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Invited Decade Review

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

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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 research 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., ultraviolet, 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 forward 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 predictions 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.

Contents

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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 μm) minus TIR (11 μm) band differencing *(ΔT)* 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 μm to 20 μm, (i.e., the midwave [MIR: 3 to 5 μm] and longwave [LWIR: 5 to 20 μm] 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.

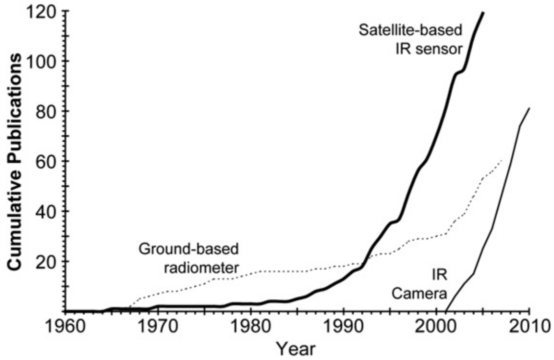

Fig. 1. Cumulative number of volcano remote sensing papers using IR data from satellite sensors, ground-based radiometers, and thermal cameras, 1960–2010.
From literature data bases of Harris (2012).

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

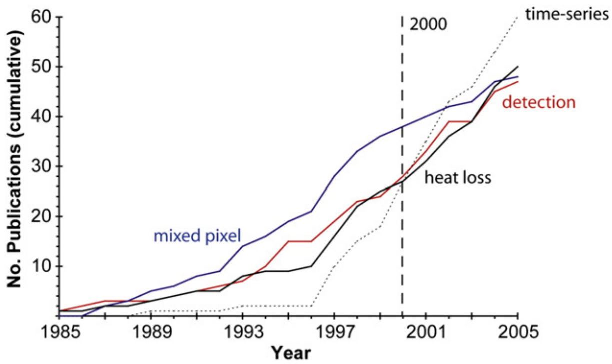

Fig. 2. Cumulative number of volcano remote sensing papers using satellite sensor IR data classified by theme, 1985–2005.
From Appendix A literature data base of Harris (2012).

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://wwwobs.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.

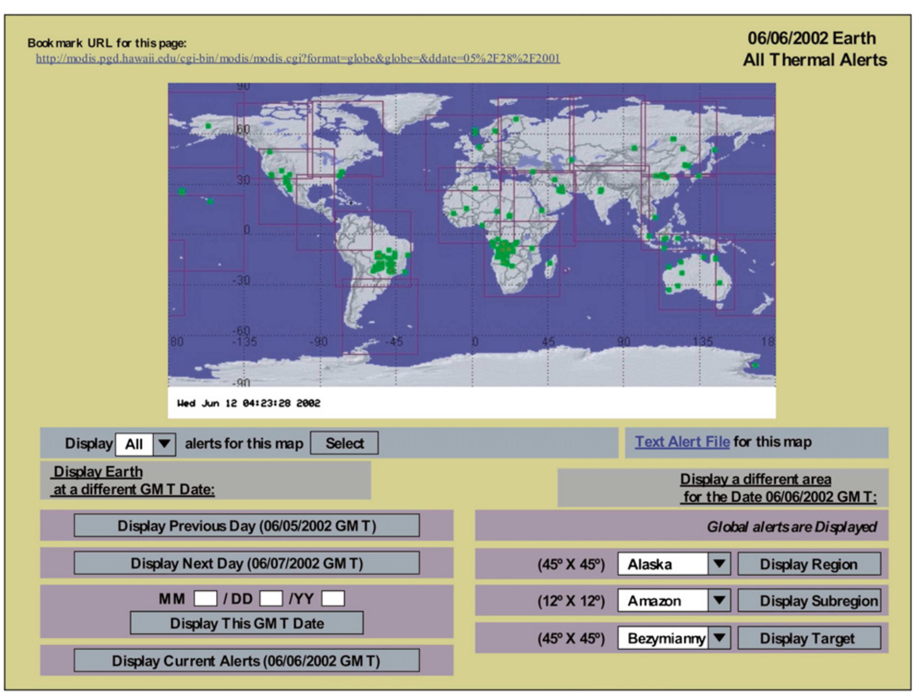

Fig. 3. Front end page for the MODIS thermal alerts website hosted and maintained by the Hawaii Institute of Planetology and Geophysics (HIGP) at the University of Hawaii as of June 2002. Screen shot is for 06-06-2002 and shows the global distribution of MODVOLC-detected hot spots on that day (by default 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.

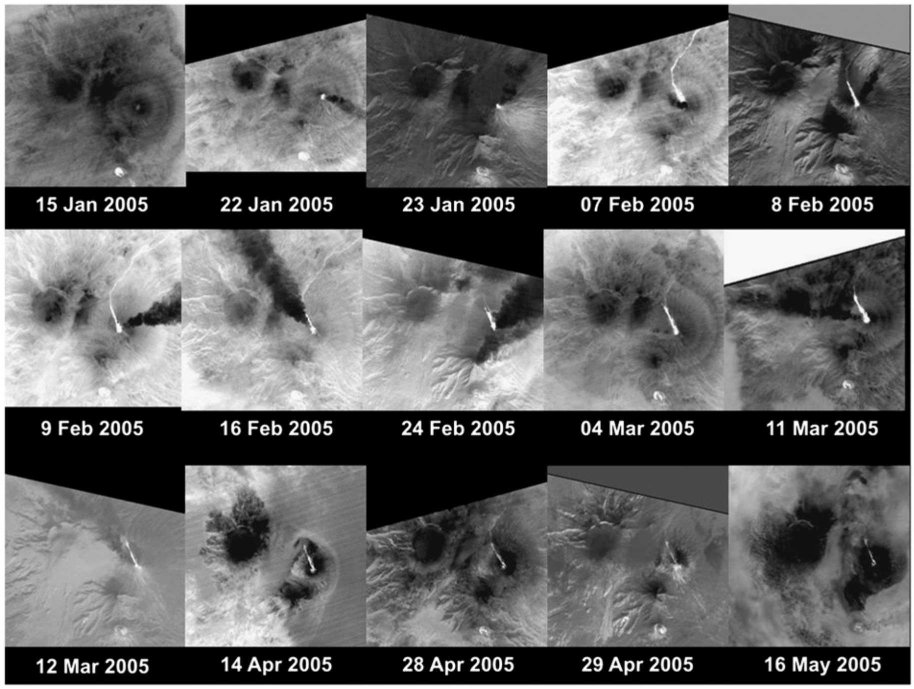

Fig. 4. Chronological subset of the sequence of ASTER IR images acquired during the first five months of 2005 showing the eruption sequence of Kliuchevskoi Volcano, Russia. These images were captured through the implementation of the ASTER Urgent Request Protocol (e.g., Duda et al., 2009) allowing the 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 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 m^3/s over an ASTER-derived land classification map and shows that such an eruption would inundate 10.7 km^2 of urban land and 15.6 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)

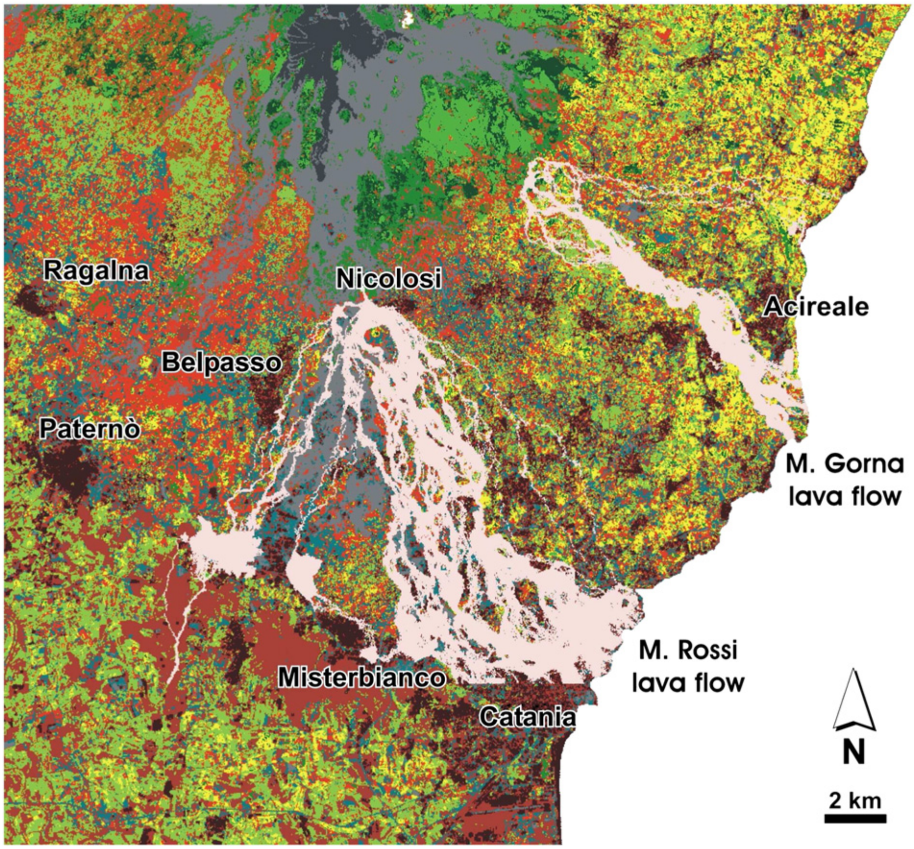

Fig. 5. Results running the FLOWGO model of Harris and Rowland (2001) iteratively over a DEM of Etna, with noise being placed in the DEM with every iteration, this being the stochastic model of Favalli et al. (2005). Model is run from two locations (1) M. Gorna and (2) M. Rossi, at 100 $m^3 s^{-1}$. 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 Santiagutio 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 μm to 13 μm 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 pistoning, with temporal resolutions of up to 54 Hz (e.g., Ripepe et al., 2001, 2002; Johnson et al., 2005; Branan 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 was being tested.

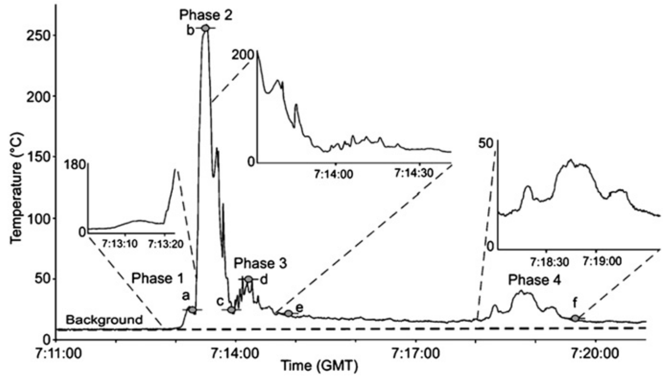

Fig. 6. Example of the temperature record during the 5 April 2003 eruption at Stromboli by an IR radiometer located about 450 m from the summit crater (after Rosi et al., 2006). The four phases of the eruption can clearly be seen in this brief temporal record, including a short-lived precursory event 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.

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
LAIRD	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

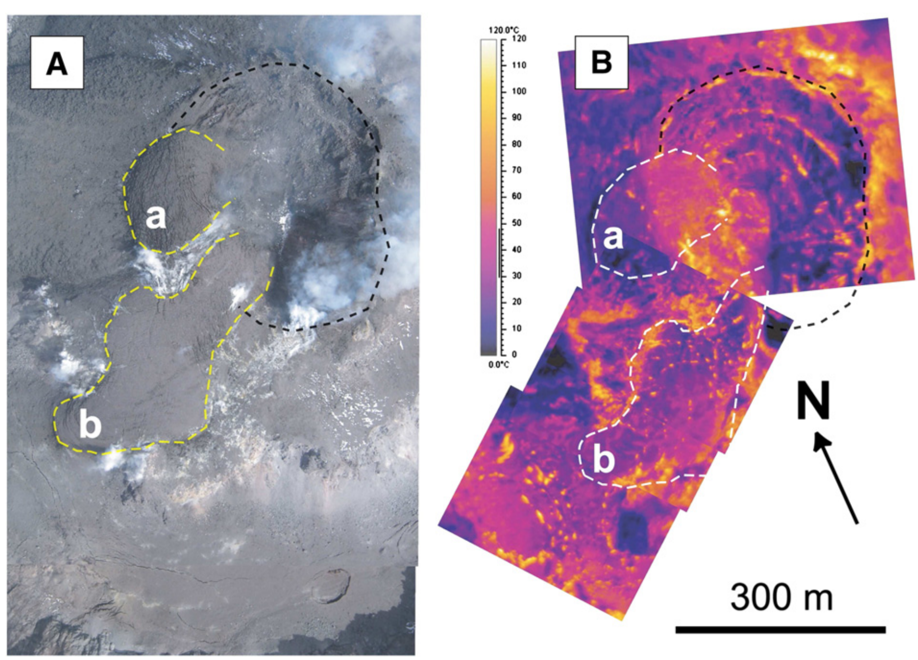

Fig. 7. Example of the use of helicopter-based FLIR data to capture the dynamic processes of Bezymianny's dome in August 2005 (modified after Carter et al., 2007). The authors used the visible and IR data to confirm the presence of a newly-formed summit crater within the existing dome (black dashed line). 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 μm and 13 μm (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-dived 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 μm 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 μm 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 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, where 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 μm) and TIR (7.5 to 13.5 μm) 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 wiskbroom scanner that operates between 7.0 μm and 12 μm with a large field of view (±45°) 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 μm to 12 μm. 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 °C versus 70 °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).

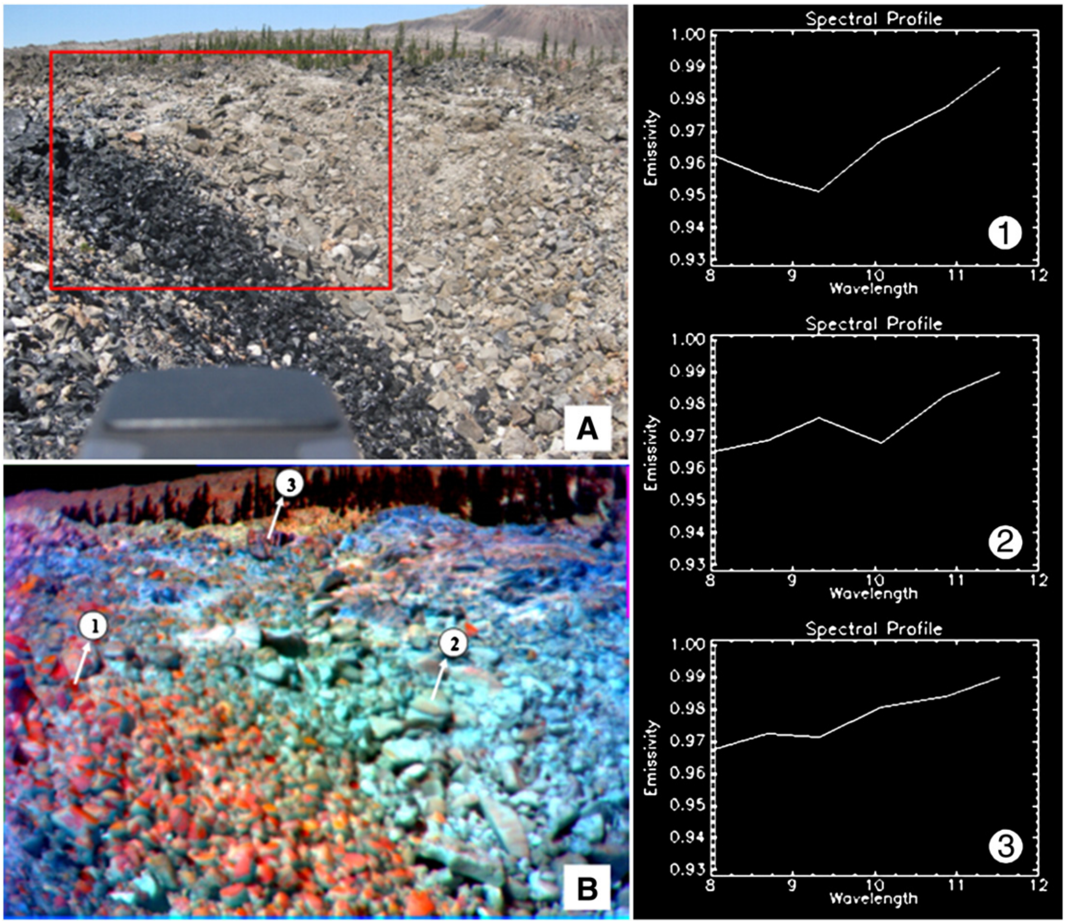

Fig. 8. Multispectral FLIR results acquired at Medicine Lake Caldera, CA. (A) Digital photograph of a region of Big Glass Mountain silicic flow showing the three main rhyolite textures: black (obsidian), white (finely vesicular pumice, FVP) and brown (coarsely vesicular pumice, CVP). The body of the 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 HyspIRI mission, which offers both high spatial and temporal resolution data in the TIR as well as saturation temperatures of ~770 °C in the TIR and ~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 HyspIRI 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" HyspIRI 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_2 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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