ANALYSIS OF TEMPERATURE TIME SERIES FROM THERMAL IR CONTINUOUS MONITORING NETWORK (TIIMNET) AT CAMPI FLEGREI CALDERA IN THE PERIOD 2004-2011

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The TIIMNet stations. The Thermal Infrared Monitoring Network (TIIMNet) is planned for continuous, long-term volcanological monitoring by acquiring daily infrared images (LWIR 8-14 ?m) of fumaroles fields in the Neapolitan volcanic areas monitored by INGV-Osservatorio Vesuviano. The network is made up of three stations located, respectively, at Vesuvius crater, inside the Solfatara crater and at Pisciarelli (Fig. 1; Vilardo et al., 2008).

The IR cameras used at Solfatara and Pisciarelli are NEC Thermo Tracer TS7302 with focal plane array (FPA) uncooled microbolometer measuring systems (320x240 pixel). The first one, operative since July 2004, acquires scenes of the SE inner slope of Solfatara at the intersection of two active, SW-NE and NW-SE main faults where are located the major fumaroles (Fig. 1a') at an average distance of about 300 m from the IR camera. The IR camera at Pisciarelli, operative since October 2006, acquires scenes of the outer eastern flank of the Solfatara tuff-cone (average distance of fumaroles is about 130 m), corresponding to an area characterized by heavy water vapor and CO_2 emissions (Fig. 1b'). Both IR cameras are inside a protective stainless steel housing, resistant to corrosive elements and with a shooting window of germanium glass, transparent to the thermal wavelengths; the cameras are connected to the Remote Monitoring Stations (RMS) which controls the shooting functionalities of IR sensors. The Control Unit, located at the surveillance center of INGV-Osservatorio Vesuviano in Naples, communicates with the RMS through GSM frequency network and it allows to configure times and shooting parameters and to run the automatic uploading of the remotely acquired thermal images. The IR camera used at Vesuvius is FLIR ThermoVision A40 (FPA uncooled microbolometer, 320x240 pixel) which has been operating since July 2011 and acquires scenes of the SW inner slope of Vesuvius crater. The camera, which is inside the same protective housing used for NEC cameras, is connected to a new RMS (Fig. 2a) with new and improved functionalities and more flexibility in respect of the old RMS used at Solfatara and Pisciarelli. The new RMS can be programmed to perform IR shots at prefixed times, with temperature and humid-

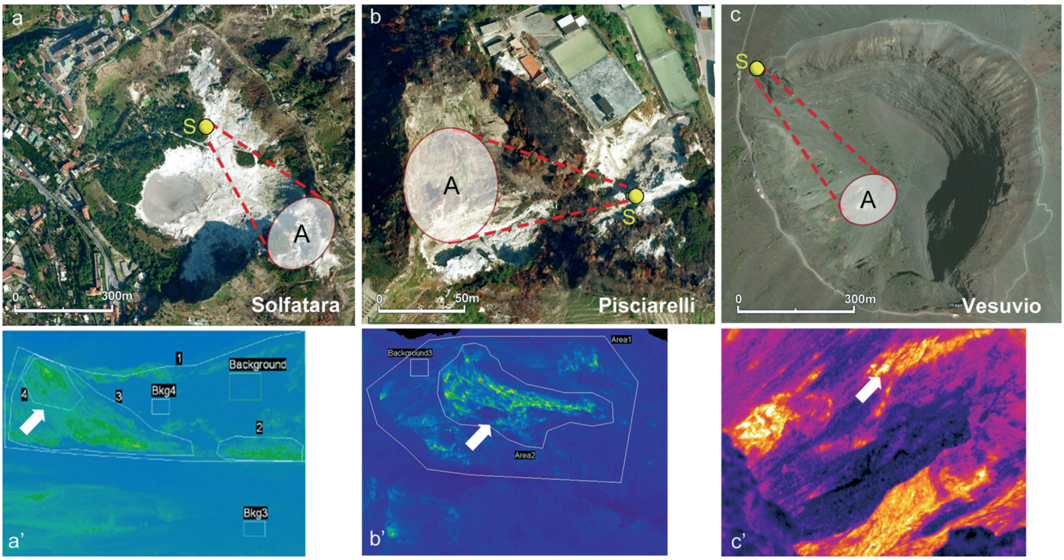

Fig. 1 – Location of TIIMNET stations at Solfatara (a), Pisciarelli (b) and Vesuvius (c) and related IR images (a', b', c'). A=area of acquired scenes; S=station. The white arrow shows the area of analysis.

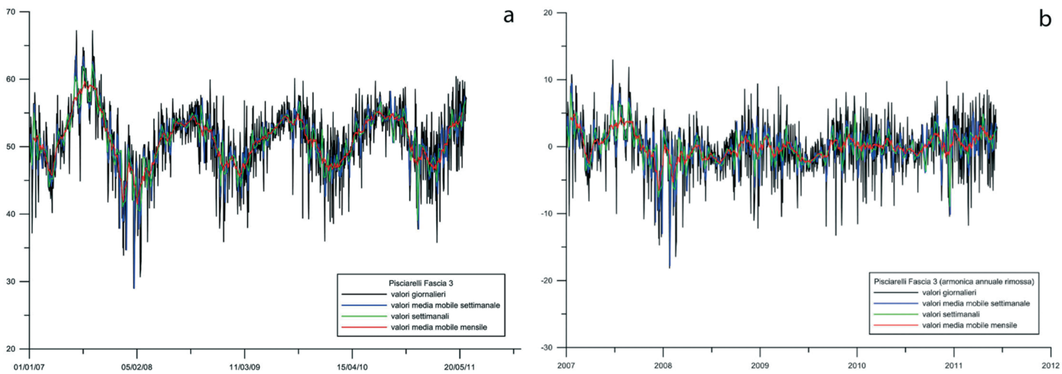

Fig. 2 – Frequency analysis of IR temperatures time series performed by FAMOUS. Plot a shows the raw IR temperatures time series; plot b shows the same IR temperature time series after the removal of the yearly harmonics.

ity corrections (using data from a T/h sensor), and to send the IR image by FTP to a specified host using Wi-Fi connection (accessible at Vesuvius crater). Whenever it is necessary and everywhere internet access is available, the IR camera can be switched on using the in-house developed ICARO software (Infrared Camera Automation for Remote Observation) whose user-friendly graphic interface allows to (a) configure and manage the camera, (b) perform real-time acquisition of IR images in several ways and (c) view and store the acquired images.

Correction and filtering methodologies. Time series of IR scenes obtained from the stations of Solfatara and Pisciarelli has been processed in different ways in order to obtain more accurate temperature values representative of surface temperatures of fumaroles fields.

The first investigation, performed just after the setting up of Solfatara station, was the in situ calibration of IR image data by comparing IR temperatures of a well identified target (mean temperature of 4 pixel of the IR image) to the temperatures measured by a K type thermocouple located on the same target. The results of comparison shown as the two sets of temperatures strictly followed the same time pattern with a excellent correlation (R_2=0.989) and suggested not to apply any correction to the rough data and to analyze the time series of IR temperatures in terms of relative temperature variations (Vilardo et al., 2008).

As second step, IR mean temperatures were merged in the same dataset with meteorological data in order to analyze the influence of environmental parameters (Chiodini et. al., 2007). As predictable, air mean temperature had a very good correlation coefficient (r=0.98) with the mean temperature of the IR scene (sky excluded); wind speed and pressure had a moderate correlation (r=-0.17 and r=-0.19) and relative humidity had no considerable correlation. In addiction a multi parametric regression analysis was computed (with mean IR temperature as dependent variable and meteorological parameters as independent variables): results showed about 96% of IR mean temperature variance is explained by air temperature. The very high correlation between air temperature and IR temperatures suggested to subtract IR temperature values of a background area from the IR temperature values of all the pixels of the same IR scene. This filtering operation, allowed to minimize the effect of environmental parameters on temperature values from IR image data, whose time variation does not exhibit the distinctive seasonal pattern due to the ambient temperature cycle (Ball et al., 2006). Recently more refined filters has been developed taking in account the trend of IR max temperature values of a selected fumaroles area and of IR max temperature values of a background area. Another significant feature which has been analyzed was IR image quality (i.e. sharpness, contrast, brightness, etc.). The Standard Deviation (SD) of IR images has been chosen as a good indicator of quality and it has been noted that the clearest images had highest SD values while the blurred, low-quality images were characterized by lowest SD values (Chiodini et. al., 2007). It has been observed that lowest SD values generally meant that there were a rainfall during image acquisition. On the other hand, too high SD values denoted scattering of IR temperature values due to enhanced air IR absorption caused by the presence of a larger plume of condensed steam in the fumaroles field (Sawyer et al., 2006; Furukawa, 2010). This remarks on meaning of SD values suggested to exclude from time series analyses the IR images whose SD values were outside a definite interval, differently determined for each area. It is noteworthy that images corrections and filtering are based on data contained in the image itself, making the procedures independent from the availability of external data.

Time series analysis performed. Two different ways to analyze time series of IR temperatures has been applied till now: a) a pixel by pixel regression of corrected IR temperatures (Chiodini et al., 2007) and b) a plot of corrected IR max temperature values versus time. Both methodologies of analysis allowed to evidence temperature anomalies in the analyzed areas and to depict a consistent representation of the temperature variations. The first methodology consists of a pixel by pixel regression of IR images background-corrected temperature values, averaged on a 10-day period. In order to exclude low-quality IR images, only scenes, whose SD values are included in a narrow SD interval, has been analyzed. As this methodology requires an accurate correlation between the pixels of different IR images, a cross-correlation analysis has been performed to carry out a co-registration of all images before computing the pixel by pixel regression. The results of regression has been mapped and evidenced the presence of some areas characterized by higher temperature increases and other areas which are being cooled. A plot of filtered temperatures of selected targets versus time has been also produced. The second methodology is based on an advanced background filtering of IR temperature values of a previously identified area of analysis. The data representation, using an average moving window applied to the filtered IR temperature time series, allow to show a pattern without the major seasonal cycle although it still contains minor cyclicity probably due to endogenous factors.

New developments in time series filtering and analysis. A further approach to time series filtering is based on the main periodicities removal performed by using the FAMOUS freeware software (Frequency Analysis Mapping On Unusual Sampling) developed by Francois Mignard, Observatoire de la Cote d'Azur-CNRS. This software is designed to find periodicities in time series irregularly spaced. The aim of this approach is to characterize the major periodicities affecting the temperature time series from IR images in order to remove them and to obtain filtered temperature series without cyclicity related to exogenous factors. An initial analysis has been performed on differently sampled IR temperature series by setting FAMOUS to search for almost three statistically significant harmonics. As preliminary result a yearly harmonic has been evidenced (Fig. 3a) and the plot obtained by removing this harmonic (Fig. 3b) do not show the typical seasonal trends of the plot not corrected. Other harmonics has been also evidenced by setting FAMOUS differently and further work is turning towards the significance of all the identified harmonics and the comprehension of each phenomena could be the source of them.

Final considerations. The filtered values obtained with the described methodologies of analysis has been compared to values from ground deformations and geochemical data (i.e. CO_2 flux and CO_2/CH_4 ratio). It is very interesting to note how the patterns of time series of these parameters are often similar to the pattern of IR temperature time series. In particular at Pisciarelli, the variation of ground level and of CO_2 flux have shown the same behavior of the variations of IR temperature series analyzed and filtered with the described methodologies. This evidences induce to continue in improving the methodologies of IR temperature time series analysis and filtering as it is proved to be a suitable tool for volcanic surveillance.

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