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Introduction

Background, motivation and essential definitions

From a geophysical point of view, volcanic eruptions produce earthquakes, deformation, gas, sound and heat. As magma ascends it fractures rock, and flows to produce seismic shocks and tremors. With ascent and intrusion the magma also deforms the Earth's surface. Exsolution of volatiles generates gas emission through the edifice flanks, fumaroles and (if present and open) from the central conduit. Upon eruption, the explosion or effusion produces sound as well as a cloud of ash and gas, and/or emission of lava. With ascent, intrusion and eruption, the magma also loses heat to the Earth's crust and atmosphere (Figure 0.1). In the case of effusion, heat loss occurs by direct radiation from the lava surface to space and convection due to wind blowing over the lava surface or, in still air conditions, generation of convection cells due to heating of the overlying air. In the case of intrusion, heat loss occurs by permeable convection across the overlying country rock, so that the heat is then lost from the surface across a geothermally heated zone or fumarole field.

Consequently, volcanoes tend to be monitored using instruments that can measure seismicity, deformation, gas emission, sound and/or heat. Thus seismometers are deployed to monitor tremor, tilt-meters for deformation, spectrometers for gas, infrasonic sensors for sound, and thermocouples or radiometers for heat. Of these quantities, volcano seismology and deformation have two dedicated texts, these being *Introduction to Volcano Seismology* by Zobin (2003) and *Volcano Deformation* by Dzurisin (2007). Gas has a number of texts, which together cover the exsolution, emission, dispersion and measurement processes (e.g., Carroll and Holloway, 1994; Oppenheimer *et al.*, 2004; Williams-Jones *et al.*, 2008). However, such manuals for infrasonic measurements at active volcanic systems or thermal remote sensing of hot volcanic phenomena are lacking. The aim of this book is to fill the thermal remote sensing gap, with our focus being on remote sensing of thermal emission during volcanic activity.

0.1 Remote sensing of terrestrial volcanic hot spots: a brief history

Since 1985, a growing body of literature has demonstrated how remote measurements of heat emitted by active lava flows, lava domes, lava lakes and erupting, or degassing, vents can provide insights into the physical processes that are both the cause and consequence of

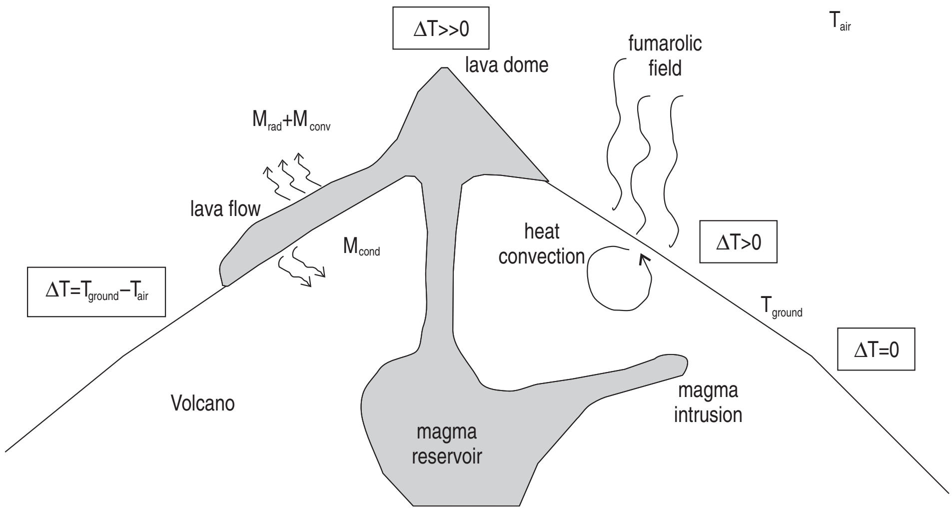

Figure 0.1 Sketch of the main sources of thermal emission that can be detected by a satellite or airborne sensor [modified from Bonneville and Gouze (1992, Fig. 1): reproduced by permission of American Geophysical Union]. In normal conditions ground (T_{ground}) and air temperature (T_{air}) are approximately equal, so that $\Delta T = T_{\text{ground}} - T_{\text{air}} \approx 0$. Over a subsurface heat supply, such as a magmatic intrusion, above which natural convection in porous, or fractured, rock carries heat to the surface, ΔT becomes positive. Over a high-temperature surface heat source, such as an active lava, ΔT becomes strongly positive. Given data collected at the correct wavelengths and spatial resolution, both anomalies can be detected by a satellite infrared sensor. The schematic diagram also shows the main sources of heat loss from an active lava body which are typically calculated using infrared data; these being radiation (M_{rad}), convection (M_{conv}) and conduction (M_{cond}).

volcanic eruptions. Although much in the field of satellite volcano-radiometry is relatively new, the first paper describing satellite observations of active volcanism was published as long ago as 1965 (Gawarecki *et al*., 1965), just five years after the first satellite dedicated to observing the Earth's surface for peaceful means, TIROS-1, was launched. However, although several papers describing serendipitous satellite observations of volcanic eruptions were published in the years following this landmark paper, it was not until the mid 1980s that serious attention was devoted to the question of what quantitative data for eruptive products and processes could be extracted from remotely sensed thermal data. We summarize the developments, themes and landmark years in thermal remote sensing of volcanic hot spots in the flow chart of Figure 0.2 (based on the literature collation of Appendix A).

A group of four papers published between 1985 and 1988 (Bonneville *et al*., 1985; Bonneville and Kerr, 1987; Francis and Rothery, 1987; Rothery *et al*., 1988) did much to establish the technique of satellite remote sensing as a viable source of data for estimating the temperatures of, and heat flux from, active lava bodies. These studies also gave impetus to a wider group of researchers who began to build upon this initial work. The work of

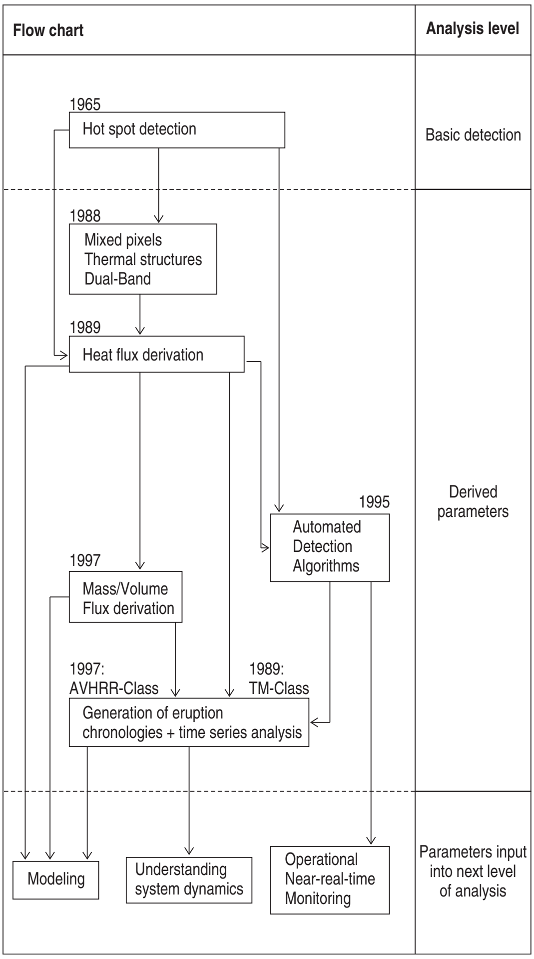

Figure 0.2 Flow chart tracing the key developments and landmark years in satellite-based thermal remote sensing of volcanic hot spots. Four main themes have developed out of the initial discovery, by Gawarecki *et al*. (1965), that hot spots related to volcanic activity could be detected in infrared data provided by satellite-flown sensors. These themes are: (1) analysis of mixed pixels to extract surface thermal structures, (2) derivation of heat and mass fluxes, (3) development of eruption chronologies, and (4) automated hot spot detection. Landmark years relate to the papers of Rothery *et al*. (1988) and Glaze *et al*. (1989) for themes (1) and (2), respectively, and to the publication of the first automated hot spot detection algorithm by Harris *et al*. (1995) for theme (4). For theme (3) we trace the first high spatial, but low temporal, resolution time series to the TM-based work of Glaze *et al*. (1989). For high temporal resolution time series, we use the development of the AVHRR- and ATSR-based work by Harris *et al*. (1997) and Wooster and Rothery (1997) as the starting point.

Rothery *et al*. (1988), for example, was mainly focused on demonstrating techniques by which the temperature of active lava domes, flows, and lakes could be determined from space at the sub-pixel scale, using high-spatial-resolution (30 to 120 m pixel) satellite data acquired by Landsat's Thematic Mapper (TM) sensor. A series of papers followed that showed how such temperature extractions could be used to derive other heat-loss parameters, and estimate the thermal budgets, for a variety of active volcanic systems (Glaze *et al*., 1989), the temperature of lava flow interiors (Pieri *et al*., 1990), and the variation in surface temperature and crust thickness with distance from the vent (Oppenheimer, 1991). These papers marked the development of a new emphasis which went beyond simply applying and testing detection and temperature retrieval techniques but, instead, also derived higher-level physical parameters.

Beginning in the mid 1990s a new developmental direction began to evolve. This began to address the fact that the dynamic nature of volcanic eruptions benefits from regular collection of thermal data at a high frequency. As a result, workers began to look towards low-spatial-resolution meteorological satellites which, out of necessity, acquire data on an hourly to daily basis. Using the Advanced Very High Resolution Radiometer (AVHRR) and the Along-Track Scanning Radiometer (ATSR) workers showed that by adapting the techniques developed using Landsat TM data, these low-spatial-resolution satellite sensors could be used to compile complete eruption chronologies and perform retrospective analyses of entire eruptive episodes (Harris *et al*., 1997a; Wooster and Rothery, 1997a). Parallel with this work, efforts to use satellite thermal data to contribute to routine, real-time monitoring efforts developed rapidly during the 1990s. This resulted in the development of algorithms to automatically detect, and give notice of new effusive activity, or to flag changes in on-going activity. This was driven largely by the increasing use of AVHRR data in an operational setting as part of the volcano monitoring efforts at the University of Alaska Fairbanks (Dean *et al*., 1996).

The start of the new millennium saw a major advance in the range of resources available for the analysis of the thermal signatures of erupting volcanoes, with the launch of several NASA spacecraft under the banner of Earth Observing System (EOS). The Terra, Landsat-7, Aqua and EO-1 (Earth Observing) spacecraft all carried sensors that allowed the thermal emission from an active volcano to be studied from space. As a result, the first truly global satellite volcano monitoring system became established, which monitored all the Earth's active and potentially active volcanoes on a daily basis (Wright *et al*., 2004). This system began operation in February 2000, and constituted an archive of the heat flux from all of the Earth's erupting volcanoes (Wright and Flynn, 2004).

The progression culminated in the use of parameters derived from satellite thermal data to drive higher-level modeling, such as flow emplacement simulations, and integration with other geophysical and physical volcanology data sets to allow improved constraint of system dynamics. Such themes thus form the current terminus to our Figure 0.2 flow chart.

Likewise, initial advances in ground-based radiometry made during the 1960s were followed up with a series of studies which steadily increased in number during the 1990s, and more rapidly after 2000. While portable spectrometers have been used to obtain point measurements of lava flows and lava lakes at hundreds of wavelengths (e.g., Flynn *et al*., 1993), radiometers have been adapted and exploited to measure thermal flux from erupting volcanoes, at intervals of a second or less, for time periods spanning weeks to years (e.g., Marchetti and Harris, 2008). A recent development has been the use of hand-held Forward Looking Infrared (FLIR) thermal-imaging cameras to acquire spatially and temporally detailed measurements of lava surface temperatures (e.g., Oppenheimer and Yirgu, 2002) and explosive events emitting high-temperature ejecta (e.g., Patrick *et al*., 2007). We will return in more detail to the development of satellite thermal remote sensing of volcanic hot spots in Chapter 1, and to ground-based approaches in Part III.

0.2 Thermal remote sensing: What it is and what we have

Chapter 1 of Curran (1985) provides a brief review of the development of remote sensing as a technique and discipline. In addition, Chapter 2 of the *Manual of Remote Sensing* provides a detailed history, tracing developments in remote sensing since the (first, or) earliest surviving photographs taken by Niepce in 1825–26 and Daguerre in 1838–39 (Fischer *et al*., 1975). First coined as a term by Evelyn L. Pruitt at the US Office of Naval Research in the 1960s, remote sensing can be defined as "the observation and measurement of an object without touching it" (p. 1, Curran, 1985). Such a definition spans many disciplines including geography, geology, botany, zoology, civil engineering, forestry, meteorology, agriculture and oceanography. This definition also spans a variety of techniques, meaning that volcanological measurements made using seismometers, infrasonic sensors, even a microprobe, fall under the banner of remote sensing. Thus, a more specific definition has been developed, this being: "the use of electromagnetic radiation sensors to record images of the environment which can be interpreted to yield useful information" (p. 1, Curran, 1985). One modification to this definition would be to replace "images" with "data," thereby including the use of spot-based temperature measurements using thermal infrared thermometers or radiometers. This definition also spans the full electromagnetic spectrum, spanning wavelengths from 3 Ångströms (X-ray-based measurements) to 3 km (radio frequencies). Thus, to narrow the definition further, we are here strictly interested in the thermal infrared portion of the spectrum. Thus, the definition, for our purposes, can be modified to: "the use of electromagnetic radiation sensors operating in the thermal infrared portion of the spectrum to record data for active volcanic phenomena which can be interpreted to yield useful information."

No satellite or commercially available ground-based thermal sensor has ever been designed primarily for a volcanological use, and no satellite mission dedicated to volcanology has ever been launched. However, there are many thermal sensors designed for military, civilian and industrial applications that can be adapted for volcanological applications. Volcanologists have thus had to use sensors and data that were never intended for volcanological roles. The data are not always perfect. Data from weather satellites, for example, provide data at wavebands and frequencies suitable for examining volcanic hot spots. However, because the meteorologist is typically interested in low temperatures associated with cloud tops and ambient temperatures associated with the ground surface, the upper limit of these sensors (in terms of temperature detection) is often rather low, meaning that they typically saturate over even quite small volcanic hot spots. The remote sensing volcanologist has to work within these limits, as well as be highly imaginative in the way he adapts to the limits of the available data. Until an appropriately designed sensor, with suitable wavebands, gain settings, spatial resolution and orbit configuration becomes available, we will have to continue to adapt data intended for other applications. The aim of this book is to provide a thorough review of technologies and methodologies that should allow continued application of remotely sensed thermal data in volcanology.

0.3 Reviews to date and the value of thermal remote sensing

Although no one book has been written which focuses entirely on remote sensing of active volcanism, a number of short reviews do exist which give the state of the discipline at the time of each review. These include the following (in chronological order).

- 1974: Cassinis, R. and Lechi, G. I. (1974). The use of infrared radiometry in geothermal areas. In *Physical Volcanology*, ed. Civetta, Gasparini, Luongo and Rapolla. Amsterdam: Elsevier, pp. 117–131.
- 1979: Francis, P. W. (1979). Infra-red techniques for volcano monitoring and prediction – a review. *Journal of the Geological Society London*, **136**, 355–359.
- 1989: Mouginis-Mark P. J., Pieri, D. C., Francis, P. W. *et al*. (1989). Remote sensing of volcanoes and volcanic terrains. *EOS*, **70**(52), 1567–1575.
- 1989: Rothery, D. A. (1989). Volcano monitoring by satellite. *Geology Today*, July–August 1989, 128–132.
- 1992: Francis, P. and Oppenheimer, C. (1992). Applications of satellite remote sensing techniques to volcanology. In *Understanding the Terrestrial Environment – the Role of Observation from Space*, ed. Mather, London: Taylor & Francis, pp. 37–52.
- 1992: Mouginis-Mark, P. J. and Francis, P. W. (1992). Satellite observations of active volcanoes: prospects for the 1990's. *Episodes*, **15**(1), 46–55.
- 1992: Rothery, D. A. (1992). Monitoring and warning of volcanic eruptions by remote sensing. In *Geohazards Natural and Man-Made*, ed. McCall, Laming and Scott, London: Chapman & Hall, pp. 25–32.
- 1992: Rothery, D. A. and Lawrence, G. (1992). Remote sensing for the study of volcanoes and earthquakes. *Geoscientist*, **3**(6), 10–11.
- 1993: Oppenheimer, C. (1993c). I spy with my infrared eye. *New Scientist*, **1876**, 26–31.
- 1996: Francis, P. W., Wadge, G. and Mouginis-Mark, P. J. (1996). Satellite monitoring of volcanoes. In *Monitoring and Mitigation of Volcano Hazards*, ed. Scarpa and Tilling. Berlin: Springer-Verlag, pp. 257–298.
- 1997: Oppenheimer, C. (1997c). Surveillance and mapping of volcanoes and their emissions by satellite remote sensing. *Geography*, **82**(4), 317–333.

- 2000: Francis, P. and Rothery, D. (2000). Remote sensing of active volcanoes. *Annual Review of Earth and Planetars Sciences*, **28**, 81–106.
- 2008: Ernst, G. G. J., Kervyn, M. and Teeuw, R. M. (2008). Advances in remote sensing of volcanic activity and hazards, with special consideration to applications in developing countries. *International Journal of Remote Sensing*, **29**(22), 6687–6723.

Following the listing of Kervyn *et al*. (2007), four main volcanological remote sensing application themes can be identified in these reviews.

(1) Detection, analysis and monitoring of thermal phenomena associated with active volcanic systems, including active lava flows, lava lakes, lava domes, degassing vents, fumarole fields, crater lakes and geothermally heated ground.
(2) Detection, analysis and monitoring of clouds of volcanic ash and gas.
(3) Mapping of volcanic deposits and morphological analysis, including spectrally based identification of mineralogical, textural and compositional differences between different units.
(4) Assessment of ground deformation, derivation of digital elevation models, volumetric assessment, and surface roughness mapping using radar.

Several of the reviews listed above consider all four of these themes, although here we are strictly concerned only with the first: remote sensing of volcanic thermal phenomena associated with active volcanic systems. Of the thirteen reviews listed, seven were written during the 1990s, with three appearing in the popular scientific literature (*Geology Today*, *Geoscientist* and *New Scientist*). This trend marks the take-off and establishment of satellite-based remote sensing as a volcanological technique during the same decade.

The most visionary of the reviews was that of Francis (1979). Published at a time when just two papers had been published dealing with volcanological applications of satellite data, Francis (1979) recognized the potential value of yet-to-be launched sensors such as Landsat's Thematic Mapper. More specific reviews focusing on satellite remote sensing of active lavas, volcanic gas plumes and ash clouds, as well as airborne scanner applications to geothermal areas, have also been provided, these being the reviews of Rothery and Pieri (1993), Symonds *et al*. (1994), Sparks *et al*. (1997), and Cassinis and Lechi (1974), respectively. In addition, reviews have been written focusing on volcanological applications of specific sensors, these being the reviews of AVHRR applications to volcanology by Oppenheimer (1998) and of Landsat TM/ETM+ by Flynn *et al*. (2000; 2001). Radar applications have also been covered by Gens and Van Genderen (1996), with uses of satellite data for deformation and digital elevation model derivation being reviewed by Dzurisin (2007) and Kervyn *et al*. (2007). Volcanological applications of sensors flown as part of NASA's Earth Observing System have been previewed by Mouginis-Mark *et al*. (1991) and reviewed by Ramsey and Flynn (2004), with Drury (2001) covering geological mapping (including volcanic terrains). For our purposes, the most relevant text to date is the review of ground- and space-based thermal infrared techniques for measuring and monitoring high and low temperature volcanic hot spots by Rothery *et al*. (1995).

What all of these reviews highlight are the five main benefits thermal remote sensing offer to volcanology. These being:

(1) Measurements that extend beyond the visible range of the electromagnetic spectrum and into the thermal infrared.
(2) Regular and fixed return periods, with sensors mounted on polar orbiting and geostationary satellites allowing repeat monitoring of a given point on the Earth's surface at a known and reliable frequency.
(3) Synoptic capability, with satellite-based sensors allowing entire volcanoes and volcanically active regions to be examined with a single image.
(4) Continuity of data acquisition, where satellite missions that operate over several decades guarantee provision of time series data in a standard and consistent format.
(5) Global capability, where polar orbiting satellites and constellations of geostationary platforms allow coverage of the entire planet, and all active and dormant sub-aerial volcanoes within their image footprints.

In addition, thermal data from satellite sensors are becoming increasingly cheap, and in many cases freely available. The fixed, calibrated, digital format data also suits automation and allows routine processing, with the data format for most satellite sensors being detailed in dedicated user manuals, such as the *Polar Orbiters User Manual* written to support unpacking of AVHRR data (e.g., Kidwell, 1991; 1995). Availability of easy-to-use, off-the-shelf image processing software also makes data analysis and interpretation straightforward. For example, MODIS data are available in a variety of calibrated and georectified formats at no cost from NASA within a few hours of acquisition and TM and ETM+ data are now also freely available in GEOTIFF format. Both data types can be read by any off-the-shelf image processing package.

Even the cost of a receiving station, which allows free, direct data reception and real-time access, can be less than US$ 5000, with system costs varying depending on sophistication of the reception system (Table 0.1). As early as 1992, Gower *et al*. (1992) detailed a receiving station comprising a 1.2 m dish (US$ 200) and steering device (US$ 400), a receiver and down-converter (US$ 1000), and a PC interface (US$ 1150) with 200 Mbytes of disk storage (US$ 2000). The entire station thus cost just US$ 4750 at 1992 prices (Table 0.1).

As a result, by the early 1990s, direct reception for volcanological analysis had even been achieved by some schools. Matthews *et al*. (1994), for example, reported use of a satellite receiving station purchased and installed at Ulverston Victoria High School in the United Kingdom. Images were received using a VHF aerial and an aimed dish. Software, provided by Dartcom (see Table 0.1) and running on a desktop computer, then allowed AVHRR, GOES and Meteosat images to be downloaded as they were transmitted, allowing the 1993 eruptions of Llaima (Southern Chile) and Rinjani (Indonesia) to be observed and reported by the students. Today satellite thermal data can also be obtained via the internet within hours of image acquisition. For example, MODIS Level 1b data can currently (October 2011) be downloaded from http://ladsweb.nascom.nasa.gov/. In addition, for more than a decade

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Table 0.1. *Costs and details of commercially available AVHRR receiving stations in 1996 (from Harris, 1996).*

System hardware and software details	Company address	Cost (date of quote)
Bradford University Research Limited	Bradford University, Bradford, UK	US$ 2700 upwards (1994)
Hardware:	Motorized antenna to track satellite, cable to PC, PC card to convert data to PC readable format.	
Software:	Automatic tracking and reception software included.	
	(HRPT and SEAWiFs compatible.)	
System installed at the Institute of Ocean Sciences	Institute of Ocean Science, Sidney V8L 4B2, Canada	US$ 4750 (Gower *et al.*, 1992)
Hardware:	PC interface board, receiver feed, combiner . . . pre-amplifier/down-converter, PC, 1.2 m dish, antenna steering device.	
Software:	Real time display of central strip of image and data archiving.	
	(Chinese Feng-Yun satellite FY–1 compatible.)	
Timestep PROsat II system	Timestep, Newmarket, CB8 8XB, UK	US$ 4800 (1995)
Hardware:	PC, 170 Mb hard drive, HR color monitor, dish antenna with all cables and associated hardware and software.	
Software:	Live display, saves full pass in full resolution, calibration, geo-referencing, satellite track prediction, image processing.	
	(GOES/Meteosat compatible.)	
SeaSpace TeraScan system	SeaSpace, San Diego, CA 92126, USA	>US$ 20 000 (1995)
Hardware:	1.0 m antenna, 1.5 m protective dome (survival conditions: −30 to +55 °C, 162 km/h winds, 22 kg/m^2 ice loading), amplifier and down-converter, cable, Sun-4/50 SPARC work station, DAT archive tape drive.	
Software:	Antenna control and data acquisition (includes automatic unattended operation), calibration, geo-location, cloud screening and image processing.	

Table 0.1. (*cont.*)

System hardware and software details	Company address	Cost (date of quote)
Dartcom winHRPT system	Dartcom, Yelverton, PL20 6SP, UK	US$ 38 000 – 62 000 (1996)
Hardware:	Pentium PCI, 1 Gb fast SCSI II hard disk, archiving drives, FST monitor, 1.2–1.8 m antenna (survival conditions: −35 to +63 °C, 210 km/h winds), down-converter and receiver, built-in GPS.	
Software:	Antenna control, image acquisition and quick look, image processing including reflectance and temperature calibration and geo-location.	

now, location and spectral radiance data for hot spots detected by the University of Hawaii's MODVOLC hot spot detection system have been downloadable from http://modis.higp.hawaii.edu/ within hours of hot spot detection. Modern, internet-based capabilities mean that, if a user wants to obtain data for a volcanic hot spot, they do not need a receiving station, just access to the internet.

0.4 Thermal remote sensing of volcanic hot spots on other planets

An excellent book has recently been published by Cambridge University Press authored by Ashley Davies and covering thermal remote sensing of active volcanic phenomena on Jupiter's moon Io (Davies, 2008). Io is the only known body in the solar system to exhibit on-going high temperature volcanism beyond Earth. As a result, Io has witnessed two thermal remote sensing missions and programs designed to measure and examine this activity (namely Galileo and the New Horizons flyby). These are reviewed by Davies (2008), as are the techniques and applications developed to measure and track active volcanism on Io using remotely sensed thermal data. However, no similar text is available for this planet.

Thus, although we originally planned to include a chapter on extra-terrestrial remote sensing of volcanic hot spots, the publication of Davies (2008) makes such a chapter redundant. In fact, that thermal remote sensing of Io required a book to adequately cover the full body of knowledge regarding missions to Io, and the science completed, shows that relegating this subject to a chapter in this book would have done Io a disservice. Here, we solely consider terrestrial thermal remote sensing of volcanic hot spots, and refer the reader to Davies (2008) for the state-of-the-art regarding extra-terrestrial remote sensing of active volcanic hot spots. We note, though, that the principles and techniques described here are equally transferable to extra-terrestrial scenarios.