Volcano Surveillance Using Shortwave Infrared Thermal Data from the ERS Along Track Scanning Radiometers

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ABSTRACT: This paper demonstrates the use of time-series infrared spectral radiance data from the ERS-1 and ERS-2 Along Track Scanning Radiometers in identifying active lava domes and lava flows and for monitoring changes in the thermal output of these volcanic features. At Lascar Volcano (Chile) and Unzen Volcano (Japan), variations in lava dome radiative output are shown to be indicative of physical changes that have importance for the prediction of explosive eruptions and/or pyroclastic flow generation. At Fernandina Volcano (Galápagos Islands), gross characteristics and physical properties of the largely unmonitored 1995 lava flow are determined from ATSR spectral radiance data, allowing the lava flow volume to be determined from the estimated total energy losses. Results agree with post-eruption field survey data and analysis of high-spatial resolution SPOT imagery. Though it is of a relatively low spatial resolution, data from ATSR is shown to be of use for the monitoring of a variety of high temperature effusive volcanic phenomena. It is likely that near real-time data from ATSR-2 and Envisat's AATSR could similarly be used to supplement existing geophysical data at many of the worlds poorly monitored volcanoes.

Introduction

The Earth is a volcanologically very active planet, with around 60 eruptions occurring every year from a total of over 1500 potentially active volcanoes (Simkin and Siebert, 1994). A multitude of geophysical techniques has been developed to assist volcanological science and to provide means of monitoring activity with a view to eruption prediction (McGuire *et al.*, 1995). However, lack of funding and political will mean that these techniques are often inadequately applied, even at volcanoes posing a significant hazard to local populations and infrastructure (Tilling, 1989). Additionally, remote volcanoes that pose no direct threat to human life remain largely unmonitored using traditional techniques, though their activity may be of scientific interest
and they may pose a risk to aircraft traffic if explosive eruptions are of sufficient magnitude.

Satellite remote sensing is capable of providing repetitive data on all potentially active terrestrial volcanoes, with ERS interferometric SAR data already being used to map surface deformations at a number of volcanic locations (Massonet and Feigl, 1998). This paper concentrates on the thermal monitoring of effusive volcanic activity using infrared radiance data collected by another ERS instrument, the Along Track Scanning Radiometer (ATSR). Shortwave infrared data from high spatial resolution instruments, such as those from the Landsat Thematic Mapper (TM), have already been shown to be of use in this regard (e.g. Rothery *et al.*, 1988) but the infrequent repeat cycle and high TM scene cost hinders the routine use of such data. ATSR provides shortwave infrared data at a very low cost and a high repetition frequency. Here we illustrate how these low spatial resolution data can provide useful information on active volcanism, potentially providing a supplement to established geophysical monitoring techniques.

Background on thermal structure of active lava

Lava flows and domes both result from the extrusion of magma from an active volcano. The viscosity of the magma generally controls whether the lava flows in a fluid-like manner or whether it piles up around the vent, forming a lava dome. Highly viscous, dome-forming magma generally contains a high proportion of dissolved volatiles, which leads to an increased likelihood of explosive activity. Such explosive eruptions are often associated with the formation of vertical eruption columns and extremely hazardous, fast-moving pyroclastic flows of pumice, ash and hot volcanic gas, the most dangerous form of eruptive activity. In contrast, lava flows moves relatively slowly and often pose no direct threat to human life, though they may severely damage infrastructure.

Whilst the chemical composition of lava flows and domes may differ, their thermal structures are relatively similar. The internal core temperature of both is close to magmatic (~ 1000 °C), whilst the upper surface of lava crust is generally much cooler (~ near ambient to around 400 °C), the crust having lost heat by radiative cooling (Fink, 1990). The crustal layer is an efficient insulator and effectively retards heat loss from the inner core, allowing near-magmatic temperatures to be maintained for a long duration. However, the continual movement of a lava flow generally causes cracks and fissures to appear in the crustal surface, which exposes the interior and allows the high temperature core to be exposed. Lava domes are more static than lava flows, with the formation of cracks related to the cooling and contraction of the dome structure. These cracks act as fumarolic vents for the degassing of the magma held below the dome and the immediately surrounding dome surfaces are heated by the escaping gas, often to temperatures approaching those of the dome interior (Fink, 1990).

With respect to surface temperature structure, both lava flows and domes can thus be considered as relatively low temperature, broad-area surfaces, interspersed with smaller very high temperature regions.

ATSR observations of active volcanic surfaces

The ATSR instruments make measurements of infrared radiance at 1.6 µm, 3.7 µm, 11 µm and 12 µm. The 1.6 µm data has been shown to be useful for thermal investigations of high-temperature volcanic surfaces since, as Fig. 1 indicates, these emit significant amounts of infrared radiance at 1.6 µm. Furthermore, the highly non-linear relationship between surface temperature and 1.6 µm spectral radiance indicates that nighttime SWIR radiance measurements made at volcanologically active locations are likely to be dominated by radiance from surfaces at or near magmatic temperatures, even if these cover a very small fraction of the sensor field-of-view (FOV). Calculations indicate that magmatic temperature areas of only ten square metres will significantly affect the ATSR 1.6 µm channel. The ATSR 3.7 µm channel is similarly sensitive to high temperature surfaces but the instrument gain settings make it susceptible to detector saturation, making it less suitable for quantitative radiance measurements. Such saturation also impedes volcanic observations using the AVHRR instrument, which unfortunately does not have a nighttime 1.6 µm channel.

In contrast to the shorter wavelengths, the near-linear relationship between surface temperature and 11 µm spectral radiance indicates that signals in this waveband are dominated by surfaces covering large areas of the sensor FOV. ATSR 11 µm data of active volcanoes will thus be largely insensitive to changes in the highest temperature surfaces since they will generally cover only a very small fraction of the sensor FOV.

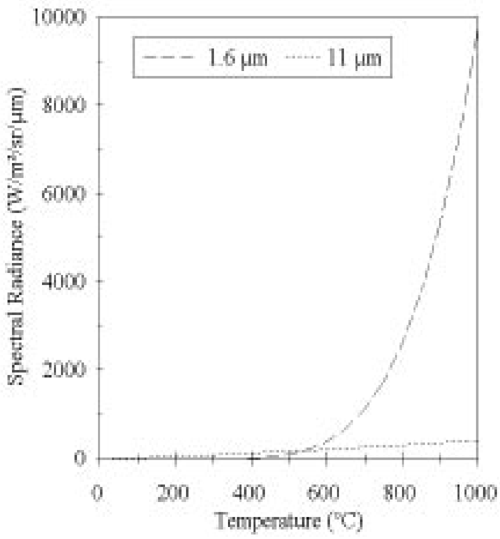


Figure 1. The 1.6 µm and 11 µm spectral radiance vs. temperature relationships for the potential range of geothermal surface temperatures.

Lava Domes: Lascar Volcano (Chile)

Lascar is a highly active but largely unmonitored volcano in the central Andes. Lascar is known to possess an active lava dome (diameter ~ 150 - 400 m) whose subsidence is believed to impede degassing and so lead to pressure build-up and thus explosive activity (Matthews et al., 1997). Most eruptions are reasonably small but large events do occur, the most notable being that of 18-20 April 1993 which produced a 7.5 km long pyroclastic flaw and an eruption column 24 km in altitude that rained ash 1500 km downwind. Using Landsat TM data, Oppenhiemer *et al.*, (1993) showed that Lascar's large explosive eruptions are preceded by a significant decrease in thermally emitted 1.6 µm spectral radiance, interpreted as a cooling of the domes fumarolically heated surface as gas flux decreases. Wooster and Rothery (1997a) showed that the same pattern could be determined using ATSR-1 data of Lascar collected between 1992 and 1995. The ATSR time series provided a much higher temporal frequency than that available from TM and has now been extended into 1999 using ATSR-2 data, with a total of 165 cloud free scenes (Fig. 2).

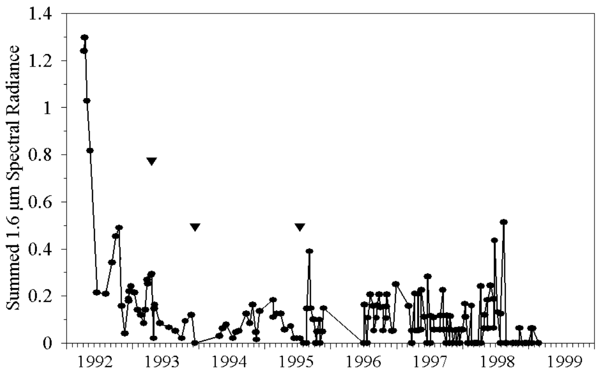
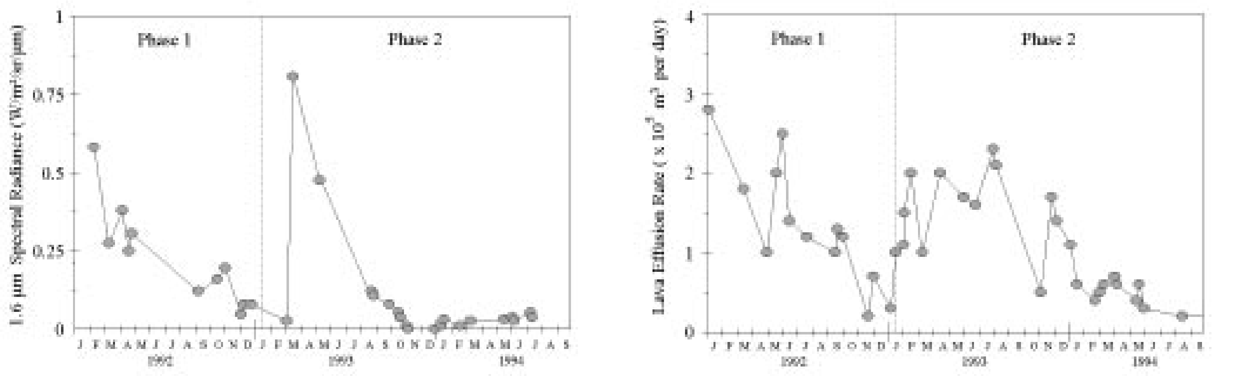


Figure 2. The time-series of ATSR 1.6 µm spectral radiance measurements made at Lascar Volcano. Though ash clouds may have been present during certain of the measurements, the closely spaced nature of the time series allows overall trends in emitted radiance to be determined. Downward pointing arrows indicate major explosive eruptions.

The data of Fig. 2 show a rapid April-June 1992 decrease in 1.6 µm spectral radiance emitted from Lascar's summit, this change exactly paralleling that found using TM data and agreeing with *in situ* observations of May and November 1992, which noted a growing and subsequently collapsed lava dome. We suggest that the magnitude of the April 1993 eruption, the largest in Lascar's recorded history, may have been related to the long (10 month) duration between the apparent collapse of the dome and the subsequent vulcanian explosive eruption. This may have allowed pressure inside the volcano to reach uncharacteristically high levels. The dome collapse is evident from the ATSR data six months before it was noticed during the November 1992 summit visit. Two more large explosive eruptions occurred after the April 1993 eruption, though they were much weaker than this largest historical event. Detailed analysis shows that these eruptions also matched the cyclic pattern of dome growth and magmatic degassing (Matthews *et al.*, 1997). The new ATSR-2 data provide evidence of a general rise in 1.6 µm signal until early 1998, when the emission falls to near zero levels which continue into 1999. If this indicates a renewed cycle of degassing and dome collapse, a further explosive eruption may be expected in the months ahead.

Lava Domes: Unzen Volcano (Japan)
Unzen Volcano is situated in a densely populated region of Kyushu, the southern-most of the four principal islands of Japan. A new lava dome began to grow at the volcano summit in May 1991 and rock-fall collapses from this growing dome generated more than 10,000 pyroclastic flows over the following four years, these being most frequent when lava effusion rates were high (Sato *et al.*, 1992). Because of the strong relationship between lava dome growth rate and the frequency of pyroclastic flow, the rate of lava effusion was monitored throughout the eruption using trigonometric and photogrammetric inspections of the summit. These data provide a quantitative comparison for the ATSR 1.6 µm time-series of Unzen, shown as Fig. 3.



(a) (b)

Figure 3. (b) The 1.6 µm spectral radiance data, extracted from 159 ATSR-1 scenes of Unzen Volcano subject to cloud-screening tests, (a) the lava effusion rate, with estimated error ± (0.3×10^5 to 1.0×10^5) m^3/day.

During the Unzen activity, two phases of magma supply were identified from the lava effusion rate data. The monotonic fall in effusion rate during phase 1 is paralleled by a near-linear decrease in 1.6 µm spectral radiance over the same period, with an correlation coefficient (r^2) of 0.8 between these two datasets. The onset of phase 2 of magma supply is also correctly identified by a sharp rise in the 1.6 µm spectral radiance, though the peak is considerably narrower than that evidenced in the effusion rate data. Studies of TM data and airborne thermal imagery have identified the dominant source of shortwave infrared spectral radiance as areas of the Unzen dome that were heated by the release of fumarolic gas with a temperature around 800 °C (Wooster and Kaneko, 1998). During phase 1 the rate of gas release was observed to be in direct proportion to the effusion rate of lava. However, the relationship was significantly more variable during phase 2 (Wooster and Kaneko, 1998) and we believe this variation is the cause of the differing relationship between effusion rate and 1.6 µm spectral radiance observed in Fig. 3.

Lava Flows: Isla Fernandina, Galápagos

The island of Fernandina is a single shield volcano in the Galápagos archipelago. Fernandina’s frequent eruptions are of great volcanological interest but the remote and uninhabited nature of the island has prevented detailed studies of previous eruptions in-progress. The January - April 1995 eruption of Fernandina was first spotted from a fishing vessel and was reported to have lasted three months. Fig. 4 shows the first cloud-free ATSR 11 µm image of the 1995 activity at Fernandina, whilst Fig. 5 shows certain of the timeseries data obtained in both the ATSR 1.6 µm and 11 µm channels.

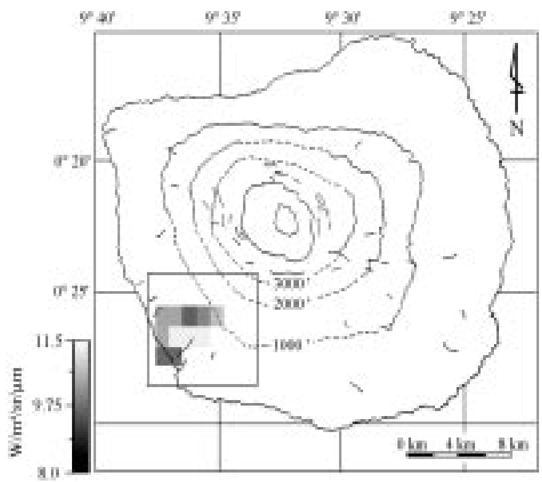


Figure 4. The 11 µm data recorded on 8 February 1995. The data are masked to show thermally anomalous (lava flow-field) pixels only and have a map of previous eruptive fissures superimposed.

Using techniques described in Wooster and Rothery (1997b), values of 1.6 µm and 11 µm thermally anomalous spectral radiance from the ATSR time-series were converted into respective areal estimates of exposed core and cooling crust of the active lava.

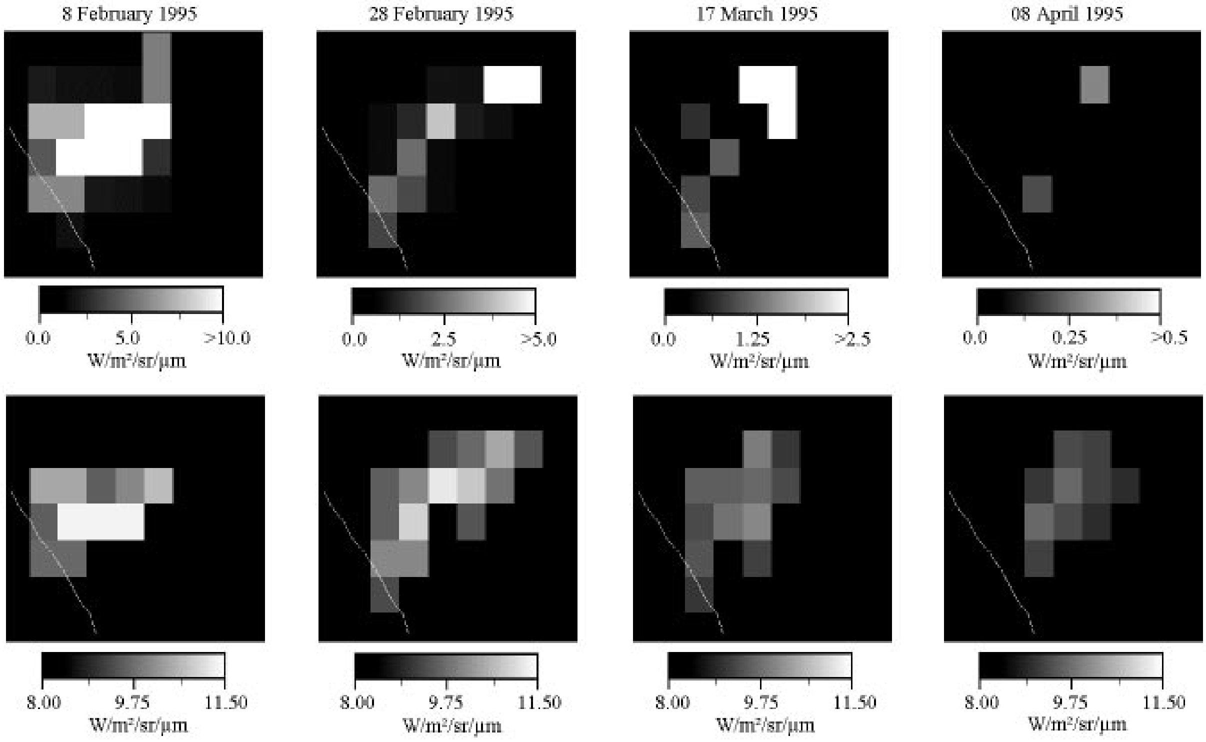


Figure 5. 1.6 µm (upper row) and 11 µm (lower row) data from four of the available eight ATSR scenes of the 1995 Fernandina eruption. The data are masked to show lava flow-field pixels only and the geographical area covered is that box outlined in Fig. 4. Large changes in the 1.6 µm signal reflect the rapid formation of sub-surface lava tubes whilst the more slowly varying 11 µm signal reflects cooling of the surface crust.

The indeterminacy of the solutions was addressed by performing the calculations for a realistic range of surface temperatures, allowing the maximum and minimum areal estimates to be determined (Wooster and Rothery, 1997b). An adaptation of the Stefan-Boltzmann equation was then calculate radiative heat losses from these temperature and area estimates. A model-based estimate of convective heat-loss then allowed the total power losses from the upper flow surface to be determined [Fig. 6].

Integration of the upper surface energy losses over the period of the eruption, coupled with model-based estimates of conductive heat loss, confirmed the total energy loss as 5×10^{16} - 9×10^{16} J. Equating this to the total energy supplied by complete cooling and solidifying of the lava allowed the volume of erupted magma to be estimated at between 10 and 20 million m^3, which agrees with estimates produced from high spatial resolution SPOT and DEM data (Rowland, 1996). A similar study has now been performed at Etna Volcano, Sicily (Wooster *et al.*, 1997c)

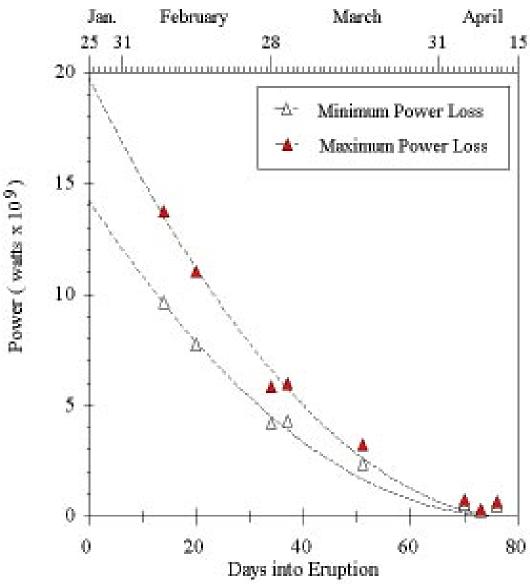


Figure 6. The minimum and maximum estimate of total power loss from the upper surface of the 1995 Fernandina lava flow, with best-fit polynomials. Losses after the eruption cessation (day > 74) are seen to be negligable.

Conclusion

The studies reported herein illustrate that low-spatial resolution infrared spectral radiance data from ATSR can be used to observe the thermal emittance from sub-pixel sized active lava bodies such as lava domes and lava flows. As such, ATSR and similar satellite-based instruments offer a means of monitoring effusive volcanic activity on a regular, danger-free, low cost basis and can be used to provide evidence of changes in activity which, at certain types of volcanoes, may then be related to the possibility of forthcoming eruptions and pyroclastic flow. At other volcanoes analyses of such data can also provide a means to estimate the characteristics of remote lava flows which may remain uninvestigated using more traditional techniques. Infrared spectral radiance data of active volcanoes will in future be readily available from the proposed ATSR near real time processing system. It is likely that use of such data can positively contribute to the scientific and geophysical monitoring carried out at a wide range of volcanic locations.

Acknowledgements

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