MONITORING MT. ETNA, A CASE STUDY -10 YEARS OF MULTI-SPECTRAL IMAGING OBSERVATIONS OF VOLCANIC ACTIVITY, FROM TIMS (1986) TO MIVIS (1997)

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1.0 Introduction

Modern geophysical techniques of volcano monitoring allow simultaneous observations of a wide variety of parameters relevant to understanding how volcanoes work. Images acquired by multispectral scanners and imaging spectrometers are able to provide important information on the surface activity and atmospheric emissions of volcanoes both during quiescent and active periods, as has been demonstrated by several studies (Kreuger *et al.* **1990,** Bluth *et al.* **1992,** Hobbs *et al.*, 1996). For instance, knowledge of volcanic plume composition and dynamics can provide information on magma movement within volcanic conduits, because $S0_2$ and $C0_2$ outputs arc influenced by the magma temperature and hydrostatic level within the volcano's internal plumbing.

Traditionally, volcanic plume composition has been investigated by direct sampling, techniques often involving considerable logistical planning and, often, personal risk. For large volcanoes such as Mt. Etna, a direct gas sampling from the summit craters is not possible. More recently, ground-based remote sensing instruments, such as the UV correlating spectrometer (COSPEC) (e. g., Millan *et al., 1985;* Realmuto et *al.*, 1997) or the Fourier transform spectrometer (Francis, *et al.,* 1995), have been used successfully, particularly where direct sampling techniques are not practical or safe.

The first attempt to use image data to retrieve SO_2 concentrations in a tropospheric volcanic plume was carried out using airborne Thermal Infrared Multispectral Scarrncr (TIMS) data acquired on Etna in 1986 (Realmuto *et al.* 1994). This work demonstrated how airborne imaging techniques could be used to monitor the gas emissions of fumaroles and plumes of active volcanoes. Since the late nineteen-eighties, the construction of airborne imaging spectrometers (AVIRIS, MIVIS and DAIS) have opened the way to more accurate remote sensing multi-spectral studies on volcanogenic atmospheric gases and surface deposits.

In this work wc present research results based on analyses of airborne image data sets acquired between 1992 and 1997 cm Mt. Etna. In particular, wc focus on (a) observations of the tropospheric volcanic plume formed by the continuous degassing from Etna summit craters, and (b) spectro-morphometric analyses of 1991-1993 Valle del Bove (Etna) compound lava flow field and its surface temperature evolution through 1997.

2.0 Some Information On Mt. Etna

Mt. Etna is located in the eastern part of the Island of Sicily. It is a tholeiitic (basal platform) through mugearitic-hawaiite basaltic shield volcano (Chester, *et al.,* 1985), and it is the largest active central-vent volcano in Europe. Its astonishingly long history of continuous scientific study, which elates back to the sixteenth century, combined with relatively easy access and extensive on-site scientific support, makes it onc of the one of the world's premiere volcanic laboratories.

The historic port city of Catania (population -500,000) lies on the southernmost part of the Etna volcanic shield, and was partly inundated with lava from Mt. Etna during the 1669 eruption. Mt. Etna has a basal diameter of about 40 km and its summit craters are situated at 3,300 meters above sea level. Etna's first volcanic activity began between 700,000 and 500,000 years before present, characterized by an initial explosive stage coupled with submarine eruptions. Then followed subaerial eruptions and a migration of the main conduits from cast to west (Romano, 1982). Etna's eruptive activity continues today, erupting nearly yearly, with the latest large eruption occurring between December 199 I through spring 1993. Onc of the volumetrically largest eruptions of this century, it was characterized by very long-lived effusive activity. Lava flows from this eruption threatened the town of Zafferana Etnea (on the eastern flank of Etna), where upslope residential areas were saved only by a pioneering lava flow diversion effort, onc of the fcw such attempts ever completed successfully (e.g., Arbersten, 1984; Barberi *et al.*, 1993). Post-tholeiitic Etnean lavas arc principally high sulfur alkali-basalts (Metrich and Clochiatti, 1989), consequently causing a high concentration of $S0_2$ in volcanic gas emissions. The mean $S0_2$ flux from Mt. Etna varies greatly (Caltabiano *et al.* 1994), but shows a mean value of about 5000 tons/day. Other studies have demonstrated that fully 10% of the global atmospheric inventory of volcanogenic sulfur dioxide originates from Etna.

3.0 Data Sets Used For Volcanological Remote Sensing Studies of Etna

Since Etna is one of the most studied volcanoes on the Earth, it is a perfect laboratory to test remote sensing instrumentation and monitoring techniques. In this study wc carried out systematic analyses of the available airborne data, inducting inter-instrurncnt comparisons of gas retrieval techniques, as well as studies related to the combined multi-instrument time-series observations. The main difficulties that wc found were in the nature of getting enough systematic repetitive acquisitions over desired sites because of (a) the high cost of mounting an airborne campaign, and (b) the complicated required planning (e.g., ground calibration support, weather, aircraft logistics) to obtain well-posed airborne data with good simultaneous ground calibration. A number of data sets exist for Mt. Etna, acquired by different sensors during the past 10 years but, in general, there are few data sets directly related to monitoring a particular outbreak of volcanic activity.

In addition to the TIMS data acquired during a NASA-Jet Propulsion Laboratory (JPL) campaign on Italian volcanoes in 1986 wc analyzed four other data sets, including (a) Airborne Thematic Mapper Simulator (ATMS) data acquired in 1992, (b) Multispectral Infrared and Visible Spectrometer (MIVIS) data acquired in 1994 and 1997, and (c) Digital Airborne Imaging Spectrometer (DAIS) data acquired in 1996. These data sets all cover the visible to thermal-infrared (TIR) spectral range. For this study wc focused on the TIR channels of these instruments.

4.0 Etna Plume Monitoring: Sulfur Dioxide Retrieval

The measure of the concentration of SO_2 gas in the Etna plume is onc of the focal points of this work. The estimation procedure presented by Realmuto *et al.* (1994) was based on LOWTRAN 7 (Kniezys *et al.*, 1988) radiative transfer code, which is used to model the radiance perceived by TIMS when it looks at the ground through a volcanic plume.

The radiance measured from a remote sensor is:

$$I.,(X,TO) = \{\varepsilon(\lambda).B(\lambda,T_o) + [1- \varepsilon(\lambda)].I/@)\} \cdot_{z(\sim)+} I_u(\lambda) \qquad (1)$$

where TO represents the temperature of the ground, $L_u(\lambda)$ and $L_d(\lambda)$ represent the atmospheric contribution to the measured radiance, $\tau(\lambda)$ is the spectral transmittance of the atmosphere. The ground radiance is the product of the Plank function $B(\lambda,T_o)$, and emissivity of the ground, $\varepsilon(\lambda)$. Equation (1) is only valid for vertical paths through the atmosphere. Angular dependencies of I, U(k), $\tau(\lambda)$, and Id(k) were omitted to simplify notation.

The atmospheric model includes the knowledge of $\varepsilon(\lambda)$, which wc estimate from TIMS radiance measurements, the distance between ground target and sensor, as well as the zenith angle, which defines the path between the sensor and point on the ground. I. OWTRAN calculates $L_u(\lambda)$, $\tau(\lambda)$, and $L_d(\lambda)$ from altitude profiles of barometric pressure, temperature, humidity and atmospheric constituents. The altitude profiles can be selected from many atmosphere models that arc packaged with LOWTRAN or entered manually. To model the presence of $S0_2$ in the volcanic plume, the altitude, thickness, and SO_2 content of the plume was specified iteratively, thus modifying the constituent profile of the radiative transfer model until a reasonable atmospheric profile was obtained that matched the imaging data radiance. The results obtained from TIMS data were encouraging, although during the initial 1986 campaign, there were no independent ground measurements (e. g., COSPEC) for comparison with the TIMS-based SO_2 retrievals.

In 1994, the MIVIS instrument (operated by the *Consiglio Nazionale dells Ricerche (CNR), Projetto LARA*; Bianchi *et al., 1994), was* first deployed for observations of Sicilian volcanoes (Abrams *et al.,* 1997). The *Istituto Nazionale di Geofisica* (ING), the University of Modena, and the *Istituto Internazionale di Vulcanologia*, with the participation of JPL, organized the ground campaign to validate and calibrate the image data (Bogliolo *et al.*, 1996). The data acquired in 1994 were studied, in detail, to develop a reliable technique for estimation of the spatial distribution of SO_2 concentration and $S0_2$ flux as derived from TIMS images, using the MODTRAN3 code (Berk *et al.,* 1989). The results obtained after 2 years of work were in good agreement with the SO_2 estimates made by COSPEC simultaneously with the MIVIS flights. Nevertheless some of the uncertainties in the model remain unsolved. In particular the thickness and altitude of the plume is a crucial variable that can greatly affect the retrieved $S0_2$ concentration values. The variation of the emissivity spectra of the surface under the plume is another potential source of error in the calculation.

In 1997, as part of a volcanology project funded by the European Community, a new MIVIS campaign was organized for Etna, in order to improve $S0_2$ retrieval methods and to test the feasibility of CO_2 plume retrievals. To better delineate the altitude and thickness structure of the Etna plume for comparison with the MIVIS retrievals, a second aircraft, equipped with instruments able to directly measure the distribution of $S0_2$ and CO_2 gases in the plume was flown parallel to the plume track, simultaneous with MIVIS acquisitions. The data collected from the most recent campaign arc now under analysis, but wc expect to be able to find an answer to the questions raised by Realmuto *et al.* (1994) in their first study of the Etna plume, but which were not completely resolved with the MIVIS 1994 campaign.

5.0 Etna Eruption Of 1991.1993

The second point on which wc focused our attention in the analysis of the Etna airborne image data sets is the evolution of the 1991-1993 eruption. For this wc used data acquired by ATMS in 1992 and from MIVIS between 1994 and 1997. Our intention was to compare the ground temperature of particular zones of the Valle del Bove area, where the thermal activity showed significant surface anomalies during the period of interest. Moreover, we also monitored summit crater thermal emission that was constantly varying in radiance, duc to flank eruption activity.

The technique used was based on modeling the atmospheric correction to instrument-pcrccivcci ground temperature by using the MODTRAN3 code. For MIVIS '94 and '97 data it was indeed possible to validate our airborne temperature estimate with ground measurements. The results of this analysis is being incorporated into the framework of a larger study carried out by D. Pieri and M.F. Buongiorno of time-series radiance variations of Etna summit craters, as seen in satellite-based and in-situ geophysical data acquired on Etna between 1986 and 1996.

6.0 Conclusions and Recommendations

The acquisition of time-series image data sets allow monitoring of the evolution of volcanic phenomena, and provide the opportunity to develop ncw analysis techniques for the retrieval of physical parameters crucial for improving our understanding of how volcanoes work. In addition, our analysis particularly emphasizes the importance of simultaneous ground measurements for calibration and validation of both data sets and retrieval algorithms. Unfortunately many flight missions occur without duc consideration and planning of associated ground campaigns, therefore reducing the scientific usc of the image data.

In the two MIVIS campaigns considered here (1994 and 1997), wc tried to acquire all the necessary ancillary field data to be able to produce reliable results with respect to retrieving the spectral properties of volcanic plumes and ground temperatures on active volcanic areas. The results of our analyses of the 1994 airborne data arc encouraging and wc hope to improve on these results with analyses of 1997 airborne campaign data.

Finally, our overall goal in this work is to develop analysis tools applicable to upcoming future satellite sensors that will be able to point their "eyes" over the many active volcanoes of the earth, and to make those tools widely available. Ideally, wc aim to make our satellite-based models as independent as possible from ground and airborne measurements. It is clear, however, that airborne image data on well-posed test sites, coupled with good ground calibration and validation activities, will continue to be crucial to the development, testing, and improvement of such self-contained orbital techniques.

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8.0 **Bibliography**

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