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# Volcanology 2020: How will thermal remote sensing of volcanic surface activity evolve over the next decade?

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**Abstract on last page.**

## 1. Introduction

At the December 2000 meeting of the American Geophysical Union (AGU), a special session entitled, "Volcanology 2010: How will the science and practice of volcanology change in the coming decade?" proposed that speakers should "imaginatively extrapolate from emerging trends in instrumentation, information sciences, and telecommunications to describe how the more highly wired society of 2010 will better respond to volcanic danger". For thermal remote sensing, we made an attempt to meet the session goal by stating that "monitoring active volcanoes at the end of the next decade will most likely rely on increasing volumes of data made available in real-time" (Harris et al., 2000). We also looked ahead to the many planned orbital sensors and argued that, "the flood of remote sensing data over many wavelengths and resolutions is becoming globally available, and future research needs to capitalize on the strengths of these instruments to provide new ways of monitor volcanic activity" (Wessels and Ramsey, 2000). We went on to propose that, because thermal data from geostationary satellites had already been shown to be of value for tracking hour-by-hour activity changes at volcanic hot spots, "higher temporal resolution (at least minute-by-minute) data is needed to better characterize the activity". Our presentations focused on both the construction and deployments of ground-based thermal sensors to track thermal activity as well as data to be returned from the Earth Observing System (EOS) sensors. We went on to suggest that "such ground-based systems should be installed on other volcanoes by 2010 in order to better monitor ongoing eruptions". The installation of such systems over the next five years led to many advances in the thermal remote sensing science of hot volcanic targets. A final prediction was that the next generation of satellite-based sensors launched as part of the EOS-era would furnish us with never-before-available TIR data sets (Wessels and Ramsey, 2000; Ramsey and Flynn, 2004). These would allow us to expand our measurement capabilities, allowing for example, the implementation of near real-time algorithms such as MODVOLC (Wright et al., 2002a).

In retrospect, we see that thermal remote sensing was poised to make the transition from an experimental to an operational activity both from the ground and from space at the time of our recommendation. That is, methodologies tried and tested during the 1980s and 1990s were about to go online using improved data from a new generation of IR capable satellites and ground-based thermal cameras, coupled with access to high speed internet and wireless systems. One caveat was that, although the data were new, the data processing, reduction techniques, and background principles used, were not. For example, MODVOLC was based on the MIR (3.9  $\mu\text{m}$ ) minus TIR (11  $\mu\text{m}$ ) band differencing ( $\Delta T$ ) detection approach, as initially proposed for fire detection by Flannigan and Vonder-Haar (1986). Other algorithms could be deemed similarly off-the-shelf, and/or based on principles that had been well-established by work completed by the fire and volcano remote sensing communities during the preceding 40 years. The dual-band method for extracting thermal structures from mixed pixels was, for example, proposed by Dozier (1981), and initially applied to volcano data by Rothery et al. (1988). It was then

modified according to various combinations of data limits during the 1990s (e.g., Oppenheimer et al., 1993; Wooster and Rothery, 1997; Harris et al., 1999), to be further applied to data offering a larger number of wavebands and higher dynamic ranges in the 2000s (e.g., Harris et al., 2003; Lombardo and Buongiorno, 2006; Hirn et al., 2008). In summary, the advances made over the previous decade were much more rapid than we initially anticipated, so that by 2005 our predictions had been mostly realized and new operational paradigms were already evolving.

In this paper we re-examine our predictions made in 2000, as well as the trends from 1960 to 2010 in the discipline of thermal remote sensing of lava effusion, fumarolic activity, open vent degassing, and persistently activity between. In so doing, we focus specifically on developments in volcano remote sensing using thermal infrared data spanning 3  $\mu\text{m}$  to 20  $\mu\text{m}$ , (i.e., the midwave [MIR: 3 to 5  $\mu\text{m}$ ] and longwave [LWIR: 5 to 20  $\mu\text{m}$ ] infrared). This analysis allows us to assess the directions in which the volcano thermal remote sensing community moved. We thus look back over the last 50 years to establish a foundation from which to project into the next decade.

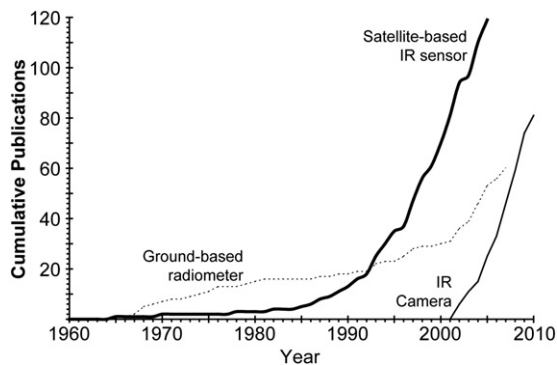
## 2. Background

### 2.1. The pivotal year 2000

We can divide thermal remote sensing of volcanic surfaces into two general classes: satellite-based and ground-based. Of these, ground-based can be further split into studies that use sensors capable of point-based measurements (i.e., radiometers) and those capable of imaging (i.e., thermal cameras). If we examine the literature database for these sensor groupings, we find approximately 200 papers were published between 1960 and 2005 in the international, peer-reviewed literature, as collated by Harris (2012).

### 2.2. The publication time-line: satellite-based studies

If we plot the number of publications per year from 1960 to 2005 we see that volcanic hot spot research using satellite-based sensors began in the mid-1960s and developed quite slowly (at a rate of 0.2 publications per year) until 1985, when the rate of publication began to increase, attaining a rate of 2 publications per year between 1985 and 1992 (Fig. 1). Thereafter, the rate of publications continued to increase at a relatively steady rate of ~8 publications per year. Thus, by the year 2000, satellite remote sensing of volcanic hot spots had reached a degree of maturity, with the publication rate being high and steady. This maturity meant that a number of established methodologies were available for application to the new datasets thus creating a recipe book and background library that could be quickly applied to improved temporal, spatial, and/or spectral resolution datasets allowing quick start up and rapid progress. A similarly quick adaptation to new data occurred when volcanologists were faced by new operational requirements and real-time data availability.



**Fig. 1.** Cumulative number of volcano remote sensing papers using IR data from satellite sensors, ground-based radiometers, and thermal cameras, 1960–2010. From literature data bases of Harris (2012).

### 2.3. The publication time-line: ground-based radiometers

We see that progress using ground-based radiometers began in 1965, the same year as that of satellite-based applications (Fig. 1). That year saw both the report by Gawarecki et al. (1965) of a hot spot detected on Kilauea by the HRIR sensor flown on the Nimbus-1 satellite, as well as the use of a radiometer to detect thermal anomalies at Mt. Rainier by Moxham et al. (1965). However, the rate of increase for radiometer-based studies proceeded at a slightly higher pace than did those for satellites. This rate was constant but relatively low (~0.8 publications per year) between 1965 and 1994. However, an increase to 3 publications per year began in 1996. Despite this, the total number of satellite-based studies overtook the total number of radiometer-based studies in 1992. As with satellite-based applications, our understanding of how we could use radiometers at active volcanic systems, and process the data acquired, had reached a degree of maturity by 2000, so that we were moving from a test to an operational phase. Indeed, our argument in 2000 was that we were at a point where permanent radiometer systems could be cheaply and easily deployed to gather near-source, real-time thermal data. What we had not foreseen was that the rapid advances occurring in thermal camera technology during the late-1990s would greatly lower their cost and make them more readily available to volcanologists. The availability would mean that the “thermal camera era” would supersede the use of radiometer data by 2008.

### 2.4. The publication time-line: hand-held thermal cameras

Making a prediction about technology is always problematic because of the pace of change. This was true for our omission of thermal cameras in 2000. To be fair, we were only just beginning to realize the available technology and its potential application to volcanology presented by the new generation of thermal cameras.

The first easy to use, relatively inexpensive self-contained thermal camera entered the market in 1995 with the ThermaCAM™ series by FLIR Systems. These cameras became even easier to operate when the first uncooled microbolometer-based system became available in 1997 (FLIR Systems, 2003). The first use of such a camera to target volcanic activity can be traced to the abstract of McGimsey et al. (1999) presented at the AGU Fall 1999 meeting. Soon after, the Alaska Volcano Observatory (AVO) purchased a hand-held, microbolometer-based thermal camera, a FLIR Systems ThermaCAM™ 595, in 2000. Two papers followed in 2002 showing how the AVO camera could be used to aid in tracking activity during the 2001 eruption of Shishaldin (Dehn et al., 2002; Nye et al., 2002), plus four papers detailing volcanological applications of other hand-held systems (Honda and Nagai, 2002; Kaneko et al., 2002; Oppenheimer and Yirgu, 2002; Wright et al., 2002a). Thereafter, publications featuring thermal camera data

dramatically increased, attaining a rate of ~10 publications per year between 2002 and 2010, and overtaking the entire number of radiometer-based publications by 2008 (see Spampinato et al. (2011) for an extensive review).

If we examine the content of the manuscripts published in the two main volcanological journals (*Bulletin of Volcanology* and *Journal of Geophysical and Geothermal Research*) we see an interesting trend (Table 1). The first papers that used thermal camera data did not focus on the thermal camera and its data specifically, but instead used the data to support event chronologies, interpretations based on other data sources and experiments. We argue that there are two reasons behind this rapid adoption. First, the off-the-shelf, commercially available, easy-to-use style of the camera lent it to immediate use without extensive testing and instrument development. Second, the targets, wavelengths and applications were identical to those considered by the radiometer and satellite-based community that had preceded the advent of thermal camera work, so that these approaches and methodologies were directly transferable. Therefore, we see that the major theme of the decade was the operational deployment of thermal cameras at active volcanic systems to allow collection of data at spatial and temporal resolutions never before seen (i.e., images with mm-to-m spatial resolutions collected at frame rates of up to 30 Hz). This high rate of data collection far exceeded our year 2000 recommendation for “higher temporal resolution (at least minute-by-minute) is needed”.

## 3. Past: satellite-based observations

### 3.1. Pre-2000

We can classify satellite-based research of active volcanic surficial deposits into four themes based on the dominant content (Harris, 2012):

- (1) Hot spot detection studies, including the capabilities, and limits, and/or use of various satellite-based infrared sensors to detect and track a thermal feature, commonly in an automated approach.
- (2) Thermal and compositional unmixing studies that developed, tested, and applied methodologies to pixel data (i.e., methods that allow us to assess the size and area of sub-pixel components).
- (3) Heat and mass flux studies that used satellite-based data at volcanic systems, commonly applying the mixture model results of the second group of studies.
- (4) Eruption chronologies and time series studies that used satellite sensor-derived data.

The sequencing of these themes is not random. We first need to detect the anomaly, then extract the basic thermal character (size, temperature and composition of the surface), before using these measurements to estimate higher-level parameters such as heat flux and/or lava discharge rate. These values can then be extracted from repeat overpasses to produce time series analysis, for example. We see that all four themes were well developed in terms of the number of publications by the year 2000 (Fig. 2), with many of the methodologies maturing in the opening years of the decade.

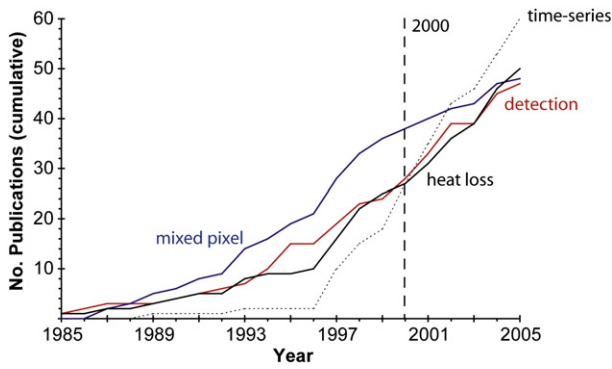
If we plot the frequency of publication for each theme we find that all four had achieved maturity by 2000, receiving detailed coverage in a total of 120 papers. By 2000 we can identify at least 28 studies that considered hot spot detection issues at a range of wavelengths, spatial resolutions (from 100 m to several kilometers) and sensor types (TM, AVHRR and GOES). In addition, three of the four main techniques of automated hot spot detection (VAST, RAT and Okmok) had been tried and tested on volcanic targets, with the fourth (MODVOLC) in the process of becoming operational (see Steffke and Harris (2010) for review). Mixture modeling accounted for an additional 38 studies, including two and three thermal component solutions using one, two

**Table 1**  
Papers appearing only in Bulletin of Volcanology (BV) and Journal of Volcanological and Geothermal Research (JVGR) containing thermal camera-derived data during 2000–2010. Papers are assigned "full article" if they are dominated by descriptions of the thermal camera and remote sensing methodology applied to thermal camera data (and associated results) or "contribution" if the thermal camera just contributes a sentence, paragraph or figure to an otherwise much larger paper.

| Author                     | Year | Journal | Vol. | No. | Target                        | Location                        | Full article | Contrib. |
|----------------------------|------|---------|------|-----|-------------------------------|---------------------------------|--------------|----------|
| Roach et al.               | 2001 | BV      | 62   | 6–7 | Unspecified                   | Pavlof volcano, Alaska          |              | X        |
| Nye et al.                 | 2002 | BV      | 64   | 8   | "Mild Strombolian activity"   | Shishaldin volcano, Alaska      |              | X        |
| Dehn et al.                | 2002 | BV      | 64   | 8   | "Mild Strombolian activity"   | Shishaldin volcano, Alaska      |              | X        |
| Stelling et al.            | 2002 | BV      | 64   | 8   | "Mild Strombolian activity"   | Shishaldin volcano, Alaska      |              | X        |
| Ohba et al.                | 2002 | JVGR    | 115  | 1–2 | "Explosion clouds"            | Usu (2000), and experimental    |              | X        |
| Caplan-Auerbach and McNutt | 2003 | BV      | 65   | 6   | "Mild Strombolian activity"   | Shishaldin volcano, Alaska      |              | X        |
| Seidl et al.               | 2003 | JVGR    | 125  | 1–2 | Active crater                 | Galeras                         |              | X        |
| Matsushima et al.          | 2003 | JVGR    | 126  | 3–4 | Degassing crater              | Iwodake, Japan                  |              | X        |
| Lautze et al.              | 2004 | JVGR    | 137  | 1–3 | Gas puffs                     | Etna                            |              | X        |
| Andronico et al.           | 2005 | BV      | 67   | 4   | Lava flow field               | Etna                            |              | X        |
| Harris et al.              | 2005 | BV      | 68   | 2   | Lava flow field               | Stromboli                       | X            |          |
| Nakada et al.              | 2005 | JVGR    | 146  | 1–3 | Active crater                 | Anatahan                        | X            |          |
| Bailey et al.              | 2006 | BV      | 68   | 6   | Open channel flow             | Etna                            | X            |          |
| James et al.               | 2006 | BV      | 69   | 1   | Lava flow                     | Etna                            | X            |          |
| Calvari et al.             | 2006 | JVGR    | 149  | 1–2 | Explosions                    | Stromboli                       | X            |          |
| Lodato et al.              | 2007 | BV      | 69   | 6   | Lava flow                     | Stromboli                       |              | X        |
| Patrick et al.             | 2007 | BV      | 69   | 7   | Explosive                     | Stromboli                       | X            |          |
| Carter et al.              | 2007 | BV      | 69   | 7   | Lava dome                     | Bezymianny                      |              | X        |
| Harris et al.              | 2007 | BV      | 70   | 1   | Lava flow                     | Review                          |              | X        |
| Huggel et al.              | 2007 | JVGR    | 168  | 1–4 | Summit                        | Iliamna, Alaska                 |              | X        |
| Del Negro et al.           | 2008 | BV      | 70   | 7   | Lava flow                     | Etna                            |              | X        |
| Berthelote et al.          | 2008 | BV      | 70   | 7   | Lava tube                     | Laboratory                      | X            |          |
| Scandone et al.            | 2008 | JVGR    | 170  | 3–4 | Lava flow                     | Stromboli                       |              | X        |
| Ball et al.                | 2008 | JVGR    | 173  | 1–2 | Lava flows                    | Kilauea                         | X            |          |
| Andronico et al.           | 2008 | JVGR    | 173  | 3–4 | Lava fountain                 | Etna                            |              | X        |
| Scollo et al.              | 2008 | JVGR    | 176  | 2   | Column height                 | Etna                            |              | X        |
| Andronico et al.           | 2008 | JVGR    | 176  | 4   | Strombolian                   | Stromboli                       |              | X        |
| Spampinato et al.          | 2008 | JVGR    | 177  | 2   | Effusive eruption             | Etna                            | X            |          |
| Tank et al.                | 2008 | JVGR    | 177  | 2   | Degassing                     | Bossoleto, Siena Graben (Italy) | X            |          |
| Dibble et al.              | 2008 | JVGR    | 177  | 3   | Strombolian and lava flows    | Erebus                          | X            |          |
| Gersy et al.               | 2008 | JVGR    | 177  | 3   | Strombolian                   | Erebus                          |              | X        |
| Calkins et al.             | 2008 | JVGR    | 177  | 3   | Lava lake                     | Erebus                          | X            |          |
| Davies et al.              | 2008 | JVGR    | 177  | 3   | Lava lake                     | Erebus                          | X            |          |
| Stevenson and Varley       | 2008 | JVGR    | 177  | 4   | Fumaroles                     | Volcan de Volima                | X            |          |
| Sahetapy-Engel and Harris  | 2009 | BV      | 71   | 1   | Lava dome                     | Santiaguito                     | X            |          |
| Harris et al.              | 2009 | BV      | 71   | 4   | Fumarole field                | Vulcano                         | X            |          |
| Sahetapy-Engel and Harris  | 2009 | BV      | 71   | 7   | Ash plume                     | Santiaguito                     | X            |          |
| Kelfoun et al.             | 2009 | BV      | 71   | 9   | Pyroclastic flow and lava     | Tungurahua                      |              | X        |
| Andronico et al.           | 2009 | JVGR    | 180  | 2–4 | Ash plume                     | Etna                            |              | X        |
| Barberi et al.             | 2009 | JVGR    | 182  | 3–4 | Lava flow                     | Stromboli                       |              | X        |
| Ripepe et al.              | 2009 | JVGR    | 182  | 3–4 | Lava flow                     | Stromboli                       |              | X        |
| Giordano and Porreca       | 2009 | JVGR    | 182  | 3–4 | Lava flow                     | Stromboli                       |              | X        |
| Marchetti et al.           | 2009 | JVGR    | 182  | 3–4 | Lava flow                     | Stromboli                       |              | X        |
| Casagli et al.             | 2009 | JVGR    | 182  | 3–4 | Lava flow                     | Stromboli                       |              | X        |
| Carapezza et al.           | 2009 | JVGR    | 182  | 3–4 | Lava flow                     | Stromboli                       |              | X        |
| Bertolaso et al.           | 2009 | JVGR    | 182  | 3–4 | Lava flow                     | Stromboli                       |              | X        |
| Atoine et al.              | 2009 | JVGR    | 183  | 3–4 | Quiescent cone                | Piton de la Fournaise           | X            |          |
| Staudacher et al.          | 2009 | JVGR    | 184  | 1–2 | Ground temperature            | Piton de la Fournaise           |              | X        |
| Rose and Ramsey            | 2009 | JVGR    | 184  | 3–4 | Whole volcano                 | Kliuchevskoi                    |              | X        |
| Webley et al.              | 2009 | JVGR    | 186  | 1–2 | Ash cloud                     | theoretical                     |              | X        |
| Mori and Burton            | 2009 | JVGR    | 188  | 4   | Strombolian gas emissions     | Stromboli                       |              | X        |
| Lyons et al.               | 2010 | BV      | 72   | 1   | Lava flows                    | Fuego                           |              | X        |
| Coppola et al.             | 2010 | BV      | 72   | 3   | Lava flow field               | Piton de la Fournaise           | X            |          |
| Applegarth et al.          | 2010 | BV      | 72   | 6   | Lava flow field               | Etna                            |              | X        |
| James et al.               | 2010 | BV      | 72   | 6   | Lava flow field               | Etna                            | X            |          |
| Vaughan et al.             | 2010 | JVGR    | 189  | 3–4 | Lava lake                     | Erebus (and Yellowstone)        |              | X        |
| Staudacher                 | 2010 | JVGR    | 191  | 1–2 | Lava flows                    | Piton de la Fournaise           | X            |          |
| Fee et al.                 | 2010 | JVGR    | 193  | 1–2 | Pyroclastic density current   | Tungurahua                      |              | X        |
| Steffke et al.             | 2010 | JVGR    | 193  | 3–4 | Whole volcano                 | Tungurahua                      |              | X        |
| Stroberg et al.            | 2010 | JVGR    | 194  | 4   | Volcanic clasts and particles | Laboratory                      |              | X        |
| Andronico and Pistolesi    | 2010 | JVGR    | 196  | 1–2 | Paroxysmal explosions         | Stromboli                       |              | X        |

or three bands of data (e.g., Oppenheimer, 1993; Oppenheimer et al., 1993; Harris et al., 1997a). With the advent of multispectral TIR data from ASTER, compositional mixture modeling also became a reality (e.g., Ramsey and Dehn, 2004; Carter et al., 2009). Methodologies for extracting heat flux had been considered since the early days of satellite-based thermal remote sensing (e.g., Friedman and Williams, 1970), and received further attention in a series of studies

during the 1990s (e.g., Pieri et al., 1990; Oppenheimer, 1991; Harris et al., 1998) so that at least 27 papers for heat flux calculations were published by 2000. A conversion to mass or volume flux was also available, based on an approach initially applied to volcanic problems by Yokoyama (1957), and later applied to obtain lava time-averaged discharge rates (TADR) from satellite thermal data by Harris et al. (1997a). Finally, a total of 27 studies had built and presented eruption



**Fig. 2.** Cumulative number of volcano remote sensing papers using satellite sensor IR data classified by theme, 1985–2005. From Appendix A literature data base of Harris (2012).

time series using satellite sensor-derived spectral radiance, or a derived higher order parameter (e.g., lava flow area, heat flux, and/or time-averaged discharge rate).

Even though volcanological remote sensing was in an operational phase by the early 2000s, limits were still present and imposed mainly by sensor dynamic ranges, the number of available bands, as well as the temporal and spatial resolution. In 2000 we recognized that the new generation of sensors (e.g., MODIS/ASTER/MTSAT/SEVIRI), would provide substantial improvements in dynamic range, spectral range, as well as spectral and spatial resolution.

### 3.2. The decade 2000–2010

As with the ground-based data, approaches in this decade tended to focus on refining existing methodologies, such as improving the performance of detection algorithms (e.g., Kervyn et al., 2008; Pergola et al., 2008; Koeppen et al., 2011), refining the dual-band method (e.g., Harris et al., 2003; Lombardo and Buongiorno, 2006; Hirn et al., 2008) or refining heat flux to mass flux conversion routines (e.g., Wright et al., 2001; Harris and Baloga, 2009; Harris et al., 2010). Gone were the studies that just used one or two images to carefully develop, apply, and assess a model and its output. Now, “plug-and-play” methodologies were being applied to tens, hundreds, thousands, and even tens-of-thousands of images. This new approach changed the paradigm to rapidly-processed, inexpensive to freely available data over the internet in an easy to ingest format, supported by technological advances and coupled with timely provision.

By the time of our first presentation in 2000, the first of the main thermal infrared capable sensors, MODIS and ASTER, had already been launched (Table 2). Launched on the Terra spacecraft as part of NASA’s Earth Observing System (EOS) in December 1999, MODIS

offered three channels in the MIR between 3 μm and 4 μm, and eight in the TIR between 8 μm and 15 μm. The nominal spatial resolution was 1 km but, most importantly, saturation levels were as high as 180 °C (for MIR Band 21), and 130 °C (for TIR Band 32). This compared with typical saturation levels of between 50 °C and 60 °C for the AVHRR sensor, which had been used for years for thermal hotspot detection. ASTER was launched on the same spacecraft and offered six bands of SWIR data between 0.8 μm and 2.5 μm at 30-m spatial resolution and five bands of TIR data between at 8 μm and 12 μm at 90-m spatial resolution. Later, SEVIRI and MTSAT were launched. Following up on the promise offered by the first geostationary sensor to carry a MIR capability (the imager flown on GOES-8), both MTSAT and SEVIRI featured a MIR band, as well as up to five bands in the TIR for SEVIRI, with MTSAT carrying a copy of the GOES Imager that had between two and three TIR bands. With the GOES Imager having already been shown to be capable of detecting even quite small volcanic hot spots since the January 1997 eruption at Kilauea’s Napau Crater (Harris et al., 1997b), the launch of MTSAT and SEVIRI in 2005 opened up the possibility of volcano imaging every 15 min for most of the Earth’s volcanoes. These new data also came in easier-to-use, formats. MODIS data, for example, were downloadable within 24 h of acquisition at no cost from <http://modis.gsfc.nasa.gov/data/>. MODIS level 1B data come calibrated and can easily be converted into a format that can be loaded into most commercially available image processing packages. This is a marked contrast to the situation in 1990, when data had to be purchased (at some cost), delivered by mail on magnetic tapes (with a delay of months), and required extensive calibration by the user through access to the header data attached to the image file.

The ready availability of EOS data resulted in the development of four new operational paradigms during the decade from 2000 to 2010:

- (1) The proliferation of online and automated (near-real-time) hot spot detection and information dissemination systems for data archiving and hazard rapid response.
- (2) The use of output from these systems, and combination with ancillary data sets, to enable studies examining volcano system and eruption dynamics.
- (3) The use of rapidly-derived eruption parameters to drive simulations and predictive modeling.
- (4) Generation and analysis of long-term heat flux inventories for single volcanoes, volcanic arcs, and the global system.

#### 3.2.1. Online and automated systems

MODVOLC is perhaps the best example of the new series of online systems for global hot spot detection and information dissemination that became available after 2000. Active throughout the decade, the system ran on incoming MODIS (MIR and TIR) data to detect hot

**Table 2**  
Past and present satellite-based IR sensors used in volcanology.

| Sensor name  | Acronym     | Platform   | Date of first launch | Wavelength region | Publications using data from sensor (1960–2005) |
|--|-------------|------------|----------------------|-------------------|---|
| High resolution infrared radiometer                            | HRIR        | Nimbus     | 1964                 | MIR, TIR          | 2   |
| Thematic mapper and Enhanced thematic mapper plus              | TM and ETM+ | Landsat    | 1972                 | NIR, SWIR, TIR    | 51  |
| Defense meteorological satellite program                       | DMSP        | DMSP       | 1973                 | NIR, TIR          | 2   |
| Advanced very high resolution radiometer                       | AVHRR       | NOAA       | 1978                 | NIR, MIR, TIR     | 47  |
| Along-track scanning radiometer                                | ATSR        | ERS        | 1991                 | SWIR, MIR, TIR    | 11  |
| JERS optical sensor  | OPS         | JERS       | 1992                 | SWIR              | 3   |
| GOES imager  | Imager      | GOES       | 1994                 | MIR, TIR          | 9   |
| Advanced spaceborne thermal emission and reflection radiometer | ASTER       | Terra/Aqua | 1999                 | NIR, SWIR, TIR    | 10  |
| Moderate resolution imaging spectroradiometer                  | MODIS       | Terra/Aqua | 1999                 | SWIR, MIR, TIR    | 8   |
| Advanced land imager   | ALI         | EO-1       | 2000                 | SWIR              | 1   |
| Hyperion   | Hyperion    | EO-1       | 2000                 | SWIR              | 0   |
| MTSAT imager   | Imager      | MTSAT      | 2005                 | MIR, TIR          | 0   |
| Spinning enhanced visible and infrared imager                  | SEVIRI      | Meteosat   | 2005                 | NIR, MIR, TIR     | 0   |

spots and provide the location and spectral radiance data for global hot spot activity (Flynn et al., 2002; Wright et al., 2002a, 2004). The MODVOLC output continues to be posted daily on <http://modis.higp.hawaii.edu/> (Fig. 3), with a global hot spot data base that now spans nearly 12 years. The system went online in February 2000, two months after the launch of the first MODIS sensor on Terra. MODVOLC was adapted by Kervyn et al. (2008) to generate a site-sensitive version of its globally-applicable parent, that was applied a single, local detection case (Oldoinyo Lengai), with Koeppen et al. (2011) combining MODVOLC and the Robust Approach (RAT) to generate another, more sensitive, “hybrid” detection algorithm.

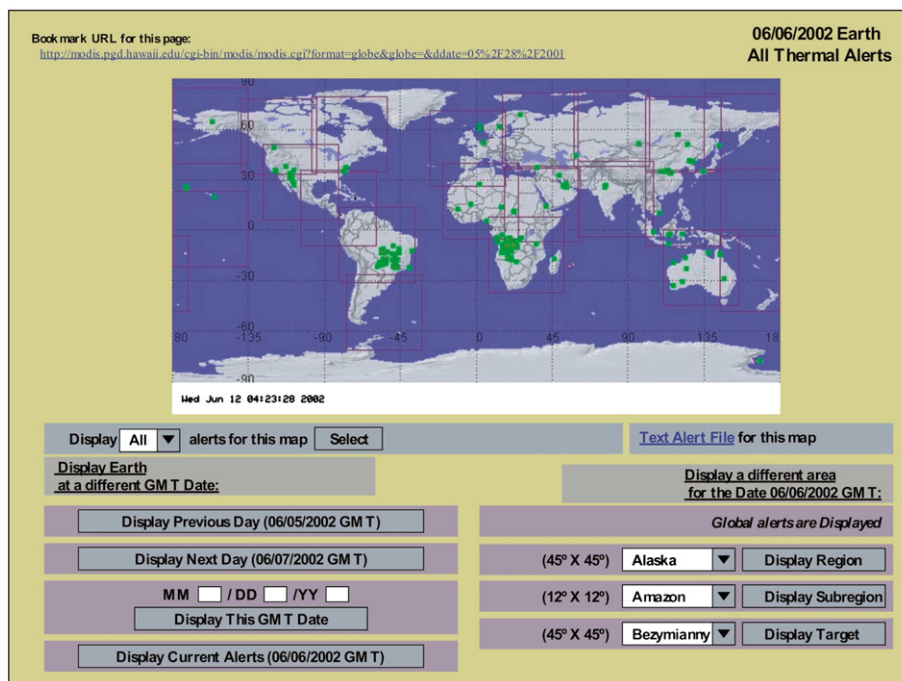
Other detection systems similarly acquired operational status and extensive usage during the decade:

- (1) The VAST algorithm of Harris et al. (1995), as fully implemented by Higgins and Harris (1997), was used as part of a MODIS hot spot detection and enquiry system designed for Etna by Ganci et al. (2011). VAST was also combined with MODVOLC, and various other permutations of the dual-band technique designed and tested during the 1990s, by Hirn et al. (2008) to generate MyVOL and MyMOD, two software packages for ingestion and processing of ASTER and MODIS data, respectively.
- (2) RAT, a system for volcano hot spot detection initially proposed by Tramutoli (1998), was applied by Pergola et al. (2001, 2004a, 2004b, 2008, 2009), Tramutoli et al. (2001), and Di Bello et al. (2004) to AVHRR data for Etna.

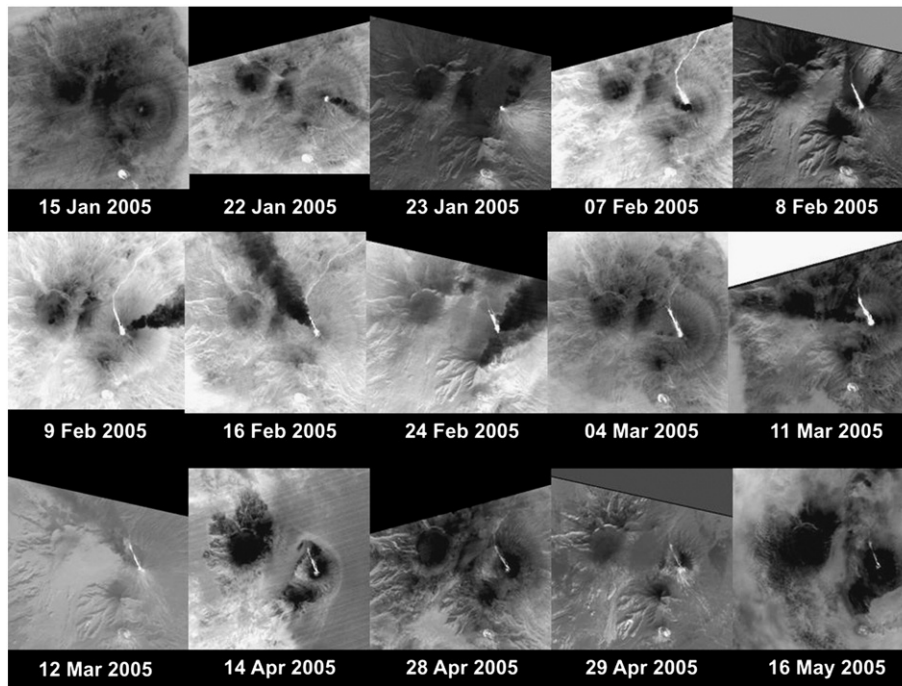
Progress in implementation of algorithm packages to detect and process volcano hot spots in satellite data was also reflected in the installation of a number of operational monitoring systems. Whereas Kaneko et al. (2002) described a prototype system for tracking AVHRR-detected hot spots at Japanese volcanoes, GOES-based automated volcano hot spot detection and information dissemination (via email) was developed at the University of Hawaii alongside MODVOLC (Harris et al., 2002). Webley et al. (2008) installed a system to allow on-reception hot spot detection and tracking in

AVHRR data received for Central America using data acquired by the Instituto Nicaraguense de Estudios Territoriales (INETER) PC-based satellite receiver in Nicaragua. Ganci et al. (2011) closed out the decade by describing a system operational at INGV-Catania (HOTSAT) that used MODIS and SEVIRI data to detect and process hot spot data, in near-real-time, for Mt. Etna, with Labazuy et al. (2010) describing an internet-based plume and hot spot detection system (HOTVOLC) that processed on-reception SEVIRI data for all volcanoes within the sensor footprint (<http://www.obs.univ-bpclermont.fr/SO/televolc/hotvolc/index.php>).

In addition to the automated systems that operated on data from one sensor, systems have also proliferated that integrate data from multiple systems flown on one or more satellites in a sensor-web approach. For example, a software system put into operational use during the past decade can perform autonomous onboard image scheduling, acquisition, and data processing for rapid analysis of volcanic events. The Autonomous Sciencecraft Experiment (ACE) operates on data collected by the Earth Observing-1 (EO-1) spacecraft and has been used to rapidly acquire data, subset the region of interest, and differentiate styles of volcanic activity on the hour time scale, all of which would have taken days to perform manually (Davies et al., 2006). In addition, constellations of satellites are now being employed to rapidly detect increases in thermal activity and subsequently image the volcano with higher spatial and spectral resolution data. Such a system has been in place since 2004 for volcanoes in the northern Pacific from the Cascades in North America to the northern Kurile Islands in the western Pacific. The system relies on near-real-time monitoring using the 3.5 μm channel of AVHRR developed in the late 1990s to detect a hot spot (Dean et al., 1998). That system applies a rules-based algorithm to screen for errors and false positives. Detections are then used as scheduling triggers for the ASTER sensor and data are made available within hours of acquisition on the internet (Ramsey et al., 2004; Duda et al., 2009). This system has increased the ASTER observational frequency to as short as 1–3 days for certain targets (Fig. 4) and is now integrated with the MODVOLC program in order to rapidly image active volcanic targets worldwide.



**Fig. 3.** Front end page for the MODIS thermal alerts website hosted and maintained by the Hawaii Institute of Planetology and Geophysics (HIGP) at the University of Hawaii as of June 2002. Screen shot is for 06-06-2002 and shows the global distribution of MODVOLC-detected hot spots on that day (by default the global hot spot map for the current day was displayed). The website also allowed interrogation of the full global hot spot data base by date and location through use of the search options at the bottom of the page. Hot spot location data could then be displayed as a map or downloaded as a text file.



**Fig. 4.** Chronological subset of the sequence of ASTER IR images acquired during the first five months of 2005 showing the eruption sequence of Kliuchevskoi Volcano, Russia. These images were captured through the implementation of the ASTER Urgent Request Protocol (e.g., Duda et al., 2009) allowing the frequency of high-resolution IR data to be greatly increased. For example, the observational “triplet” (7–9 Feb 2005) would not have been possible.

### 3.2.2. Data synergy

The acceptance and validity of satellite data-derived time series, as well as their availability in near-real-time, led to their use in support of trends, patterns and inferences drawn from, or suggested by, other geophysical data sets. Examples include:

- (1) Wright et al. (2002b) and Ortiz et al. (2003) used GOES-based spectral radiance and seismic data to define and explain repeating eruption cycles at Popocatepetl (Mexico) and Villarrica (Chile).
- (2) Ripepe et al. (2005) used MODIS-derived TADRs with gas flux, infrasonic and seismic data to define the transition from effusive back to explosive activity at Stromboli during 2003.
- (3) Coppola et al. (2009) used MODIS-derived TADRs and real-time seismic amplitude (RSAM) data for effusive activity at Reunion during 2003–2007 to classify two types of eruption at Reunion (summit and flank) and tie them to the degassing history of the magma involved in each eruption type.
- (4) Lyons et al. (2010) used MODIS-derived heat flux together with seismic and acoustic data to define repeating patterns of eruptive behavior at Fuego volcano (Guatemala).
- (5) Steffke et al. (2011) used COSPEC-derived gas fluxes with AVHRR and MODIS-derived lava discharge rates to examine patterns in the balance between erupted and non-erupted magma fluxes during effusive events at Etna. Similarly, Gouhier and Coppola (2011) used satellite-derived gas flux and lava discharge rate data for the 2007 eruption of Piton de la Fournaise (Reunion) to examine patterns in the magma flux.
- (6) Ramsey et al. (2012) used time series temperature data from ASTER in conjunction with long-distance, ground-based photography to track the position and extrusion rate of the 2005 lava dome at Shiveluch volcano (Russia).

All these studies point to a decade during which satellite sensor spectral radiance, and the derived thermal products, were used with other geophysical metrics to help track and understand activity at erupting systems and therefore aid in real-time monitoring. Indeed,

MODIS-based daily updates were used to aid in reporting duties during the 2003 eruptive crisis of Stromboli, and for the follow-up studies of Ripepe et al. (2005), Calvari et al. (2005) and Lodato et al. (2008).

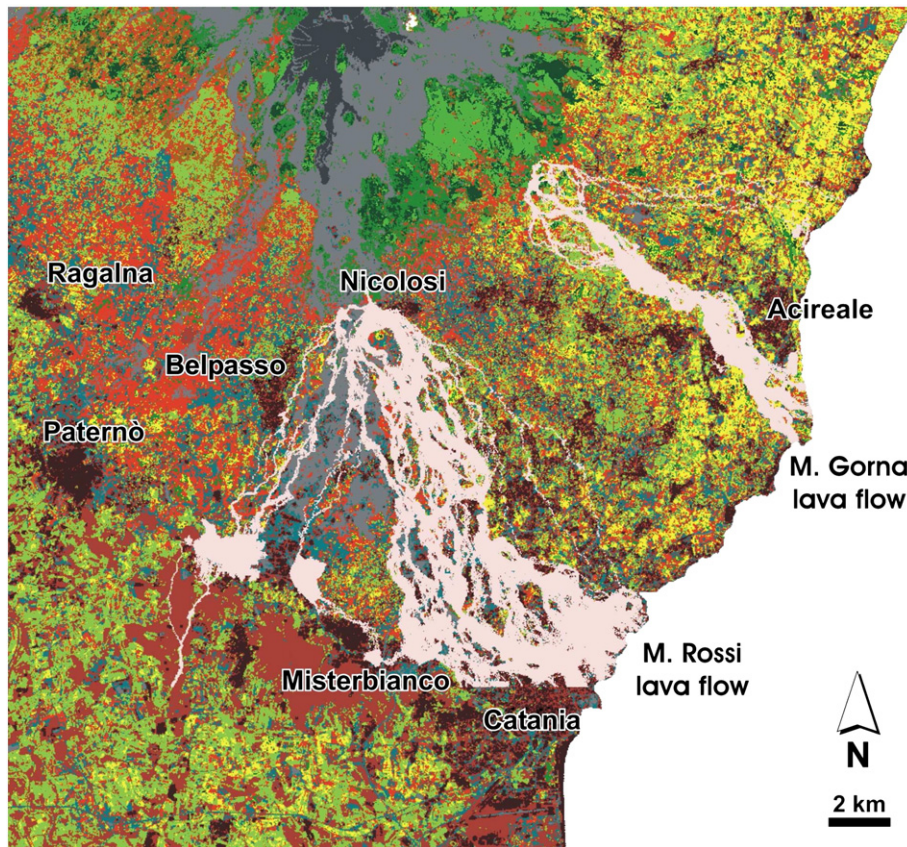
### 3.3.3. Modeling

Full integration of satellite-based output into ground-based monitoring and modeling is best illustrated using a few recent studies that have relied upon satellite-derived lava flow discharge rates to support lava flow emplacement modeling. One example is that of Wright et al. (2008) who used AVHRR-derived TADRs obtained during Etna's 1991–1993 eruption to run a merged version of the Harris and Rowland (2001) FLOWGO model and the DOWNFLOW model of Favalli et al. (2005). A second example was that of Vicari et al. (2009) who used MODIS-derived TADRs acquired during Etna's 2006 eruption to run the MAGFLOW lava flow emplacement model of Del Negro et al. (2008).

This exciting direction takes satellite-based remote sensing to its ultimate destination. Derived quantitative parameters from the data are output in real time and then used to run simulations and projections in order to aid future hazard assessment, reporting, and response. Although not a real-time example, Fig. 5 shows how such an application could be used to better aid in hazard assessments. For this simulation, Harris et al. (2011) located a hypothetical new vent opening in the same location as Etna's 1669 vent. The simulation is run at  $100 \text{ m}^3/\text{s}$  over an ASTER-derived land classification map and shows that such an eruption would inundate  $10.7 \text{ km}^2$  of urban land and  $15.6 \text{ km}^2$  of agricultural land.

### 3.3.4. Inventories

MODVOLC-type systems, as well as the GOES-MSG-MTSAT geostationary constellation, allow global coverage at high-temporal frequencies. Furthermore, some databases now extend over decades (data bases for MODIS, GOES and AVHRR now span 11, 14, and 32 years, respectively). Thus, studies examining spatial and temporal trends and patterns in spectral radiance (and its derivable products)



**Fig. 5.** Results running the FLOWGO model of Harris and Rowland (2001) iteratively over a DEM of Etna, with noise being placed in the DEM with every iteration, this being the stochastic model of Favalli et al. (2005). Model is run from two locations (1) M. Gorna and (2) M. Rossi, at  $100 \text{ m}^3 \text{ s}^{-1}$ . The predicted zone of lava inundation is given in pink (labeled M. Gorna and M. Rossi lava flows, respectively) and is overlain on an ASTER-derived land classification map. Urban areas are shown in brown, with the main towns being labeled.

Fig. 9 of Harris et al. (2011)

have increased in the first decade of the 21st century. High-temporal resolution IR data for any volcano on the globe are now available from GOES-MSG-MTSAT, allowing detailed time series to be produced for any (cloud-free) short-lived and transient events, such as fire fountains (e.g., Ganci et al., 2011; Gouhier et al., 2011; Vicari et al., 2011). At the same time, the longevity of data sets such as those provided by AVHRR, TM and MODIS allow long-term trends in volcanic activity to be tracked and understood (e.g., Wooster, 2001; Harris et al., 2011; Coppola et al., 2012).

Time series analysis span studies of single volcanoes, through patterns in regional activity, to global inventories. The ease with which data can be downloaded also makes time series easy to assemble. For example, Patrick et al. (2005) used MODIS and ASTER data to provide an inventory of activity at an otherwise unmonitored remote volcano (Mount Belinda), and Wright et al. (2005) did the same for Anatahan using MODIS data. In a regional sense, Rothery et al. (2003) showed how MODVOLC data could be used to map hot spot patterns for a single country, reporting on hot spots due to industrial gas flares and burning of cattle carcasses during the 2001 outbreak of foot-and-mouth disease in the UK. Rothery et al. (2005) also examined volcano hot spot patterns across the whole of Melanesia using MODVOLC. The ultimate spatial scale across which a heat flux inventory can now be built was demonstrated by Wright and Flynn (2004) who used MODVOLC to assess global volcanic heat fluxes during 2001 and 2002. Delle Donne et al. (2010) took advantage of this global data base to cross-correlate the global seismic database with the MODVOLC database for volcanic hot spots from 2000 to 2006 to show the statistical relations between regional earthquakes and increases in heat flux at persistently active (open) volcanic systems.

These studies are also based on time series spanning periods lasting a few days, through eruptions (or eruption sequences) that last months to years (and even decades). For example, Harris and Ripepe (2007) used MODVOLC data to show that there was a near-immediate heat flux response to the magnitude 6.4 regional earthquake at the persistently active (open systems) of Merapi and Semeru (both located on Java) during the nine-day-long response itself. Kaneko et al. (2006) used MODIS data spanning January 2004 to April 2005, with ancillary gas and seismic data to track the 2004–2005 activity at Asama volcano, Japan. Time series spanning decadal time-scales had already been shown capable of picking out trends and relations in volcanic activity (Wooster and Rothery, 1997; Harris et al., 2000).

Satellite data sets spanning years to decades now allow construction of detailed heat flux inventories extending over periods of: one year (e.g., the SEVIRI-derived time series for fountaining at Etna constructed by Ganci et al. (2012)); two years (e.g., the MODIS-derived global volcanic heat flux inventory of Wright and Flynn (2004)); four years (e.g., the volcanic heat flux inventory derived for Melanesia from the MODVOLC data base by Rothery et al. (2005)); nine years (e.g. the ASTER-derived inventory for volcanic activity for Shiveluch of Carter and Ramsey (2010)); twelve years (e.g., the MODIS-derived activity log for Stromboli presented by Coppola et al. (2012)); fourteen years (e.g., the TM and ETM+ based chronology of activity at Santiaguito given by Harris et al. (2003)); seventeen years (e.g., the TM and ATSR spectral radiance inventory for Lascar, begun by Glaze et al. (1989), Oppenheimer et al. (1993) and Wooster and Rothery (1997), and completed by Wooster (2001)); and thirty years (e.g., the AVHRR-based record of effusive activity at Etna spanning 1981 through 2011 given by Harris (2012)). If the



continuity of spaceborne IR missions continues, these data sets will only become spatially and temporally more extensive, and hence powerful (from a scientific and baseline point-of-view) as we move through the current decade.

#### 4. Past: ground-based observations

##### 4.1. Pre-2000

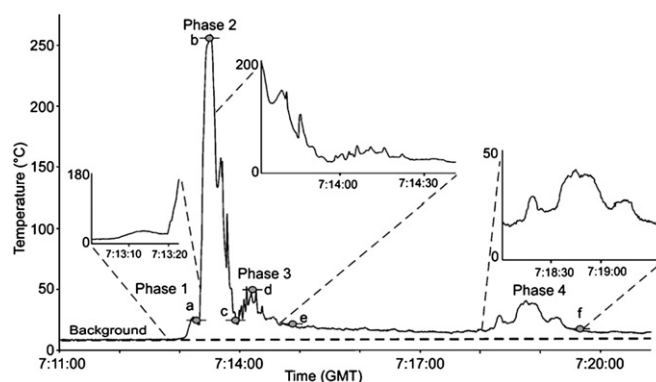
Ground-based (hand-held or tripod-mounted) IR radiometers operate in the 8  $\mu\text{m}$  to 13  $\mu\text{m}$  region, and have been regularly used to support volcano thermal studies since their first use at active volcanic systems in the mid-1960s. As a result, many of the approaches, applications, and methodologies now applied to radiometer (as well as thermal camera) data were already well-established by the mid-1970s (see Harris, 2012):

- (1) Moxham et al. (1965) and Decker and Peck (1967) had shown how aircraft and ground-based radiometer surveys could be used for thermal profile construction. The profiles of Decker and Peck (1967) were taken across a cooling lava lake and showed how that data could be converted to heat flux.
- (2) Wright et al. (1968) showed how optical pyrometers could be used to obtain spot temperature across and active lava lake surface.
- (3) Both Tazieff (1970) and Shimozuru (1971) used continuously recording radiometers to compare thermal waveforms acquired during explosive activity to different styles of activity.
- (4) Several years later, Birnie (1973) completed a spatial survey of Santiaguito's active lava dome and the surface of Pacaya's McKinney cone to produce detailed thermal maps.

These approaches underpin modern ground-based radiometry, with the radiometer having been used regularly from 1970 to 2000 (Fig. 1). Ground and airborne-based scanners and imagers were also used, but were typically bulky and required equally cumbersome acquisition and cooling systems. As a result, as we approached 2000, the new generation of low power consumption, light weight and low cost radiometers were much more attractive than IR cameras for temporary and/or permanent deployments aimed at tracking highly dynamic thermal phenomena in harsh field conditions.

##### 4.2. The year 2000

The centerpiece of our presentation in 2000 was a ground-based radiometer, set up in such a way that it was protected from gas and weather effects, viewing the target from within a sealed case through a selenium–germanium–arsenide window (Harris et al., 2005). They were also robust, operational and capable of long-term deployment to allow time series data to be collected (e.g., Marchetti and Harris, 2008), as well as capture the rare but violent events (e.g., Rosi et al., 2006; Harris et al., 2008; Ripepe et al., 2008) such as the 5 April 2003 explosion at Stromboli (Fig. 6). Between 1999 and 2004, this radiometer system was deployed at ten volcanoes viewing eight different activity types: Stromboli (explosions), Santiaguito (silicic lava flow), Kilauea (skylights), Pacaya (degassing), Poas (crater lake), Masaya (gas puffing), Villarrica (gas puffing), Fuego (explosions), Erta Ale (lava lake), and Soufriere Hills (lava dome). In addition, permanent systems were installed at Kilauea, Popocatepetl, El Chichon, and Stromboli. The advantage of the radiometer was that it was low cost (the widely used Omega OS554 was available for ~US\$750), could acquire at high sampling rates, and provided output as a continuous voltage, which was easy to collect together with other geophysical (e.g., infrasonic and seismic) data. As a result, radiometers were used to examine and parameterize the dynamics of explosive processes, e.g., Strombolian eruptions, gas bursting and gas pistonning, with temporal resolutions of up to 54 Hz (e.g., Ripepe et al., 2001,



**Fig. 6.** Example of the temperature record during the 5 April 2003 eruption at Stromboli by an IR radiometer located about 450 m from the summit crater (after Rosi et al., 2006). The four phases of the eruption can clearly be seen in this brief temporal record, including a short-lived precursory event and a waning tale (phases 1 and 4); the violent explosive phase (phase 2); and the extrusion of a scoria flow deposit (phase 3). Phases 2 and 3 were responsible for ejecting almost the entire mass of the pyroclastic products.

2002; Johnson et al., 2005; Branam et al., 2008). However, as already discussed, just as the potential of field portable radiometers was realizing its full worth, new light weight and robust thermal cameras were being tested.

##### 4.3. The decade 2000–2010

For thermal remote sensing of active volcanoes, the first ten years of the 21st century was the decade of the thermal camera (Table 3). Not as cheap as the radiometer, the new generation of research-grade uncooled, bolometer-based cameras was still affordable at ~US\$50,000. Initially offered by FLIR Systems™ these cameras boasted field portability (being the size and weight of a camcorder), low power requirements (operating for up to 2 h on a single, internal battery), ease of use, and provision of a 320 × 240 pixel image of calibrated (and atmospherically corrected) temperature at rates of up to 30 Hz. Several commercial companies now offer similar instruments including Mikron, Fluke, ICI, Thermoteknix, and Optotherm to name a few. The rapid acceptance and use of these hand-held thermal cameras was not surprising, and their dominance in the literature reflects that acceptance. The number of publications using satellite-based infrared sensors between 2000 and 2005 was 58; the publication number for studies using ground-based radiometer data during the same period was 24 publications; whereas the number of publications using thermal infrared cameras was 66.

**Table 3**

Past and present ground-based IR sensors used in volcanology.

| Camera manufacturer | Model(s)    | Studies supported (2000–2010) |
|---------------------|-------------|-------------------------------|
| FLIR systems        | S40         | 23                            |
| FLIR systems        | 695         | 19                            |
| FLIR systems        | 595         | 15                            |
| Other               | –           | 11                            |
| Agema               | 550 and 470 | 4                             |
| NEC                 | TS7302      | 4                             |
| FLIR systems        | A40         | 3                             |
| FLIR systems        | SC200       | 1                             |
| FLIR systems        | 160         | 1                             |
| FLIR systems        | S2000       | 1                             |
| FLIR systems        | A20         | 1                             |
| FLIR systems        | P65         | 1                             |
| LAIIRD              | 3A          | 1                             |
| Avio                | TVS-650     | 1                             |
| Sony                | Handycam    | 1                             |

As reviewed by Spampinato et al. (2011), thermal camera studies of volcanic phenomena could be divided into five areas:

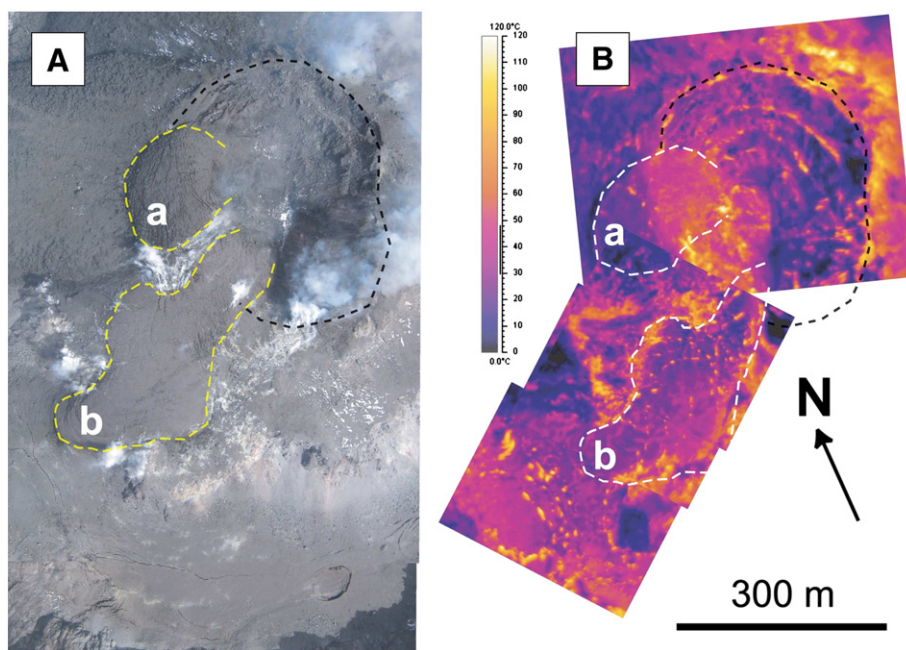
- (1) Hydrothermal features and fumaroles (e.g., Matsushima et al., 2003; Chiodini et al., 2007; Harris et al., 2009), including crater lakes (Hernández et al., 2007). In these cases, the thermal camera can be used to examine spatial and temporal changes in fumarole distribution, temperature, and heat flux.
- (2) Lava bodies including lava flows (e.g., Harris et al., 2005; Bailey et al., 2006; Ball et al., 2008), lava tubes and skylights (e.g., Kauahikaua et al., 2003; Coppola et al., 2007; Witter and Harris, 2007), lava lakes (e.g., Oppenheimer and Yirgu, 2002; Calkins et al., 2008; Spampinato et al., 2008), and lava domes (e.g., Carter et al., 2007; Schneider et al., 2008; Sahetapy-Engel and Harris, 2009a). For active lava bodies, the thermal camera can be used to examine spatial and temporal changes in temperature distributions, heat and mass fluxes, as well as provide measurements for flow dimensions and dynamics (Fig. 7).
- (3) Explosive plumes (e.g., Patrick, 2007; Patrick et al., 2007; Sahetapy-Engel and Harris, 2009b), including degassing/gas puffing (e.g., Harris and Ripepe, 2007; Gurioli et al., 2008). For an ascending plume Patrick (2007) described the main parameters that can be measured with the camera data, including vent exit and plume ascent velocity, spreading rate, and height. These data also allowed the definition of emission type, componentry (ash versus bombs/blocks), trajectories, and identification of eruptive phases (e.g., Calvari et al., 2006; Patrick et al., 2007; Harris et al., 2008).
- (4) Pyroclastic flow deposits (e.g., Carter et al., 2008; Carter and Ramsey, 2009). Thermal distribution patterns within the flows were linked to emplacement mechanism (i.e., dome vs. column collapse), distribution of blocks and block size, as well as long-term cooling derived from the thermal inertia of the deposits.
- (5) Surveys of fracturing, as well as structural and morphological studies (e.g., Calvari and Pinkerton, 2004; Bonaccorso et al., 2005; Calvari et al., 2005).

These advances in temporary or one-time deployments of thermal cameras at active volcanic systems have now been matched by widespread installation of permanently recording camera systems much like the radiometer systems of the previous decade. These systems directly transmit images from the camera site to reception centers, at rates of up to 1 Hz, allowing data to be incorporated into real-time monitoring activities (e.g., Andò and Pecora, 2006). For example, a network of two thermal cameras maintained by INGV-Catania operates at Mt. Etna (Calvari et al., 2011). Other permanent cameras are being deployed at Vulcano (Lodato et al., 2008), Stromboli, and Campi Flegrei-Vesuvius (Vilardo et al., 2008) to support monitoring efforts at Italian volcanoes. Similar camera systems have also now been installed permanently on Kilauea to support the monitoring efforts of the Hawaiian Volcano Observatory (Orr and Patrick, 2009).

## 5. Future: volcanology 2020

### 5.1. Satellite-based technology in 2020

As we again look ahead to predict where IR-based technology will advance volcanology during the next decade, we foresee satellite-based instruments and technology continuing as the primary synoptic tool. However, most of the new instruments scheduled for launch are focused on atmospheric science rather than geology/geophysical community. Furthermore, the development will continue to focus mainly on lower spatial resolution operational infrared systems in both geostationary (GEO) and polar low Earth (LEO) orbits (Table 4). For example, the Spinning Enhanced Visible and Infrared Imager (SEVIRI) sensor in GEO orbit has continued the tradition of high-temporal/low spatial resolution (15 min with 3 km/pixel) data and has the capability to detect hotspots. The planned Geostationary Satellite system (GOES-R) satellite will be greatly improved over past GOES sensor systems, including 11 more spectral channels (with 7 of these being in the mid IR and thermal IR wavelengths), an improved temporal resolution (5 min), and an improved spatial resolution in the IR (2 km). The recently launched LEO Visible Infrared Imager Radiometer Suite (VIIRS) instrument has improved detection capabilities from that of



**Fig. 7.** Example of the use of helicopter-based FLIR data to capture the dynamic processes of Bezymianny's dome in August 2005 (modified after Carter et al., 2007). The authors used the visible and IR data to confirm the presence of a newly-formed summit crater within the existing dome (black dashed line). The thermal distribution of the internal crater structure and the rim-draping lava flows (a and b) provided evidence for a magma withdrawal/crater collapse event rather than an explosively-formed crater origin. (A) Visible camera mosaic of the new dome crater and lava flow lobes. (B) Corresponding TIR data mosaic acquired at the same time.

MODIS, because of its higher spatial resolution (250–750 m/pixel) and dynamic range, but has a lower spectral resolution. Each of these sensors has several TIR channels and at least one MIR channel making them well-suited to detect larger/hotter thermal anomalies and characterize the thermal distribution within those pixels using a multiband modeling approach. But all of these mission lack the higher spatial and spectral resolution critically needed for understanding volcanological processes at the meter to decameter scale. Future missions designed primarily for the measurement of atmospheric composition will have TIR or MIR channels available for temperature measurements. These instruments have been recommended in the Earth Science Decadal Survey report to NASA (NRC, 2007), although they have yet to be approved for official development by the agency (i.e., “Phase A”). Included in that list is the Global Atmospheric Composition Mission (GACM). From the standpoint of hot spot detection, missions such as GACM do not offer significant advancement in either spatial or temporal resolution over past instruments, nor do they dramatically improve the technology of their predecessors for rapid detection of thermal anomalies on the surface because they are designed primarily to study the atmosphere. However, they will provide a continuation of detection capabilities from space, which is critical for volcanological remote sensing. Also included in the Decadal Survey report is the only optical imaging instrument with a strong focus on volcanology, the Hyperspectral Infrared Imager (HyspIRI) mission. HyspIRI does offer the unique possibility of high spatial resolution data with significant advances such as increased spectral resolution and saturation temperatures of up to 770 °C in the TIR, as well as perhaps most significant, a wide swath width providing repeat data coverage of between one and five days.

One area of spaceborne instrumentation that does hold the potential for significant advancement in eruption detection and monitoring in the next decade is advent of small satellite technology launched by consortiums of universities, local/regional governments, and/or businesses. These relatively inexpensive satellites can be outfitted with IR imaging instruments and launched individually or in clusters for high-temporal coverage of eruptions. One example of this approach is the ongoing work at the Hawaii Space Flight Laboratory, which will design, build, launch, and operate several small satellites in the coming decade (Sorensen et al., 2009). One of these satellites, due for launch within the next year, will carry a TIR instrument called the Thermal Hyperspectral Imager (THI). The THI is designed to acquire calibrated radiance images with a 20 wavenumber spectral resolution, equivalent to ~100 wavelength bands between 7  $\mu\text{m}$  and 13  $\mu\text{m}$  (Crites et al., 2011).

Another area that should see improvement over the current decade is the use of available data for new and more accurate algorithms designed for rapid data analysis and parameterization of volcanic effusive phenomena. For example, data acquired synchronously in the TIR and MIR wavelength regions could be exploited to more accurately describe the range of surface temperatures and their percentages within thermally-anomalous pixels. Infrared radiant flux data that are both accurate, and not saturated, provide the best possibility for determining lava temperature, area, discharge rate, and constraints on the composition of the flow surface.

Furthermore, improvements can potentially be made in the temporal resolution of sensors already (or soon to be) in orbit by way of changes to flight operational software, which would thus limit the need to launch new systems with improved resolution. For example, image subsetting in near-real time using scan modes such as the Super Rapid Scan Operations (SRSO) for the GOES sensors provides data of transient phenomena such as hurricanes every minute (compared to every 15 min in normal scan mode). However, this type of acquisition mode does exclude all other areas of the scene except for that of the target, and has not yet been applied to volcanic eruptions (as far as we can tell). The SRSO mode has enormous potential for volcanological applications such as tracking dynamic ash plumes or thermal output. If this style of observation could be quickly and automatically initiated, it would capture the detailed transient thermal features of the initial stages of large eruptions, or transient, rapidly-evolving and/or short-lived eruptions, such as fire fountain events. Similarly, if initiated prior to eruption (perhaps targeted because of ground-based triggers such as increased heat flux detected from permanently deployed IR cameras) a high data rate scan mode could capture event onset with 60-second precision. Future application of onboard processing software such as ACE on EO-1, rapid-response scanning modes such as SRSO on the GOES satellites, and sensor-web approaches such as ASTER-URP will provide the most rapid response to volcanic events and the quickest dissemination of data to scientists and emergency managers while the science community waits for satellite-based sensors designed specifically for the unique needs of accurate volcanic observations.

## 5.2. Ground and airborne-based technology in 2020

The potential for technological advances in the sphere of ground-based infrared equipment remains the most promising and exciting area throughout the next decade. The relative ease of use of the instruments, continued expansion of infrared technology by the private sector, and use of data by more and more volcanologists, has already spurred a rapid growth in the application of ground-based thermal remote sensing as we have already discussed. Hand-held thermal cameras continue to proliferate in terms of the number of models, with a great variety of spatial and temporal resolutions, as well as price. Cameras now produce images that are twice the size from a decade ago with frame rates twice as fast and costs that are declining. Furthermore, new models come on line every year including micro IR cameras half the size of cell phone. It seems obvious to say that we expect the collation of thermal camera based studies in the volcanological journals (shown in Table 1) to be at least twice as long by 2020.

But what could be new in the next decade? On answering this question, we see the potentially new data and capabilities sub-divided into three primary themes: (1) improved spectral resolution; (2) new airborne technology; and (3) fusion of the data with to improve detection and measurement capabilities.

The improved spatial and/or spectral resolution of MIR and TIR instruments provide both the ability to resolve a larger number of high

**Table 4**  
Recently launched and planned IR sensors with possible applications for volcanology.

| Sensor name                                 | Acronym | Launch date | Platform         | Wavelength region   | Spatial resolution (m) |
|---|---------|-------------|------------------|---------------------|------------------------|
| Visible infrared imager radiometer suite    | VIIRS   | 2011        | Spaceborne (LEO) | NIR, SWIR, MIR, TIR | 250–750                |
| Mineral and gas identifier                  | MAGI    | 2011        | Airborne         | TIR                 | 1–20                   |
| Hyperspectral thermal emission spectrometer | HyTES   | 2012        | Airborne         | TIR                 | 1–20                   |
| Landsat data continuity mission             | LCDM    | 2013        | Spaceborne (LEO) | NIR, SWIR, TIR      | 15–100                 |
| Thermal hyperspectral imager                | THI     | 2013        | Spaceborne (LEO) | TIR                 | 230                    |
| Geostationary satellite system              | GOES-R  | 2015        | Spaceborne (GEO) | MIR, TIR            | 2000                   |
| Hyperspectral infrared imager               | HyspIRI | >2020       | Spaceborne (LEO) | NIR, MIR, TIR       | 60                     |
| Global atmospheric composition mission      | GACM    | >2020       | Spaceborne (LEO) | SWIR, MIR           | T.B.D.                 |

temperature sub-pixel temperature components as well as the compositional and textural variation of those deposits. This was documented by Flynn et al. (2000) who used data from a hyperspectral field spectrometer in the 2.0 to 2.5  $\mu\text{m}$  wavelength range to constrain the number of high temperature components on an active basalt flow. Wright and Flynn (2003) followed this study with a similar objective. They used the statistical distribution of temperatures measured in the 76,800 pixels of a TIR camera image to document at least seven dominant temperatures in active basalt flow field. We expect future studies in this area will be possible with rapid data processing, the results of which will be used for more accurate modeling of lava flow emplacement and validation of spaceborne data.

An increase in the number of wavelength bands in the TIR region allows for more precise temperature extractions because the derivation of radiant temperature is intimately linked to the accuracy by which one can estimate the surface emissivity. This move toward hyperspectral TIR emissivity data is also critical for accurate determine surface and plume composition. Emissivity is a fundamental wavelength-dependant property controlled by the vibrational (e.g., bending and stretching) frequencies of the atomic bonds of the material. For example, in silicate minerals, the Si–O–Al bonds determine the magnitude and wavelength location of the emissivity absorption in the TIR region. These values in turn control the rate of IR emission from the surface and hence affect the cooling rate, degree of crust formation, and flow length for example. By separating the emissivity for the complex thermal structure of volcanic deposits, it can also be used to estimate the mineralogical and textural components of the targeted surface (e.g., Ramsey and Fink, 1999; Christensen et al., 2005; Carter et al., 2009). Previous studies have focused on laboratory, airborne, or spaceborne data to deconvolve the complex compositional mixing patterns in targeted rocks. New advances in ground-based multispectral sensors have recently expanded this capability allowing field-scale measurements to be made on active processes at the small-scale. For example, Prata and Bernardo (2009) describe a camera operating in the 7–14  $\mu\text{m}$  wavelength region that contains five filters mounted in a spinning filter wheel assembly. They show the utility of using such a set up to acquire rapid spectral information of dynamic process such as  $\text{SO}_2$  and ash emission at volcanic vents. Furthermore, Ramsey (2009) describes an approach of merging TIR wavelength filters with a commercial FLIR infrared camera. These filters subdivide the wavelength region detected by the camera into six discrete bands which, when separated from the surface temperature component of each pixel, produces a multi channel emissivity image cube of the surface. This was demonstrated on the mixed (rhyolite/dacite) Big Glass Mountain Flow at Medicine Lake Caldera, California (Fig. 8). The multispectral FLIR camera was able to discriminate both compositional and textural variations across the flow surface with derived emissivity spectra that look similar to those acquired in controlled laboratory settings. In glassy silicic lavas, the depth of the spectral absorption correlates with the degree of vesicularity, and the wavelength position of the absorption feature correlates with the composition. These variations are responsible for the colors seen in Fig. 8 making the multispectral FLIR a promising mapping instrument for compositional analysis of lava flows. By automating the data acquisition process and mounting the camera in weather-proof enclosure similar to that used for radiometer in the last decade, this approach could be applied to monitor dynamic volcanic processes such as lava flows, gas emission, and ash plumes.

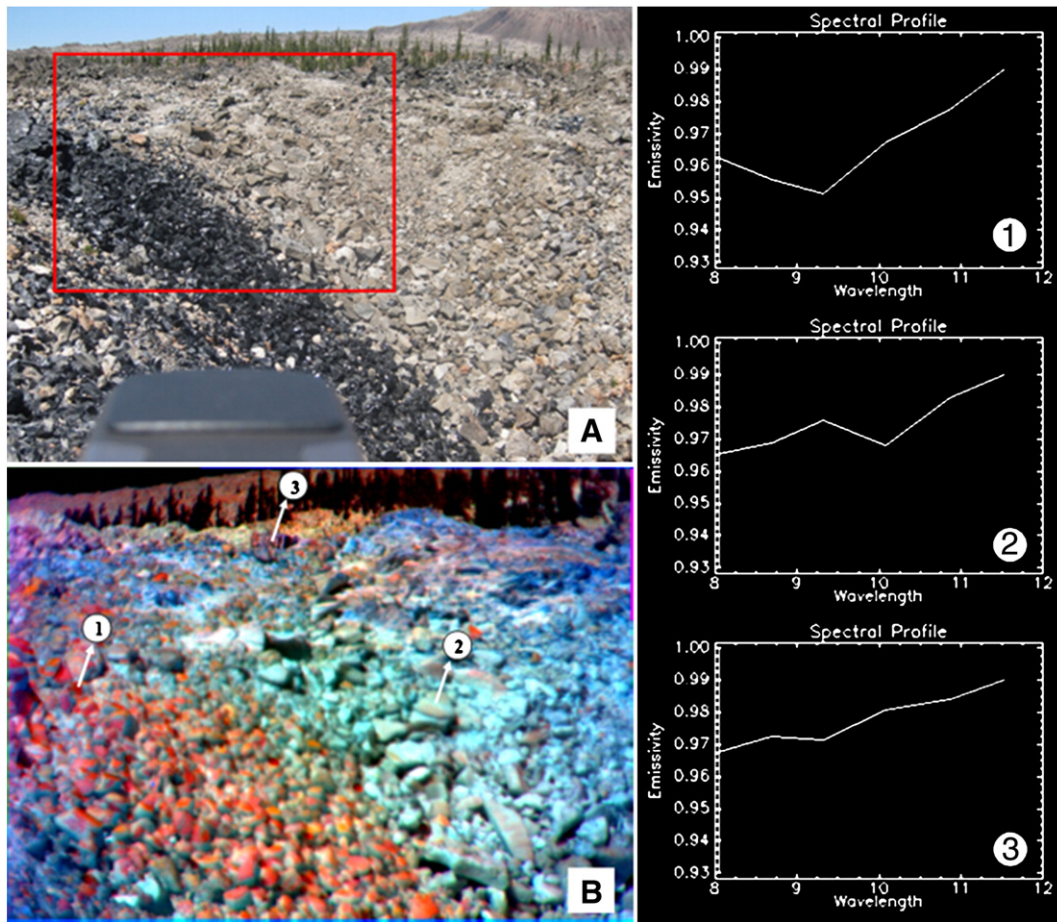
We also include airborne systems because they commonly serve as predecessors to future satellite systems and are also more closely akin to ground-based instruments in their style of deployment and data resolution. These sensors also offer the possibility of unique, high spatial and spectral resolution infrared data for future volcanic targets. Hyperspectral airborne TIR data have been acquired since deployment of the Spatially Enhanced Broadband Array Spectrograph System (SEBASS) instrument (Hackwell et al., 1996). SEBASS has

128 channels in the MIR (2.5 to 5.2  $\mu\text{m}$ ) and TIR (7.5 to 13.5  $\mu\text{m}$ ) wavelength regions. Although the system is large and requires cooling by liquid helium, SEBASS has acquired data at numerous locations for mineral mapping, geothermal exploration, and analog studies (Calvin et al., 2002; Vaughan et al., 2003; Reath, 2011). Newly-funded NASA airborne instruments are about to come online and include the Mineral and Gas Identifier (MAGI) and the Hyperspectral Thermal Emission Spectrometer (HyTES) (e.g., Hall et al., 2008; Johnson et al., 2011). MAGI is a 32 channel whiskbroom scanner that operates between 7.0  $\mu\text{m}$  and 12  $\mu\text{m}$  with a large field of view ( $\pm 45^\circ$ ) and therefore a much wider swath width than SEBASS. The number of channels was determined to be the minimum number needed in order to accurately resolve all significant gases and minerals and still maintaining the best possible signal to noise ratio (Hall et al., 2008). The sensor has a unique modified Dyson spectrometer optical design that allows a very compact and optically fast system (see Hall et al., 2008). The focal plane array is a cooled HgCdTe composition with proven lineage in the airborne TIR instrument history. HyTES also relies on a Dyson-inspired optical design with a similarly large field of view, but with 256 spectral channels between 7.5  $\mu\text{m}$  to 12  $\mu\text{m}$ . Another key difference between MAGI and HyTES is that HyTES uses a quantum well infrared photodetectors (QWIPs) focal plane array. This FPA requires more significant cooling (40  $^\circ\text{C}$  versus 70  $^\circ\text{C}$ ) than the HgCdTe arrays but generally has a higher spatial uniformity. Both instruments are being designed as potential test beds for future spaceborne TIR instruments such as HyspIRI.

A final aspect of rapidly growing technology and data analysis in the next decade is the concept of data fusion, or the merging of high spatial resolution thermal data (from ground-based cameras and airborne scanners, for example) with topographic data acquired by tripod and aircraft mounted LIDAR shows great promise (e.g., James et al., 2008). Repeat airborne LIDAR surveys have already shown how the volumetric and three-dimensional form of an active lava flow field can be tracked over time-scales of minutes to hours, depending on the flight plan (Favalli et al., 2010). Therefore, airborne missions carrying co-located thermal cameras, visible imagers, and LIDAR systems, although currently quite costly, will greatly enhance our ability to measure, model, monitor, and understand the emplacement of volcanic flows. Another concept of data fusion is the application of new image analysis approaches such as super-resolution (e.g., Hughes and Ramsey, 2010). This approach creates radiometrically-accurate IR data at a much higher spatial resolution using data from the visible/near infrared. Such a data fusion approach can be applied to airborne or spaceborne data and should help to augment the looming lack of high spatial resolution spaceborne IR data in the next decade.

## 6. Summary

In this paper, we summarized advances in volcanological remote sensing of volcanic surfaces since our AGU presentations of December 2000. We then tried to look ahead to the end of the current decade in order to forecast the direction and science of the infrared observations of volcanoes. The use of remote sensing for detection, monitoring, and modeling of volcanic activity has expanded enormously during the past 25 years. This growth has been fueled by a vast array of new satellite sensors, the application of new technologies, and the involvement of an increasing number of scientists working in the field of thermal remote sensing of volcanoes around the world. The number of publications using remote sensing to explore specific volcanic processes has grown from just a handful in the mid 1980s to around 200 some two decades later. More importantly, these publications have transitioned from remote sensing specific journals to volcanological-oriented ones, which indicate the growing use and acceptance of IR remote sensing as a tool for volcanologists (Harris, 2012).



**Fig. 8.** Multispectral FLIR results acquired at Medicine Lake Caldera, CA. (A) Digital photograph of a region of Big Glass Mountain silicic flow showing the three main rhyolite textures: black (obsidian), white (finely vesicular pumice, FVP) and brown (coarsely vesicular pumice, CVP). The body of the FLIR is in the foreground and the red box indicates the area imaged by the FLIR that is shown in (B). (B) Color composite of the area show in (A) formed from three FLIR wavelength channels. Numbers indicate the locations of the six-point emissivity spectra extracted: (1) obsidian, (2) FVP and (3) CVP.

During the 2000 AGU Meeting, we presented two dominant themes regarding the next decade of volcano remote sensing. The first was that of the upcoming “Age of EOS”—the NASA Earth Observing System consisting of numerous satellites/sensors, many of which were well-suited to volcano science from space. Included in this potential was the possibility of data fusion and sensor webs that would integrate data streams and enhance the benefit of just a single sensor. The second major theme was the increasing volumes of TIR data made available in real-time, which included thermal data from geostationary satellites and ground-based systems. We described how these systems of hypertemporal resolution data would better characterize changes in activity on the second-to-minute time scale. We predicted that such systems would be installed at many volcanoes by 2010 and the data from the EOS sensors would be applied to numerous others to better monitor ongoing eruptions. Both of these predicted themes were proven true. However, the capacities (technological, computing/processing and algorithm capability) advanced faster than we thought possible in 2000. In many ways, the first decade of this century could be seen as the “golden age” of volcanological IR remote sensing because of the sheer number of IR systems observing volcanoes and the start of the operational phase of a vast number of space- and ground-based remote sensing applications in volcanology.

Unfortunately, the next decade does not hold the promise of the last in terms of spaceborne data. The exception to that will be the next generation of operation systems such as GOES and AVHRR, which will be launched before 2020. However, our pessimistic view does hold true

for scientific (non-operational) sensors such as the HypsIRI mission, which offers both high spatial and temporal resolution data in the TIR as well as saturation temperatures of  $\sim 770$  °C in the TIR and  $\sim 1470$  °C in the single MIR channel. Despite being recommended as a second-tier mission in the Earth Science Decadal Survey, the proposed launch date of 2013 for HypsIRI was recently delayed by NASA up to as many as ten years due to a priority refocus to climate-specific measurements. This delay will now certainly cause a data continuity gap after the end of ASTER, and will severely limit the availability (and continuity) of high resolution multispectral TIR data from space. Unfortunately, there will be little doubt that we will be talking about a “future” HypsIRI mission in 2020 when we write our next decadal review. Furthermore, the next generation of Landsat (the Landsat Data Continuity Mission or LCDM) for years was scheduled to launch with no TIR capability—for the first time since Landsat 4 in 1982. After much debate and input from the scientific community, this decision was changed and the Thermal InfraRed Sensor (TIRS) was added, which will provide 100 m data in two spectral bands. Sadly, compared to the five spectral bands of ASTER data at 90 m spatial resolution or one 60 m band of TIR data provided by ETM+, TIRS cannot be seen as an improvement in any way from what ASTER and ETM+ provided over a decade earlier. Perhaps small satellite sensors (“small sats”) launched by consortiums of universities and industry will help augment these looming data gaps caused by the ever-changing priorities and budgets of governmental space agencies.

With a looming gap in spaceborne TIR data, we do envision a more rapid expansion of many of the ground-based technologies, however. Much of this will be focused on technology to advance rapid, real-

time imaging with sub-second temporal resolution with ever-increasing spatial resolution. These data will become routine input into integrated monitoring, modeling, and hazard appraisal. For example, as thermal infrared camera data become less expensive and easier to use, these sensors will be expanded into multispectral devices and placed around active volcanoes in order to capture spatial patterns of temperature, composition, and surface texture at the second-to-minute time scale (e.g., Ramsey, 2009; Calvari et al., 2011). Similar sensors are now being developed for possible inclusion into commercial aircraft for real-time ash hazard avoidance (Prata, 2009). In other wavelength regions, smaller and more portable systems are also being developed for SO<sub>2</sub> detection in the ultraviolet region (Bluth et al., 2007), thermal detection using the microwave region (Wadge et al., 2005), and the high-precision, rapid scanning LIDAR systems for changes in surface topography (Favalli et al., 2010). New algorithms will also continue to appear in order to quickly ingest this high volume data and make it available for the real-time modeling (e.g., Ganci et al., 2011).

No matter what the source of the new data, it must not become so complex, expensive, and difficult to acquire so as to make it unusable in a timely manner during volcanic crises. This is always a concern with new satellite data that may impose operational constraints, costs, and processing delays when a sensor is considered experimental rather than operational in nature. However, regardless of the source, volcanological remote sensing will continue to expand as both a tool and research area. It is now a truly a discipline in its own right, supported by an extensive literature base, and as such is unlikely to go away. Any unforeseen technology advances over the next ten years will likely propel this discipline far beyond what we can currently envision making "Volcanology: 2020" another exciting time to reassess volcanological remote sensing's paradigms and progress, and assess the naivety of the statements made here.

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## References

Andò, B., Pecora, E., 2006. An advanced video-based system for monitoring active volcanoes. *Computers & Geosciences* 32, 85–91. <http://dx.doi.org/10.1016/j.cageo.2005.05.004> (ISSN 0098–3004).

Bailey, J.E., Harris, A.J.L., Dehn, J., Calvari, S., Rowland, S.K., 2006. The changing morphology of an open lava channel on Mt. Etna. *Bulletin of Volcanology* 68, 497–515. <http://dx.doi.org/10.1007/s00445-005-0025-6>.

Ball, M., Pinkerton, H., Harris, A.J.L., 2008. Surface cooling, advection and the development of different surface textures on active lavas on Kilauea, Hawai'i. *Journal of Volcanology and Geothermal Research* 173, 148–156.

Birnie, R.W., 1973. Infrared radiation thermometry of Guatemalan volcanoes. *Bulletin of Volcanology* 37, 1–36. <http://dx.doi.org/10.1007/BF02596879>.

Bluth, G.J.S., Shannon, J.M., Watson, I.M., Prata, A.J., Realmuto, V.J., 2007. Development of an ultra-violet digital camera for volcanic SO<sub>2</sub> imaging. *Journal of Volcanology and Geothermal Research* 161, 47–56. <http://dx.doi.org/10.1016/j.jvolgeores.2006.11.004> (ISSN 0377–0273).

Bonaccorso, A., Cianetti, S., Giunchi, C., Trasatti, E., Bonafede, M., Boschi, E., 2005. Analytical and 3-D numerical modeling of Mt. Etna (Italy) volcano inflation. *Geophysical Journal International* 163, 852–862. <http://dx.doi.org/10.1111/j.1365-246X.2005.02777>.

Branan, Y.K., Harris, A., Watson, I.M., Phillips, J.C., Horton, K., Williams-Jones, G., Garbeil, H., 2008. Investigation of at-vent dynamics and dilution using thermal infrared radiometers at Masaya volcano, Nicaragua. *Journal of Volcanology and*

*Geothermal Research* 169, 34–47. <http://dx.doi.org/10.1016/j.jvolgeores.2007.07.021> (ISSN 0377–0273).

Calkins, J., Oppenheimer, C., Kyle, P.R., 2008. Ground-based thermal imaging of lava lakes at Erebus volcano, Antarctica. *Journal of Volcanology and Geothermal Research* 177, 695–704. <http://dx.doi.org/10.1016/j.jvolgeores.2008.02.002> (ISSN 0377–0273).

Calvari, S., Pinkerton, H., 2004. Birth, growth and morphologic evolution of the "Laghetto" cinder cone during the 2001 Etna eruption. *Journal of Volcanology and Geothermal Research* 132, 225–239. [http://dx.doi.org/10.1016/S0377-0273\(03\)00347-0](http://dx.doi.org/10.1016/S0377-0273(03)00347-0).

Calvari, S., Spampinato, L., Lodato, L., Harris, A.J.L., Patrick, M.R., Dehn, J., Burton, M.R., Andronico, D., 2005. Chronology and complex volcanic processes during the 2002–2003 flank eruption at Stromboli Volcano (Italy) reconstructed from direct observations and surveys with a hand-held thermal camera. *Journal of Geophysical Research* 110. <http://dx.doi.org/10.1029/2004JB00312>.

Calvari, S., Spampinato, L., Lodato, L., 2006. The 5 April 2003 vulcanian paroxysmal explosion at Stromboli volcano (Italy) from field observations and thermal data. *Journal of Volcanology and Geothermal Research* 149, 160–175.

Calvari, S., Salerno, G.G., Spampinato, L., Gouhier, M., La Spina, A., Pecora, E., Harris, A.J.L., Labazuy, P., Biale, E., Boschi, E., 2011. An unloading foam model to constrain Etna's 11–13 January 2011 lava fountaining episode. *Journal of Geophysical Research*. <http://dx.doi.org/10.1029/2011JB008407>.

Calvin, W., Coolbaugh, M., Vaughan, R.G., 2002. Geothermal site characterization using multi- and hyperspectral imagery. *Geothermal Resources Council Transactions* 26, 483–484.

Carter, A.J., Ramsey, M.S., 2009. ASTER- and field-based observations at Bezymianny Volcano: focus on the 11 May 2007 pyroclastic flow deposit. *Remote Sensing of Environment* 113, 2142–2151.

Carter, A.J., Ramsey, M.S., 2010. Long-term volcanic activity at Shiveluch Volcano: nine years of ASTER spaceborne thermal infrared observations. *Remote Sensing* 2 (11), 2571–2583. <http://dx.doi.org/10.3390/rs2112571>.

Carter, A.J., Ramsey, M.S., Belousov, A.B., 2007. Detection of a new summit crater on Bezymianny Volcano lava dome: satellite and field-based thermal data. *Bulletin of Volcanology*. <http://dx.doi.org/10.1007/s00445-007-0113-x>.

Carter, A.J., Girina, O., Ramsey, M.S., Demyanchuk, Y.V., 2008. ASTER and field observations of the 24 December 2006 eruption of Bezymianny Volcano, Russia. *Remote Sensing of Environment* 112, 2569–2577. <http://dx.doi.org/10.1016/j.rse.2007.12.001>.

Carter, A.J., Ramsey, M.S., Durant, A.J., Skilling, I.P., Wolfe, A.L., 2009. Micron-scale roughness of volcanic surfaces from thermal infrared spectroscopy and scanning electron microscopy. *Journal of Geophysical Research* 114, B02213. <http://dx.doi.org/10.1029/2008JB005632>.

Chiodini, G., Vilardo, G., Augusti, V., Granieri, D., Caliro, S., Minopoli, C., Terranova, C., 2007. Thermal monitoring of hydrothermal activity by permanent infrared automatic stations: results obtained at Solfatara di Pozzuoli, Campi Flegrei (Italy). *Journal of Geophysical Research* 112, B12206. <http://dx.doi.org/10.1029/2007JB005140>.

Christensen, P.R., McSween, H.Y., Bandfield, J.L., Ruff, S.W., Rogers, A.D., Hamilton, V.E., Gorelick, N., Wyatt, M.B., Jakosky, B.M., Kieffer, H.H., Malin, M.C., Moersch, J.E., 2005. Evidence for magmatic evolution and diversity on Mars from infrared observations. *Nature* 436, 504–509.

Coppola, D., Staudacher, T., Cigolini, C., 2007. Field thermal monitoring during the August 2003 eruption at Piton de la Fournaise (La Reunion). *Journal of Geophysical Research* 112, B05215. <http://dx.doi.org/10.1029/2006JB004659>.

Coppola, D., Piscopo, D., Staudacher, T., Cigolini, C., 2009. Lava discharge rate and effusive pattern at Piton de la Fournaise from MODIS data. *Journal of Volcanology and Geothermal Research* 184, 174–192. <http://dx.doi.org/10.1016/j.jvolgeores.2008.11.031> (ISSN 0377–0273).

Coppola, D., Piscopo, D., Laioli, M., Cigolini, C., Delle Donne, D., Ripepe, M., 2012. Radiative heat power at Stromboli volcano during 2000–2011: twelve years of MODIS observations. *Journal of Volcanology and Geothermal Research* 215–216, 48–60.

Crites, S.T., Lucey, P.G., Wright, R., Garbeil, H., Horton, K.A., 2011. A low cost thermal infrared hyperspectral imager for small satellites. *Proceedings of SPIE* 8044. <http://dx.doi.org/10.1117/12.886535>.

Davies, A.G., Chien, S., Wright, R., Miklius, A., Kyle, P.R., Welsh, M., Johnson, J.B., Tran, D., Chaffer, S.R.S., Sherwood, R., 2006. Sensor web enables rapid response to volcanic activity. *EOS, Transactions of the American Geophysical Union* 87, 1–5.

Dean, K.G., Servilla, M., Roach, A., Foster, B., Engle, K., 1998. Satellite monitoring of remote volcanoes improves study efforts in Alaska. *EOS, Transactions of the American Geophysical Union* 79 (413), 422–423.

Decker, R.W., Peck, D.L., 1967. Infrared radiation from Alae lava lake, Hawaii. U.S. Geological Survey Professional Paper 575D, 169–175.

Dehn, J., Dean, K.G., Engle, K., Izbekov, P., 2002. Thermal precursors in satellite images of the 1999 eruption of Shishaldin Volcano. *Bulletin of Volcanology* 64, 525–534.

Del Negro, C., Fortuna, L., Herault, A., Vicari, A., 2008. Simulations of the 2004 lava flow at Etna volcano using the magflow cellular automata model. *Bulletin of Volcanology* 70, 805–812. <http://dx.doi.org/10.1007/s00445-007-0168-8>.

Delle Donne, D., Harris, A.J.L., Ripepe, M., Wright, R., 2010. Earthquake-induced thermal anomalies at active volcanoes. *Geology* 38, 771–774. <http://dx.doi.org/10.1130/G30984.1>.

Di Bello, G., Filizzola, C., Lacava, T., Marchese, F., Pergola, N., Pietrapertosa, C., Piscitelli, S., Scaffidi, I., Tramutoli, V., 2004. Robust satellite techniques for volcanic and seismic hazards monitoring. *Annals of Geophysics* 47. <http://dx.doi.org/10.4401/ag-3258>.

Dozier, J., 1981. A method for satellite identification of surface temperature fields of subpixel resolution. *Remote Sensing of Environment* 11, 221–229.

Duda, K.A., Ramsey, M., Wessels, R., Dehn, J., 2009. Optical satellite volcano monitoring: a multi-sensor rapid response system. In: Ho, P.P. (Ed.), *Geosci. Rem. Sens. INTECH Press, Vukovar, Croatia*. ISBN: 978-953-307-003-2, pp. 473–496.

- Favalli, M., Pareschi, M.T., Neri, A., Isola, I., 2005. Forecasting lava flow paths by a stochastic approach. *Geophysical Research Letters* 32, L03305. <http://dx.doi.org/10.1029/2004GL021718>.
- Favalli, M., Harris, A.J.L., Fornaciai, A., Pareschi, M.T., Mazzarini, F., 2010. The distal segment of Etna's 2001 basaltic lava flow. *Bulletin of Volcanology* 72, 119–127. <http://dx.doi.org/10.1007/s00445-009-0300-z>.
- Flannigan, M.D., Vonder-Haar, T.H., 1986. Forest fire monitoring using NOAA satellite AVHRR. *Canadian Journal of Forest Research* 16, 975–982.
- FLIR Systems, 2003. *ThermaCAM™ S40 Operator's Manual*. FLIR Systems. Publication No. 1 557 539 Rev. C, 136 pp.
- Flynn, L.P., Harris, A.J.L., Rothery, D.A., Oppenheimer, C., 2000. High-spatial-resolution thermal remote sensing of active volcanic features using landsat and hyperspectral data. *Remote Sensing of Active Volcanism*, Geophysical Monograph vol. 116, pub. AGU, pp. 161–177.
- Flynn, L.P., Wright, R., Garbeil, H., Harris, A.J., Pilger, E., 2002. A global thermal alert system using MODIS: initial results from 2000–2001. *Advances in Environmental Monitoring and Modelling* 1 (3), 37–69.
- Friedman, J.D., Williams, R.S., 1970. Changing patterns of thermal emission from Surtsey, Iceland, between 1966 and 1969. *U.S. Geol. Survey Prof. Paper* 700-D, pp. 116–124.
- Ganci, G., Vicari, A., Bonfiglio, S., Gallo, G., Del Negro, C., 2011. A texton-based cloud detection algorithm for MSG-SEVIRI multispectral images. *Geomatics, Natural Hazards and Risk* 2, 279–290.
- Ganci, G., Harris, A.J.L., Del Negro, C., Guehenneux, Y., Cappello, A., Labazuy, P., Calvari, S., Gouhier, M., 2012. A year of lava fountaining at Etna: volumes from SEVIRI. *Geophysical Research Letters* 39, L06305. <http://dx.doi.org/10.1029/2012GL051026>.
- Gawarecki, S.J., Lyon, R.J.P., Nordberg, W., 1965. Infrared spectral returns and imagery of the Earth from space and their application to geological problems: scientific experiments for manned orbital flight. *American Astronautical Society, Science and Technology* 4, 13–133.
- Glaze, L.S., Francis, P.W., Self, S., Rothery, D.A., 1989. The 16 September 1986 eruption of Lascar volcano, north Chile: satellite investigations. *Bulletin of Volcanology* 51, 149–160. <http://dx.doi.org/10.1007/BF01067952>.
- Gouhier, M., Coppola, D., 2011. Satellite-based evidence for a large hydrothermal system at Piton de la Fournaise volcano (Reunion Island). *Geophysical Research Letters* 38. <http://dx.doi.org/10.1029/2010GL046183>.
- Gouhier, M., Harris, A., Calvari, S., Labazuy, P., Guéhenneux, Y., Donnadié, F., Valade, S., 2011. Lava discharge during Etna's January 2011 fire fountain tracked using MSG-SEVIRI. *Bulletin of Volcanology* 1–7. <http://dx.doi.org/10.1007/s00445-011-0572-y>.
- Gurioli, L., Harris, A.J.L., Houghton, B.F., Polacci, M., Ripepe, M., 2008. Textural and geophysical characterization of explosive basaltic activity at Villarrica volcano. *Journal of Geophysical Research* 113, B08206. <http://dx.doi.org/10.1029/2007JB005328>.
- Hackwell, J.A., Warren, D.W., Bongiovi, R.P., Hansel, S.J., Hayhurst, T.L., Mabry, D.J., Sivjee, M.G., Skinner, J.W., 1996. LWIR/MWIR imaging hyperspectral sensor for airborne and ground-based remote sensing. *Proceedings of SPIE* 2819, 102–107. <http://dx.doi.org/10.1117/12.258057>.
- Hall, J.L., Hackwell, J.A., Tratt, D.M., Warren, D.W., Young, S.J., 2008. Space-based mineral and gas identification using a high-performance thermal infrared imaging spectrometer. *Proceedings of SPIE* 7082, 70820M. <http://dx.doi.org/10.1117/12.799659>.
- Harris, A.J.L., 2012. *Radiometry of Active Volcanoes: A User's Manual*. Cambridge University Press. Contractual delivery date: 15 February 2012.
- Harris, A.J.L., Baloga, S.M., 2009. Lava discharge rates from satellite-measured heat flux. *Geophysical Research Letters* 36, L19302. <http://dx.doi.org/10.1029/2009GL039717>.
- Harris, A., Ripepe, M., 2007. Temperature and dynamics of degassing at Stromboli. *Journal of Geophysical Research* 112, B03205. <http://dx.doi.org/10.1029/2006JB004393>.
- Harris, A.J.L., Rowland, S.K., 2001. FLOWGO: a kinematic thermorheological model for lava flowing in a channel. *Bulletin of Volcanology* 63, 20–44. <http://dx.doi.org/10.1007/s004450000120>.
- Harris, A.J.L., Swabey, S.E.J., Higgins, J., 1995. Automated thresholding of active lavas using AVHRR data. *International Journal of Remote Sensing* 16 (18), 3681–3686.
- Harris, A.J.L., Butterworth, A.L., Carlton, R.W., Downey, I., Miller, P., Navarro, P., Rothery, D.A., 1997a. Low-cost volcano surveillance from space: case studies from Etna, Krafla, Cerro Negro, Fogo, Lascar and Erebus. *Bulletin of Volcanology* 59, 49–64.
- Harris, A.J.L., Blake, S., Rothery, D.A., Stevens, N.F., 1997b. A chronology of the 1991 to 1993 Etna eruption using AVHRR data: implications for real time thermal volcano monitoring. *Journal of Geophysical Research* 102, 7985–8003.
- Harris, A.J.L., Flynn, L.P., Keszthelyi, L., Mougini-Mark, P.J., Rowland, S.K., Resing, J.A., 1998. Calculation of lava effusion rates from Landsat TM data. *Bulletin of Volcanology* 60, 52–71.
- Harris, A.J.L., Flynn, L.P., Rothery, D.A., Oppenheimer, C., Sherman, S.B., 1999. Mass flux measurements at active lava lakes: implications for magma recycling. *Journal of Geophysical Research* 104, 7117–7136.
- Harris, A.J.L., Murray, J.B., Aries, S.E., Davies, M.A., Flynn, L.P., Wooster, M.J., Wright, R., Rothery, D.A., 2000. Effusion rate trends at Etna and Krafla and their implications for eruptive mechanisms. *Journal of Volcanology and Geothermal Research* 102, 237–270.
- Harris, A.J.L., Pilger, E., Flynn, L.P., 2002. Web-based Hot Spot Monitoring using GOES: what it is and how it Works. *Advances in Environmental Monitoring and Modeling* 1 (3), 5–36 (<http://www.kcl.ac.uk/advances>).
- Harris, A., Johnson, J., Horton, K., Garbeil, H., Ramm, H., Pilger, E., Flynn, L., Mougini-Mark, P., Pirie, D., Donegan, S., Rothery, D., Ripepe, M., Marchetti, E., 2003. Ground-based infrared monitoring provides new tool for remote tracking of volcanic activity. *EOS, Transactions American Geophysical Union* 84 (40) (409, 418).
- Harris, A., Pirie, D., Horton, K., Garbeil, H., Pilger, E., Ramm, H., Hoblitt, R., Thornber, C., Ripepe, M., Marchetti, E., Poggi, P., 2005. DUCKS: low cost thermal monitoring units for near-vent deployment. *Journal of Volcanology and Geothermal Research* 143, 335–360.
- Harris, A.J.L., Ripepe, M., Calvari, S., Lodato, L., Spampinato, L., 2008. The 5 April 2003 explosion of Stromboli: timing of eruption dynamics using thermal data. In: Calvari, S., et al. (Eds.), *The Stromboli Volcano: An Integrated Study of the 2002–2003 Eruption*: AGU Geophysical Monograph Series, 182, pp. 305–316.
- Harris, A.J.L., Lodato, L., Dehn, J., Spampinato, L., 2009. Thermal characterization of the Vulcano fumarole field. *Bulletin of Volcanology* 71, 441–458. <http://dx.doi.org/10.1007/s00445-008-0236-8>.
- Harris, A.J.L., Favalli, M., Steffke, A., Fornaciai, A., Boschi, E., 2010. A relation between lava discharge rate, thermal insulation, and flow area set using lidar data. *Geophysical Research Letters* 37. <http://dx.doi.org/10.1029/2010GL044683>.
- Harris, A.J.L., Steffke, A., Calvari, S., Spampinato, L., 2011. Thirty years of satellite-derived lava discharge rates at Etna: implications for steady volumetric output. *Journal of Geophysical Research* 116. <http://dx.doi.org/10.1029/2011JB008237>.
- Hernández, P.A., Pérez, N.M., Varekamp, J.C., Henriquez, B., Hernández, A., Barrancos, J., Padrón, E., Calvo, D., Melian, G., 2007. Crater lake temperature changes of the 2005 eruption of Santa Ana volcano, El Salvador, Central America. *Pure and Applied Geophysics* 164, 2507–2522.
- Higgins, J., Harris, A.J.L., 1997. VAST: a program to locate and analyse volcanic thermal anomalies automatically from remotely sensed data. *Computers & Geosciences* 23 (6), 627–645.
- Hirn, B., Di Bartola, C., Laneve, G., Cadau, E., Ferrucci, F., 2008. SEVIRI onboard Meteosat second generation, and the quantitative monitoring of effusive volcanoes in Europe and Africa. *Proc. IGARSS 2008*, 4–11 July 2008.
- Honda, K., Nagai, M., 2002. Real time volcano activity mapping using ground-based digital imagery. *ISPRS Journal of Photogrammetry and Remote Sensing* 57, 159–168.
- Hughes, C.G., Ramsey, M.S., 2010. Super-resolution of THEMIS thermal infrared data: creating radiometrically-accurate, sub-100 meter resolution images of Mars. *Icarus* 208, 704–720. <http://dx.doi.org/10.1016/j.icarus.2010.02.023>.
- James, M.R., Lane, S.J., Corder, S.B., 2008. Modeling the rapid near-surface expansion of gas slugs in low viscosity magmas. In: Lane, S.J., Gilbert, J.S. (Eds.), *Fluid Motion in Volcanic Conduits: A Source of Seismic and Acoustic Signals*. Geological Society, London, pp. 147–167.
- Johnson, J.B., Harris, A.J.L., Hoblitt, R., 2005. Thermal observations of gas pistonning at Kilauea Volcano. *Journal of Geophysical Research* 110, B11201. <http://dx.doi.org/10.1029/2005JB003944>.
- Johnson, W., Hook, S.J., Mouroulis, P., Wilson, D.W., Gunapala, S.D., Realmuto, V., Lamborn, A., Paine, C., Mumolo, J.M., Eng, B.T., 2011. HyTES: thermal imaging spectrometer development. *Aerospace Conference, 2011 IEEE*, pp. 1–8 (5–12 March 2011). <http://dx.doi.org/10.1109/AERO.2011.5747394>.
- Kaneko, T., Munekane, H., Wooster, M.J., Kagiya, T., 2002. Monitoring of eruption plumes at Usu Volcano (Japan) using thermal infrared camera imagery broadcast via the internet. *Advances in Environmental Monitoring and Modeling* 1 (3), 153–166.
- Kaneko, T., Takasaki, K., Yasuda, A., Aoki, Y., 2006. Thermal surveillance of the Asama 2004–2005 activity using MODIS nighttime infrared images. In *Japanese Bulletin of the Volcanological Society of Japan* 51 (4), 273–282.
- Kauhikaua, J., Sherrod, D.R., Cashman, K.V., Heliker, C., Hon, K., Mattox, T.N., Johnson, J.A., 2003. Hawaiian lava flow dynamics during the Pu'u'Ō'o-Kupaianaha eruption: a tale of two decades. *U.S. Geological Survey Professional Paper* 1676, 63–87.
- Kervyn, M., Ernst, G.G.J., Harris, A., Mbede, E., Belton, F., Jacobs, P., 2008. Thermal remote sensing of the low-intensity carbonatite volcanism of Oldoinyo Lengai, Tanzania. *International Journal of Remote Sensing* 29, 6467–6499.
- Koepfen, W.C., Pilger, E., Wright, R., 2011. Time series analysis of infrared satellite data for detecting thermal anomalies: a hybrid approach. *Bulletin of Volcanology* 73, 577–593. <http://dx.doi.org/10.1007/s00445-010-0427-y>.
- Labazuy, P., Gouhier, M., Harris, A., Guéhenneux, Y., Hervu, M., Bergès, J.C., Cacault, P., Rivet, S., 2010. Near real-time monitoring of the April–May 2010 Eyjafjallajökull ash cloud. In: *13th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes*, June 1–4, Paris, France.
- Lodato, L., Spampinato, L., Harris, A.J.L., Dehn, J., James, M.R., Pecora, E., Biale, E., Curcuruto, A., 2008. Use of forward looking infrared thermal cameras at active volcanoes. In: Marzocchi, W., Zollo, A. (Eds.), *Conception, Verification and Application of Innovative Techniques To Study Active Volcanoes*. Istituto Nazionale di Geofisica e Vulcanologia (Italy), pp. 427–434.
- Lombardo, V., Buongiorno, M.F., 2006. Lava flow thermal analysis using three infrared bands of remote-sensing imagery: a study case from Mount Etna 2001 eruption. *Remote Sensing of Environment* 101, 141–149.
- Lyons, J.J., Waite, G.P., Rose, W.I., Chigna, G., 2010. Patterns in open vent, Strombolian behavior at Fuego volcano, Guatemala, 2005–2007. *Bulletin of Volcanology* 72, 1–15. <http://dx.doi.org/10.1007/s00445-009-0305-7>.
- Marchetti, E., Harris, A.J.L., 2008. Trends in activity at Pu'u 'Ō'o during 2001–2003: insights from the continuous thermal record. In: Lane, S.J., Gilbert, J.S. (Eds.), *Fluid Motions in Volcanic Conduits: A Source of Seismic and Acoustic Signals*. Geol Soc London Spec. Pub., 307, pp. 85–101.
- Matsushima, N., Kazahaya, K., Saito, G., Shinohara, H., 2003. Mass and heat flux of volcanic gas discharging from the summit crater of Iwodake volcano, Satsuma-Iwojima, Japan, during 1996–1999. *Journal of Volcanology and Geothermal Research* 126, 285–301.
- McGimsey, R.G., Schneider, D.J., Neal, C.A., Roach, A.L., 1999. Use of FLIR observations during eruption response at two Alaskan volcanoes. *EOS, Transactions of the American Geophysical Union* 80 (46) (Fall Meet. Suppl., Abstract V32A-07).
- Moxham, R.M., Crandell, D.R., Marlatt, W.E., 1965. Thermal features at Mount Rainier, Washington, as revealed by infrared surveys. *U.S. Geological Survey Bulletin* 1326, 1–83.

- National Research Council (NRC). 2007. *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. The Natl. Acad. Press, Washington, D.C. 978-0-309-10387-9. 428 pp.
- Nye, C.J., Keith, T.E.C., Eichelberger, J.C., Miller, T.P., McNutt, S.R., Moran, S.C., Schneider, D.J., Dehn, J., Schaefer, J., 2002. The 1999 eruption of Shishaldin Volcano, Alaska: monitoring a distant eruption. *Bulletin of Volcanology* 64, 507–519. <http://dx.doi.org/10.1007/s00445-002-022-2>.
- Oppenheimer, C., 1991. Lava flow cooling estimated from Landsat Thematic Mapper infrared data: the Lonquimay eruption (Chile, 1989). *Journal of Geophysical Research* 96, 21865–21878.
- Oppenheimer, C., 1993. Infrared surveillance of crater lakes using satellite data. *Journal of Volcanology and Geothermal Research* 55, 117–128.
- Oppenheimer, C., Yirgu, G., 2002. Thermal imaging of an active lava lake; Erta 'Ale Volcano, Ethiopia. *International Journal of Remote Sensing* 23, 4777–4782.
- Oppenheimer, C., Francis, P.W., Rothery, D.A., Carlton, R.W.T., Glaze, L., 1993. Infrared image analysis of volcanic thermal features: Lascar Volcano, Chile, 1984–1992. *Journal of Geophysical Research* 98, 4269–4286.
- Orr, T.R., Patrick, M.R., 2009. What has driven degassing events during the 2008–2009 summit eruption of Kilauea Volcano, Hawai'i? *EOS, Transactions of the American Geophysical Union* 90 (52) (Fall Meet. Suppl., abstract V43G-2330).
- Ortiz, R., Moreno, H., García, A., Fuentealba, G., Astiz, M., Peña, P., Sánchez, N., Tárraga, M., 2003. Villarrica Volcano (Chile): characteristics of the volcanic tremor and forecasting of small explosions by means of materials failure method. *Journal of Volcanology and Geothermal Research* 128, 247–259.
- Patrick, M.R., 2007. Dynamics of Strombolian ash plumes from thermal video: motion, morphology, and air entrainment. *Journal of Geophysical Research* 112, B06202. <http://dx.doi.org/10.1029/2006JB004387>.
- Patrick, M.R., Smellie, J.L., Harris, A.J.L., Wright, R., Dean, K., Izbekov, P., Garbeil, H., Pilger, E., 2005. First recorded eruption of Belinda volcano (Montagu Island), South Sandwich Islands. *Bulletin of Volcanology* 67, 415–422.
- Patrick, M.R., Harris, A.J.L., Ripepe, M., Dehn, J., Rothery, D.A., Calvari, S., 2007. Strombolian explosive styles and source conditions: insights from thermal (FLIR) video. *Bulletin of Volcanology* 69, 769–784. <http://dx.doi.org/10.1007/s00445-006-0107-0>.
- Pergola, N., Pietrapertosa, C., Lacava, T., Tramutoli, V., 2001. Robust satellite techniques for volcanic eruptions monitoring. *Annals of Geophysics* 44, 167–177.
- Pergola, N., Tramutoli, V., Marchese, F., Scalfidi, I., Lacava, T., 2004a. Improving volcanic ash cloud detection by a robust satellite technique. *Remote Sensing of Environment* 90, 1–22.
- Pergola, N., Marchese, F., Tramutoli, V., 2004b. Automated detection of thermal features of active volcanoes by means of Infrared AVHRR records. *Remote Sensing of Environment* 93, 311–327.
- Pergola, N., Marchese, F., Tramutoli, V., Filizzola, C., Ciampa, M., 2008. Advanced satellite technique for volcanic activity monitoring and early warning. *Annals of Geophysics* 51, 287–301.
- Pergola, N., D'Angelo, G., Lisi, M., Marchese, F., Mazzeo, G., Tramutoli, V., 2009. Time domain analysis of robust satellite techniques (RST) for near real-time. *Physics and Chemistry of the Earth* 34, 380–385.
- Pieri, D.C., Glaze, L.S., Abrams, M.J., 1990. Thermal radiance observations of an active lava flow during the June 1984 eruption of Mount Etna. *Geology* 18, 1018–1022.
- Prata, A.J., 2009. Satellite detection of hazardous volcanic clouds and the risk to global air traffic. *Natural Hazards* 51, 303–324. <http://dx.doi.org/10.1007/s11069-008-9273-z>.
- Prata, A.J., Bernardo, C., 2009. Retrieval of volcanic ash particle size, mass and optical depth from a ground-based thermal infrared camera. *Journal of Volcanology and Geothermal Research* 186, 91–107. <http://dx.doi.org/10.1016/j.jvolgeores.2009.02.007> (ISSN 0377–0273).
- Ramsey, M.S., 2009. What more have we learned from thermal infrared remote sensing of active volcanoes other than they are hot? *EOS, Transactions of the American Geophysical Union* 90 (52) Fall Meet. Suppl., Abst. V24B-01.
- Ramsey, M.S., Dehn, J., 2004. Spaceborne observations of the 2000 Bezymianny, Kamchatka eruption: the integration of high-resolution ASTER data into near real-time monitoring using AVHRR. *Journal of Volcanology and Geothermal Research* 135, 127–146.
- Ramsey, M.S., Fink, J.H., 1999. Estimating silicic lava vesicularity with thermal remote sensing: a new technique for volcanic mapping and monitoring. *Bulletin of Volcanology* 61, 32–39.
- Ramsey, M.S., Flynn, L.P., 2004. Strategies, insights, and the recent advances in volcanic monitoring and mapping with data from NASA's Earth Observing System. *Journal of Volcanology and Geothermal Research* 135, 1–11.
- Ramsey, M.S., Dehn, J., Wessels, R., Byrnes, J., Duda, K., Maldonado, L., Dwyer, J., 2004. The ASTER emergency scheduling system: a new project linking near-real-time satellite monitoring of disasters to the acquisition of high-resolution remote sensing data. *EOS, Transactions of the American Geophysical Union* 85 (47) Fall Meet. Suppl., Abstract SF23A-0026.
- Ramsey, M.S., Wessels, R.L., Anderson, S.A., 2012. Surface textures and dynamics of the 2005 lava dome at Shiveluch Volcano, Kamchatka. *Geological Society of America Bulletin* 124, 678–689. <http://dx.doi.org/10.1130/B30580.1>.
- Reath, K.A., 2011. *Hyperspectral thermal infrared analysis of the Salton Sea geothermal field*. M.S. Thesis, University of Pittsburgh, 110 pp.
- Ripepe, M., Ciliberto, S., Della Schiava, M., 2001. Time constraints for modeling source dynamics of volcanic explosions at Stromboli. *Journal of Geophysical Research* 106, 8713–8727.
- Ripepe, M., Harris, A.J.L., Carniel, R., 2002. Thermal, seismic and infrasonic evidences of variable degassing rates at Stromboli volcano. *Journal of Volcanology and Geothermal Research* 118, 285–297.
- Ripepe, M., Marchetti, E., Ulivieri, G., Harris, A.J.L., Dehn, J., Burton, M.R., Caltabiano, T., Salerno, G.G., 2005. Effusive to explosive transition during the 2003 eruption of Stromboli volcano. *Geology* 33, 341–344. <http://dx.doi.org/10.1130/G21173.1>.
- Ripepe, M., Delle Donne, D., Harris, A., 2008. Dynamics of Stromboli activity. In: Calvari, S., Inguaggiato, S., Puglisi, G., Ripepe, M., Rosi, M. (Eds.), *Learning from Stromboli: AGU Geophysics Monograph Series*, 182, pp. 39–48.
- Rosi, M., Bertagnini, A., Harris, A.J.L., Pioli, L., Pistolesi, M., Ripepe, M., 2006. A case history of a paroxysmal explosion at Stromboli: timing and dynamics of the April 5, 2003 event. *Earth and Planetary Science Letters* 243, 594–606. <http://dx.doi.org/10.1016/j.epsl.2006.01.035>.
- Rothery, D.A., Francis, P.W., Wood, C.A., 1988. Volcano monitoring using short wavelength infrared data from satellites. *Journal of Volcanology and Geothermal Research* 93, 7993–8008.
- Rothery, D.A., Thorne, M.T., Flynn, L.P., 2003. MODIS thermal alerts in Britain and the North Sea during the first half of 2001. *International Journal of Remote Sensing* 24, 817–826.
- Rothery, D.A., Coppola, D., Saunders, C., 2005. Analysis of volcanic activity patterns using MODIS thermal alerts. *Bulletin of Volcanology* 67, 539–556.
- Sahetapy-Engel, S.T., Harris, A.J.L., 2009a. Thermal structure and heat loss at the summit crater of an active lava dome. *Bulletin of Volcanology* 71, 15–28. <http://dx.doi.org/10.1007/s00445-008-0204-3>.
- Sahetapy-Engel, S.T., Harris, A.J.L., 2009b. Thermal-image-derived dynamics of vertical ash plumes at Santiaguito volcano, Guatemala. *Bulletin of Volcanology* 71, 827–830. <http://dx.doi.org/10.1007/s00445-009-0284-8>.
- Schneider, D.J., Vallance, J.W., Wessels, R., Logan, M., Ramsey, M.S., 2008. Use of thermal infrared imaging for monitoring renewed dome growth at Mount St. Helens, 2004. In: Sherrod, D.R., Scott, W.E., Stauffer, P.H. (Eds.), *A volcano rekindled: the renewed eruption of Mount St. Helens, 2004–2006*. U.S. Geological Survey Professional Paper 1750, pp. 347–360.
- Shimozuru, D., 1971. Observation of volcanic eruption by an infrared radiation meter. *Nature* 234, 457–459.
- Sorensen, T.C., Hude, C.V., Kobayashi, M.H., Pilger, E.J., Sanyal, A.K., Yoneshige, L.K., 2009. LEO-1: Development of a University Microsatellite for Flight Testing New Technologies. Am. Instit. Aeronaut. Astronaut. Space 2009 Conf. Expo., Pasadena, CA. Paper #2009-6812.
- Spampinato, L., Calvari, S., Oppenheimer, C., Lodato, L., 2008. Shallow magma transport for the 2002–2003 Mt. Etna eruption inferred from thermal infrared surveys. *Journal of Volcanology and Geothermal Research* 177, 301–312. <http://dx.doi.org/10.1016/j.jvolgeores.2008.05.013>.
- Spampinato, L., Calvari, S., Oppenheimer, C., Boschi, E., 2011. Volcano surveillance using infrared cameras. *Earth-Science Reviews* 106, 63–91. <http://dx.doi.org/10.1016/j.earscirev.2011.01.003>.
- Steffke, A.M., Harris, A.J.L., 2010. A review of algorithms for detecting volcanic hot spots in satellite infrared data. *Bulletin of Volcanology* 73, 1109–1137.
- Steffke, A.M., Harris, A.J.L., Burton, M., Caltabiano, T., Salerno, G.G., 2011. Coupled use of COSPEC and satellite measurements to define the volumetric balance during effusive eruptions at Etna, Italy. *Journal of Volcanology and Geothermal Research* 205, 45–53. <http://dx.doi.org/10.1016/j.jvolgeores.2010.06.004>.
- Tazieff, H., 1970. New investigations on eruptive gases. *Bulletin of Volcanology* 34, 421–438.
- Tramutoli, V., 1998. Robust AVHRR techniques (RAT) for environmental monitoring: theory and applications. In: Cecchi, G., Zilioli, E. (Eds.), *Earth Surface Rem. Sens. II: Proceedings of SPIE*, vol. 3496, pp. 101–113.
- Tramutoli, V., Di Bello, G., Pergola, N., Piscitelli, S., 2001. Robust satellite techniques for remote sensing of seismically active areas. *Annals of Geophysics* 44, 295–312.
- Vaughan, R.G., Calvin, W.M., Taranik, J.V., 2003. SEBASS hyperspectral thermal infrared data: surface emissivity measurement and mineral mapping. *Remote Sensing of Environment* 85, 48–63.
- Vicari, A., Cirauda, A., Del Negro, C., Herault, A., Fortuna, L., 2009. Lava flow simulations using discharge rates from thermal infrared satellite imagery during the 2006 Etna eruption. *Natural Hazards* 50, 539–550. <http://dx.doi.org/10.1007/s11069-008-9306-7>.
- Vicari, A., Ganci, G., Behncke, B., Cappello, A., Neri, M., Del Negro, C., 2011. Near-real-time forecasting of lava flow hazards during the 12–13 January 2011 Etna eruption. *Geophysical Research Letters* 38 (13). <http://dx.doi.org/10.1029/2011GL047545>.
- Vilardo, G., Bronzino, G., Alessio, G., Bellucci Sessa, E., Nappi, R., 2008. GeoDATA Finder Il sistema di consultazione on-line della banca dati territoriali del Laboratorio di Geomatica e Cartografia dell'INGV-OV. [http://ipf.ov.ingv.it/dbnas/login\\_user.asp](http://ipf.ov.ingv.it/dbnas/login_user.asp).
- Wadge, G., Macfarlane, D.G., Robertson, D.A., Hale, A.J., Pinkerton, H., Burrell, R.V., Nortond, G.E., James, M.R., 2005. AVTIS: a novel millimetre-wave ground based instrument for volcano remote sensing. *Journal of Volcanology and Geothermal Research* 146, 307–318.
- Webley, P., Wooster, M., Strauch, W., Saballos, J., Dill, K., Stephenson, P., Stephenson, J., Wolf, E., Matias, O., 2008. Experiences from near real-time satellite-based volcano monitoring in Central America: case studies at Fuego, Guatemala. *International Journal of Remote Sensing* 29, 6621–6664.
- Wessels, R., Ramsey, M.S., 2000. Multi-sensor/multi-wavelength data fusion over steep volcanic terrain: analysis challenges in the next era of remote sensing. *EOS, Transactions of the American Geophysical Union* 81 (48), F1255.
- Witter, J.B., Harris, A.J., 2007. Field measurements of heat loss from skylights and lava tube systems. *Journal of Geophysical Research* 112. <http://dx.doi.org/10.1029/2005JB003800>.
- Wooster, M.J., 2001. Long-term infrared surveillance of Lascar Volcano: contrasting activity cycles and cooling pyroclastics. *Geophysical Research Letters* 28. <http://dx.doi.org/10.1029/2000GL011904>, 847–850.
- Wooster, M.J., Rothery, D.A., 1997. Time series analysis of effusive volcanic activity using the ERS along track scanning radiometer: the 1995 eruption of Fernandina Volcano, Galapagos Island. *Remote Sensing of Environment* 69, 109–117.



- Wright, R., Flynn, L., 2003. On the retrieval of lava-flow surface temperatures from infrared satellite data. *Geology* 31, 893–896.
- Wright, R., Flynn, L., 2004. Space-based estimate of the volcanic heat flux into the atmosphere during 2001 and 2002. *Geology* 32 (3), 189–192.
- Wright, T.L., Kinoshita, W.T., Peck, D.L., 1968. March 1965 eruption of Kilauea volcano and the formation of Makaopuhi lava lake. *Journal of Geophysical Research* 73, 3181–3205.
- Wright, R., Blake, S., Harris, A., Rothery, D., 2001. A simple explanation for the space-based calculation of lava eruptions rates. *Earth and Planetary Science Letters* 192, 223–233.
- Wright, R., Flynn, L., Garbeil, H., Harris, A., Pilger, E., 2002a. Automated volcanic eruption detection using MODIS. *Remote Sensing of Environment* 82, 135–155.
- Wright, R., De La Cruz-Reyna, S., Harris, A., Flynn, L., Gomez-Palacios, J.J., 2002b. Infrared satellite monitoring at Popocatepetl: explosions, exhalations, and cycles of dome growth. *Journal of Geophysical Research* 107, 2153. <http://dx.doi.org/10.1029/2000JB000125>.
- Wright, R., Flynn, L.P., Garbeil, H., Harris, A.J.L., Pilger, E., 2004. MODVOLC: near-real-time thermal monitoring of global volcanism. *Journal of Volcanology and Geothermal Research* 135, 29–49. <http://dx.doi.org/10.1016/j.jvolgeores.2003.12.008> (ISSN 0377–0273).
- Wright, R., Carn, S.A., Flynn, L.P., 2005. A satellite chronology of the May–June 2003 eruption of Anatahan volcano. *Journal of Volcanology and Geothermal Research* 146, 102–116.
- Wright, R., Garbeil, H., Harris, A.J.L., 2008. Using infrared satellite data to drive a thermo-rheological/stochastic lava flow emplacement model: a method for near-real-time volcanic hazard assessment. *Geophysical Research Letters* 35, L19307. <http://dx.doi.org/10.1029/2008GL035228>.
- Yokoyama, I., 1957. Energetics in active volcanoes. *Bulletin of the Earthquake Research Institute* 34, 75–97.

**Abstract:** Volcanological remote sensing spans numerous techniques, wavelength regions, data collection strategies, targets, and applications. Attempting to foresee and predict the growth vectors in this broad and rapidly developing field is therefore exceedingly difficult. However, we attempted to make such predictions at both the American Geophysical Union (AGU) meeting session entitled *Volcanology 2010: How will the science and practice of volcanology change in the coming decade?* held in December 2000 and the follow-up session 10 years later, *Looking backward and forward: Volcanology in 2010 and 2020*. In this summary paper, we assess how well we did with our predictions for specific facets of volcano remote sensing in 2000 the advances made over the most recent decade, and attempt a new look ahead to the next decade. In completing this review, we only consider the subset of the field focused on thermal infrared remote sensing of surface activity using ground-based and space-based technology and the subsequent re-search results. This review keeps to the original scope of both AGU presentations, and therefore does not address the entire field of volcanological remote sensing, which uses technologies in other wavelength regions (e.g., ultra-violet, radar, etc.) or the study of volcanic processes other than the those associated with surface (mostly effusive) activity. Therefore we do not consider remote sensing of ash/gas plumes, for example. In 2000, we had looked for-ward to a “golden age” in volcanological remote sensing, with a variety of new orbital missions both planned and recently launched. In addition, exciting field-based sensors such as hand-held thermal cameras were also becoming available and being quickly adopted by volcanologists for both monitoring and research applications. All of our pre-dictions in 2000 came true, but at a pace far quicker than we predicted. Relative to the 2000–2010 timeframe, the coming decade will see far fewer new orbital instruments with direct applications to volcanology. However ground-based technologies and applications will continue to proliferate, and unforeseen technology promises many exciting possibilities that will advance volcano thermal monitoring and science far beyond what we can currently envision.