THE ROLE OF SATELLITE REMOTE SENSING IN VOLCANIC HAZARD MITIGATION

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Abstract

Remote sensing can contribute to mitigation of volcanic hazard through identification and characterisation of potentially active volcanoes; preparation of hazard maps; detection of eruption precursors; monitoring of erupting volcanoes; damage assessment; and planning of relief operations. Applications are restricted at present by data costs, delays in acquisitions, and complex software but future developments have great potential. Two key developments are the use of all-weather radar satellites to construct and rapidly up-date highly accurate DEMs of volcanoes, and vastly improved centralised systems for coordinated dissemination of large data sets from many sensors.

1. Introduction

Most natural hazards are clearly identifiable phenomena. For example, floods, the commonest natural disasters, are self-descriptive, while earthquakes invariably entail destruction of buildings by seismic waves. Volcanic eruptions, however, present far more diverse hazards In numerical terms, the largest numbers of casualties have been caused by massive tsunamis generated by edifice failure, or sudden emplacement of erupted material into the sea. This happened at Krakatau in 1883, and Tambora in 1815. In each case, tens of thousands of people died when tsunamis ravaged the coasts of Indonesia. Pyroclastic flows (essentially glowing avalanches that cascade down the flanks of volcanoes) are relatively common, and destroyed St Pierre (Martinique) in 1902, causing more than 20,000 casualties. Mud-flows triggered by a minor eruption of Nevado del Ruiz (Colombia) in 1985 killed about 25,000 people when they swept through the town of Armero. More recently, mud-flows following long after the great eruption of Mt. Pinatubo (Philippines) have caused numerous fatalities.

Although explosive eruptions, generating thick ash falls, may seem likely to present the greatest hazards, they have only rarely caused great disasters. The AD 79 eruption of Vesuvius which buried Pompeii is the classic example, but even here, the majority of the 20,000 + casualties was probably caused by a variety of pyroclastic flow, not ash fall Lava flows are generally too slow flowing to cause major casualties, although an exceptional breach of a the crater lake of Nyiragongo in 1977 killed scores of people Eruption of about 14 cubic kilometres of lava in Iceland in 1783, however, was accompanied by emission of such prodigious quantities of acid gas (sulphur dioxide) that environmental havoc was widespread, leading to the deaths of about 25% of Iceland's population from famine.

2. Assessment of volcanic hazard: what we can do *today*

While monitoring of volcanoes by satellite is not yet routine, we can expect dramatic changes in our capabilities over the next few years. Remote sensing can contribute in several ways to the mitigation of volcanic hazard: notably the identification and characterisation of potentially active volcanoes; monitoring of precursory unrest at active volcanoes, monitoring of erupting volcanoes; preparation of hazard maps; damage assessment, and planning of relief operations. My aim here is to illustrate some *practical* applications of satellite monitoring to volcanology, rather than its technical background. Full details will be found in the references cited.

Existing sources of data
Several different types of satellite data are available for civilian applications:

1. High spatial resolution sensors primarily designed for agricultural, mineral resources and environmental remote sensing surveys. These typically have resolutions of 10-30 m and work in visible, near infrared (VNIR) and short wavelength infrared (SWIR) parts of the spectrum. An example is the American Landsat Thematic Mapper (TM).

2. Synthetic aperture radar (SAR) sensors were initially designed mostly for oceanographic work and studies of ice distributions in high latitudes, but have many other applications, notably in topographic mapping They have the enormous advantage that they can 'see through' the cloud cover that obscures the Earth to visible and infra-red wavelengths. An

example is the European remote sensing satellite ERS-1

3. Sensors aboard satellites used for routine world-wide weather observations provide the most widely accessible data These work in both visible and thermal infra-red parts of the spectrum and have low spatial resolutions (1- several km), but whereas high resolution remote sensing satellites typically provide coverage of an individual volcano only once every 5-16 days, meteorological satellites may provide data as often as every 30 minutes.

While satellite monitoring of volcanoes cannot replace conventional ground-based techniques, technical developments in future generations of sensors will ensure that it forms a routine component of efforts to mitigate volcanic hazards. Satellite remote sensing offers two outstanding advantages over conventional, ground-based techniques:

1 *Global coverage* Because satellites are constantly in orbit, they uniquely offer the opportunity to initiate monitoring of any volcano in the world at short notice, or even retrospectively, using archived data sets Once initiated, coverage can be essentially continuous, and interpretation of the resulting data is facilitated by forming part of a globally coherent data set, covering other volcanoes and eruptions. This capability is particularly important because several disastrous eruptions (e.g. El Chichón, 1982) have taken place at obscure volcanoes, not hitherto well-studied on the ground Other eruptions, such as that of Mt Lamington, Papua New Guinea (1951) have taken place at sites not even known to be volcanoes.

2 *Multispectral capability* Satellite sensors scan the spectrum from ultraviolet to microwave. This means that independent parameters can be monitored simultaneously (ranging from thermal emissions to eruption plume height and ground deformation), greatly enhancing the value of the data. Many of these observations require manipulation of complex algorithms by remote sensing specialists: it is the task of the volcanologist to synthesize and interpret them

3. Applications of satellite monitoring

Identification and characterisation of potentially active volcanoes

Determination that any volcano is potentially active requires identification of evidence that it has erupted in the recent geological past, by convention the last 10,000 year (Simkin *et al* 1981). For these studies, the simplest forms of image data are suitable, and high spatial resolution is more important than spectral resolution: the image interpretation is essentially conventional photogeology applied to volcanic terrains In a Landsat TM study of the volcanoes of the Central Andes (Francis and de Silva, 1989; de Silva and Francis, 1991) geomorphological evidence of eruption was used to determine that 44 volcanoes out of more than 1.000 volcanic constructs are potentially active

Characterisation of the likely future behaviour of a volcano requires identification of previous patterns of its eruptive activity, and is essential in understanding its potential hazard to surrounding communities. Morphological and spectral data from satellites can be used to infer the compositions of existing lava flows, and the gross structural or magmatic evolution of the volcano in terms of changing magma chemistry can be elucidated if the flows are well exposed. For example, volcanoes likely to experience future episodes of dacitic dome growth and hot avalanche emplacement may be identifiable from their morphology and aprons of existing deposits. Such interpretations must necessarily be cautious, and tempered by experience. For example, although Mt. St. Helens was closely monitored, the character of its May 1980 eruption surprised everyone. In future, however, this style of behaviour will be included in hazard assessments.

Visible manifestations of eruptions

In remote regions satellite monitoring may provide the only evidence of eruptions. Fernandina (Volcan Cumbres, Galapagos islands) was in 1968 the site of the largest caldera collapse event on a basaltic volcano in history; some 1-2 km^3 of material being engulfed. SPOT images acquired before (27 April) and after (25 October) were used to document the collapse event and subsequent eruption. Similarly, satellite studies of Láscar volcano, north Chile, were used to identify extrusion of a summit lava dome before confirmation from ground studies (Glaze *et al.* 1989).

Monitoring ground deformation - radar interferometry

Radar has the overwhelming advantage of all-weather capability: it can 'see' through clouds. Measurements of the displacement field of the 1992 magnitude 7.3 Landers earthquake (California) provide an instructive example of the potential of satellite Synthetic Aperture Radar (SAR) interferometry to detect ground deformation of the scale that may precede a volcanic eruption (Massonet *et al*, 1993; Rossi, this volume). The unprecedented precision and dense spatial sampling of the deformation field of SAR demonstrated by the Landers study offer exceptional opportunities for volcanologists, given that eruptions may be preceded by significant ground deformations - more than 1 metre per day at Mt St. Helens, for example

Monitoring thermal phenomena

Multispectral sensors such as Landsat TM carried aboard standard remote sensing satellites are designed to work in the visible, short-wavelength infrared and thermal infrared Fortuitously, these sensors are capable of detecting *emitted* thermal radiation from hot sources such as volcanoes, as well as reflected and re-radiated solar energy.

Infrared sensors are extremely sensitive. Thus, the short wavelength infra-red detectors on the Landsat TM at an altitude of 705 km are capable of detecting unambiguously the radiant thermal flux from a 1000°C source only 0.1 m^2 in area (Francis and Rothery 1987, Rothery *et al.* 1988). Similarly, in the thermal infra-red it is possible to detect changes in surface temperature of a few tenths of a degree Celsius, a capability widely used in precise measurements of sea-surface temperatures. The same sensors can easily detect magmatic features such as the Mt. Erebus lava lake, even though these are far smaller than the 1 km or greater resolution of the sensor Active lava tubes on Kilauea volcano were revealed by the thermal infra-red band of Landsat TM, although the 120 m pixel size of this sensor is far greater than the <10 m width of the tubes.

Changes in temperature of aqueous crater lakes can provide clear indications of unrest at a volcano (e.g. Taal volcano in 1965) Because synoptic temperatures integrated over many thousands of square metres of water surface are obtained by satellite studies, they should be more meaningful than measurements made by hand at one or two points around the margin of such a lake (Oppenheimer, 1993). If two or more bands of data are available, it is possible to derive temperature and size estimates of thermal anomalies far smaller than the size of a pixel. These quantitative studies can be helpful in interpreting the nature of thermal anomalies. for example discriminating between fumaroles and hot lavas (Oppenheimer, 1993). An extensive literature on these issues exists, conveniently summarised in Rothery *et al.* (1994)

Monitoring eruption plumes

Volcanic gas flux and chemistry are sensitive indices of the magmatic evolution of active volcanoes, and, along with geophysical measurements, offer critical information in attempts to predict volcanic eruptions. When a volcano erupts explosively, a complex mixture of steam, acid gases and silicate particles is injected into the atmosphere. If the eruption column is confined to the troposphere, it is relatively rapidly dispersed, but if injected into the stratosphere (> 18 km), the SO_2 is oxidised to sulphuric acid The residence time of acid aerosols in the stratosphere is long (many months), and thus the scattering to space and absorption of incident solar radiation by aerosol particles causes significant surface cooling. Satellite monitoring is thus called on to track separately the silicate, gas and aerosol components of eruption plumes.

While massive eruptions leading to catastrophic ash fall accumulations take place only two or three times per century, much more frequent smaller eruptions present an increasing hazard to world aviation. Disasters due to aircraft encountering ash plumes have only narrowly been averted after eruptions of Redoubt in Alaska, Galunggung in Indonesia and Pinatubo in the Philippines (Casadevall, 1992). Satellite monitoring is the only way that synoptic data can be gathered rapidly enough to detect such hazards Understanding of the heights attained by volcanic plumes and their rate of spreading is also essential input to models used to forecast areas at risk from volcanic ash fall and in tracking the downwind extent and dispersal of large eruption clouds. Holasek and Rose (1991) have reviewed the use of Advanced Very High Resolution Radiometer (AVHRR) data in studying eruptions from more than 40 eruptions

4. Hazard mitigation

Remotely sensed data can be employed to help provide management information concerning volcanic hazards before crises arise. Hazard maps can be compiled from data on the location, magnitude and frequency of previous events and their spatial relationship to human habitation and communications Sometimes the extent of the most dispersed deposit from the volcano can be mapped with ease from TM or SPOT images and this can form the basis of a worst-case scenario

Many of the most hazardous volcanic manifestations involve gravity-driven flow over the volcano's topography A compelling example of the importance of topographic control was the destruction of Armero by lahars triggered by the 1985 eruption of Nevado de Ruiz. Located precisely in the mouth of the long, narrow Lagunillas canyon, the vulnerability of the town of Armero was predicted from knowledge of the topography of the volcano Other phenomena such as lava and pyroclastic flows present more complex problems, but both are governed by the laws of motion under gravity. Several models have been developed to predict the likely run-out of volcanic flows (e.g. McEwen and Malin, 1989) and their dynamic evolution (e g. Wadge *et al.*, 1994) and these and future models all require accurate digital models of volcano topography

While conventional topographic maps or stereo air photographs can be used to provide the digital topographic data base for such models, satellite remote sensed data are becoming an increasingly important data source, because of their potentially universal availability Furthermore, DEMs created from conventional data sources are essentially 'one off' products, which can only be laboriously updated at great cost, whereas satellite-derived DEMs can be readily modified in response to changes taking place on an volcano during a continuing eruption. Stereo scenes obtained from the SPOT satellite have been used in conjunction with automated pattern-recognition photogrammetric software to create digital elevation models, but these are limited by cloud cover and accuracy (about 10m vertical resolution) Satellite-derived high resolution digital topographic data that provide slope and surface roughness with precisions similar to that of airborne SAR (e.g TOPSAR) promise to transform our current capabilities for assessing the potential hazards presented by lava and pyroclastic flows, and should form part of the basic monitoring and hazard management philosophy of volcano observatories

Relief mapping

In the event of a major eruption necessitating the involvement of outside agencies to provide aid to stricken communities and re-establish facilities, remote sensing has the potential to provide an overview of the situation. It may be able to give information such as which roads are passable, which rivers are flooded, which bridges destroyed and the areas most in need of immediate effort. The prime requirement is that the data should be available immediately Although satellite radar may seem to have some advantages here, imaging radar is inherently more difficult for remote sensing novices (e.g relief workers) to understand visually than optical images. The 1991-92 eruption of Mt Pinatubo and the subsequent lahar hazard was a challenging task in this regard. Here the deposition of very large amounts of ash has meant the remobilisation of new lahars during all subsequent cyclonic weather, making the disaster a very complex and long-lived one to monitor and manage.

Remote monitoring of volcanoes and data management

Rather than forecasting volcanic eruptions, most effort to date has been *ad hoc*, and involved 'hind-casting' - that is, looking back at archived remotely sensed data for an event that has already happened to determine if the sequence of events could be satisfactorily modelled (e.g. Rothery *et al*., 1988) This situation arises partly because satellite data are currently too expensive to be routinely useful. The maximum frequency possible for general purpose sensors like Landsat is determined by the orbit repeat of the satellite (16 days in the case of Landsat). Even if a volcano observatory could afford to acquire data at this frequency, a volcanic crisis could develop over a much shorter time scale. If routine data acquisitions are not scheduled, delays involved in scheduling a satellite to make a special acquisition of a volcano causing concern can be much of an inhibition to the use of remote sensing data in volcano monitoring as cost.

At the present day, only one type of satellite data is routinely and reliably available· recent developments in computer technology and data processing mean that images from meteorological satellites can be acquired using simple turn-key equipment consisting mostly of an antenna and PC-computer based processing unit. This equipment is available commercially at only modest cost ($2-3000) and is capable of providing volcano observatories with real time images of eruption plumes and large thermal anomalies. Such equipment is becoming part of the normal facilities of many agencies charged with hazard studies.

In the future, many different kinds of remotely sensed data may be acquired routinely. The proper managing, archiving and interpretation of such data sets must be done using a computer information system. Much thought and effort is being put into the development of such general systems (e.g. EOSDIS, the Earth Observing System Data and Information System) for the management of data from the next generation of Earth observation satellites (Mouginis-Mark *et al* 1991). The budget for EOSDIS is a large fraction of the whole of the EOS program NASA is implementing EOSDIS using a distributed, open system architecture, allowing for the distribution of EOSDIS elements to various locations in the USA to take best advantage of different institutional capabilities and science expertise. Although physically distributed, EOSDIS will appear a single logical entity to the user. Thus, although data from different EOS platform instruments will be processed at different locations, this will not be evident to a volcanological user accessing EOSDIS from an observatory or university. It is probably only when systems such as EOSDIS are working routinely that remotely sensed data will become an operational component of volcano observatory practice

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Discussion

Dr. Francis emphasised that the meteorological satellites did have a very useful role to play in volcanological monitoring. However, for many potential uses in volcano hazard mitigation the ideal spatial resolution would be about 10 m Dr Walter (NASA) praised Dr. Francis's contributions in the past in identifying volcanoes with hazard potential.