increasing stacking length.

As Passive Image Interferometry technique we adopt the methodology described first by Poupinet *et al*. (1984): the Multi Window Cross-Spectral analysis. Their application was on doublet codas, and then Brenguier *et al*. (2008a) adapted this technique to the ambient noise cross-correlations. The details of the methodology are described also in Clarke *et al*. (2011).

We merge together all station couple information in order to obtain a more stable result (less dependent on the source variations). And finally we get a time series of the relative variations of seismic velocity of the medium inside the network and in a few km depth (depending on the penetration of the Rayleigh waves) at Campi Flegrei.

This study has been conceived for testing the resolution capability of Passive Image Interferometry in a volcanic environment at the time of very slight changes of the stress field, possibly also due to the hydrothermal activity in the shallower superficial layers of crust in response to deeper magmatic injection. We expect that the soft material and very plastic behavior of the Campi Flegrei area will emphasize the small variations occurring at depth, although we expect that the high level of noise of anthropogenic origin may complicate the results.

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