REMOTE SENSING OBSERVATIONS FOR VOLCANO MONITORING AND HAZARD MITIGATION

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ABSTRACT

Volcanic eruptions are spectacular but dangerous phenomena to study on-site, and they present many challenges because of the diversity of activity and their remote locations. Indeed, the tragic loss of life at Galeras and Mt. Unzen volcanoes in the early 1990s illustrates the dangers associated with studying active volcanoes at close quarters. However, much progress has been made in volcano remote sensing during the last decade, and further substantive developments are expected over the next few years as several countries fly next-generation spacecraft. In particular, NASA's Terra spacecraft will provide unprecedented capabilities for volcano monitoring, and a team of 20 remote sensing volcanologists have been working for almost a decade to develop algorithms for the routine monitoring of active volcanoes. Aircraft data also provide valuable data sets, and serve as experimental test beds for future spaceborne topographic and thermal infrared mapping systems. Many parts of the spectrum, from UV to microwave wavelengths are now employed to study such phenomena as volcanic ash clouds, the thermal anomalies associated with active lava flows and domes, ground deformation due to intrusions. Topographic mapping has also been conducted from satellites and aircraft in order to detect surface changes due to erosion of pyroclastic flows or the formation of new lava flow fields. This paper reviews many of these methods, drawing upon ERS-2, GOES, Landsat, RADARSAT, SPOT and TOPSAR data collected for volcanoes in Hawaii, the Galapagos Islands and the Philippines. The value of radar remote sensing observations of volcanoes in remote parts of the world (e.g., South America, Central Africa, and Indonesia) will also be described. On-going techniques that permit the near real-time satellite observation of volcanic eruptions will be discussed in order to provide a basis for assisting volcano disaster mitigation.

1 INTRODUCTION

1.1 Volcanic Hazards

There are numerous types of volcanic hazards, including lava flows, mudflows (called "lahars"), pyroclastic flows, and giant eruption clouds (*Tilling*, 1989). Indeed, people are at risk not only on the ground, but also in the air since jet aircraft are particularly susceptible to failure if ash from a volcanic eruption cloud is ingested into the engines (*Casadevall*, 1994a, b). Frequently, field conditions are challenging and/or dangerous (Fig. 1), so that there is a significant effort underway within the United States, the United Kingdom, and Australia to develop remote sensing techniques to interpret on-going eruptions (*Mouginis-Mark et al*., 2000a). Often it is in the recovery stage of an eruption where satellite remote sensing data are most helpful to the disaster manager, but it is also important that archives of satellite data are developed to allow remote sensing scientist to aid in disaster mitigation via studies of the pre- and post-eruption characteristics of the surface.

Figure 1. As part of a NASA-funded research project, field work has been conducted on Mt. Pinatubo in the Philippines, which had a major eruption in June 1991. Here we see a field party (people in foreground provide scale) exploring one of the many river valleys that were initially buried under pyroclastic flows, but have then been eroded by heavy rains to produce major mudflows ("lahars") that threaten downslope settlements. Numerous remote sensing efforts to use imaging radar, SRTM, TOPSAR, Landsat and Ikonos data to evaluate the risks in the area are underway in the United States and the Philippines.

2 REMOTE SENSING CAPABILITIES

Much progress has been made in the use of remote sensing observations of active volcanic processes during the 1990's, and further substantive developments are to be expected over the next few years as next-generation spacecraft are launched by the United States, Europe, Canada, and Japan. For instance, now that the Landsat-7 spacecraft has become an operational Earth observatory, there is a long term plan for the acquisition of data via routine imaging of all of Earth's land surface [*Goward et al*., 1999]. As a result, many volcanoes around the world are now being imaged on a routine basis for the first time. The other recently-launched U.S. spacecraft (Terra) is the first part of the Earth Observing System (EOS) and, at the time of writing, has just started to return test data sets.

Research into the volcanological uses of EOS data has been conducted for almost a decade [*Mouginis-Mark et al*., 1991], and similar preparations have been made for the use of other orbital remote sensing data. For instance, Landsat-7 and Terra will be joined in the next few years by the highly capable Environmental Satellite (ENVISAT) and the Advanced Earth Observing Satellite 2 (ADEOS II) spacecraft, flown by Europe and Japan respectively. Both ENVISAT and ADEOS II carry visible- and infrared-wavelength sensors, and ENVISAT will also have an imaging radar system. Dedicated imaging radar missions, such as RADARSAT-2 and the advanced land observing system (ALOS), will be flown in the 2001–2004 timeframe by Canada and Japan, respectively.

There have been several reviews of satellite remote sensing of volcanoes (e.g., *Francis*, 1989; *Mouginis-Mark and Francis*, 1992; *Mouginis-Mark et al*., 1993; *Rothery and Pieri,* 1993; *Self and Mouginis-Mark*, 1995; *Francis et al*., 1996; *Sparks et al*., 1997; and *Oppenheimer*, 1998). These earlier reviews have tended to focus on individual sensors, wavelength regions, or techniques. But each volcano has a unique history of activity and individual eruptions can evolve over time periods ranging from hours to more than a decade, so that many volcanic hazards must be studied via a range of techniques. Fortunately, many aspects of an eruption can now be studied at some level using either airborne or spaceborne remote sensing techniques. This paper illustrates some of these techniques and their relevance for volcano hazard monitoring and recovery.

3 EXAMPLES FROM RECENT ERUPTIONS

3.1 Hawaii, 1983 - 2000

Kilauea volcano, Hawaii, has been in near continuous eruption since January 1983. It has therefore proven to be an excellent study area to develop diverse remote sensing methods. For instance, hyperspectral techniques for the analysis of lava flow temperatures (*Flynn and Mouginis-Mark*, 1992), the mapping of total thermal flux from active lava flows (*Flynn et al*., 1994; *Harris et al*., 1998), the estimation of lava production rates from interferometric radar (*Zebker et al.,* 1996), mapping the flux rate of sulfur dioxide using thermal infrared images (*Realmuto et al.,* 1997), and the analysis of topographic change via comparison of digital elevation models (*Rowland et al.,* 1999), have all been developed at Kilauea. Routine automated methods for frequent monitoring the thermal output of the volcano (*Harris et al*., 1997, 2000) using geostationary satellite data have also been developed at Kilauea.

This wide range of remote sensing data sets has also provided an excellent opportunity for the use of Kilauea and Mauna Loa volcanoes as calibration and validation sites for spaceborne sensors. For instance, the summit of Mauna Loa volcano is an ASTER calibration target for the Terra mission, while digital elevation data collected by the TOPSAR airborne radar (*Rowland et al.,* 1999) will also be used to validate measurements made by the Shuttle Radar Topography Mission (SRTM) and the Vegetation Canopy Lidar (VCL) mission.

3.2 Galapagos Islands, 1998

The September 1998 eruption of Cerro Azul volcano in the Galapagos Islands provided an excellent opportunity to monitor an on-going eruption in a part of the world where field logistics were difficult and expensive (*Mouginis-Mark et al*., 2000b). The GOES-8 weather satellite collected 520 visible and thermal daytime images, and 815 nighttime thermal images, during the 36-day eruption of Cerro Azul. A sub-set of these images that cover the onset of the eruption on September 15th 1998 is shown in Figure 2 to illustrate the high temporal resolution that can be obtained from geostationary orbit. Numerous features of the eruption were observed in the GOES data, including eruption plumes and their dispersal patterns, the thermal anomalies due to intra-caldera activity, and the active lava flows on the eastern flank. Particularly important was the use of the GOES data to obtain accurate times for the start and termination of the eruption, as well as the identification of the location of the active vents both within and outside the summit caldera. Retrospective analysis of field observations also indicates that other aspects of the eruption were seen in the GOES data, including smoke from burning vegetation at the edge of the active flows, and haze plumes produced from degassing at the vents.

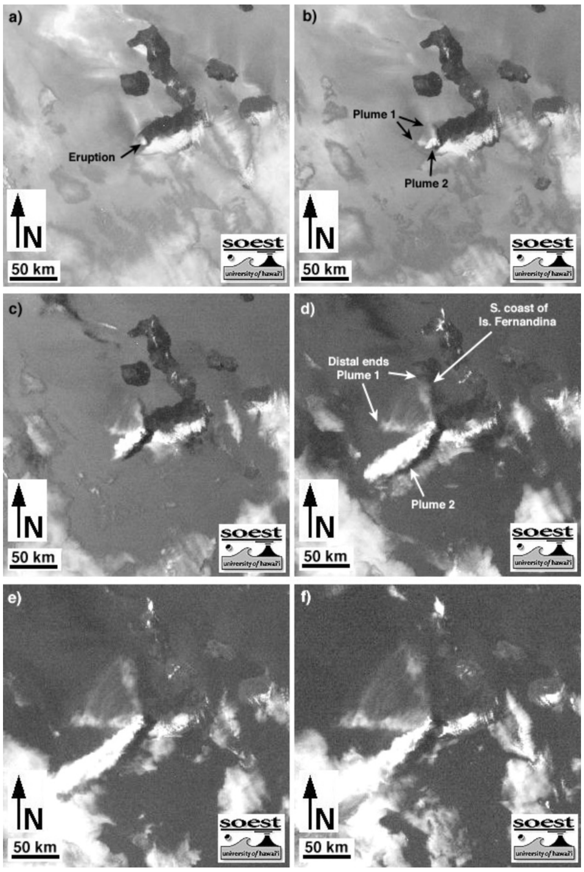

Figure 2. A series of GOES-8 satellite images was collected over Cerro Azul volcano during its September 1998 eruption. Here we see band 1 (0.52 – 0.72 μm) GOES observations of the first two eruption plumes detected on Sept. 15th, 1998. Images were obtained at the following local times: a) 13:28; b) 13:59; c) 14:28; d) 14:58; e) 15:28; and f) 15:58. No plume was present in the 12:59 image (not shown). Notice that in the final image (f), the edge of Plume 2 is becoming distorted. The next image in this series (not shown) indicated that the event producing this plume had shut off and that the plume was dissipating. Images from *Mouginis-Mark et al*. (2000b).

3.3 Mt. Pinatubo, Philippines, 1991 - 2000

The 1991 eruption of Mount Pinatubo, Philippines, provided a unique opportunity to study the effects of a large volcanic eruption in part because it took place after the advent of advanced remote-sensing technology. For the first time, there are high-resolution (20 m/pixel) satellite data for a region both before and after a major explosive eruption. Mt. Pinatubo generated large volumes of pyroclastic flows, producing a vast ignimbrite deposit with an estimated volume of ~6 km^3. Using remote sensing data collected at microwave (3.0 – 68.0 cm), thermal infrared (8.0 – 12 μm), short-wave infrared (1.0 – 2.4 μm) and visible wavelengths, it is possible to quantify the temporal evolution of the new landscape by investigating its thermal properties, vegetation cover, drainage pattern evolution and erosion of the deposits.

A holistic overview can be derived of the physical dynamics of the landscape as they influence the volcano's geomorphology and thermal energy. This in turn allows the identification of the inter-related aspects of the local hydrologic cycle, vegetation re-growth, and the creation of volcanic hazards. Such processes occur over large areas and take place so rapidly that the surface processes have hitherto gone unstudied following large eruptions. Changes to the landscape can be observed for many years or decades after the eruption, so that recovery from the eruption can easily be studied via remote sensing techniques. Here we focus on three aspects of change at Mt. Pinatubo that can be studied via satellites.

1) When they were emplaced, the Mt. Pinatubo ignimbrite sheets were at temperatures of a few hundred degrees centigrade. Even after more than 8 years after the eruption, the thermal anomalies associated with hot water springs around the volcano can be seen in nighttime thermal infrared (TIR) Band 6 data from Landsat-7. When these images are cloud free, the pattern of the hot streams coming out of the deposit can be mapped (Fig. 3).

2) Erosion of the non-welded deposits within the river valleys has been widespread around the summit of Mt. Pinatubo during periods of heavy rains. This rainfall is typically associated with the passage of typhoons through this part of Luzon Island. Many of these erosional events have generated large lahars that have swept down the flanks of the volcano and inundated adjacent low-lying areas. Because these lahars are generated during the rainy season, it is frequently not possible to rapidly obtain optical or infrared wavelength data for the region. Fortunately, the radar backscatter properties of the lahars are such that there is often a strong contrast between the lahar and the surrounding areas (*Chorowicz et al*., 1997); lahars in general tend to have a low radar backscatter at the wavelength of both ERS-2 and RADARSAT (C-band, 5.6 cm). As the surrounding area is re-vegetated, or human settlement becomes re-established, the landscape is generally radar-bright, so that the planimetric shape of the new lahars can be easily identified even under cloudy conditions. However, we note that it has not been possible to conduct radar interferometric studies of the region at C-band, since there is often large spatial variations in water vapor, and the vegetation cover decorrelates the scene.

3) The third aspect of the on-going changes of the area around Mt. Pinatubo is the rate of re-growth of the vegetation cover. Monitoring the distribution of vegetation is particularly valuable to disaster managers for hazard mitigation and the assessment of the area's recovery, since it appears that the vegetation acts to stabilize the ash deposits that may erode to form the lahars. This vegetation cover can be easily shown using the short-wave IR channels on satellites provided, of course, that there is cloud-free coverage. A three-band visible/near-IR SPOT image clearly

defines areas cover with vegetation and comparison to images for other years shows how the area coverage changes. In Figure 4 we show four SPOT images (obtained in 1991, 1994, 1996 and 1998), that illustrate the rate of re-vegetation of the summit of the volcano. While still in the development phase, an objective of our future work is to see if there is any correlation between the thermal signatures and vegetation re-growth, since we expect the high soil temperatures to inhibit plant growth.

4 REAL-TIME CAPABILITIES

Satellite remote sensing can yield an improved understanding of volcanic processes and volcanic hazards simply by providing more frequent observations at a wide variety of wavelengths. But to be of greatest value to the disaster management community it is important that the data are made available as soon as it is technically possible. Scientific validation of some of these data is also critical as a disaster manager never has the time to check the validity of a data product during a crisis. To try to respond to this objective, considerable use is being made of the World Wide Web for the display of satellite data of volcanoes. Near real-time satellite observations of the thermal properties of several volcanoes are also presented on the University of Hawaii's web site (*Harris et al.,* 2000). The NASA EOS Volcanology Team also maintains a page focused on the techniques and algorithms that will be used during these upcoming missions. The addresses for these two sites are as follows:

http://volcano1.pgd.hawaii.edu/goes/
http://volcano2.pgd.hawaii.edu/eos/

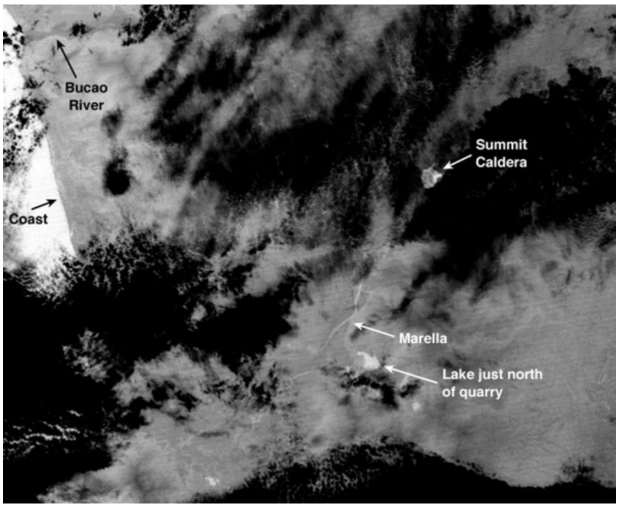

Figure 3: Landsat 7 has started to obtain some fascinating new insights into recently active volcanoes. Here we see a band 6 (10.4 – 12.5 µm) nighttime image of the western side of Mt. Pinatubo. Hot water in the river systems draining off of the 1991 deposits is shown in white.

5 CONCLUSIONS

This paper illustrates the capabilities of remote sensing systems for a few active volcanoes around the world. However, in only a few cases (such as the thermal properties of volcanoes) does a routine satellite-monitoring program already exist. It is nevertheless expected that remote sensing will play an increasingly greater role in hazard monitoring as more near real-time observations become available; many of the volcanic eruptions seen by spacecraft will have immediate social and economic impacts for local communities.

As real-time satellite data for eruptions become more readily available to the remote sensing community, care will have to be taken to follow the appropriate agency procedures when contacting the responsible officials [e.g., *IAVCEI*, 1999]. Care should also be taken when press releases are written by remote sensing scientists and agencies such as NASA. The establishment of strong collaborative ties with foreign volcano observatories through joint collection and analysis of satellite data is one method to ensure that local issues remain of paramount importance.

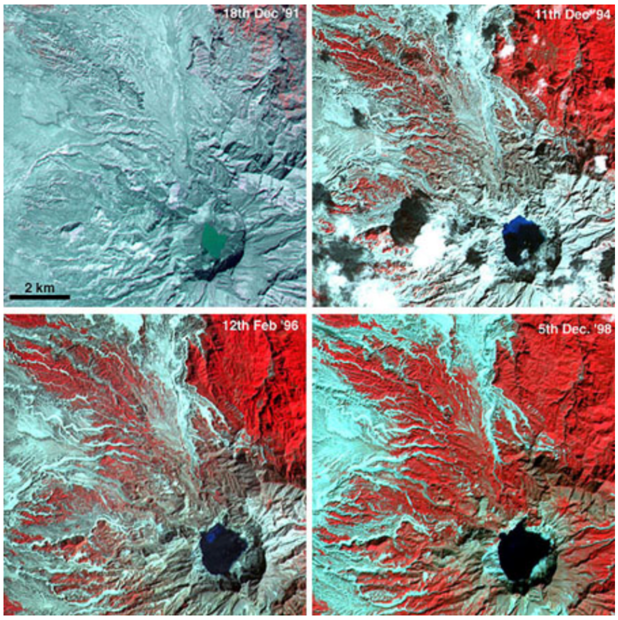

Figure 4: Sequence of four SPOT MSS images obtained over Mt. Pinatubo showing the regrowth of vegetation on the NW flank between Dec. 1991 (top left), Dec. 1994 (top right), Feb. 1996 (lower left) and Dec. 1998 (lower right). © SPOT Image Corp.

While the GOES data greatly enhance the capabilities to observe the thermal properties of eruptions in North and South America (*Harris et al.,* 2000), real-time monitoring cannot currently be conducted on a global scale, and so is of less than ideal utility to disaster managers around the world. Indeed, it is the frequency of observations provided by geostationary satellites that is most helpful when studying transient eruptions. However, only the GOES-8 and GOES-10 geostationary satellites have the 3.9 µm band which is required for the hot spots to be detected and monitored. Thus this type of thermal monitoring cannot be carried out in the western Pacific because the only data set of this area provided by a geostationary satellite (the Japanese GMS-5 spacecraft) lacks the appropriate mid-infrared coverage. Additional geostationary satellites spaced at different longitudes around the globe would be needed to provide frequent observations of volcanic thermal anomalies.

This recognition that observations need to be made many times per day for thermal monitoring of volcanoes is disconcerting from a hazard mitigation perspective, since many of the satellites (e.g., Landsat 7, Terra, ENVISAT, ALOS) have repeat intervals of a few days to about a month. Eruptions are sufficiently transient (or fast-developing) phenomena that important aspects of the eruption may be missed by spacecraft in low-Earth orbit. Other strategies will have to be developed by the remote sensing community and disaster managers to accommodate this need for high temporal resolution. Using satellite data for hazard mitigation and recovery may prove to be a valuable application, even if hazard response may not be possible for many aspects of a volcanic eruption due to the long time interval between successive satellite overpasses.

Volcanoes in Africa, such as Mt. Cameroon (Cameroon) and Nymuragira (Zaire), fall into this category of suitable “High Risk” volcanoes appropriate for satellite monitoring because they are difficult to monitor on the ground during both the mitigation and recovery phases of activity. For example, *Mackay et al*. (1999) have demonstrated the value of using digital topographic data (comparable to SRTM observations) for the analysis of the thickness of lava flows on Karisimbi volcano, Zaire. *Rowland et al*. (1999) have taken this analysis of digital topography data for volcanoes one step further, and used data derived from an aircraft interferometric radar to estimate the year-long effusion rate of Kilauea volcano, Hawaii. Key to the study by *Rowland et al*. (1999) was the existence of a reference data set for the volcano against which subsequent data could be compared. Such reference data sets currently exist for only a few of the world’s volcanoes, but developing a data base is equally relevant for radar interferometry studies of volcanoes, the thermal monitoring of active lava domes and flows, or flux measurements of volcanic gases. Constructing this diverse reference data base for many of the world’s active volcanoes is seen as one of the major challenges facing the remote sensing community over the coming decade if satellite remote sensing of active volcanoes is going to be of greatest value to disaster managers.

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