Volcano Monitoring Using Data from the ERS Along Track Scanning Radiometer

Martin Wooster
Department of Earth Sciences, The Open University, Milton Keynes, MK7 6AA, U.K
m.j.wooster open.ac.uk

http://exodus.open.ac.uk/

David Rothery
Department of Earth Sciences, The Open University, Milton Keynes, MK7 6AA, U.K
d.a.rothery open.ac.uk

http://exodus.open.ac.uk/

Abstract

We demonstrate the use of time-series shortwave (1.6 µm) and longwave (11 µm) infrared spectral radiance data from the ERS Along Track Scanning Radiometer (ATSR) 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 effusive volcanic phenomena. It is likely that data from ATSR, AATSR and EOS MODIS could be used to supplement existing geophysical techniques at many of the worlds poorly monitored volcanoes.

Keywords: ATSR, Volcano, thermal, infrared, hazard, monitoring

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 [Ref. 1]. A multitude of geophysical techniques has been developed to assist volcanological science and to provide means of monitoring activity with a view to eventual eruption prediction [Ref. 2]. However lack of funding and political will mean that these techniques are often inadequately applied, even to volcanoes that pose a significant threat to local population and infrastructure [Ref. 3]. In addition, 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 volcano surface deformation that is the result of large-scale magma movement [Ref. 4]. This paper concentrates on the thermal monitoring of effusive volcanic activity using infrared radiance data from the ERS Along Track Scanning Radiometer (ATSR). High spatial resolution commercial datasets, such as those from the Landsat Thematic Mapper (TM), have already been shown to be of use in this regard [e.g. Ref. 5] but the infrequent repeat cycle and high data cost hinders their routine use. If ATSR's low spatial resolution (~ 1 km^2) radiance measurements can be shown to be of similar value, the frequent, low-cost data could potentially provide a useful supplement to established geophysical monitoring techniques.

Background

The Thermal Structure of Active Lava Bodies

Lava flows and domes are both products of magma being exuded out of an active volcanic vent. 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, a lava flow moves relatively slowly and often poses no direct threat to human life, though it may do enormous infrastructure damage.

Whilst the chemical composition of lava flows and domes may differ, their thermal structures are relatively similar. The internal core temperature of both are close to magmatic (~ 1000 °C), whilst the upper surface of lava crust is generally much cooler (~ 70 - 400 °C), having lost heat by radiative cooling [Ref. 6]. 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 radiative cooling from the high temperature core to continue. 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, with neighbouring dome surfaces heated by the escaping gas, often to temperatures approaching those of the dome interior [Ref. 7].

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 high temperature regions.

Radiance observations at 1.6 and 11 µm

ATSR makes measurements of thermal infrared radiance at 3.7 µm, 11 µm and 12 µm, primarily for conversion into accurate estimates of sea surface temperature. Daytime cloud detection is enhanced by the use of pseudo-reflectance data from the 1.6 µm shortwave infrared (SWIR) waveband, which is allied to an onboard calibration system on ATSR-2 and has had a post-launch calibration applied on ATSR-1 [Ref. 8].

Night-time SWIR data is also useful for thermal investigations of high-temperature surfaces (> 400 °C) 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 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). The 3.7 µm waveband is similarly sensitive to high temperature surfaces but the instrument gain settings make it susceptable to detector saturation, making this channel unsuitable for quantitative radiance measurements over hot features.

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. Additionally 11 µm data of active lava bodies will be largely insensitive to changes in the highest temperature surfaces since they will generally cover only a very small fraction of the FOV.

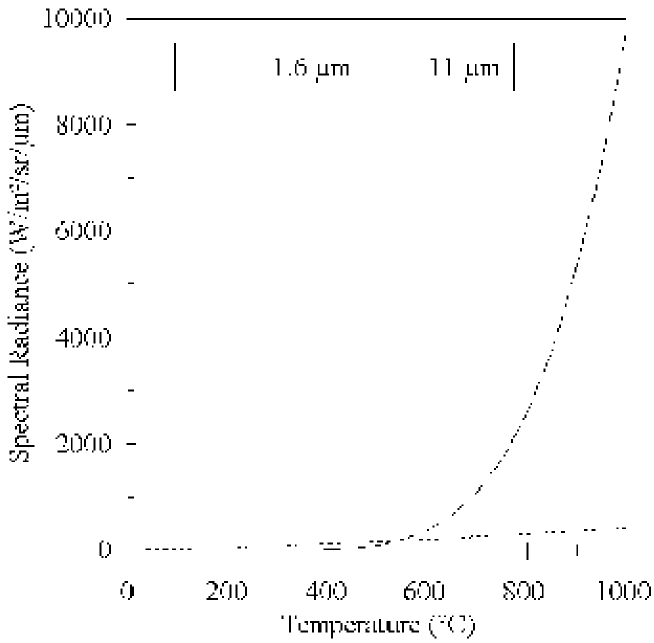


Figure 1: The 1.6 µm and 11 µm spectral radiance vs. temperature relationships for the potential range of geothermal surface temperatures.

Lava Domes
Lascar Volcano, Chile (22.37 °S, 67.73 °W)

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 [Ref. 9]. 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 high spatial resolution data from the Landsat Thematic Mapper (TM), Ref. 9 indicates that certain Lascar eruptions are preceded by a significant decrease in thermally emitted 1.6 µm spectral radiance, modelled as a cooling of the domes fumarolically heated surfaces as gas flux decreases. To determine whether low-spatial resolution data could provide a similar monitoring capability, 125 ATSR-1 and ATSR-2 ascending node (night-time) scenes covering Lascar between 1992 and 1995 were selected and subjected to cloud screening tests designed to eliminate data affected by gross and sub-pixel clouds [Ref. 10]. The nadir-view 1.6 µm signal at Lascar's location was then extracted, there being no 3.7 µm data for the majority of the time-series due to the failure of the ATSR-1 3.7 µm channel in May 1992.

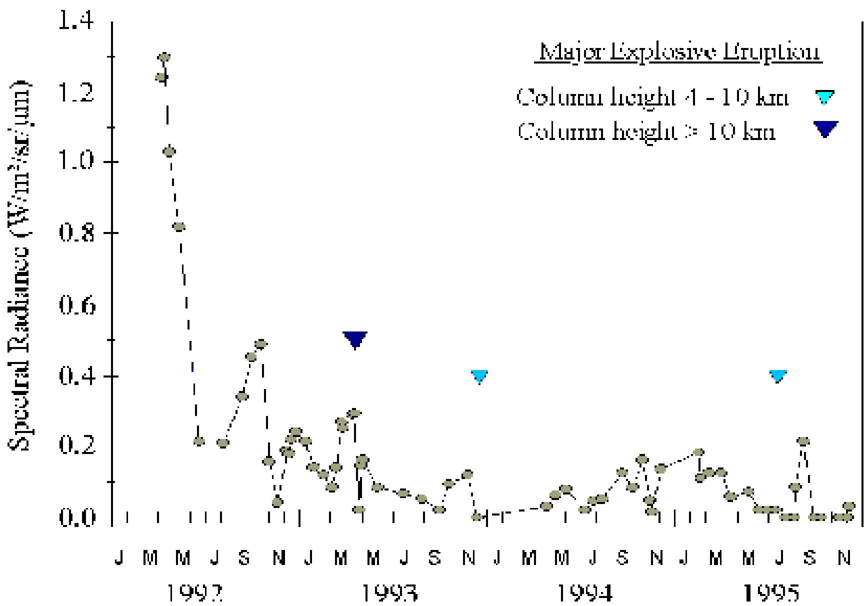


Figure 2: The time-series of ATSR 1.6 µm spectral radiance measurements made at Lascar Volcano. Though ash clouds may have been present during certain of the measurements the closely spaced nature of the time series allows overall trends in emitted

radiance to be determined.

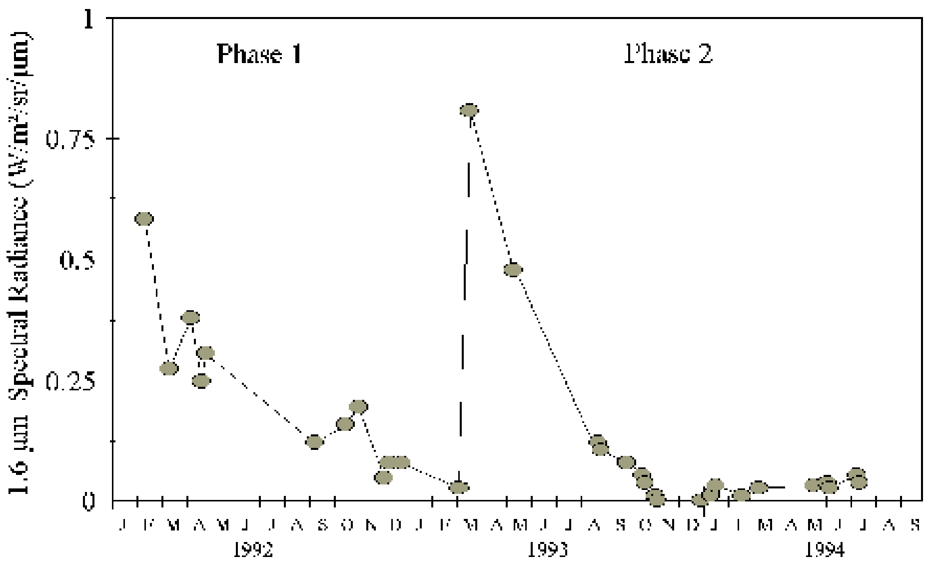
The cloud-cleared 1.6 μm dataset is plotted as Fig. 2, and shows a rapid April-June 1992 decrease in SWIR spectral radiance, this change exactly paralleling that found using TM SWIR data and agreeing with *in situ* observations of May and November 1992 which noted a growing and subsequently collapsed lava dome [Refs. 7, 9]. 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, which 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. After the April 1993 eruption, the shortwave infrared radiance is seen to fall to zero, indicating that the dome was destroyed in the eruption. A subsequent aircraft overflight indicted the rapid re-growth of a new lava dome, which is also evidenced by the return of a 1.6 μm signal in late April 1993.

After April 1993 there are two further significant periods of signal rise and fall, October-November 1993 and April 1994-May 1995. We attribute both these periods to dome growth/collapse events or to other phenomena that caused variations in magmatic degassing. As predicted by the Lascar model [Ref. 10], both cycles were followed by large explosive eruptions, with columns extending between 4 and 10 km height. A final signal rise in August 1995 is interpreted at the arrival of a new lava body, or an increase in magmatic gas flux increasing the temperature of crater surfaces.

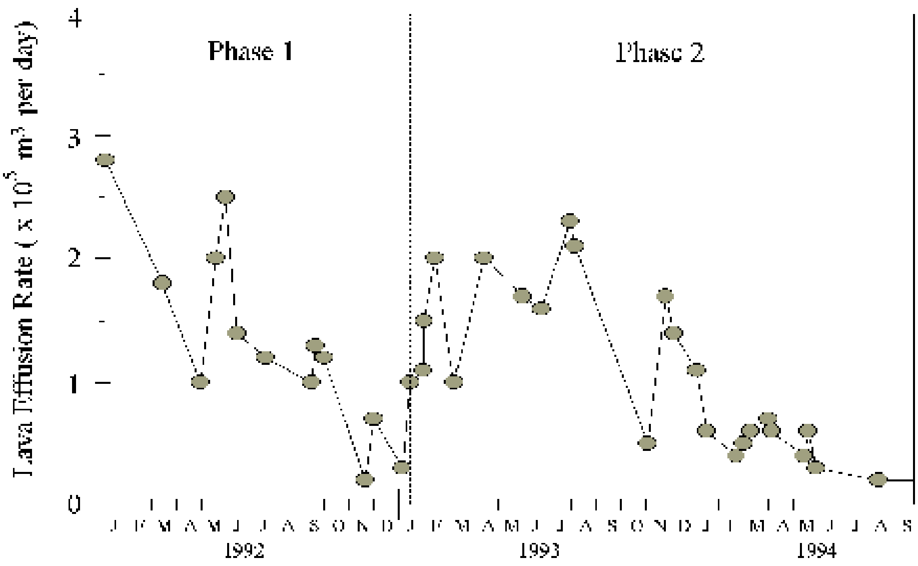
Unzen Volcano, Japan (32.77 °N, 130.28 °E)

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 [Ref. 11]. Periods of most intense flow necessitated the evacuation of 12,000 local inhabitants. Because of the strong relationship between lava dome growth rate and the frequency of pyroclastic flow, the lava effusion rate was monitored throughout the eruption using trigonometric and photogrammetric data of the summit [Ref. 11]. These data provide a quantitative comparison for the 1.6 μm time-series of Unzen, produced from 159 cloud-screened ATSR scenes of the volcano and shown alongside the effusion rate dataset in Fig. 3.

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 r^2 value 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 SWIR 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 (temperature ~ 800 °C) [Ref. 12]. During phase 1 the rate of gas release was observed to be in direct proportion to the effusion rate of lava, thus explaining the positive and significant relationship between effusion rate and SWIR spectral radiance of phase 1. However, the degassing rate was noted to be significantly more variable during phase 2 [Ref. 12] and we believe this variability caused weakening of the phase 2 effusion rate - SWIR radiance relationship.



(a)



(b)

*Figure 3. (a) The 1.6 µm spectral radiance data of Unzen Volcano , (b) the lava effusion rate, with estimated error (0.3 x 10*5 *to 1.0 x 10*5) m3/day.

Lava Flows
Isla Fernandina, Galápagos (0.37 °S, 9.53 °W)

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 most recent Fernandina eruption occurred in January - April 1995 and was first spotted from a fishing vessel. Fig. 4 shows the first cloud-free ATSR 11 µm data of the 1995 activity at Fernandina, which was later reported to have lasted for around three months duration.

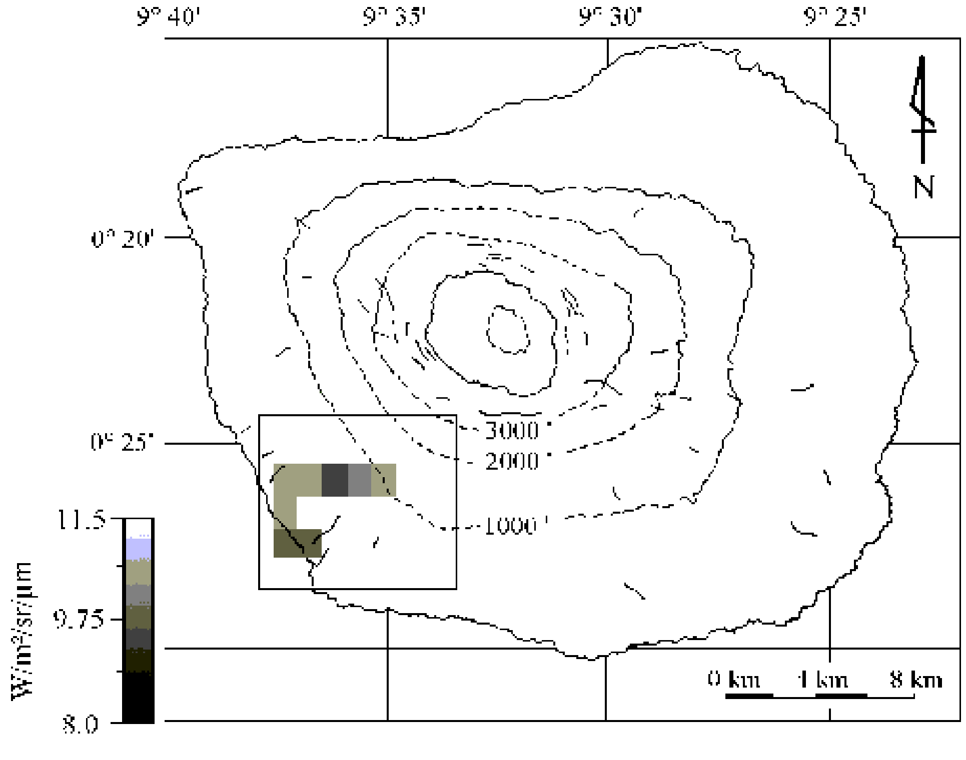


Figure 4: The 11 µm data recorded on 8 February 1995. The data are masked to show thermally anomalous (lava flow-field) pixels only and have a map of previous eruptive fissures superimposed.

Using techniques described in Ref. 13, values of 1.6 µm and 11 µm thermally anomalous spectral radiance [Fig. 5] were extracted from eight cloud-free ATSR scenes of the eruption and were respectively converted into areal estimates of exposed core and cooling crust.

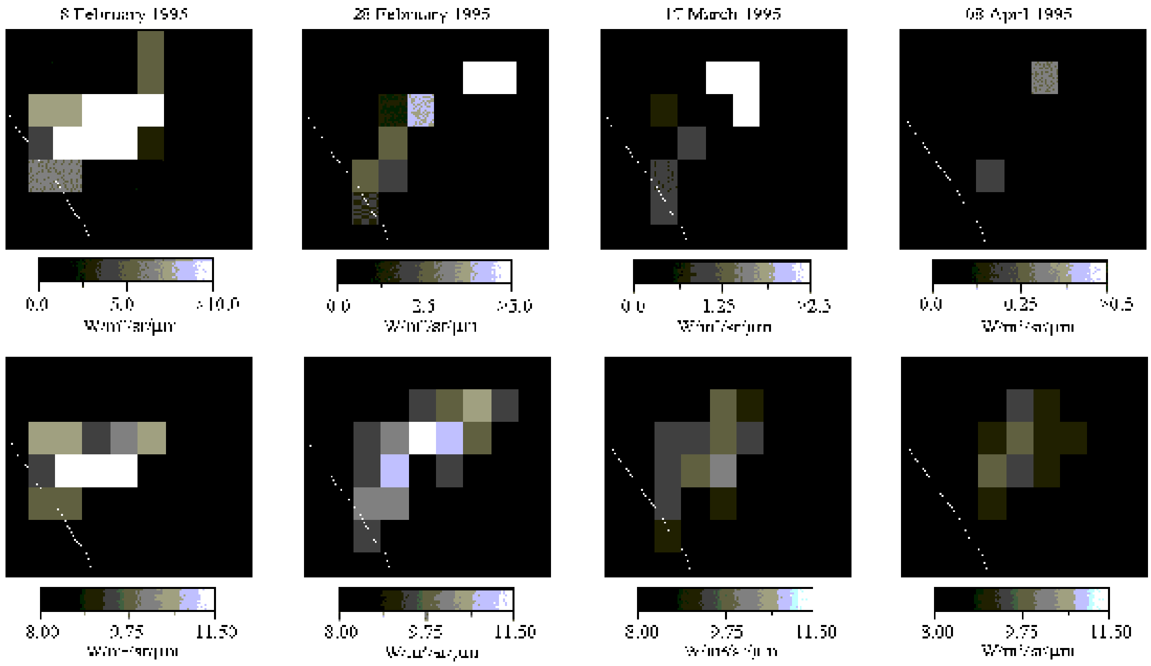


Figure 5: 1.6 µm (upper row) and 11 µm (lower row) data from four of the eight available scenes of the 1995 Fernandina eruption. The data are masked to show lava flow-field pixels only and the geographical area covered is that box outlined in Fig. 4. Large changes in the 1.6 µm signal reflect the rapid 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 maximum and minimum areal estimates to be determined. An adaptation of the Stefan-Boltzmann equation was then used to calculate the radiative power losses, with estimates of the convective loss provided by numerical models. Addtion of these heat losses allowed the total power losses from the upper flow surface to be determined [Fig. 6].

Integration of the upper surface power loss over the period of the eruption, coupled with model-based estimates of conductive energy losses, confirmed the total energy lost from the lava as 5 x 1016 - 9 x 1016 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 as 10 - 20 million m3. This agrees with estimates produced from high spatial resolution SPOT imagery combined with DEM data [Ref. 14] and is within the range observed for previous Fernandina lava flows.

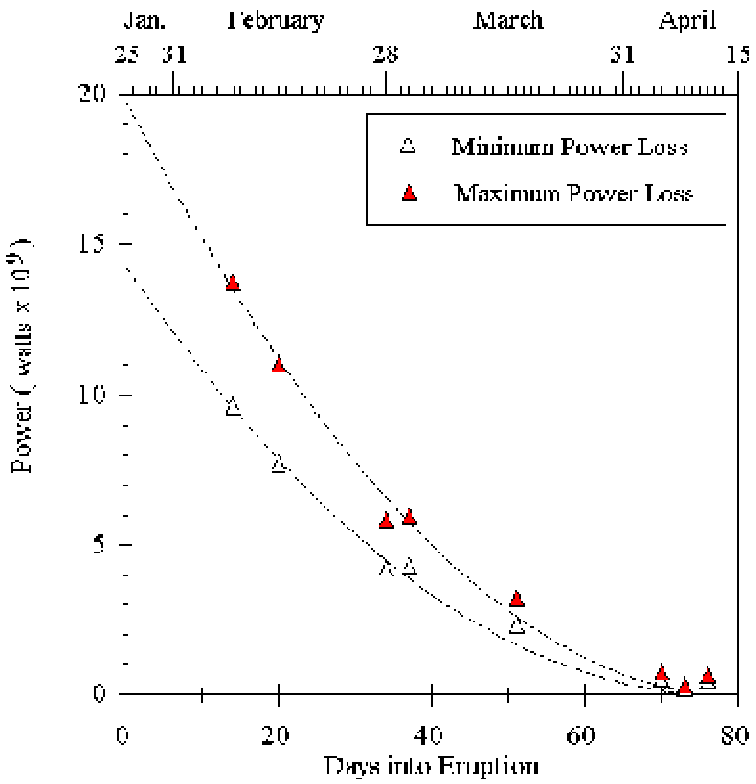


Figure 6: The minimum and maximum estimates of total power loss from the upper flow surface, with best-fit polynomials fitted to the data.

Conclusions

These studies lead us to the conclusion that low-spatial resolution infrared spectral radiance data 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 certain other volcanoes analyses of such data can also provide a means to estimate the characteristics of remote lava flows, which may remain uninvestigated using traditional techniques. Infrared spectral radiance data will in future be readily available, both from ENVISAT's Advanced ATSR and from the MODIS instrument onboard NASA's EOS satellites. It is likely that use of such data can positively contribute to the scientific and monitoring studies carried out at a wide range of volcanological locations.

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