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The automated infrared thermal imaging system for the continuous long-term monitoring of the surface temperature of the Vesuvius crater

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ABSTRACT

Infrared remote sensing monitoring is a significant tool aimed to integrated surveillance system of active volcanic areas. In this paper we describe the realization and the technological evolution of the permanent image thermal infrared (TIR) surveillance system of the Vesuvius volcano. The TIR monitoring station was installed on the Vesuvius crater rim on July 2004 in order to acquire scenes of the SW inner slope of Vesuvius crater that is characterized by a significant thermal emission. At that time, it represented the first achievement all over the world of a permanent surveillance thermal imaging system on a volcano. It has been working in its prototypal configuration till May 2007. The experience gained over years about the engineering, management and maintenance of TIR remote acquisition systems in extreme environmental conditions, allows us to design and realize a new release of the TIR monitoring station with improved functionalities and more flexibility for the IR image acquisition, management and storage, which became operational in June 2011. In order to characterize the thermal background of the Vesuvius crater at present state of volcanic quiescence, the time series of TIR images gathered between July 2004 and May 2012 were analyzed using a statistical approach. Results show no significant changes in the thermal radiation during the observation periods, so they can be assumed as representative of a background level to which refer for the interpretation of possible future anomalies related to a renewal of the volcanic dynamics of the Vesuvius volcano.

1. Introduction

Seismic and ground-deformation monitoring networks have been the main surveillance networks at volcano observatories for many decades. In the last years, advances in remote sensing for studies of volcanic activity made data from ground-based, airborne and spaceborne sensors an essential component of a volcano surveillance systems [e.g. Ernst et al. 2008].

Among the several new remote sensing techniques for volcano monitoring, ground-based thermal image data collection has proved to be particularly useful to investigate quick processes associated to volcanic eruptions such as: lava flow fields evolution, lava dome activities, morphological variations at vents, opening of eruptive fissures, crater floor collapses, and pyroclastic flow deposit emplacement and cooling. A comprehensive overview of the use of infrared thermal cameras at active volcanoes can be found in Spampinato et al. [2011].

Applications of infrared thermal cameras in combination with geophysical and geochemical signals have also demonstrated that qualitative use of thermal images is essential for prompt real-time evaluation of eruptive scenarios and for hazard assessment [Spampinato et al. 2011]. In order to quantify and constrain the variety of parameters related to volcanic processes, the main requirement of a ground-based IR monitoring system is to retrieve quantitative information from continuous IR data recorded by permanent installations [Chiodini et al. 2007, Spampinato et al. 2011]. This is particularly efficient to improve the understanding of volcanic processes affecting low dynamics quiescent volcanoes which can release large amount of energy by diffuse degassing in restricted areas, commonly associated with regions of high permeability due to faults and fractures [Chiodini et al. 2001].

The energy dissipated by hydrothermal and volcanic gaseous emissions is an important component of the energy balance of the volcanic system [Chiodini et al. 2005, Chiodini et al. 2007]; therefore, multi-temporal acquisition of thermal spatial data can provide information about temperature changes, opening/closure of fumaroles and their migration, which in turns provide insights into the subsurface processes occurring in magmatic and hydrothermal systems.

The continuous collection of thermal images by permanent installation allows to develop methodolo-

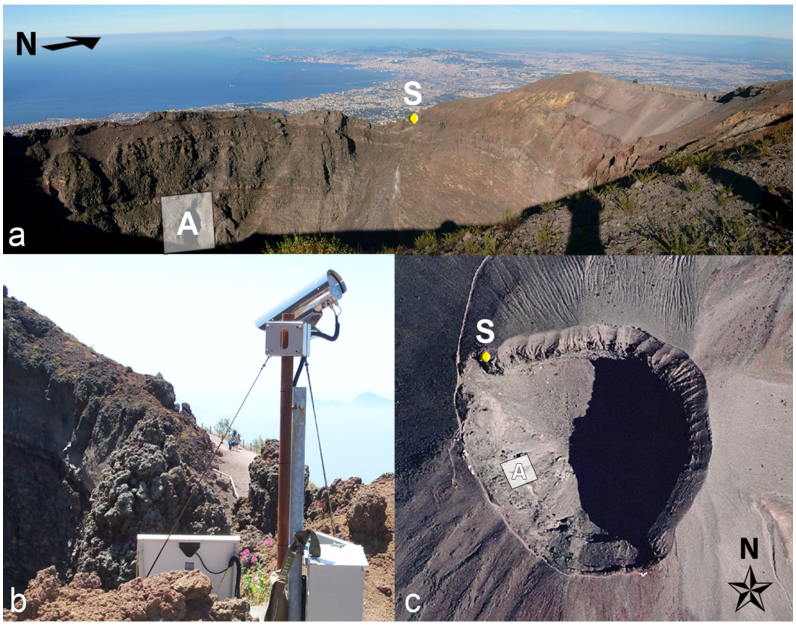

Figure 1. a) View from eastern rim of Vesuvius crater: b) ICARO station installation; c) top view of Vesuvius crater. S = ICARO station location, A = area acquired by IR camera.

gies aimed to avoid most of the problems related to influences of external factors (e.g. emissivity and surface roughness of target, viewing angle, atmospheric effects, path length, presence of volcanic gas, etc) on the radiation detected by the thermal camera [Chiodini et al. 2007]. A long period IR images time series analysis allows to quantify the influence of seasonal temperature variations on the thermal heat released from fumarole areas and to perform the seasonal trend removal in order to highlight any long and short-term subtle temperature variations of the source [Chiodini et al. 2007, Sansivero et al. 2011, Sansivero et al. 2012].

We present herein a description of the surface temperature monitoring system at Vesuvius. In the first part of the paper we described the technical aspects of the IR acquisition system and of the remote control system. In the second part of the paper the entire IR data set is analyzed with the purpose of evaluating the main thermal features of the monitored scene at the Vesuvius crater in the observation period.

2. Geological outline

The Somma-Vesuvius is one of the world most dangerous volcanoes, as more than 600,000 people live within 10 km of the crater and the big town of Naples is only 15 km far. It is a stratovolcano consisting of a recent edifice, the Vesuvius Cone, grown within a summit caldera of the older Mt. Somma volcano. The volcano is located at the intersection of NW-SE, and NE-SW trending, oblique-slip faults, and E-W trending normal faults [Bianco et al. 1998, Ventura and Vilardo 1999a].

In the last 22 ka Somma-Vesuvius volcanic activity produced four high-magnitude, plinian eruptions (Pomici di Base, Pomici di Mercato, Pomici di Avellino and A.D. 79 Pompeii eruptions) and almost four subplinian eruptions and intense low-intensity strombolian and effusive activity. In the period between Avellino eruption (3.9 ka B.P.) and A.D. 79 Pompeii eruption at least eight explosive eruptions from subplinian to violent strombolian occurred. After A.D. 79 the activity became more frequent and discontinuous open-conduit strombolian to violent strombolian activity alternated to the A.D. 512, A.D. 472 and 1631 subplinian eruptions. Summit or lateral lava effusions and semi-persistent strombolian activity prevailed in the most recent period (1631–1944) characterized also by several violent strombolian and poly-phased eruptions like the 1906 and 1944 ones [Santacroce 1987, Cioni et al. 1999, Santacroce et al. 2005, Cioni et al. 2008].

At present time Somma-Vesuvius is quiescent and only seismic [Saccorotti et al. 2002, Del Pezzo et al. 2004] and fumarole activity occurs. The degassing manifestations at Vesuvius are concentrated in the crater area [Caliro et al. 2011]. Fumaroles from the crater bottom have a composition that shows H_2O and CO_2 as the major components and discharge temperature of about 95 °C. Fluids discharged by fumarole vents placed over the crater rim have relatively low temperatures (<75 °C) and are mainly composed of atmospheric components.

3. The first prototype of TIR remote monitoring system

The TIR monitoring system has been conceived in order to meet the requirements of continuous long-term volcanological surveillance in extreme environmental conditions as those affecting the top of the Vesuvius crater. The station was located on the north-western sector of the Vesuvius crater rim (Figure 1) and the IR frame includes part of the south-western inner slope of the crater, which show significant thermal anomalies.

The engineering of the whole surveillance system, started in 2003, has been characterized by heavy technological integration and development of specific tools that has not previous noteworthy example to refer to. The prototype system was operative from July 2004 till May 2007 and consisted of: a) a infrared camera (NEC Thermo Tracer TS7302) placed inside a protective stainless steel housing, with uncooled focal plane array (FPA) measuring systems (microbolometer technology, 320×240 pixel) that operates in the spectral range from 8 to 14 μm across a 29° (H) × 22° (V) FoV; b) a permanent Remote Monitoring Station (RMS) with remote control of the camera calibration shooting functionalities and upload of IR image; and c) a Control Unit that manages the system by setting the session parameters through a communication system based on a primary transmission system via GSM frequency network and an emergency system based on radio frequency network. The control unit also runs the automatic uploading of the remotely acquired thermal images in NEC proprietary graphic format (.sit) and performs a real-time data conversion in digital ASCII matrix used for further processing.

The time taken for a complete cycle of IR acquisition, including upload to Control Unit, was of about 12 minutes.

This instrument system, which was at the forefront when it was conceived, has shown over time some criticalities which could be grouped into the technical and the environmental ones.

The main technical criticalities are due to RMS development:

a) the acquired image is temporary stored and downloadable by the control unit till another acquisition is performed. If data transmission errors occurs between two IR scene acquisitions, the older image is permanently lost as new acquired image erase the older one;

b) no temperature, distance and humidity corrections can be made on the acquired IR scene as thermal camera doesn't allow it;

c) no real-time control of camera and shooting operations are possible with RMS;

d) IR acquisition and transmission to Surveillance Centre is a time-expensive procedure (it takes about 12 minutes);

e) the setting of shooting parameters (i.e. emissivity and distance) and camera internal clock, is only possible by a direct connection to camera. This implies the removal of IR camera from the protective housing;

IR detector	Focal Plane Array (FPA) uncooled microbolometer
Resolution	320×240 px
Thermal sensitivity (50/60Hz)	80 mK @ +25°C
Spatial resolution (IFOV)	1.3 mrad
Spectral range	7.5 to 13 μm
Accuracy	± 2 °C or 2% of reading
Focal ratio (24° lens)	1.0

Table 1. FLIR A40 technical specifications.

f) any hardware update to RMS is very hard due to its very poor modularity;

g) data transmission is possible only by using GSM network or a radio-modem and RMS doesn't allow cabled or Wi-Fi fast connections;

h) control unit and RMS software are not in-house developed and any little change implies to contact the developer spending time and resources.

Concerning environmental criticalities, these are related to the extreme weather conditions of instrumentation operability. As a consequence, the Vesuvius TIR imagery strongly suffers of bad IR scene quality related to the cloudily weather conditions which frequently affect the top of the volcano (the station is located at 1,165 m a.s.l.). The Vesuvius monitoring station was also affected by problems related to the electrostatic discharges from lighting that damaged electronics of both the RMS and the thermal camera and by the failure of the washer impermeability of the protective housing containing the thermal camera.

4. The new TIR remote monitoring system: ICARO

In order to solve the most critical technical issues and improve the flexibility of the entire instrumental chain, as well as to make any future upgrade easy, a new remote monitoring station was developed and installed at Vesuvius crater on July 2011. The new remote station at Vesuvius, named ICARO (Infrared Camera Automation for Remote Observation), consists of a new IR camera and an in-house developed Remote Monitoring Station (RMS) which operates a fully real-time control of data acquisition functionalities and transfer procedures.

The IR camera used at Vesuvius is FLIR ThermoVision A40 positioned inside a stainless steel protective housing with a shooting window made of germanium glass. FLIR A40 camera specifications are shown in Table 1.

The camera has also a RJ-45 Ethernet connection and the firmware allows air temperature and humidity corrections before the acquisition and guarantees compatibility with ThermoVision System Developers Kit

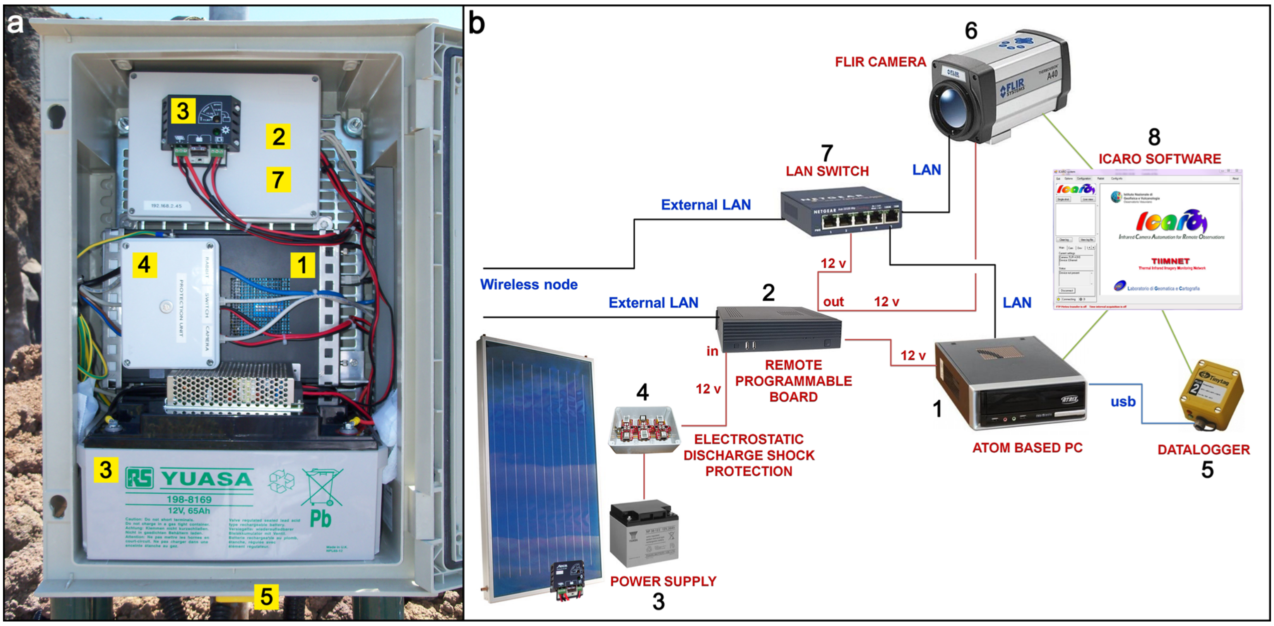

Figure 2. ICARO Remote Monitoring Station at Vesuvius (a) and the related logical scheme (b).

(SDK) which provides full access to camera measurements using Windows ActiveX and MS .Net programming environment.

4.1. The Remote Monitoring Station (RMS)

The RMS is made up of several components whose task is the acquisition of IR images and their uploading to the Surveillance Center. A detailed scheme of RMS components is reported in Figure 2.

The RMS is composed of:

1. An Atom based mini-ITX PC (Figure 2, no. 1) running the ICARO acquisition software on a Windows XP O.S.

2. A Remote Programmable Board (RPB; Figure 2, no. 2) which is continuously connected to the Surveillance Centre of the Osservatorio Vesuviano (Italian National Institute of Geophysics and Volcanology, Naples section) by Vesuvius wireless node and manages the power on of all components on request or at fixed times.

3. A power supply system composed of a battery, a Solar panel and a DC voltage controller (Figure 2, no. 3).

4. An electronic protection of external connections to shocks due to electrostatic discharges from lightings during thunderstorms (Figure 2, no. 4).

5. A USB datalogger (mod. TinyTag; Figure 2, no. 5) for air temperature and humidity measurements.

6. The IR camera (FLIR mod. A40; Figure 2, no. 6) with LAN connection.

7. A LAN switch to connect PC and IR camera to the Osservatorio Vesuviano Surveillance Centre by using Vesuvius wireless node (Figure 2, no. 7).

The procedures for IR image acquisitions consist of the following phases:

a) on the basis of programmed times for IR acquisition, the RPB switches on the Atom PC, the IR camera and the LAN switch;

b) the Atom PC connects to TinyTag datalogger and acquires air temperatures and humidity values;

c) the ICARO software (Figure 2, no. 8) running on Atom PC connects to IR camera and configure it with all necessary parameters including the acquired air temperature and humidity values;

d) the IR camera acquires IR scene which is stored on Atom PC;

e) the ICARO software on Atom PC connects to the Osservatorio Vesuviano Surveillance Centre by Vesuvius wireless node and upload IR image data just acquired;

f) the ICARO software uploads daily temperature and humidity data to Surveillance Centre servers and eventually downloads new configuration to use for next IR image acquisitions;

g) when all acquisition procedures ended the RPB switches off Atom PC, IR camera and LAN switch and remains in stand-by mode ready for any request of connection from the Surveillance Centre or waiting to perform the next daily acquisition at the scheduled time.

The RPB allows also a real-time activation of the Atom PC and IR camera in order to acquire scenes on demand or reconfigure the system by using ICARO software or a Remote Desktop connection from any Windows PC.

The flow-chart of main station procedures is reported in Figure 3.

The RMS, in absence of any connection with the Surveillance Centre, can acquire data for months as it can rely on a large internal data storage capability.

Optionally, the station can be easily equipped with a conventional video camera which can transmit the analog signal using a video server hardware.

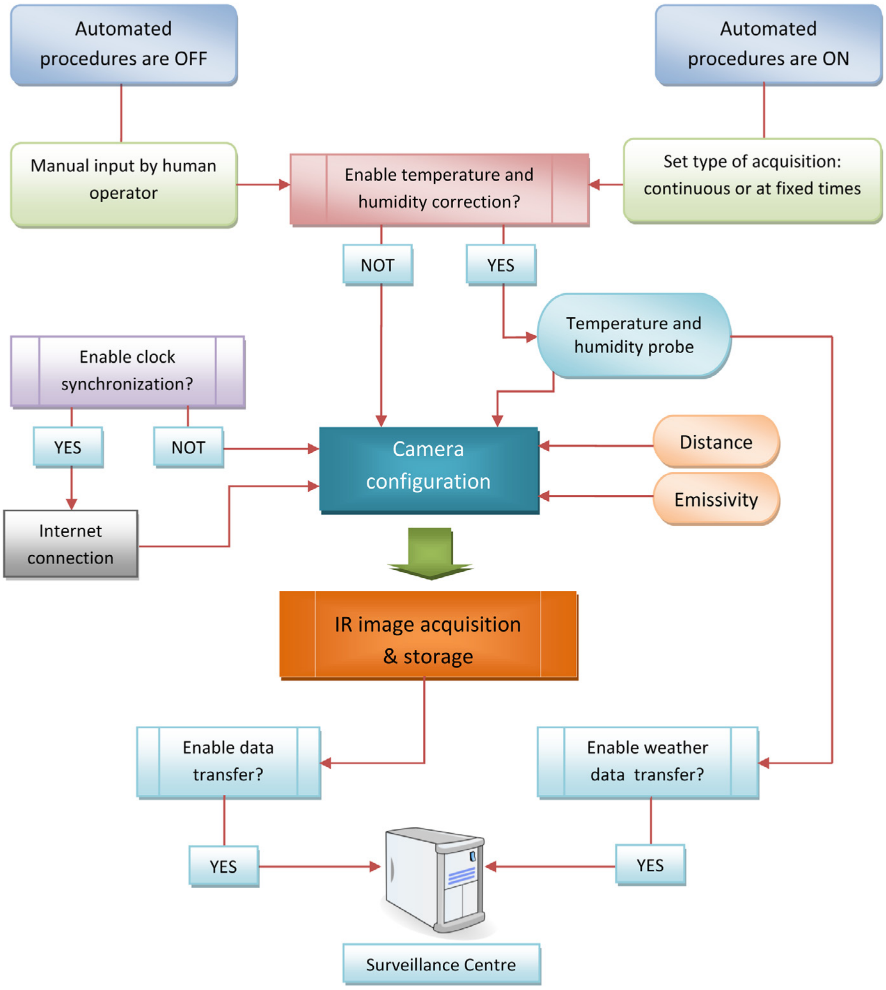

Figure 3. Flow-chart of ICARO station's main procedures.

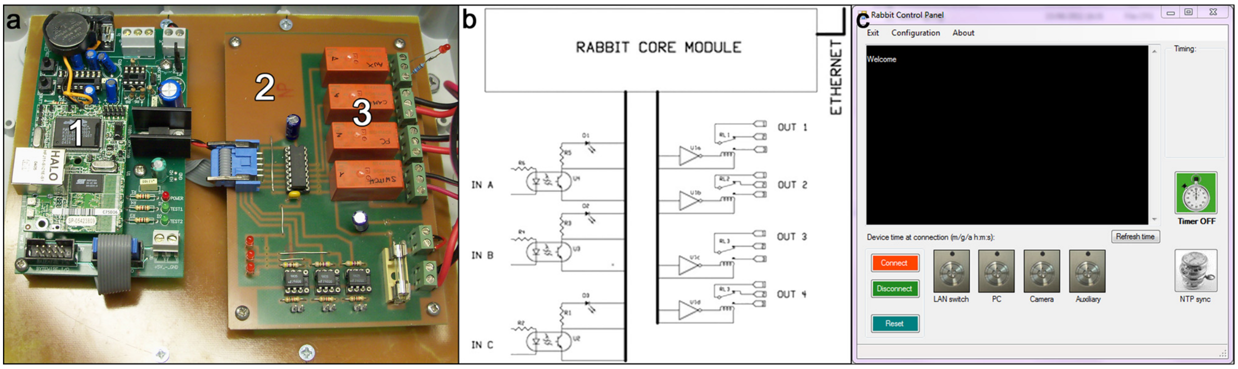

Figure 4. Remote Programmable Board (RPB). a) Processor board with Rabbit 2000 (1); secondary board with I/O lines controller (2); ULN2003A I/O relays on the secondary board (3). b) electric schema of I/O secondary board. c) RPB software control panel.

4.1.1. The Remote Programmable Board (RPB)

A key element of the acquisition system is the Remote Programmable Board (RPB). This component is equipped with Ethernet port, for the TCP/IP connections, and a control interface to manage the input/output lines. It consists of two logical sections (Figure 4a): 1) a programmable microcontroller card based on a series 2000 Rabbit processor board; 2) a secondary board controlling ULN2003A 4 relays capable of handling loads up to 5A.

The firmware inside the microcontroller allows to: a) configure a timer for no. 4 I/O lines on the secondary board (Figure 4a, no. 3); b) synchronize the timer with NTP clock or manually; c) turn on and off manually each I/O line; d) reset to default parameters.

The bootstrap phase initializes the I/O lines, as well as, the parameters needed to properly configure the Ethernet interface and start the server daemon, which will remain on hold to accept connections on a

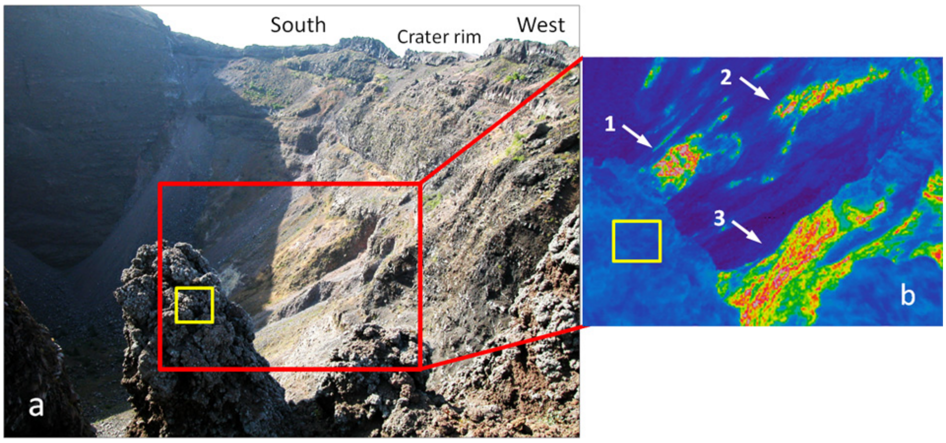

Figure 5. View from Northwestern rim of Vesuvius crater (a) and IR acquired image(b). The arrows point toward the areas affected by the thermal anomaly characterized by the most radiant pixels of the IR scene. The yellow box represents the background area used for the analysis.

particular TCP socket. When a connection is activated the RPB can switch ON/OFF the I/O lines by interpreting the user command. Commands can be send through a simple Telnet session or by using a the graphic UI of ICARO software (Figure 4c).

4.1.2. The ICARO acquisition software

The main purpose of ICARO acquisition software (Figure 2b, no. 8) is to automate the connection with FLIR infrared cameras by allowing the configuration of all the parameters necessary for the IR scene acquisition at established times or continuously. The software performs also TCP-IP transmission of acquired images from camera (or remote station) to any PC linked to the same network. As the connection with IR camera is by TCP-IP protocols, the software can run either on the remote station or on a local PC. A specific module of ICARO also performs the connection with a probe which measures external air temperature and humidity in order to configure the camera and correct these parameters before IR image acquisition. As ICARO implements totally automated procedures, it can work with or without interaction of a human operator.

	Distance (m)				
	10	**30**	**100**	**300**	**500**
NEC (prototype) Pixel size (mm)	16	48	160	480	800
FLIR (actual) Pixel size (mm)	13	40	133	399	664

Table 2. Pixel size of NEC and FLIR cameras *vs* viewing distance.

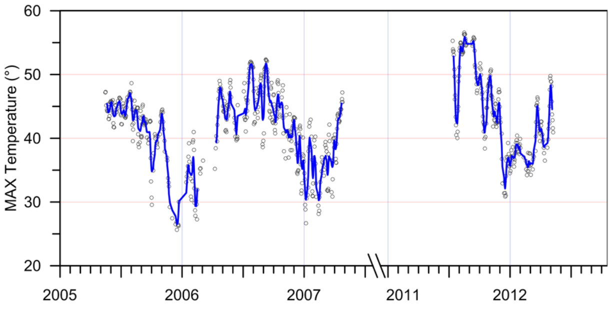

Figure 6. Chronograms of the maximum temperature of the whole scene. Circles and line represent one and two-pass 7 samples moving averaged time series.

5. Analysis of the TIR image series

The installation of the remote monitoring station at Vesuvius crater rim ended in the mid of July 2004. After tests performed on the whole system on April 2005 the systematic thermal imaging acquisition began. IR images were night-time collected with the rate of three images per night (acquisition time: 23:00, 01:00, 03:00 UTC). The scene that the station systematically acquires is shown in Figure 5 in both the visible and the spectral IR range. This scene includes part of the SE inner slope of the Vesuvius crater where most radiant pixels correspond to the location of the major surface thermal anomalies (Figure 5b, nos. 1, 2, 3) with the highest temperatures strongly clustered in the area no. 1 (Figure 5b).

The TIR image framing covers a viewing distance that ranges from 100 m up to a maximum of about 400 m, with the main thermal anomalies located at average distances from about 150 m up to 300m. The increasing viewing distance implies an increase in the pixel size as reported in Table 2 and consequently a decrease in spatial resolution.

In order to quantify temperature changes of the shallow thermal structure of the Vesuvius crater we consider the time variation of the maximum temperature values of the scenes acquired at 03:00 A.M. (Figure 6).

Due to the breaks in the image acquisition, related to the operation restoration, the whole TIR image dataset shows two gaps in the time series; the first from February to April 2006 and a much longer second one from May 2007 to July 2011. In spite of gaps in sampling, the chronograms of the maximum the IR temperatures shows a strong seasonal control due to the strict de-

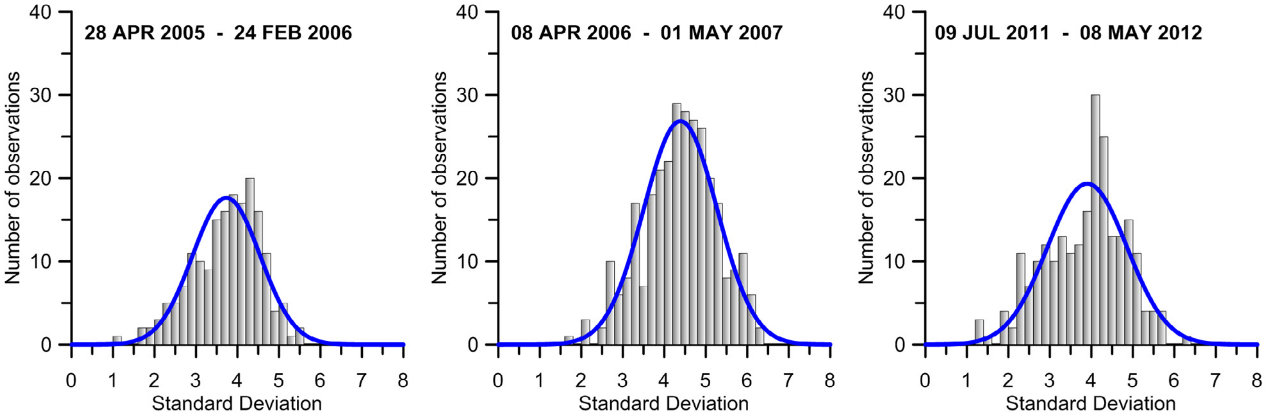

Figure 7. Standard deviation of the scene for the three different IR image time series.

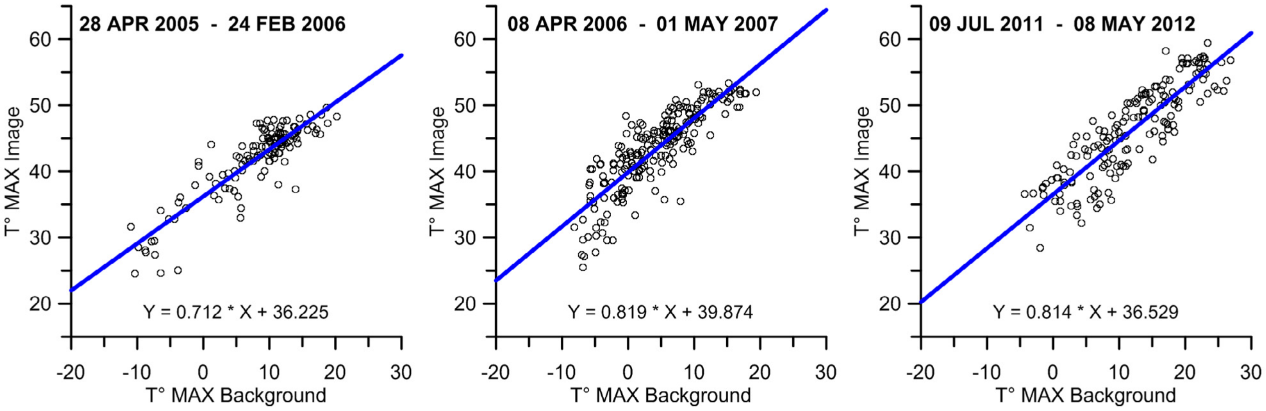

Figure 8. Scatter plots showing the correlation between the maximum temperatures of the scene (T_S) and the maximum temperature value of the background area of the same image (T_{BKG}), reported for the three different IR image time series.

pendence of the IR temperature on air temperature [Chiodini et al. 2007]. The chronogram in Figure 6 shows the lowest values in winter time and the highest ones in the summer season with maxima IR temperatures in the range 45-65 °C. An offset between temperature values extracted from images acquired by the former equipment (2005-2007) and those from the new ICARO system (2011-2012) can be detected too. It is due to the more reliable temperature values (in terms of absolute values) from IR image data acquired by ICARO monitoring system as it performs air temperature and humidity corrections before IR image acquisition.

In order to remove the dominant seasonal effect of environmental parameters on the time variation of the maximum temperature values of the scenes (Figure 6) and to better highlight possible temperature changes caused by variations in the endogenous source, a processing methodology was applied to time series of the considered thermal parameter extracted from the IR scenes. The methodology is aimed to remove or reduce most of the influences on IR radiation related to external factors (e.g. emissivity and surface roughness of target, viewing angle, atmospheric effects, path length, presence of volcanic gas, etc) detected by the thermal camera [Chiodini et al. 2007, Sansivero et al. 2012]. This methodology has been performed by taking into account, as first step, the quality (i.e. sharpness, contrast, brightness, etc.) of the IR scene.

As blurred and low-quality images are characterized by low or very high Standard Deviation (SD) values of the IR scene [Chiodini et al. 2007], the SD of IR images was chosen as a good indicator of quality. Generally SD outliers values meant rainfall during image acquisition or scattering of IR temperature values due to enhanced air IR absorption caused by fog or the presence of a larger plume of condensed steam in the fumaroles field [Sawyer and Burton 2006, Furukawa 2010].

The changes made to instruments operating on the field (e.g. IR camera or germanium glass) substantially affected the temperature values matrix, so the previously described procedure was applied to three separate IR image time series belonging to the three different acquisition periods: 1) from April 28, 2005, to February 24, 2006; 2) from April 8, 2006 to May 1st, 2007; 3) from July 9, 2011 to May 8, 2012.

First, in order to have a more homogeneous dataset, outliers were excluded by eliminating IR images whose SD values were outside the 2σ interval, as defined by

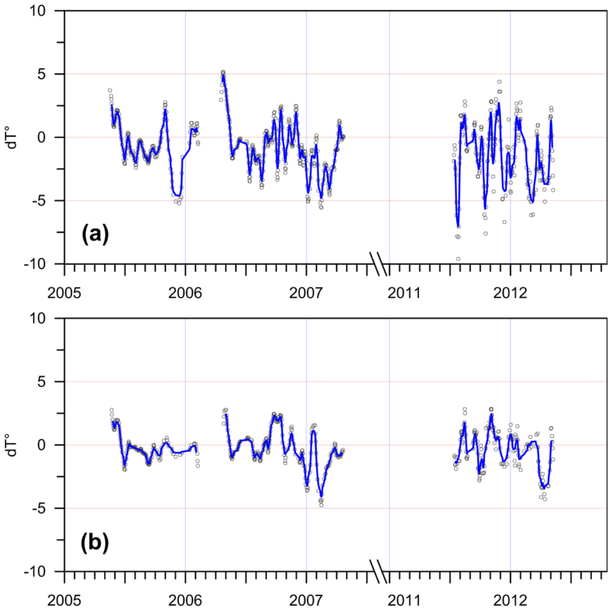

Figure 9. Relative temperature variations (dT) for 2σ (a) and 1σ (b) IR image time series. Circles and line represent one and two-pass 7 samples moving averaged time series.

Gaussian fit (Figure 7). As second step, to build up time series, only maximum temperature values of the IR scenes belonging to 2σ and 1σ interval has been taken in account. Then, a background correction was chosen among different methodologies of IR time series filtering of influence of environmental factors [Chiodini et al. 2007, Sansivero et al. 2012].

The background filtering procedure is a simple effective method in removing the seasonal pattern from the time series of IR temperature [Sansivero et al. 2012]. The correction that we applied is based on the high linear correlation observed between the maximum temperatures of the scene (T_S) and the maximum temperature value of the background area of the same image (T_{BKG}) (Figure 8). This linear relationship is due to the reliance of the temperature values detected by thermal camera on the ambient temperature [Chiodini et al. 2007]. The choice of the background area is critical: a necessary condition to correctly apply this method is that the background area must be carefully identified in the IR image as a region not affected by thermal anomaly due to variations of the endogenous source. At Vesuvius the background area is a sector of 25 × 25 pixels in the lower-left corner of the scene (Figure 5) and corresponding to a portion of a lava pinnacle located in an area of the crater rim not affected by any thermal emission.

After choosing the background area, the correction is based on the estimation of the parameters of the straight line that best fits the distribution of T_{BKG} *vs* T_S. In our case (Figure 8), these parameters of the linear relationship between T_S and T_{BKG} has been determined taking into account only images in the 1σ interval.

At the end, the correction is performed by subtracting to the maximum IR temperature values observed in each scene ($T_S(i)$) the expected values ($T_{LF}(i)$) estimated inserting $T_{BKG}(i)$ as X value in the equation representing the linear relationship between T_s and T_{BKG}.

The results of this filtering procedure are reported in Figure 9a,b in which, the time series of the temperature residuals values ($dT = T_S - T_{LF}$) , belonging to 2σ and 1σ interval respectively, are shown. In order to make long term trend clearer, the residual random noise has been further reduced by applying to the dT time series a moving average filter (two-pass on 7 sample).

The processed time series of temperature residuals (dT; Figure 9) no longer exhibit both the seasonal pattern and the offset between data acquired by different equipments which instead characterize the raw IR measured temperatures (Figure 6). Higher frequency fluctuations (with a nearly monthly periodicity) centered at zero value can be observed (Figure 9) with temperature residuals values strongly clustered in the +2°C interval (Figure 9b) without any evidence of long-term temperature trends.

Also the extension and position of the main thermal anomalies (Figure 5b) do not show appreciable changes in time as evidenced by the stable position of pixels with the highest temperature of the images belonging to the three different acquisition periods (Figure 10).

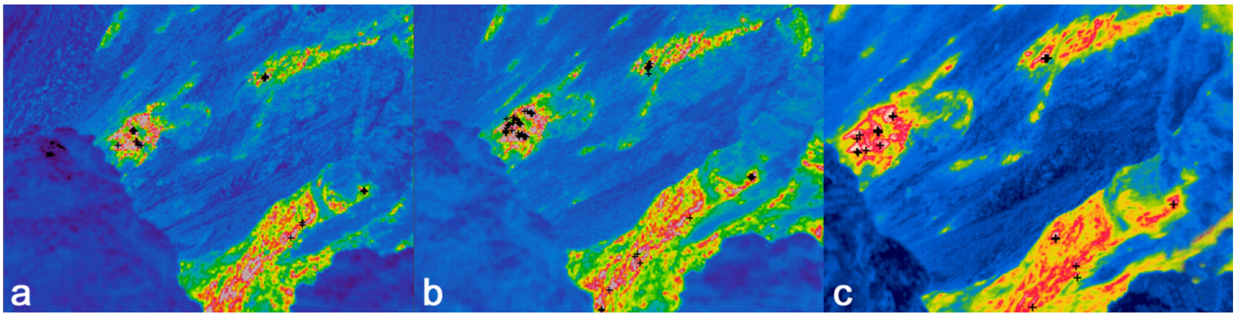

Figure 10. Location of the maximum temperature pixels (black crosses) of the three IR image time series belonging to the three different acquisition periods. Little differences between images a and b and the image c are due to change in camera type (NEC for a and b, FLIR for c image) and different software used to display IR image data.

The lack of evidence of both long-term temperature trends and variations in the extent or position of the thermal anomaly area fully agrees with geophysical and geochemical data [e.g. Ventura and Vilardo 1999b, Madonia et al. 2008, Giudicepietro et al. 2010, Caliro et al. 2011] which depict the present Vesuvius volcanic system as characterized by a very low level of activity.

6. Conclusions

The instrumental system for the continuous IR monitoring of the surface temperatures of the Vesuvius crater in 2004 has been a pioneering equipment without equals in the world. As a prototype, the system has show over time limits and criticalities mainly due to RMS technology and subordinately to environmental conditions. Some limits as the loss of data due to lack of connection with Surveillance Centre, the slow connection for data uploading, the absence of environmental corrections on IR images, and the weakness to counter weather bad conditions, have become over time a penalty for the system. The need for a more flexible and resistant instrumentation has given birth to a new station called ICARO (Infrared Camera Automation for Remote Observation) which was designed and engineered at the Osservatorio Vesuviano. The new monitoring system resolved most of the criticalities of the older one. It allows a fully real-time control of IR camera, of data acquisition settings and transfer procedures, with total access to the system at any time by using the ICARO software module. In addiction the correction of air temperature and humidity before IR image acquisition lets us minimize the influence of weather parameters over the quality of data.

Although the continuous monitoring suffered of two main gaps in acquisition, the analysis of the maximum temperature values detected in the IR image data acquired in the last seven years provided useful information on the present state of the Vesuvius volcano dynamics.

In particular, the chronogram of the temperature residuals (Figure 9) does not show any evidence of an overall temperature trend affecting the shallow thermal structure of the Vesuvius crater. As the observed soil temperature at surface is related to the flux rate of fumarole fluids [Chiodini et al. 2007, Cusano et al. 2008], whose variations are in turn related to changes of the deep source (the hydrothermal-magmatic system), the previous result suggests the absence of any significant anomaly in the Vesuvius volcano dynamics. In addition, the comparison of extension and position over time of the areas in the IR scene with highest temperature pixels do not evidence any significant change (Figure 10).

Higher frequency fluctuations with very low amplitude are observed in the time series of Figure 9, but further deep analyses are required in order to make hypotheses on the origin of this temperature modulation.

As concluding remark it is worth noticing that the results on the temporal pattern of the surface thermal features refer to a volcanic system characterized by a very low level activity and it is expected that even small future signals of a possible volcanic unrest will be detected by the thermal monitoring system.

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