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Remote sensing and interdisciplinary approach for studying volcano environment and activity

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Abstract

Remote sensing (RS), also known as "Earth Observation (EO)", is a well-established methodology for multidisciplinary applications and represents a neuralgic tool both for research and didactics, since it makes it possible not only to obtain very useful and interesting data and information but also to implement and make use of an integrated approach for collecting inputs from different sources, processing and interpreting them and presenting the results through a variety of multimedia outputs. That is obviously true also in the case of volcanic environments and activities, in the quiescence, activity and post-event phases. During the last years, the applications of satellite and aerial images, generated from data acquired in different spectral bands, namely in the visible, infrared and microwave parts of the electromagnetic spectrum, have enormously increased. Thus, in this paper, after a brief framework about some basic elements of remote sensing, we above all provide a literary review, underlying some important examples which permit us to develop interdisciplinary approaches and to highlight different fields of application. Then, after having provided some input in a didactic perspective, we synthetically describe the main peculiarities and kind of activities that characterise some volcanoes, for which the European Space Agency (ESA-ESRIN) has provided relevant images. Then, for each volcano, we propose an interpretive analysis of these images, supported by the previous explanations, in order to propose a possible scheme of referral and some guidelines to define a geographical and interdisciplinary framework aimed at showing new didactic and research horizons, where theoretical, methodological and applicative knowledge and skills converge, collaborating in a socially useful operative field.

Keywords: Remote Sensing, Satellite and Aerial Images, Interferometry, Volcanoes, Interdisciplinary Approach

1. Some basic elements of remote sensing

Images acquired in the Visible, Near- and Mid-Infrared spectral bands show the reflectance of solar light by the observed objects, on the Earth's surface in the case of a clear sky or otherwise from the top of the clouds, when the

Earth's surface cannot be observed; in the Thermal Infrared band images provide a thermal map of the surface observed, again terrain or clouds as the atmosphere is not transparent in the optical spectral bands. In the Microwave bands, instead, the radiation has a much longer wavelength and the atmosphere is basically transparent to radar pulses and return echoes. Therefore, radar images permit the observation of the Earth's surface in all-weather conditions and during the night: the information they provide is related to the object's surface roughness and electric properties, namely electric conductivity and humidity.

A very useful approach is the generation of multispectral images, where the information from different spectral bands is merged in order to increase the significance of the final product. That is very important for the visualization of the data: inserting data from different bands in the three electronic channels RED (R), GREEN (G) and BLUE (B) of a monitor, the interpretation of data is improved by taking into account the "spectral signature" of each object observed. For instance, by inserting into the RGB channels the data acquired in the red, green and blue spectral bands, respectively, the multispectral image offers a view of the observed scene very similar to the one our eyes would see from an aircraft flying over that scene and that band combination is called natural colours; any different one is called false colours. A very useful false colour image is the one where data from the Near Infrared spectral band is inserted into the RED channel of the monitor: in this case, vegetated areas appear in red, because leaves have a very strong reflectance in the Near Infrared band and very little in the Visible band (where the solar light is mostly absorbed by the photosynthesis). Similarly, in a multispectral image where data from different sensors are inserted in the RGB channels the final colours enhance the integrated characteristics of the observed objects as detected by each sensor.

Finally, data collected in the Microwave spectral band provides information not only on the intensity (amplitude) of the return signal (echo) but also on its phase: this information is not used to generate an image but is essential to define the distance between the radar and the object illuminated by the radar pulse. In fact, when data from Synthetic Aperture Radars (SAR) are acquired in consecutive passes, an accurate digital elevation model (DEM) of the area can be generated and its changes in time can be detected by processing the phases measured in the various steps: this method is called SAR interferometry (InSAR) and differential interferometry (DInSAR), respectively, through which terrain movements upwards and downwards can be detected and accurately measured.

This paper and the literary review which characterises its first part provides some basic elements that would help to better understand the potentialities of remote sensing in an interdisciplinary perspective and support which is here described in specific cases concerning various volcanoes, examined in the second part in a geographical, geophysical and geomatics framework.

2. Aerial and satellite images for studying volcanoes and their activities

As underlined in a previous work: "The photographs – which 'catch' and reproduce the image of a certain reality at a precise moment – offer us a faithful account of the physical and anthropic peculiarities of the area being investigated and can record any event of geographical importance. Their explicatory value becomes particularly evident during the studies in volcanic environments, as they act as an indispensable support to evaluate the geophysical-morphological evolutions, and to corroborate the considerations on the variations recorded at infrastructural dwelling level. A fundamental contribution can then be given by the photos taken from an airplane (or helicopter)", just as from satellite ones. The use of these images from very high up "is, for example, more and more frequent in the phases of quiescence or during the return of volcanic activity, insofar as they can give extremely useful pictures of the whole situation in a short time, rich in details, of areas that are difficult to access" (Giacomelli and Pesaresi, 2005, pp. 23-24).

So different researches have for example shown the applicative importance of aerial and satellite images for:

- the study of environment subject to seismic and volcanic events;
- the interpretative analysis of the territory and specific morphological aspects (which can be put in clear evidence with Radar Interferometry);
- the observation of sensitive areas due to the presence of faults;
- the monitoring of volcanoes and ground deformation;
- the evaluation of possible directions of lava and pyroclastic flows and volcanic ash clouds;
- the particular characteristics of the different phenomena emitted;
- the potential effects and social consequences of volcanic eruptions and earthquakes;
- a general quantitative evaluation, as support to statistical data, of people and buildings subject to risk in the case of a new volcanic event and in relation to the infrastructural and road system of the study areas;
- the land use change and vegetation regeneration.

For example Pergola et al. (2004) showed the importance of improving volcanic ash cloud detection by a robust satellite technique. In their work they asserted that "Automated and reliable satellite-based techniques are strongly required for volcanic ash cloud detection and tracking. In fact, volcanic ash clouds pose a serious hazard for air traffic and the synoptic (and possibly frequent) coverage offered by satellites can provide exciting opportunities for monitoring activities as well as for risk mitigation purposes" (p. 1). On the other hand: "Some volcanoes are carefully studied and monitored by means of specific ground-based measurement devices (seismic networks, gas emission measurements, SO_2 plume content, electric, magnetic and electromagnetic devices, etc). However, ground based surveillance systems can often be unsatisfactory and inadequate. The event to be monitored, in itself, may damage the instruments making them no longer usable. Moreover, a lot of volcanoes are located in inaccessible areas, therefore unreachable by the traditional, in situ surveillance techniques. Furthermore, such methods are absolutely inadequate to monitor large scale and rapid space-time dynamics phenomena like eruptive ash cloud spread and dispersion in atmosphere" (p. 1). Therefore, considering these problematic aspects and the social and economic relevance of having a detailed framework of the situation concerning the direction and density of volcanic ash clouds, it is easy to understand the necessity to experiment specific detection techniques able to provide updated information in near real time; therefore they underlined and discussed the strength points of a dynamic approach, with multi-temporal analysis of historical, long-term satellite records, and of a new ash cloud detection algorithm applied for two eruptions of Mount Etna (Italy) in order to test an innovative strategy of satellite data analysis.

In more recent years, Prata (2009) has shown as: "Remote sensing instruments have been used to identify, track and in some cases quantify atmospheric constituents from space-borne platforms for nearly 30 years.

These data have proven to be extremely useful for detecting hazardous ash and gas (principally SO_2) clouds emitted by volcanoes and which have the potential to intersect global air routes. The remoteness of volcanoes, the sporadic timings of eruptions and the ability of the upper atmosphere winds to quickly spread ash and gas, make satellite remote sensing a key tool for developing hazard warning systems" (p. 303). He concluded that "Vulnerability maps can be developed based on proxies for air traffic densities, which provide a good indication of the air traffic spatial habit. Atmospheric dispersion models are now capable of providing reliable forecasts of volcanic cloud movement for several days from the onset of eruption, provided good injection height information is available. The air traffic density maps, dispersion model runs, volcano locations and wind analyses provide the ingredients to develop scenarios for aviation/volcanic cloud encounters.

These scenario generators can be used for examining risks and vulnerabilities and for examining potential problems should HSCT [high-speed civil transport] aircraft become operational" (p. 321). Thus, the synergic integration between geotechnologies, as remote sensing and Geographic Information Systems (GIS), permit a very important interaction between collaborative fields of scientific research which can generate detailed and socially useful maps.

Corradini et al. (2010) underlined the interesting results which can be obtained from the comparison between the volcanic cloud SO_2 and ash retrievals derived from different instruments, to have a more specific and exhaustive framework in the case of volcanic events. For example "The Kasatochi 2008 eruption [Alaska] was detected by several infrared satellite sensors including Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Very High Resolution Radiometer (AVHRR), and Atmospheric Infrared Sounder (AIRS)" (p. 1) to conduct a rigorous analysis of the eruption.

As far as concerns the monitoring of volcanoes with the use of satellite images, in 2005 Pieri and Abrams used thermal infrared images for the observation of thermal anomalies preceding the April 2003 eruption of Chikurachki volcano (Kurile Islands, Russia) and these images showed "that thermal anomalies existed within the summit crater and on one flank of the volcano at least two months before the major explosive eruption in April 2003" (p. 91), giving interesting input regarding volcanic precursor phenomena and possible changes in the state of the volcano. It is worthy of note that in the same year, Tramutoli et al. conducted a study to assess the potential of thermal infrared satellite surveys for monitoring seismically active areas. They set out to propose an approach able "(at least) to exploit, on new scientific bases, already in place and incoming TIR [thermal infrared spectral range] satellite systems offering unique (global coverage, more than 20 years of historical records, high time repetition, low cost etc.) observational capabilities" which take on a very important role "considering the lack of observational systems (having similar space–time coverage) presently available for seismological studies and the lack of knowledge of the physical processes associated with earthquake preparation phases that makes it difficult even to identify the right parameters to measure in order to improve such knowledge and our capability to mitigate seismic risk" (2005, pp. 424-425). One year later, in the perspective of the use of remote sensing, and seismotectonic parameters, for geodynamic hazard analysis, Sitharam et al. (2006) showed the relevance of satellite images and remote sensing data in order to identify lineaments and risk elements in the Bangalore area (India). Thanks to the integration of the data concerning past earthquakes, seismotectonic maps, several field studies and the use of satellite remote sensing images, they evaluated the general situation of the study area and proposed a seismic re-classification of this area, suggesting a passage from current Indian Seismic Zone II to Seismic Zone III for Bangalore and its vicinity. Therefore similar works highlighted how as a rigorous and interdisciplinary use of satellite images can provide notable inputs both for volcanic and seismic events, in the prevention phase and in the study of possible precursor phenomena. Furthermore, satellite and aerial images can give an important added value also in the post event phase, for example in the delicate phases of: intervention planning; strategic choices for restarting; evaluation of strategies adopted in the first months immediately following the seismic events; identification of most damaged buildings, monuments and zones which continue to require particular attention. This kind of studies has been recently carried out in order to test a specific methodology and geographical tools for the study of territories damaged by the L'Aquila earthquake of April 6th 2009, after having conducted an overflight of the most damaged Abruzzi localities with equipment made up of photo and thermo cameras to obtain aerial images in both visible and thermal light (Pesaresi and Casagrande, 2012; Pesaresi et al., 2013).

Moreover, interesting aspects, regarding the monitoring of volcanic state of activity, had already been offered by Fernández et al. in 2003. In particular, they used satellite techniques for the measurement of ground deformation and showed the added value which can derive from the combination of remote sensing and GPS tools, with an exemplification in the volcanic Island of Tenerife (Canaries, Spain), showing another time the key role of geospatial technologies used in a synergic way.

In other cases, specific applications have made it possible to "examine the balance between the volume of magma supplied to the shallow volcanic system (using ground-based SO_2 data) and the volume erupted (using satellite thermal data)" (p. 47), as for example in the case of some eruptions of Mount Etna between 2002 and 2006, studied by Steffke et al. in 2011.

Furthermore, interesting projects have been carried out in the Phlegraean Fields (*Campi Flegrei*) and Vesuvius area (Italy) where the monitoring system – together with the studies aimed at the volcanic hazard assessment (Alberico et al., 2011; Bellucci Sessa et al., 2008; Marzocchi and Woo, 2009; Marzocchi et al., 2004; Mastrolorenzo et al., 2006) – constitute an essential element to avoid impressive consequences and social disasters. In fact the levels of risk for the municipalities around these volcanoes are very high due to both the possible explosiveness of a future eruption and above all the amount and density of population and houses (Scandone et al., 1993; Scandone and D'Andrea, 1994; Alberico et al., 2002, 2004; Pesaresi et al., 2008; Petrosino et al., 2004) which would make a strict educational programme for the population necessary (Scandone and Giacomelli, 2012, pp. 31-32). As far as concerns the Phlegraean Fields, the study carried out by Vilardo et al. in 2010 has applied Permanent Scatterers Synthetic Aperture Radar Interferometry (PSInSAR) and GPS "to investigate the most recent surface deformation of the Campi Flegrei caldera. The PSInSAR analysis, based on SAR data acquired by ERS-1/2 sensors during the 1992–2001 time interval and by the Radarsat sensor during 2003-2007, identifies displacement patterns over wide areas with high spatial resolution. GPS data acquired by the Neapolitan Volcanic Continuous GPS network provide detailed ground velocity information of specific sites". Particularly, "the satellite-derived data" has made it possible "to characterize the deformation pattern that affected the Campi Flegrei caldera during two recent subsidence (1992-1999) and uplift (2005-2006) phases" (p. 2373). To be more precise, the Neapolitan Volcanic District (including the Somma-Vesuvius volcanic complex, the Phlegraean Fields and the Island of Ischia) has already been under control with satellite and DInSAR (Differential SAR Interferometry) techniques since the beginning of 2000 in the context of the MINERVA project (Monitoring by Interferometric SAR of Environmental Risk in Volcanic Areas), as a result of the collaboration between the Vesuvius Observatory (National Institute of Geophysics and Volcanology), the European Space Agency and the Institute for Electromagnetic Sensing of the Environment (National Research Council), and aimed at monitoring the ground movements and deformations continuously and in real time (Tampellini et al., 2004)[1].

Similarly, the use of advanced SAR Interferometry (InSAR) techniques, which involves mathematically combining different radar images, is permitting in Italy to monitor the behaviour of Mount Etna in order to obtain neuralgic data and information to understand how the volcano's surface may be deformed during its "breathing" and prior to and during the emission of magma[2]. On the other hand, this methodology has interesting applications also for the study of the surface deformations in the case of seismic events and during the phase of the following aftershocks, as in the L'Aquila earthquake of April 6th 2009, where the use of InSAR and the integration of two or more radar images of the same ground location, before and after an earthquake, supports important and precise measurements and elaborations useful in terms of monitoring and analysis[3].

Moreover, satellite images are useful for "obtaining information on the surfaces and

[1] See also http://www.esa.int/Our_Activities/Observing_the_Earth/Envisat/Renewed_volcanic_activity_at_the_Phlegrean_Fields_tracked_by_Envisat; http://www. esa.int/ Our_Activities/Observing_the_Earth/Satellites _join _watch_on_Naples_volcanic_hinterland.

[2] http://www.esa.int/Our_Activities/Observing _the_ Earth / Envisat/Hot_stuff_15_years_of_satellite_data_ over_ Mt._nobr_Etna_nobr.

[3] http://www.esa.int/Our_Activities/Observing _the_ Earth /Envisat/Satellites_show_how_Earth_moved_ during_Italy_quake.

volumes of the lava field flows, but also on its nature and behavior" and for developing automatic mapping processes of the lava flows. For example this kind of application can be very useful in "a tropical environment such as La Reunion [Indian Ocean], where the climatological context presents a strong cloudiness", as shown by Servadio et al. in 2012 (p. 201), and there is the need to define rigorous systems based on the combination of thermal images and images acquired in the visible and near infrared in a technological environment where different data can be integrated, mapped and analyzed. In a similar perspective also aimed at saving time and effort for mapping processes and at reducing the risks due to fieldwork on active volcanoes, Kahle et al. since 1995, referring to Mauna Loa (Hawaii), had underlined that: "The availability of digital multispectral data, acquired from satellite or airborne instruments, offers specific information relating to the chemical and physical state of eruptive products" (p. 145).

From a more general point of view, Tralli et al. in 2005 have affirmed that: "Satellite remote sensing is providing a systematic, synoptic framework for advancing scientific knowledge of the Earth as a complex system of geophysical phenomena that, directly and through interacting processes, often lead to natural hazards. Improved and integrated measurements along with numerical modeling are enabling a greater understanding of where and when a particular hazard event is most likely to occur and result in significant socioeconomic impact" (p. 185). Therefore the accurate analysis of satellite images is becoming a neuralgic factor in the context of decision support, disaster management and strategic planning in areas subject to high risk. Particularly they provided a series of important considerations and exemplifications concerning earthquake, volcano, flood, landslide and coastal inundation hazards, showing the numerous fields of application where remote sensing can determine significant developments in terms of risk management. In fact, the combined use of satellite images and other geotechnologies can support the experimentation of innovative and integrated methodologies and can be useful to deal with different kinds of natural events.

Thus, an interesting review paper, written by Ramsey and Harris (2013), has recently summarized advances in volcanological remote sensing and has offered some exemplifications concerning the use of satellite images "for detection, monitoring, and modeling of volcanic activity", underlining that the developments achieved are due to "a vast array of new satellite sensors, the application of new technologies, and the involvement of an increasing number of scientists working in the field of thermal remote sensing of volcanoes around the world" (p. 228). Sensitive developments can be obtained only with a continuous test of new technologies in a rigorous interdisciplinary approach, which must not be considered as the sum of single parts and fields of research but as a whole approach where the different scientific sectors provide inputs for an overall optimum. Surely in this delicate process of skills and knowledge, union and convergence, geography can take on a very strategic role, because there is the need to make an evaluation in a framework of systems – and with the support of geomatics – of the geophysical, geological, social-demographic, economic, historical and archaeological aspects.

3. The didactic perspective

As far as concerns the didactic perspective, the possible benefits which can derive from a rigorous observation and interpretation of satellite and aerial images are equally notable, for many reasons.

First of all, similar images provide a great deal of important didactic information, stimulating the theoretical, methodological and applicative knowledge and skills. They are moreover beautiful and impressive and capture the attention of students and researchers observing them, supporting the processes of meticulous analysis of the photos and consequently of the specific details and relations among elements, into a general context which permit several considerations regarding the whole framework and the relationship between the different elements. Furthermore, satellite and aerial images promote a participative and collaborative analysis among people with different competences and attitudes. In this way, as affirmed by Bignante (2011), it is possible to "directly involve the participants in visual research activity", so as to better highlight the "relationships between subjects and social spaces" (p. 158). Therefore: "Education, exchange, *empowerment* are the objectives of these processes, in which what is important is not only the production of new knowledge, but also the setting off, […], of social change processes, creating greater awareness, self-esteem and trust in people" (p. 160).

Similar considerations acquire particular meaning in the case of volcanic risk and hazard, because the importance of educational level, social participation and awareness of the danger is evident. From a didactic point of view, interesting inputs have been for example recently provided by volume 37 (number 2) of the journal *Teaching Geography*, which focus the attention on risks, with different papers that underline: the implications of living subject to natural disasters, or other kind of risks, and the geographical and pedagogic keys of analysis (Lane, 2012); the "conceptualising" of risk and the need of a engaging discussion between teachers and students, who should be involved in well organized and safe fieldwork which provide excellent opportunities to experience and learn about risks (Cook, 2012) and to expand their geographical horizons with an exciting approach (House et al., 2012); new educational strategies to "incorporate" fieldworks in personal scheme of work in the classrooms, equipped with computer, satellite images, maps, data regarding the density and distribution of population and other materials useful to simulate a volcanic eruption or a hurricane and their impacts, in order to create a participative and collaborative atmosphere, where students work in groups for making analysis, evaluate different data, propose interventions and experience a dynamic and very interesting learning process of geography (Hill, 2012). In all these cases, the satellite images have relevant and different didactical potentialities and make it possible to work with innovative, engaging and targeted strategies that exalt the theoretical-applicative and social-educational roles of geography.

Particularly, in the case of volcanic environments, satellite and aerial images can provide important information regarding:

- morphological aspects, the physiognomy of the main crater, the eventual presence of secondary eruptive craters and the possible changes recorded in time;
- the existence of particular elements which could hinder or favour the propagation of different flows;
- the main phenomena produced by an eruption and the height of ash and gas cloud or the distance reached by lava and pyroclastic flows;
- the eventual modification recorded in the eruption state and in terms of volcanic structure, above all for very explosive events which can strongly demolish the volcanic edifice;
- the number of houses (and consequently of people) and monuments which are potentially subject to risk in the area;
- the urban characteristics and structure, the road system, and in case of aerial images with high resolution and big geographical scale the presence of sensitive buildings (industries, hospitals, schools);
- the cultivated soils, the land use and its variations in time.

An interesting study in this sense was conducted in 2000 by Mouginis-Mark. In his work, aimed to show the importance of remote sensing observations for volcano monitoring and hazard mitigation, he also showed the possible applications of satellite images concerning different years to illustrate and evaluate the rate of re-vegetation of the summit of the Mount Pinatubo (Philippines) whose last eruption was recorded in 1991. Similar aims have also been pursued by Kuzera et al. (2007), who applied the potential of remote sensing, satellite images in false colour and change vector analysis for monitoring vegetation regeneration and deforestation in the proximity of Mount St. Helens (United States) – responsible for the violent eruption of 1980 – between 1986 and 1996.

The information which can be derived from remote sensing is very useful both for highly explosive volcanoes, whose eruption could provoke social disasters, and for prevalently effusive volcanoes, which however may determine damage to buildings, historical and cultural heritage, cultivated lands. In this perspective, satellite and aerial images are precious tools to apply theoretical knowledge in a didactic process which allows the use of the visual language of geography. Thus, it is for example possible to make comparisons between: volcanoes with similar eruptive characteristics and social-demographic aspects; volcanoes with similar eruptive characteristics but very different social-demographic aspects; volcanoes with different eruptive characteristics and consequently different eruptive phenomena. During this comparative observation and interpretation of images concerning various volcanoes it is possible to investigate the causes which have brought about particular conditions, to carry out research on the main historical phases and activities, to analyse the possible interventions necessary to reduce the level of risks and to support the alarming phases in the case of emergency. Therefore thanks to satellite images, which if georeferenced can also be imported and analysed in the GIS platform, it is possible to promote dynamic interesting lessons aimed at acquiring important tools, skills and knowledge in order to support a bidirectional and synergic interaction between research and didactics. The analysis of images in false colours and radar images is also exciting and useful both at educational level and for a professional future, since it is possible to obtain a series of additional information and data which stimulate interdisciplinary collaboration and improved computer skills and are able to open new didactic and research horizons. On the other hand, students have now a "natural" computer skill predisposition and generally know the technical use of image visualizers from the air and satellites, so that they are ready for the acquisition of more complex and specific skills, which must be supported by an appropriate and rigorous didactic approach which is usually absent in Italian schools (Pesaresi, 2012).

4. The volcanoes of the islands of Hawaii

Hawaii is made up of a series of volcanic islands and underwater mountains which streatchi for 2,400 km in the Pacific Ocean. Their formation is attributed to the presence of a source of deep heat (called hotspot), anchored to the Earth's mantle.

The oldest islands are about 75 million years old, are not longer active and have been dragged towards the North-West by the movement of the lithospheric plate of the Pacific. The more recent ones, Maui (active until 1759) and Hawaii (subject to almost uninterrupted volcanic activity), are at the other end of the chain.

Of the three volcanoes of the northern sector of the island, only Hualalai has had eruptions in recent times in 1800-1801 (the brief darker flow on the left hand slope of the volcano).

Mauna Loa (Long Mountain, in Hawaiian) is a huge volcano over 4,000 m above sea level, to which are added 5,000 m underwater and another 8,000 m of volcanic structure sunk into the ocean plate. At the top the Mokuaweoweo caldera ("Moku" refers to a coastal land section or islet; "`aweoweo" is a type of red Hawaiian fish. Literal translation is fish section; the red of the fish suggests red lava) represents the point of encounter of two rift zones along which are aligned numerous craters. The activity consists in fluid lava flows which run down to the ocean, often accompanied by fountains of lava. In July 1975, after a period of quiescence of 25 years, in only two days it erupted 30 million square meters of lava. From 1843 to 1984, the date of the last eruption, it has had 33 eruptions.

On the South-eastern side of Mauna Loa, is Kilauea, a volcano 1,200 m above sea level and extending for 3,700 m underwater. It began to form about 300,000-600,000 years ago and emerged from the sea as an island perhaps 50,000-100,000 years ago. About 90% of the surface of Kilauea is formed of lava flows less than about 1,100 years old; 70% of the volcano's surface is younger than 600 years. The caldera at the summit, 4 km long, 3.2 km wide and about 120 m deep, contains the circular crater, l'Halema'uma'u, inside which a lava lake often stagnates. During the beginning of May (2013) the circulating lava lake occasionally rose and fell in the deep pit. On the eastern rift are numerous cones aligned and pit craters (Chain of Craters), among which the Pu'u O'o, where an eruption has been going on since January 1983. The southern side of the volcano, towards the ocean, is interrupted by almost vertical faults that form a slope of 300 m. In 1912 the American Geological Survey built the Hawaiian Volcano Observatory on the edge of the Halema'uma'u caldera.

4.1 Analysis of the images concerning the volcanoes of Hawaii

The image of the Island of Hawaii, generated from data acquired by the Thematic Mapper (TM) instrument of the Landsat-5 satellite on 15 July 2000 (Figure 1), is visualized in false colours through the RGB 742 combination, namely by inserting data detected by the TM Mid-Infrared band 7 sensor in the RED channel of the monitor, data from the Near-Infrared band 4 in the GREEN channel, and the green-yellow Visible band 2 in the BLUE channel.

The sea water appears black, since it absorbs the solar light totally in these three spectral bands. Small good-weather cumulus clouds are visible in white with their black shadows (image taken in early morning, sun illuminating from SE) over the planes in the North-East and in the South-West, whereas more compact cloudiness appears over the northern areas. Looking only at the satellite image, the whitish colours at the centre could be interpreted either as water vapour smokes from the caldera of Mauna Loa or as some cloudiness developed around it or possibly both: ground information would certainly help to resolve the question! Green areas along the coasts indicate the presence of healthy vegetation (strong signal in the NIR band), probably forest and woods.

The radar image was acquired in the Microwave spectral band by the ASAR instrument of the ESA Envisat satellite on 10 May 2010 (Figure 2); as it is not georeferenced, it must be rotated clockwise by 10° in order to become geographically corrected.

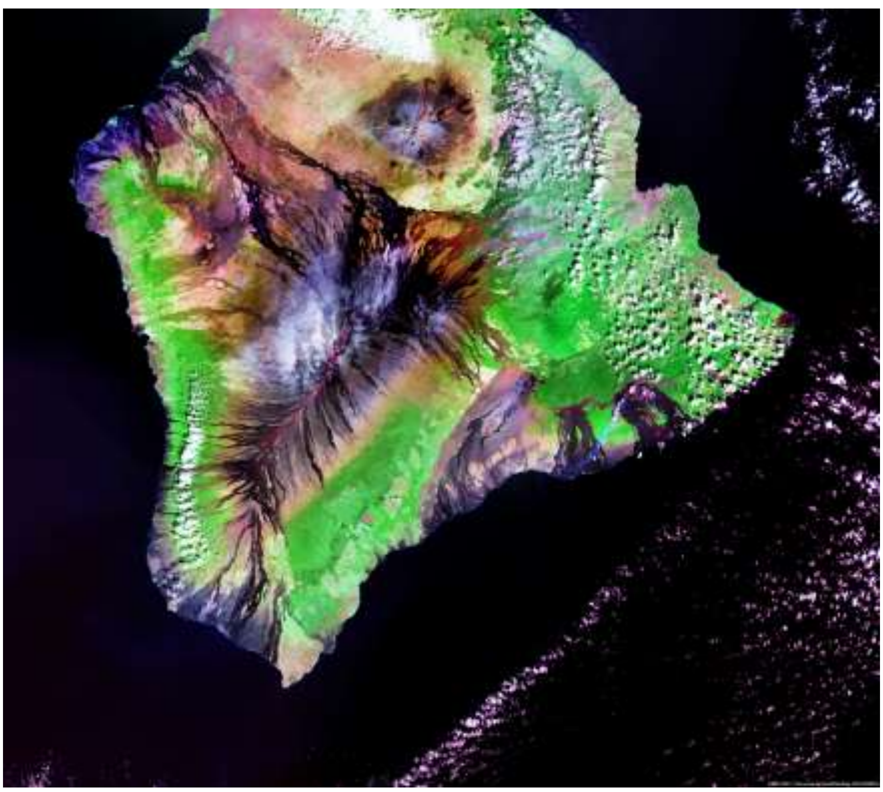

Figure 1. Island of Hawaii, Thematic Mapper, Landsat-5, 15 July 2000, RGB 742.
Source: ESA-ESRIN.

Figure 2. Island of Hawaii, radar image, ASAR, ESA Envisat, 10 May 2010.
Source: ESA-ESRIN.

Like most SAR images, it provides a cloud- and smoke-free view of the territory and enhances the terrain topography in detail because of the radar oblique viewing: it shows the high crater of Mauna Kea in the northern side, the wide caldera of Mauna Loa at the centre, and the caldera of Kilauea just on the right hand side. It also depicts the gentle volcanic slopes that encompass the whole Island and the cliffs along the coast. In addition, the oblique viewing marks the slopes differently that are oriented towards the satellite, making then appear brighter and more compressed, from those oriented in the opposite direction, which appear darker and stretched; this effect is proportional to the slope's local incidence angle: the smaller the angle brighter and the more compressed the ones towards the satellite (darker and more stretched the opposite ones).

5. Mount St. Helens

Mount St. Helens is an active volcano, located in the western Cascade Range of North America. Its volcanic activity is usually divided into nine eruptive periods, from the beginning dated about 40-50,000 years ago, until 2,200 years ago, when effusive and explosive eruption formed the older St. Helens edifice. It was the most active volcano in the Cascade Range during the Holocene, but few lava flows extended beyond the base of the volcano.

The modern edifice has no traces of glacial erosion, so it is possible to establish that it was constructed during the last 2,200 years. Historical eruptions in the 19th century originated from the Goat Rocks area on the north flank, and were witnessed by early settlers.

Before May 18, 1980, Mount St. Helens

formed a conical, youthful volcano, the smallest of the Washington State big volcanoes. It was so perfectly symmetrical that it looked almost the same from any direction.

During the 1980 eruption, the upper 400 m of the summit were removed by slope failure, leaving a 2 x 3.5 km horseshoe-shaped crater, now partially filled by two lava domes. The triggering landslide was caused by the collapse of a bulge growing on the north flank of Mount St. Helens and hiding an intrusion of magma. The spectacular 1980 eruption, initiated with small phreatic explosions, reached the paroxysmal phase when the slope failure decompressed the magma stopped near to the surface, resulting in a violent lateral blast which completely devastated 550 km^2 of forest along with the lives of 57 people. The eruption continued for eight hours with a vertical column plume and pyroclastic flows. Several more eruptions occurred in the summer of 1980. Episodic activity lasted until 1986 with the slow effusion of a dome within the crater. The eruption renewed in 2004 to 2008 with the grown of a new dome next to the previous one.

5.1 Analysis of the images concerning the Mount St. Helens

Satellite data, acquired by the ETM instrument of Landsat-7 satellite on 17 October 2002 over the Mount St. Helens region (Figure 3), is visualized in false colours (RGB 742) and shows the forested area and the lakes in the region and the icy top of the Mount Adam on the right hand side. The image illustrates also the northwards wide mud flow and the pyroclastic flow that were caused by the collapse of the upper part of the volcanic cone during the eruption on 18 May 1980 and on which no vegetation has grown till today. The image generated from the data acquired by the AVNIR-2 instrument of the ALOS satellite on 10 October 2006 (not fully georeferenced, since it should be still rotated by some 3° clockwise) confirms the above considerations in both visualizations (Figures 4 and 5), namely in natural colours (RGB 321) and false colours (RGB 431): the mud icy flow caused by the volcanic explosion arrived to the Spirit Lake and still today has not allowed vegetation to grow on it again.

Figure 3. Mount St. Helens region, ETM, Landsat-7, 17 October 2002, RGB 742.
Source: ESA-ESRIN.

Figure 4. Mount St. Helens, AVNIR-2, ALOS, 10 October 2006, RGB 321.
Source: ESA-ESRIN.

Figure 5. Mount St. Helens, AVNIR-2, ALOS, 10 October 2006, RGB 431.
Source: ESA-ESRIN.

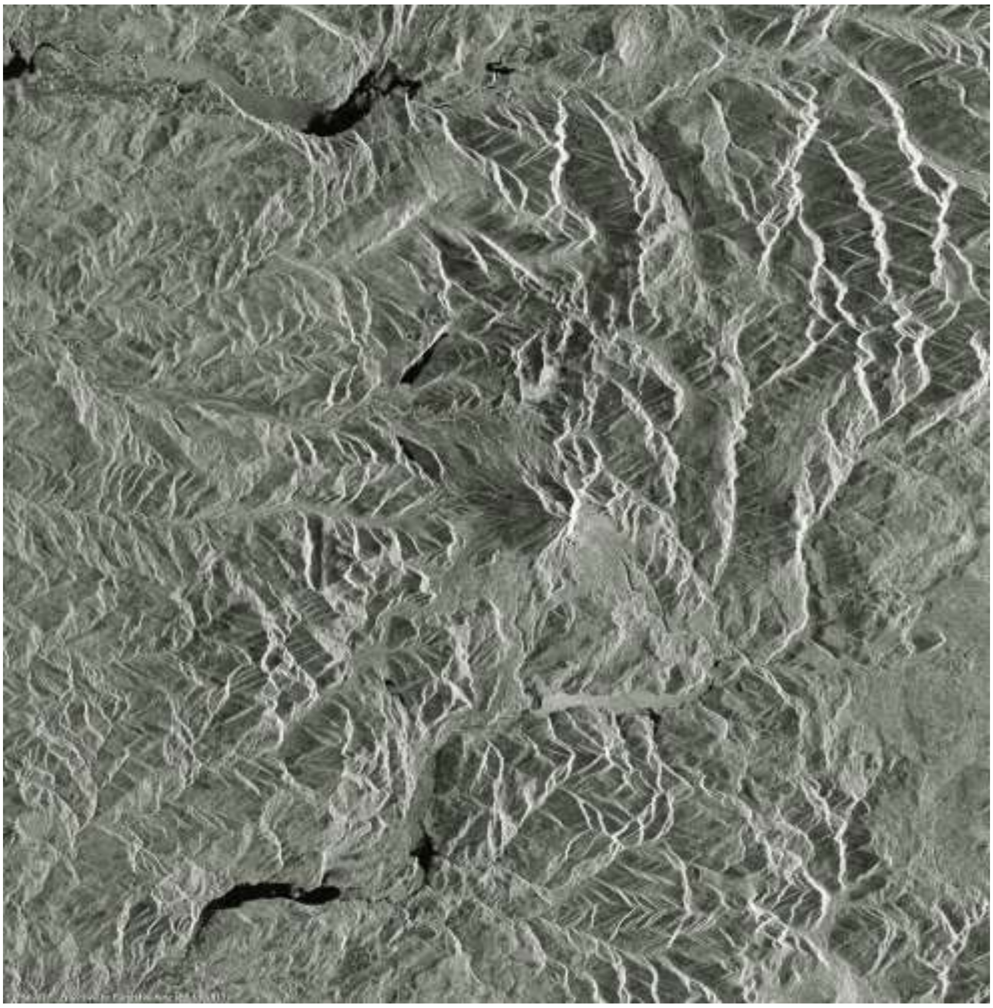

Figure 6. Mount St. Helens, radar image, ASAR, ESA Envisat, 4 September 2009.
Source: ESA-ESRIN.

The radar image, acquired by the ASAR instrument of the ESA Envisat satellite on 4 September 2009 (Figure 6), shows the St. Helens volcanic mountain in the middle and well illustrates the collapse of the upper conic top and the consequent wide caldera oriented northwards: in fact, the image is not georeferenced and has to be rotated 10° clockwise to obtain the correct geographic orientation. The Spirit Lake appears as a sort of bow with variable grey tones, more or less bright, most probably due to wind effect in making rough the surface of the lake waters and generating radar echoes back to the satellite; at the contrary, the Coldwater Lake at NNW appears as a black elongated spot, since calm water acts as a mirror to the radar pulse illuminating it and reflects them away, whereby no radar echoes return back to the satellite: a situation of no signal back is visualized in black tones, meaning that the surface of the illuminated object is flat and not rough.

6. Mount Pinatubo

Mount Pinatubo is one of the highest peaks along a chain of volcanoes that constitutes the Luzon volcanic arc in Philippine. Prior to 1991 it was a relatively unknown, heavily forested lava dome complex located 100 km NW of Manila with no records of historical eruptions. Its top consisted of a rounded, steep-sided, domelike mass that rose about 700 meters above a broad, gently sloping, deeply dissected apron. The basal apron is composed of voluminous pyroclastic flow and lahar (pyroclastic flow and volcanic mud flow) deposits, which told of large prehistoric explosive eruptions. At least six major eruptive periods, interrupted by lengthy quiescent periods, have occurred during the past 35,000 years.

After more than four centuries, Pinatubo awoke in June, 1991. The eruption, one of the world's largest of the 20^{th} century, second in size only to an eruption in Katmai, Alaska, in 1912, and ten times larger than the eruption of Mount St. Helens in 1980, lowered the height of the summit from 1,745 to 1,486 m and created a new 2.5-kilometer-diameter wide caldera, centered slightly North-West of the pre-eruption summit.

The caldera formed because of the collapse of the volcano's summit on June 15, during a period of severe, large earthquakes in response to withdrawal of a large volume of magma, about 5 cubic km, from the reservoir beneath the volcano. A lake began to fill the caldera in September, 1991.

During the eruption, a giant ash cloud rose 30-35 km into the sky above the volcano's vent and hot blasts seared the countryside. Valleys that had existed in the pyroclastic apron were largely filled by eruptive products; valleys that had been carved into older volcanic terrain, and partly filled by prehistoric eruptions, were partly filled once again.

Tephra-fall deposits, 5 cm or more thick, buried crops and covered a land area of about 4,000 km^2 surrounding Pinatubo. The weight of the tephra, rain-saturated by typhoon Yunya, caused numerous roofs collapses in the Philippine communities and on the two large U.S. military bases. Clark Air Base lies to the East of the volcano, within 25 km of the summit, and Subic Bay Naval Station is about 40 km to the South-West.

For months, the ejected volcanic materials remained suspended in the atmosphere where the winds dispersed them to envelope the Earth, reaching as far as Russia and North America.

Before the eruption, more than 30,000 people lived in small villages on the volcano's flanks. A much larger population, about 500,000, continues to live in cities and villages around the alluvial fans surrounding the volcano. Philippine authorities were able to evacuate 60,000 people from the slopes and valleys, and the American military evacuated 18,000 personnel and their dependents from Clark Air Base. But more than 800 people lay dead, 184 injured, 23 missing, and more than 1 million people displaced.

Widespread lahars that redistributed products of the 1991 eruption have continued to cause severe disruption. Most of these have produced major pyroclastic flows and lahars that were even more extensive than in 1991.

6.1 Analysis of the images concerning Mount Pinatubo

Satellite images demonstrate that the relatively recent situation of the volcanic mountain Pinatubo still show some important signs of the terrible explosion that caused major impacts in the region and around the world on June 1991. Optical image data acquired by the ETM instrument of the Landsat-7 satellite on 26 November 2001 (Figure 7), just ten years after the eruption, and visualized in false colours (RGB 742) shows in black colours the water lake that was formed in the caldera within few months after the explosion and in grey tones the material debris transported by many lahars that tragically affected the local population in several instances. An image generated by data, acquired by the AVNIR-2 instrument of ALOS on 6 December 2009 (Figure 8), 18 years after the event shows that no major changes occurred afterwards: in blue colours the water lake is still in the caldera and in light grey tones the material debris transported by lahars is still apparent. When considering the vegetation, the visualization in natural colours (RGB 321) confirms the recovery of the tropical forest after that destructive event: dark green indicates dense and healthy forest, whereas lighter green suggests less dense and possibly shrub type of vegetation. The same is illustrated by the false colour visualization (RGB 431), where red and orange-brown have the same meaning of the dark and light green, respectively (Figure 9).

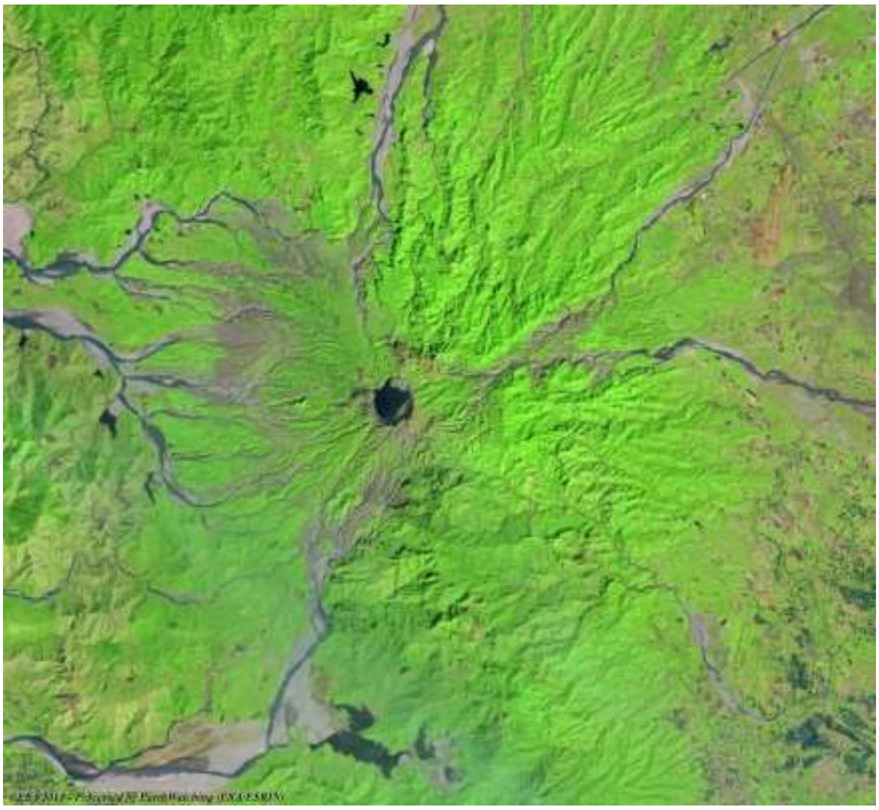

Figure 7. Mount Pinatubo, ETM, Landsat-7, 26 November 2001, RGB 742.
Source: ESA-ESRIN.

Figure 8. Mount Pinatubo, AVNIR-2, ALOS, 6 December 2009, RGB 321.
Source: ESA-ESRIN.

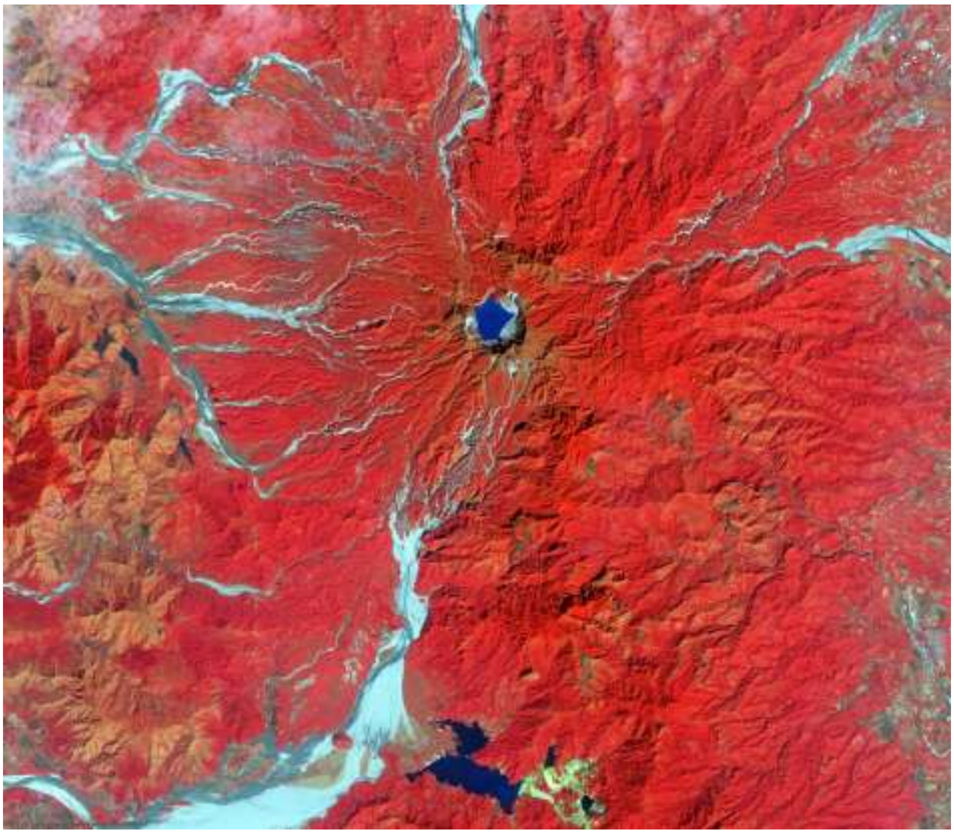

Figure 9. Mount Pinatubo, AVNIR-2, ALOS, 6 December 2009, RGB 431.
Source: ESA-ESRIN.

The eruption was so strong that the ash plume reached the lower levels of the stratosphere and, at that latitude, was trapped by easterly winds and created an opaque ash cloud that, as mentioned above, for almost one year disturbed satellite observations. In particular, it affected directly the measurements of sea surface temperatures in the equatorial regions, which had to be stopped because the ash cloud strongly absorbed the outgoing Thermal Infrared radiation, making the ocean surfaces appearing much colder than they actually were and no corrections were possible due to the random characteristics of that effect.

The radar image, acquired by the ASAR instrument of Envisat on 15 September 2011 (Figure 10), illustrates the topography of the Pinatubo area very well: the volcanic mountain stands out in the centre of the image and the flattish mud flown down westwards can be distinguished on the left of the volcano at the time of the eruption, on top of which vegetation prevailed and grew again in that tropical region.

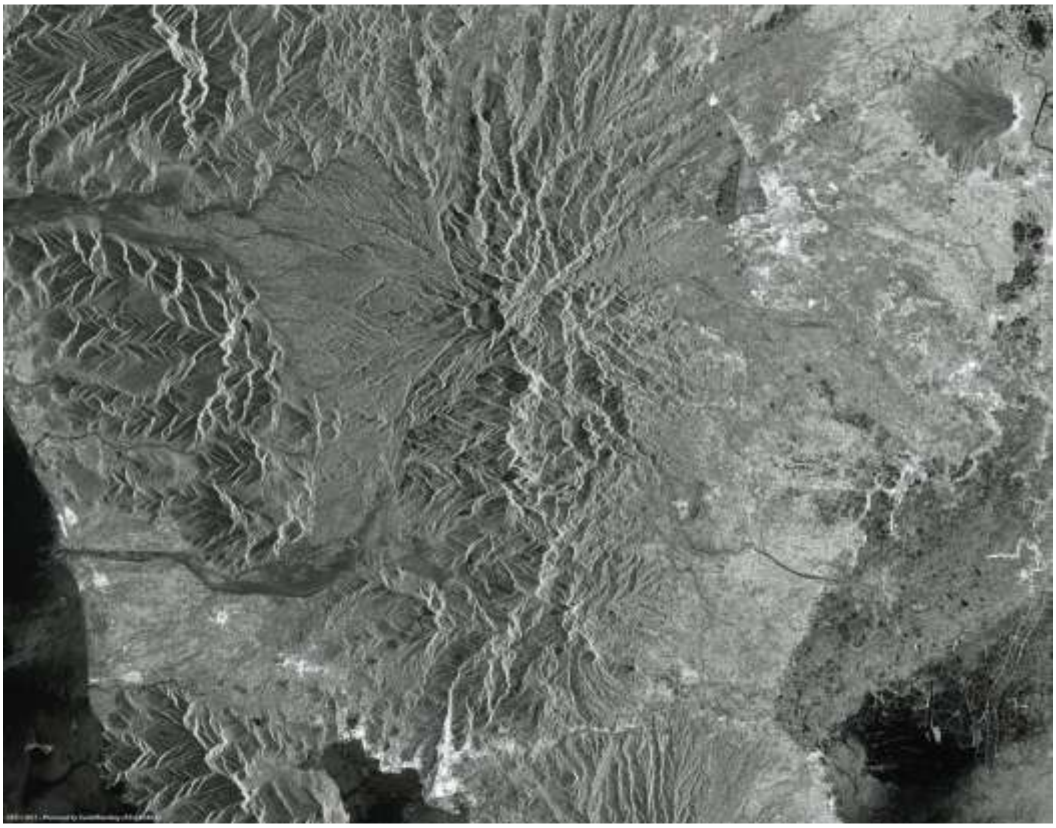

Figure 10. Mount Pinatubo, radar image, ASAR, Envisat, 15 September 2011.
Source: ESA-ESRIN.

7. Piton de la Fournaise and the Reunion Island

The massive Piton de la Fournaise is a basaltic shield volcano, located in the South-East of Reunion Island, with an elevation of 2,631 meters, grown by repeated extrusion of lava from the summit area and from fissures on its flanks. The volcano is similar in many respects to Hawaiian ones, both growing on the flanks of much larger shield volcanoes in intraplate tectonic environments, above a "hotspot" or melting anomaly in the upper mantle.

Much of its more than 530,000 year history overlapped with eruptions of the extinct Piton des Neiges shield volcano, located to the North-West of the Island.

The structural features of Fournaise are a summit caldera and down faulted trough, a family of broadly curving faults that are nested around the caldera, and three rift zones. Numerous scoria cones dot the floor of the calderas and their outer flanks.

The nested faults become younger to the East-South-East and record one of the effects of a migration of the focus of volcanism, which has advanced at least 30 km in that direction from neighbouring Piton des Neiges.

It is possibly to identify at least three periods of caldera collapse, at around 250,000, 65,000, and less than 5,000 years ago. Each of the caldera collapses has been probably breached by large landslides and by progressive eastward slumping of the volcano, like those that occur on the South flank of Kilauea Volcano in Hawaii.

In the last 300 years, it has been one of the world's most active volcanoes, with more than 100 eruptions of fluid basaltic lava flows. Most of historical eruptions originated from the summit and flanks of a 400-meter-high lava shield that grew within the youngest caldera (Enclos Fouqué), which is 8 km wide and breached to below sea level on the eastern side. Only six eruptions, in 1708, 1774, 1776, 1800, 1977, and 1986, have originated from fissures on the outer flanks of the caldera.

The last eruption occurred in 2010. From 14 August, to 10 September, an increase in the number and magnitude of earthquakes was recorded. Inflation of the summit area began in late August and on 13 September there was a localized deformation West of the Dolomieu crater. On 24 September, a seismic crisis occurred in conjunction with 3 cm of inflation, characterized by several tens of earthquakes located beneath Dolomieu crater.

The eruption began on 14 October from a fissure near the Château Fort crater, about 1.5 km South-East of the Dolomieu crater rim, after a new seismic crisis detected a few hours before. Lava fountains were 10-15 m high, and rose from two vents. By 16 October, a lava flow had travelled 1.6 km, confined inside the Fouqué caldera. It continued to be active and to travel East-South-East until 27 October, while lava fountains occurred from four vents and a small lava lake was observed in the cone. The next day tremor slightly decreased, and then significantly decreased on 29-30 October, when the eruption stopped.

Reunion Island was known to the Arabs and visited by the Portuguese in the early 1500s. The first of its known eruptions was in 1640, and France claimed the Island around 1662. It has been French virtually continuously since then. Settlers moved in from 1715, and 600,000 people now live on the 2,510 km^2 Island. A modern volcano observatory was established there in 1980.

7.1 Analysis of the images concerning the Piton de la Fournaise and the Reunion Island

The optical images of the Reunion Island, acquired by the AVNIR-2 instrument of the ALOS satellite on 29 August 2009 (Figures 11 and 12), show the entire Island, partly covered by cumulonimbus clouds, in two different visualizations: in natural colours (RGB 321) and in false colours (RGB 431). Both colour combinations make it possible to identify forested areas and the two main volcanic areas, the one of Piton des Neiges and Alizés on the left, both extinct thousands of years ago, and the other of the younger and active Piton de la Fournaise on the right. However, the false colour combination allows a better discrimination among different situations: lack of RED colour certainly indicates lack of healthy vegetation, but also the different cyan tones are related to different objects: more greenish (or less bluish) is due to the prevailing of the signal from the red spectral band with respect to the signal detected in the blue band of the Visible, which often is the case for barren lands and urban areas. The grey-bluish tones suggest bear soils and, in the South, possibly old flows of lava and debris. Recent lava flows are illustrated by the dark tones in the eastern and South-eastern areas up to the coast, and the dark area on the right shows the collapsed caldera from where they were originating.

In fact, a confirmation comes from the radar image, acquired by the ASAR instrument of the Envisat satellite on 22 May 2010 (Figure 13). Here, the volcanic building, collapsed towards the sea eastwards is well visible on the right hand side. The light grey tones along the coast are due to the multiple reflection of radar pulses by buildings and illustrate the distribution of villages all around the Island, often threatened by volcanic lava flows.

The Reunion Island has been systematically studied by making use of differential interferometry techniques (DInSAR) and thousands of interferograms have been generated by scientists in cooperation with the European Space Agency, in order to monitor the volcanic activity in the Island. On 30 March and 4 April 2007 two eruptive mouths appeared, the first one in the primary cone near Chateau Fort and the second in the caldera at the basis of the Grandes Pentes; this latter produced magma fountains up to 100 m high and very fast lava flows that in a few hours arrived at sea, by crossing the coastal road. Due to the magma output, the top of the Dolomieu crater underwent an enormous collapse, creating the huge depression 300 m deep that can be easily observed in the radar image: it corresponds to some 50 million cubic meters of material having disappeared from the site!

The optical image showing the Island and the surrounding ocean was acquired by the instrument MERIS of the Envisat satellite on 5 April 2007 and illustrates the ash and gas plume from the volcano after the eruption (Figure 14).

Figure 11. Reunion Island, AVNIR-2, ALOS, 29 August 2009, RGB 321.
Source: ESA-ESRIN.

Figure 12. Reunion Island, AVNIR-2, ALOS, 29 August 2009, RGB 431.
Source: ESA-ESRIN.

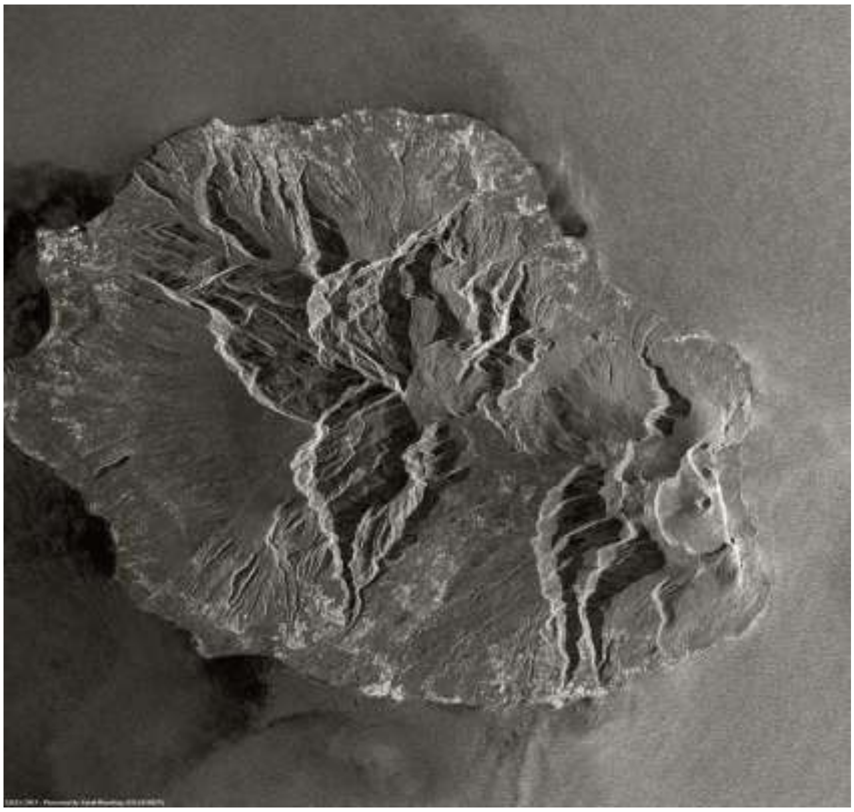

Figure 13. Reunion Island, radar image, ASAR, Envisat, 22 May 2010.
Source: ESA-ESRIN.

Figure 14. Reunion Island and the surrounding ocean, MERIS, Envisat, 5 April 2007.
Source: ESA-ESRIN.

8. Mount Etna

Mount Etna, towering above Catania, is an active basaltic strato-volcano, the highest and most voluminous in Italy. It has one of the world's longest documented records of historical volcanism, dating back to 1500 B.C.

Its base, formed by products of older eruptions, has a diameter of over 33 km and a surface of 1,600 km^2. The Steep summit cone, the Mongibello, is the most recent part on which four craters are to be found: Bocca Nuova, Voragine, North-East Crater and South-East Crater.

The Voragine was formed first before 1950 and the Bocca Nuova in 1968. The North-East Crater was formed at 3,100 m in 1911 and was continuously active between 1960 and 1970. In 1978 it reached 3,345 m above sea level. The South-East Crater has existed since 1971 and got bigger after 1978. It was particularly active from 1998, and in January 2001 reached 3,300 m high, overtaking the height of the other cones with eruption of August of the same year. Since 2004 it often has Strombolian explosions, with episodes of violent fountains of lava and columns of ash, which have changed its shape and dimension.

On the eastern side of the volcano is the Valle del Bove, a depression 8 km long and 5 wide, formed around 60,000 years ago by landslide, perhaps triggered by the explosive eruptions. The slopes, to very low levels, are dotted with cones of the lateral eruptions of various dimensions.

Two styles of eruptive activity typically occur at Etna. Persistent explosive eruptions, sometimes with minor lava emissions, take place from one or more of the four prominent summit craters. Flank eruptions, typically with higher effusion rates, occur less frequently and originate from fissures that open progressively downward from near the summit.

Geologically Etna forms part of the convergence processes which began millions of years ago, and of ongoing compression processes between the African and European plates. The powerful thrusts between continents create fractures in the Earth's crust that are so deep as to facilitate the formation and rising of magmas to the surface.

Between 700,000 and 200,000 years ago, the eruptions (called pre-Etnean) took place in a gulf that stretched over the area included between the Monti Peloritani and Iblei. Of the lavas that emerged below sea level the spectacular rock of Aci Castello can still be seen, while examples of intrusions that have remained under the marine sediments are to be seen in the Isole dei Ciclopi.

About 170,000 years ago, there might have been a wide cone above sea level (ancient or primordial Etna) and, about 90,000 years ago, of numerous active centres corresponding to today's volcano. 40,000 years ago the structure of the Mongibello began to be defined, which about 15,000 years ago collapsed to form a crater of about 4 km in diameter, called the Ellittico, in which the present Mongibello grew.

Of the historical eruptions the one of 1614-24 can be remembered for its duration, the one of 1669, which destroyed part of Catania, and, among the more recent ones, the one of 1991-93 are known also for the attempts to divert the lava flows.

Particularly after 2001, the episodes with columns of ash, usually between 2 and 5 km high, have had serious repercussions on air traffic and the economy of the area.

8.1 Analysis of the images concerning the Mount Etna

The satellite image of Sicily was acquired by the MERIS instrument of Envisat on 14 May 2011 (Figure 15) and is visualized in natural colours (for this 15 bands superspectral instrument the natural colours are achieved by using its bands 7, 5 and 2 respectively). It shows the eastern location of the Mount Etna and its cloudy cap during a period of no remarkable volcanic activity. The dark brownish colours of the higher part of the mountain illustrate the volcanic nature of the terrain and traces of recent and old lava flows. Another image, acquired by the TM instrument of Landsat-5 on 10 September 2008, shows, instead, the mountain during an eruption: the visualization in natural colours (RGB 321) demonstrates that the erupting mouths were two, one just at SW of the other and even at this scale the two smoke columns are seen merging a few km South, driven by northerly winds (Figure 16). In this image the harbour of the city of Catania can be noticed along the coast in the SE: during strong eruptions, the airport of Catania is closed because of the danger caused by ash plumes. If the same image is visualized in a combination of false colours to enhance vegetation, namely RGB 431 (Figure 17), then the different lava flows becomes evident in dark grey or black tones, whilst the ash plume is detectable as a light bluish filament reaching the western part of Catania. When, instead, the image is visualized still in false colours but with a different combination (RGB 742), which includes the Mid-Infrared of the TM band 7, then the actual lava can also be seen, namely as a red flow blowing out of a mouth opened eastwards the smoking craters (Figure 18).

The radar image acquired by the ASAR instrument of Envisat demonstrates the isolated structure of Mount Etna (Figure 19).

The instrument illuminated the volcanic building from the East during a descending orbit (North Pole to South Pole), therefore the eastern slope containing the old collapsed Bove Valley is compressed and very bright, whilst the western one is much darker and stretched. The city of Catania can be localised in the SE by the white spots caused by the multiple reflections of the town buildings. Etna is also monitored continuously by scientists and the National Institute of Geophysics and Volcanology (INGV) of Italy through DInSAR techniques. Specifically, the volcano "breathing" is kept under control by using long time series of differential interferograms measured from space through the SAR instruments of ERS-1, ERS-2, Envisat and COSMO-SkyMed satellites, whereby inflation and deflation movements are monitored at centimetric level from a thousand km aloft; that also makes it possible to calculate the volume of magma involved in the volcanic activities of Mount Etna.

Figure 15. Sicily, MERIS, Envisat, 14 May 2011.
Source: ESA-ESRIN.

Figure 16. Mount Etna, TM, Landsat-5, 10 September 2008, RGB 321.
Source: ESA-ESRIN.

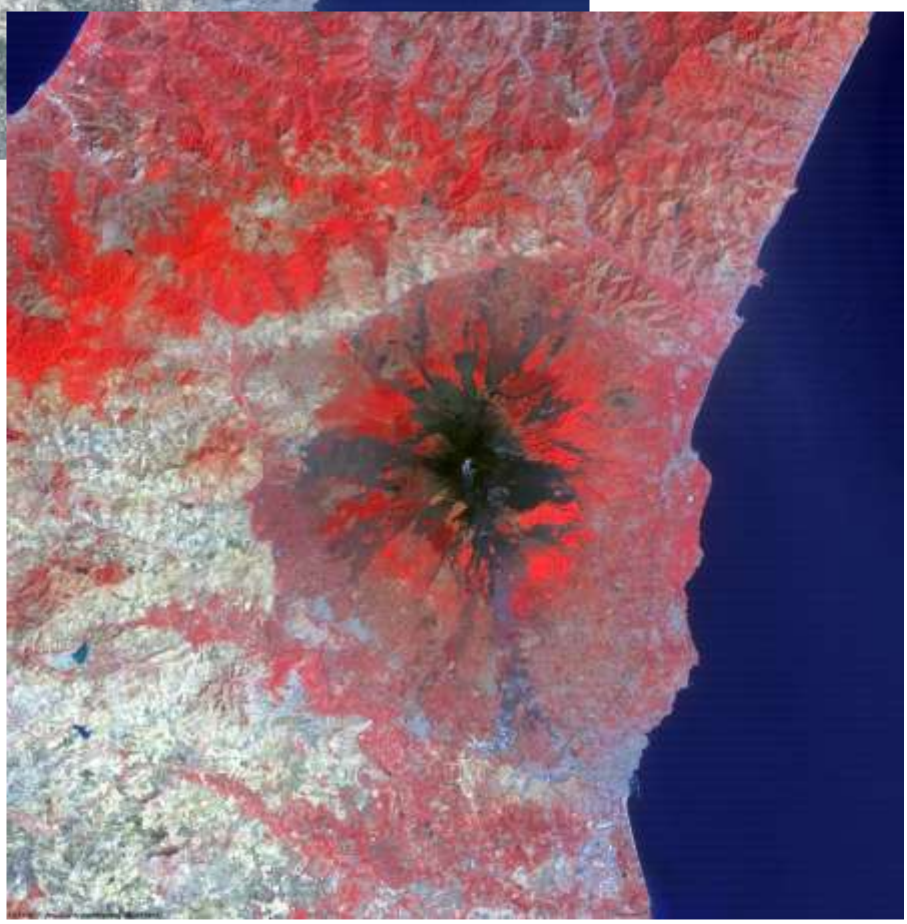

Figure 17. Mount Etna, TM, Landsat-5, 10 September 2008, RGB 431.
Source: ESA-ESRIN.

Figure 18. Mount Etna, TM, Landsat-5, 10 September 2008, RGB 742.
Source: ESA-ESRIN.

Figure 19. Mount Etna, radar image, ASAR, Envisat, 6 April 2009.
Source: ESA-ESRIN.

9. Vesuvius

Vesuvius is an active volcano, located on Italy's West coast, which has produced the most recent eruptions in the Campanian plain. It overlooks the bay and city of Naples and sits in the crater of the ancient Somma volcano, so much so that the Somma-Vesuvio complex is known as enclosure volcano. Its activity spans the period between 25,000 years ago and recent times. The oldest products, the Codola pumice formation, overlie the products of the so-called "Campanian Ignimbrite", dated at 39,000 years ago.

One of the most violent eruption of Vesuvius, called the "Pomici Basali or Sarno eruption", took place about 17,000 years ago. Other eight Plinian or Subplinian eruptions occurred after 17,000 years, the last three of which were recorded in 79 A.D. and which destroyed Pompeii and Herculaneum in 472 and 1631.

The 79 A.D. eruption of Vesuvius gave the name of "Plinian" to any large volcanic eruption, because of Pliny the Younger, a Roman historian who wrote the oldest surviving description of an explosive volcanic event. This term has long been used to describe large-volume, violent eruptions that produce sustained mushroom-shaped clouds of pyroclasts and gases, which rise tens of km into the atmosphere.

After 79 A.D., two large eruptions are reported in 472 and 512, and several others may be verified in 685, 787, 968, 991, 993 and 999.

The last eruption, before a long quiescent period, occurred on the 1st of June 1139. According to various sources, it was a strong explosive eruption. It lasted eight days and ashes covered Salerno, Benevento, Capua and Naples. Following this no reliable report of volcanic activity is available until 1500. Probably no eruption occurred from 1500 until to 1631, because records are good during that period, and none mention volcanic activity.

Then, in the night between 15 and 16 December of 1631, another considerable explosive eruption began. Several months before, people near the volcano felt some earthquakes. The seismic activity, which must considered as an important precursory phenomenon, became more severe in the days leading up to the eruption, whose paroxysmal stage went on for two days. This eruption has a role of great importance also owing to the fact that it is often considered the Maximum event expected should Vesuvius, around which are towns with highest population density in Italy, become active once again in the medium to short term.

From 1631 the volcano entered a stage of almost persistent activity with numerous effusive-explosive eruptions that lasted, with a few breaks, until 1944. During this period the main explosive eruptions were of limited magnitude but displayed a peculiar trend. The eruptions always began with an effusive phase, with lava outpouring from a fracture in the cone or from the rim of the cone. After a few days of such activity, accompanied by mild Strombolian explosions, a more explosive phase followed with lava fountaining up to 2-4 km height. The last phase, characterized by the formation of a sustained eruption column, 5-15 km high, was followed by a collapse in the central crater. After the most violent phase and the collapse of the crater, a period of quiescence went on for several years. Quiet lava emissions characterized the new outbreak of activity.

The last eruption of Vesuvius was recorded in 1944, and the still lasting quiescent period is much longer than the reposes observed in the period 1631-1944. The possible future activity at Vesuvius represents a great demographic, social and economic menace to the busy surrounding cities, including the metropolis of Naples.

9.1 Analysis of the images concerning Vesuvius

The mountain of Vesuvius is here illustrated by making use of satellite images at different resolution, thereby with different details, in order to demonstrate the use of remote sensing methodology at different levels. To start with, the image acquired by the MERIS instrument of Envisat on 11 April 2011 at 300 m of ground resolution (Figure 20) shows most of the Campania region and permits a better understanding of the geological structure of the area, where two clear volcanic cones are visible: Roccamonfina in the NW and Vesuvius in the Neapolitan area. By using TM data acquired by Landsat-5 RGB 321 on 26 June 2010 at 30 m resolution (Figure 21), the danger of a volcanic eruption of Vesuvius becomes evident: the mountain, whose caldera is clearly visible on its top, is surrounded by an extremely dense urbanisation in the province of Naples, which includes the city and its important harbour on the West side and the tragically famous villages of Herculaneum and Pompeii on the South-East side.

The radar image, generated by microwave data acquired by the ASAR instrument of Envisat on 2 October 2010 (Figure 22), confirms the characteristic terrain topography and the ASAR side-looking from the East deforms the volcanic cone by compressing and making brighter the eastern volcanic slope, whilst stretching and making the western part of the mountain darker, and deforming the caldera westwards, which in addition appears black because of the radar shadow, that is to say that no radar pulses can reach its lower levels inside and no radar echoes can be generated.

This dramatic contrast between natural hazard and human development is even more noticeable in optical false colour combinations, where the original scene data set is still the same (the 7 optical bands acquired simultaneously by the TM instrument), but different triplets of spectral bands are visualized on the screen. The Landsat-5 RGB 431 one is very impressive (Figure 23), because vegetation appears in red (strong leaf signal in the Near Infrared Landsat-5 band 4) and urban areas in cyan tones (very little or no red colour, due to lack of vegetation in built-up zones): here, one can better appreciate that human housing “climbs” on the volcanic flank, particularly on the SW side, where the coastal land available is very limited; the RGB 742 one (Figure 24) shows vegetation in bright green (spectral band 4) and urban areas in magenta (lack of vegetation), and takes advantage of the important reflectance of minerals and cement in the Mid Infrared spectral band (No. 7 in the TM of Landsat-5).

Figure 20. Most of the Campania region, MERIS, Envisat, 11 April 2011.
Source: ESA-ESRIN.

Figure 21. Vesuvius and the near municipalities, TM, Landsat-5, 26 June 2010, RGB 321.
Source: ESA-ESRIN.

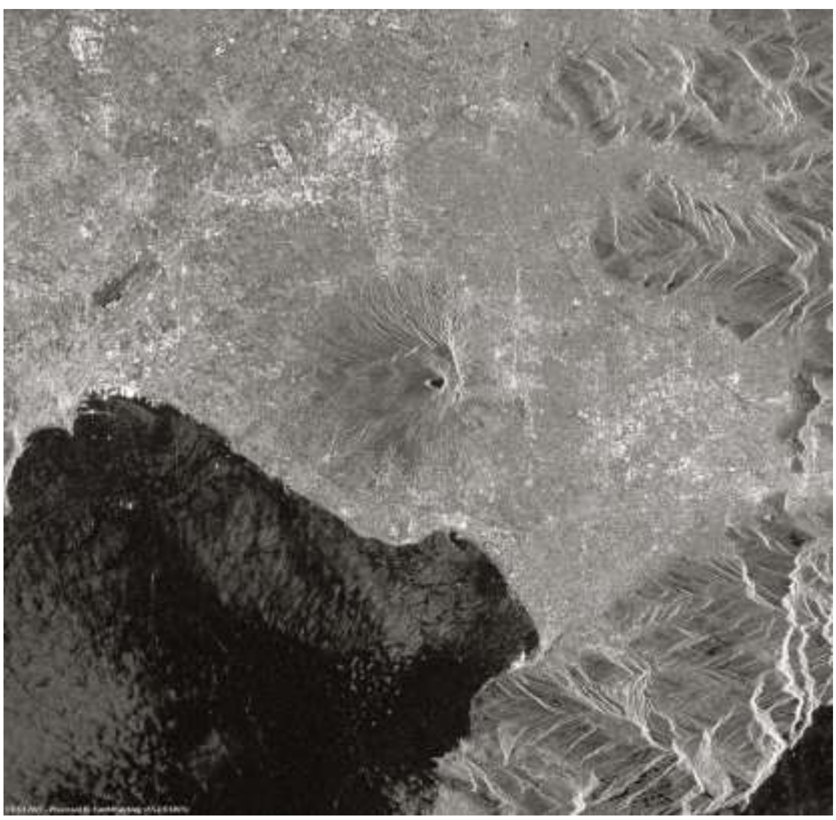

Figure 22. Vesuvius, radar image, ASAR, Envisat, 2 October 2010.
Source: ESA-ESRIN.

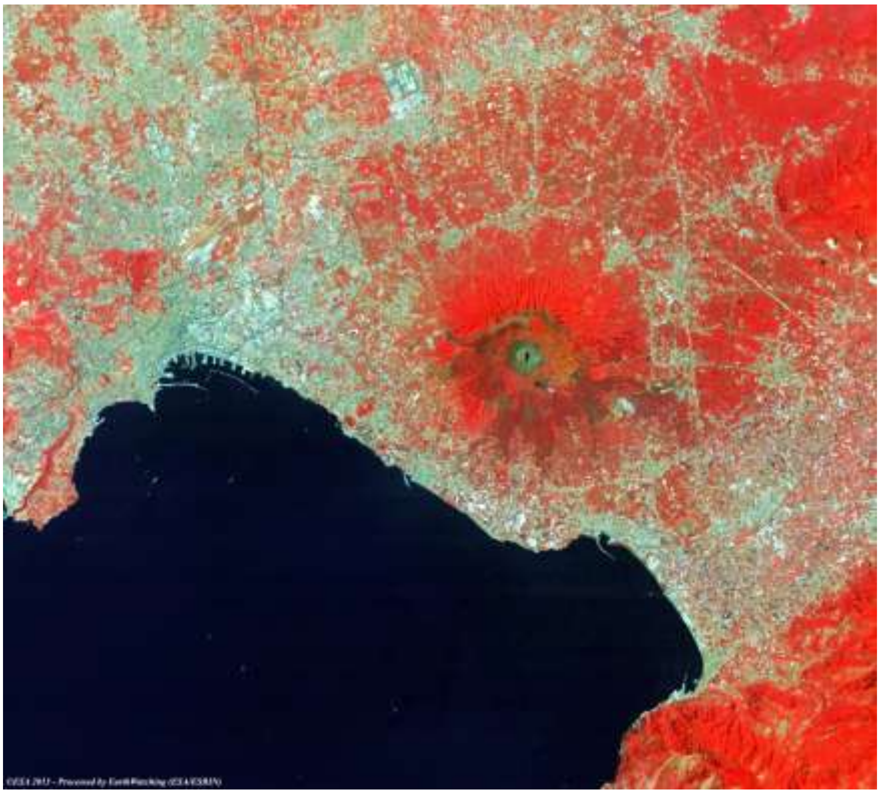
Figure 23. Vesuvius and the near municipalities, Landsat-5, 26 June 2010, RGB 431.
Source: ESA-ESRIN.

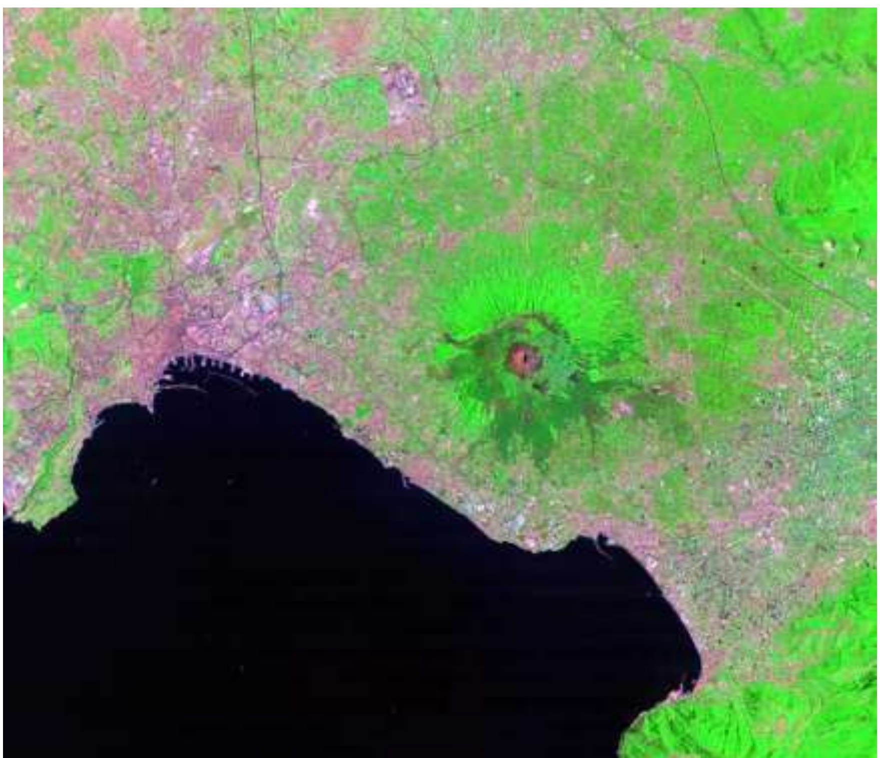
Figure 24. Vesuvius and the near municipalities, Landsat-5, 26 June 2010, RGB 742.
Source: ESA-ESRIN.

Figure 25. Vesuvius and the near municipalities, with a focus on the South-East side, AVNIR-2, ALOS, 16 June 2009 (natural colours). Source: ESA-ESRIN.

Figure 26. Vesuvius and the near municipalities, with a focus on the South-East side, AVNIR-2, ALOS, 16 June 2009 (false colours). Source: ESA-ESRIN.

This image confirms the high risk for civil protection procedures and shows where vegetation leaves the soil to old and recent lava flows (better distinguishable in colours than in the previous RGB 321 and 431 visualizations) on the top of the volcanic cone. With the images acquired by the AVNIR-2 instrument of the ALOS satellite on 16 June 2009 and visualized in natural and false colours (Figures 25 and 26), respectively, the above details appear even more dramatic: an impressive number of people would need to be evacuated in the case of an eruption, which is potentially statistically closer and closer!

Acknowledgements

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