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Journal of Volcanology and Geothermal Research 135 (2004) 1–11

Journal of volcanology and geothermal research

www.elsevier.com/locate/jvolgeores

Strategies, insights, and the recent advances in volcanic monitoring and mapping with data from NASA's Earth Observing System

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Accepted 5 December 2003

Abstract

In 1991, the U.S. National Aeronautics and Space Administration (NASA) launched a comprehensive program to study the Earth as one environmental system. Now called the Earth Science Enterprise (ESE), this coordinated monitoring effort was initially comprised of free-flying satellites and Space Shuttle missions, as well as airborne and ground-based studies. The satellite component of the ESE is known as the Earth Observing System (EOS), which has now entered a planned long-term global monitoring phase. The first EOS satellite, Terra, was launched in December of 1999 and offers integrated measurements of numerous solid earth and atmospheric processes, including volcanic activity. There are currently 10 NASA EOS-designated satellites carrying over thirty instruments, all of which are providing integrated measurements of the interactions between the Earth's global cycles. Included in this effort are science investigations that examine the solid earth cycle and the natural hazards that are an inevitable result of that cycle. For volcanologists, the new higher spatial, spectral, and temporal resolution EOS data have spawned a variety of new algorithms and methodologies to monitor changes in volcanic activity, map volcanic surfaces, and investigate volcanic processes. Thermal anomaly detection, plume chemistry and mass flux, lava composition and textural properties, interaction of ash with the natural and human environment, and mitigation of hazards are but a few of the topics being addressed with these data sets. In this paper, we summarize the current state of volcanic remote sensing in the new EOS era and introduce the more detailed papers that follow in this special issue. This work stems from a special session at the Fall 2001 American Geophysical Union (AGU) meeting that was convened to showcase the current research in volcanic systems and processes using the new EOS satellite data sets. That session was also intended to provide a forum for field, aircraft, and other satellite-validated observations of volcanic edifices and processes. Our aim in this special issue is to focus on a series of detailed examples where the authors have used EOS data to investigate a specific question, rather than a generalized overview of all possible volcanological applications of remote sensing data.

Keywords: NASA; earth; volcanic monitoring

1. Introduction

In this paper, we describe the NASA Earth Science Enterprise Program with specific emphasis on volcanological processes and the unique remote sensing tools needed to analyze them. We also introduce the

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doi:10.1016/j.jvolgeores.2003.12.015

subsequent papers featured in this special issue of the Journal of Volcanology and Geothermal Research and, finally, look to the future of the science. This collection should be viewed as a snapshot in time highlighting the first volcanologic results from the EOS instruments. It logically follows a similar compendium of papers from the late 1990s that laid the groundwork for these new data sets (Mouginis-Mark et al., 2000). Although this issue does not cover the breadth of that previous monograph, our focus was to bring these papers to press quickly with the goal of exposing the community to these rapidly developing tools for monitoring and studying volcanoes.

In the time interval between the 1997 special session of AGU and the publication of Mouginis-Mark et al. (2000), several very important advances have taken place in the EOS program. The most important was the actual deployment of the main EOS constellation of satellites leading to the acquisition of new remote sensing data sets (Fig. 1). Among the newly deployed satellites were Landsat 7 with the Enhanced Thematic Mapper Plus (ETM+) instrument, the first EOS satellite (Terra) containing five instruments to study land and atmospheric processes, and the experimental Earth Observing (EO-1) satellite with three engineering test instruments (Fig. 1). These sensors are being utilized for a wide variety of environmental and scientific observations. Among these are volcanic eruptions, which are being imaged in unique ways and with new wavelength regions for the first time with the EOS satellites. Therefore, it was critical to relay this fast-paced technology and convene another special session in the Fall of 2001. This expanded upon the

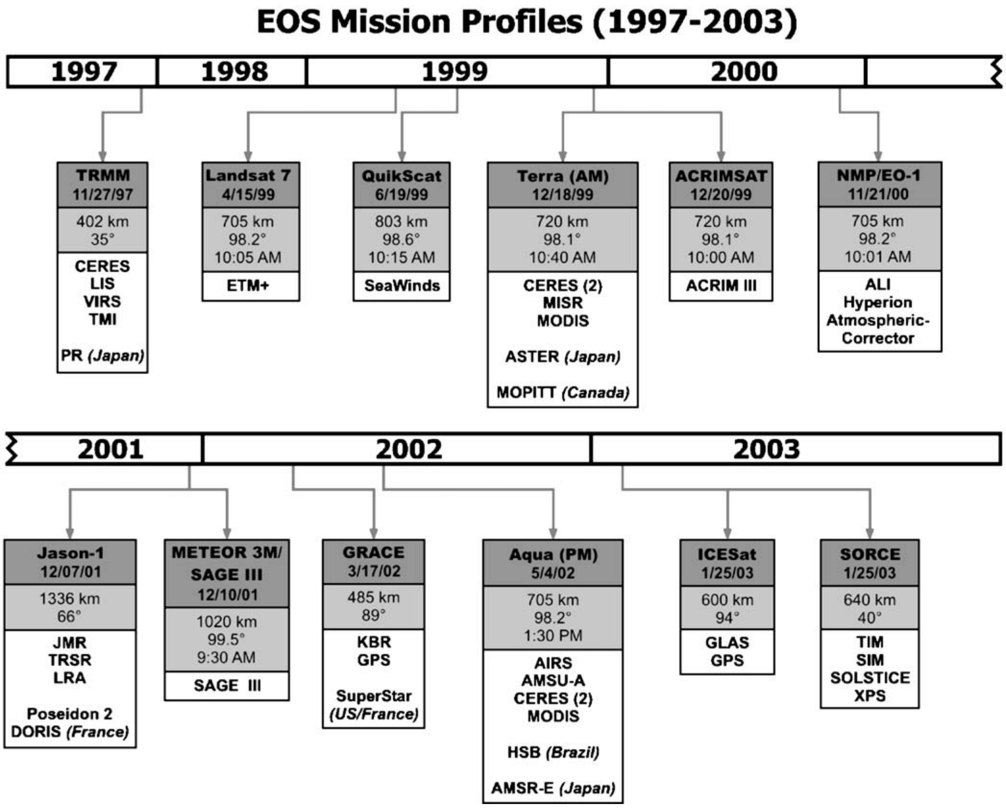

Fig. 1. Current NASA Earth Observing System orbital platforms showing launch date, orbital configuration, and sensor payload. Listed here are only the successfully launched and operating missions carried on a NASA-provided spacecraft. Not all missions and/or instruments are designed for volcanic observations, and numerous other orbital instruments not part of the EOS program are being used for such purposes (modified from the NASA EOS website: http://www.eospso.gsfc.nasa.gov/).

1997 special session and its resulting monograph by focusing directly on the utilization of the new EOS instruments. The 2001 special session, entitled "Volcanic Observations From Space: New Results From the EOS Satellite Instruments" had 22 presentations, which were divided between an oral and poster session. The original concept for this special issue was to rapidly convert these presentations into scientific papers in order to disseminate the information as quickly as possible. In addition, many of the papers focus on recent and ongoing eruptions, making this collection of papers important reference material not only for remote sensing scientists but also for volcanologists, government officials concerned with natural hazards, Earth system science policy analysts, and planetary geologists.

1.1. The NASA Earth Observing System

The NASA Earth Observing System program was officially established in 1991 in order to provide a scientific baseline from which to monitor and understand the function of all the Earth's systems. As part of the larger Earth Science Enterprise, EOS is dedicated to understanding the total Earth system and the effects of natural and human-induced changes on the global environment. Examining the Earth system from space provides a synoptic view of the land, atmosphere, ice, oceans, and biota that can contribute to the development of environmental policy and economic investment decisions. Perhaps even more importantly, natural and man-made variations in these systems can be identified and quantified with the high precision data required to model longer-term processes. The observation strategy, missions, and funding levels have varied over the past decade. However, a primary tenet remains in the program: the need to monitor the Earth's "vital signs" through simultaneous, calibrated, and continuous measurements, ultimately developing global predictive models (Baron et al., 1999).

NASA's Earth Science Enterprise has developed technologies and applications of remote sensing for solving practical societal problems in such diverse areas as food and fiber production, natural hazard mitigation, water pollution, and national resource management (Baron et al., 1999). The study of the Earth from space combines rigorous scientific analyses with an application to sustainability. A major focus of the EOS program is the global energy balance and its coupling to the atmosphere, hydrosphere, and cryosphere. However, another facet of the program is the investigation of solid earth processes, including natural hazards, changes in land use/cover, and the internal dynamics of the planet.

Volcanic eruptions are unique in that they impact both solid earth and atmospheric processes as well as produce scientific investigations from the purely theoretical to the extremely applied. Depending on the magnitude, volcanic eruptions have the capability to impact local, regional, and global climate as well as local to regional land cover and hazards (Fig. 2). The synergistic approach of utilizing different EOS sensors, wavelength regions, and data analysis techniques on a common objective (e.g. understanding active volcanological processes) is now a reality (Fig. 3).

The application of EOS data to volcanology began over a decade ago with the formation of the NASA interdisciplinary science (IDS) team on volcanology (Mouginis-Mark et al., 1991). This team of volcanologists and remote sensing scientists were tasked with deriving the monitoring and hazard mitigation tools that would use the new data expected from the upcoming EOS satellite instruments. The IDS team has also authored numerous papers and reports that aimed to focus future instrument development by NASA, which are summarized in Hartmann and Mouginis-Mark (1999) and the references therein. Although the team has changed in both focus and membership, its work has lead to many of the concepts and techniques described in the following papers. That groundwork was synthesized in a monograph of 13 scientific papers written prior to the launch of the core EOS satellites in late 1990s (Mouginis-Mark et al., 2000). As with this issue, that compilation of research stemmed from a special session at a fall AGU meeting (1997). Its primary stated goal was to provide volcanologists with an introduction to the evolving discipline of remote sensing of volcanoes, and how this discipline has become yet another tool to be used with the more established techniques of volcanology. With this special issue, we continue that goal and expand it to include some of the first images, data processing strategies, and scientific results from the EOS satellite instruments.

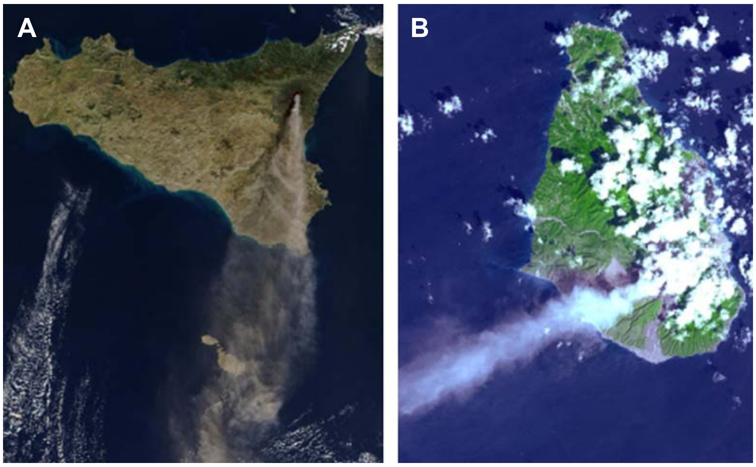

Fig. 2. Comparison of active eruptions and the associated ash plumes imaged by instruments on the Terra spacecraft. (A) MODIS 1 km spatial resolution true color image (bands 1, 4, 3 in R, G, B, respectively) of Mt. Etna Volcano on the island of Sicily acquired on 27 October 2002 (courtesy of the MODIS Land Rapid Response System). The image is approximately 320 km across. (B) ASTER 15 m spatial resolution false color image (bands 2, 3, 1 in R, G, B, respectively) of Soufrière Hills Volcano on the island of Montserrat acquired on 29 October 2002 (courtesy of US/Japan ASTER Science Team). The image is approximately 17 km across. North is up in each image.

1.2. Volcanological remote sensing

For field-based studies active volcanoes, the personal risks involved in data collection can be quite high. Commonly, a volcanologist must venture into dangerous areas in order to sample, map, and monitor volcanic processes. This risk is undertaken for the ultimate goal of gaining a more complete scien-

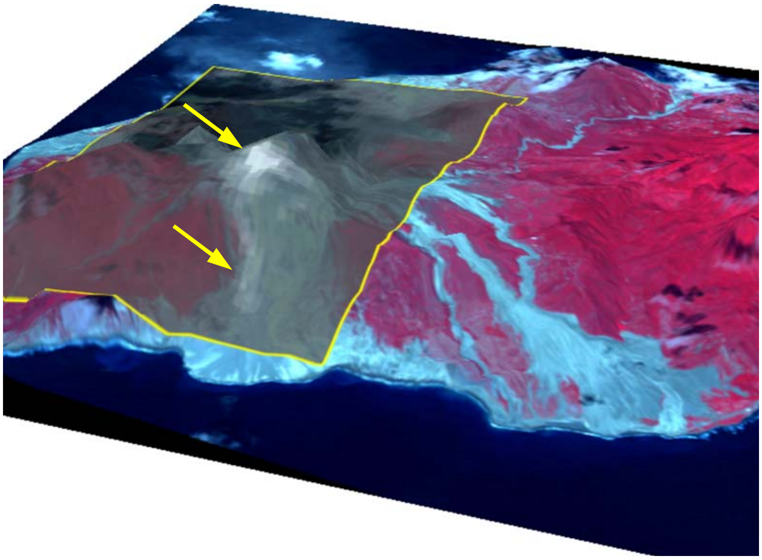

Fig. 3. Multi-temporal, multi-spatial data fusion capabilities of ASTER for Soufrière Hills Volcano, Montserrat. False color visible/near infrared (VNIR) image (bands 3, 2, 1 in R, G, B, respectively) acquired on 2 April 2002 is draped over the digital elevation model (DEM) derived from the same VNIR data set. View is to the SW looking back up the Tar River Valley. The upper-most data layer outlined in yellow is a nighttime thermal infrared (TIR) image (band 11) acquired on 28 December 2000, which shows thermal anomalies as brighter pixels over the summit and Tar River Valley (highlighted by arrows). For scale, the image is approximately 10 km across.

tific understanding of how volcanoes work and the hope of eventually reducing the future risk to the people and property subject to volcanic hazards. Because of these inherent dangers to researchers in the field, remote monitoring of active volcanoes by satellite, airborne or other geophysical techniques is highly advantageous.

Volcano monitoring from space is a tool that has been used for nearly three decades (Friedman et al., 1976; Francis and McAllister, 1986). Early volcanological applications of remote sensing were constrained by a number of factors including instrument performance, data availability, and revisit frequency. Pre-EOS satellite remote sensing instruments were very limited in both the location and the number of spectral bands they offered and this also restricted the types of studies that could be undertaken. Commonly, Landsat 4 and 5 as well as other high spatial resolution data sets had to be ordered months in advance. Data delivery was equally slow, requiring weeks for reel-to-reel tapes to arrive. The number of times that any one high spatial resolution satellite instrument could image a target was poor owing to the facts that tasking plans to methodically acquire data, such as long-term acquisition plans and off-nadir instrument pointing on satellites, did not exist. Lower spatial/higher temporal resolution instruments designed mainly for weather monitoring provided better areal and temporal coverage than the Landsat series. The Geostationary Operational Environmental Satellite (GOES) series provided excellent regional to hemispherical coverage over the Americas and the Advanced Very High Resolution Radiometer (AVHRR) provided regional coverage where local receiving stations were available. However, there was no organized observational volcanic monitoring programs utilizing these data sets, nor were these data archived for any length of time or over remote regions of the world.

Pre-EOS era remote sensing studies are abundant in the literature and can be divided into high spatial resolution mapping studies (e.g. Flynn et al., 2000) or high temporal resolution regional monitoring efforts (e.g. Oppenheimer, 1998; Harris et al., 2000; Dean et al., 2002). Observations of volcanic activity and quantitative data extraction from satellites has trended toward the use of high spatial (≤ 30 m) and spectral (≥ 15 wavelength bands) resolution driven primarily by the data availability. Clearly, such data cannot be used for routine monitoring because of the lower temporal resolution (days). Landsat 7 ETM+ and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) both have higher spatial resolution visible and thermal infrared bands where compared to GOES and AVHRR. Importantly, these data are now available by File Transfer Protocol (ftp) via the Internet, effectively reducing the interval between data acquisition and delivery from weeks to several days. In terms of high temporal resolution studies, the Moderate Resolution Imaging Spectrometers (MODIS) on Terra and Aqua are the first instruments that benefit from a worldwide receiving station network. This provides daily global coverage with a collection-to-delivery lag of 2–10 h, depending on the location on the globe.

Advances in remote sensing technology in the past decade have also translated into significant advances in volcanological research. This quantum leap has been achieved because of the remarkable improvements in both airborne and spaceborne instrumentation and the ingenuity of the scientists using those data. The quantitative data extracted from remote sensing measurements have been used to accurately model effusion rates, SO_2 degassing, thermal flux, and many other parameters (Realmuto et al., 1994; Harris et al., 1998; Ramsey and Fink, 1999; Flynn et al., 2000). In addition, the detection and calculation of radiant temperature has been used successfully as a monitoring tool for volcanoes in remote regions (Flynn et al., 2002; Dean et al., 2002; Wright et al., 2002).

Improvements in data availability including higher observational revisit frequency, lower data purchasing costs, and rapid data processing have encouraged researchers to find new and innovative ways to apply remote sensing data to volcanology. These techniques are diverse and include the development of new software applied to existing data sets (Watson et al., 2004-this issue); the application of quantitative flow/heat loss models using remote sensing (Harris et al., 2004-this issue); the collection of new ground and airborne data in order to validate remote sensing measurements from space (Byrnes et al., 2004-this issue; Hellman and Ramsey, 2004-this issue); as well as the utilization of new spaceborne data never before collected over volcanic targets (Donegan and Flynn, 2004-this issue; Ramsey and Dehn, 2004-this issue). The human skills needed to process and interpret these large data sets over ever-changing targets are very different than many other aspects of the geosciences. They require competency in the physics of energy/matter interactions and its capture by way of technology, in the volcanic processes and subsequent hazards, and in the socio-economic impacts that arise during a volcanic eruption crisis.

2. Summaries of the papers

This special issue contains 10 papers that fall into the following three categories: (1) global monitoring; (2) volcanic ash and aerosols; and (3) volcanic flows, domes, and other surfaces. Some of the authors focus on one instrument and/or technique, whereas others combine not only spaceborne data sets from multiple EOS instruments but also from older, more established instruments such as AVHRR. In the first section, two papers highlight the unique capabilities of instruments on the Terra spacecraft for large-scale volcanic observations. Pieri and Abrams, both members of the ASTER science team, describe that instrument's global data collection effort over active volcanoes. They also discuss the many unique aspects of ASTER, including off-nadir pointing in all wavelength bands, multi-spectral thermal infrared at high spatial resolution, and digital elevation model (DEM) generation, which make the data ideal for a number of volcanological applications. Wright et al. follow with a detailed description of thermal anomaly detection using the MODIS instruments. They show that an automated algorithm reliably detects thermal anomalies at a large number of persistently and sporadically active volcanoes, which encompass the full range of common eruptive styles.

Three papers comprise the second section, which focuses on volcanic plumes and detection of the material found in them. The first paper by Ellrod examines the accuracy of volcanic ash detection using a non-EOS satellite instrument, the GOES Imager and Sounder. Future versions of this instrument will lack the 12-μm thermal infrared band, which is currently widely used for the discrimination of ash and water vapor in volcanic plumes. Ellrod details the impact of this loss as well as how it may be supplemented with data collected by the EOS instruments. Next is a paper by Watson et al. that explores the capabilities of the thermal infrared data of MODIS to retrieve information about volcanic ash, ice, sulphates, and sulfur dioxide. They focus on the eruptions of Hekla Volcano in Iceland and Cleveland Volcano in Alaska. The March 2001 Cleveland eruption is also examined in detail in the last paper of this section by Dean et al.. They compare and contrast data sets from numerous sensors including MODIS, AVHRR, and GOES for accuracy in the detection of the Cleveland plume over time. Higher resolution Landsat 7 ETM+ and field data are also utilized for validation purposes.

The last section contains five papers that focus on a wide range of topics from lava flows to hydrothermal deposits. The first by Donegan and Flynn compares two EOS instruments [the ETM+ on Landsat 7 and the Advanced Land Imager (ALI) on EO-1] for the purposes of extracting sub-pixel thermal information on basaltic lava flows of Mt. Etna, Italy. Byrnes et al. also focus on the interpretation of basaltic flow fields using EOS data. However, unlike the previous paper, the authors use ASTER data to map surface texture, composition and morphologies of the Mauna Ulu flows of Kilauea Volcano, Hawaii. Transitioning to more silicic lava surfaces, the next two papers examine active eruptions at Bezymianny Volcano, Russia and Santiaguito Volcano, Guatemala. Ramsey and Dehn primarily use the thermal infrared wavelengths of ASTER to explore the late 2000/early 2001 eruption of Bezymianny. The spatial and spectral resolutions unique to ASTER allowed the authors to map subtle thermal, textural, and compositional variations on the lava dome and new pyroclastic deposits. Harris et al. focus on the Caliente dome of Santiaguito Volcano using ETM+ and field data to describe the evolution and characteristics of this silicic dome complex. They are able to extract quantitative parameters such as extrusion rates, viscosity, and cooling rates from the satellite data in order to model the advance of an extremely slow moving, well-insulated flow. Finally, the last paper of the issue by Hellman and Ramsey examines the hydrothermal activity and deposits of Yellowstone National Park. Using ASTER as well as the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) instrument, they identify thermal features, map recent and relic mineral deposits, and identify differences in the large geyser basins of the region. The combined use of multiple sensors, wavelength regions, and spatial resolutions provides an excellent summation to this special issue and looks forward to future studies using EOS data elsewhere on Earth and similar instruments now orbiting Mars, such as the Thermal Emission Imaging System (THEMIS) instrument (Christensen et al., 2003).

3. Future strategies and directions

Most discussions of the expansion and new directions of technology applied to spaceborne applications are outdated before they are published. This arises mainly from the uncertainty of predicting the future, the rapid pace of changes in technology, and because of the nearly constant refocusing of science goals in large and complex programs such as EOS. In the past two decades for example, computational processing, data storage, satellite downlink transfers, and imaging technology have all undergone astonishing advancements, which have resulted in new spaceborne concepts being realized. Five advances in technology are outlined below, which have been introduced or significantly improved during the EOS era.

3.1. Hyperspectral imaging

Capturing data in more than 100 wavelength bands is commonly defined as hyperspectral. The EO-1 spacecraft contains Hyperion, which is an engineering test instrument that produces a ~ 7.5-km-wide image with spectral coverage in 220 spectral bands between 0.4 and 2.5 μm. The narrow swath results in an extremely accurate targeting coordinate requirement, and therefore synoptic studies commonly require significant mosaicing of many swaths. Initial results with Hyperion show the utility of using these data for distinguishing basaltic lava flow units by their reflective character, monitoring the effects of volcanic aerosols on nearby vegetation, and studying the temperatures of active lava flows (Fig. 4). The wealth of spectral information provided by Hyperion clearly helps to resolve sub-pixel features such as thermal anomalies and spectrally distinct materials. As satellite recording and downlink capabilities increase, spaceborne hyperspectral instruments having wider swath widths will become a possibility.

3.2. Interferometric synthetic aperture radar (InSAR)

During the past decade, InSAR has evolved from the ‘‘proof of concept’’ stage to routine use for numerous volcanological applications. Although not part of the current EOS program, SAR instruments with the ability to be used in an interferometric mode have been launched by Japan, Europe, and Canada. Based on the results obtained from these instruments for detection of large-scale deformational processes, NASA is also considering an InSAR constellation of satellites in the future (Solomon, 2002). It is clear that advances such as these will continue to occur in as-of-yet-unrealized ways.

3.3. Ultra-high spatial resolution data

Ultra-high spatial resolution data sets such as that provided by QuickBird (67 cm panchromatic, 2.8 m color visible) and IKONOS (1 m panchromatic, 4 m color visible) will become more available for a variety of detailed mapping applications in volcanology. Meter-scale data may be used to accurately delineate flow boundaries, mark features such as fumarole fields, and monitor changes in volcanic edifices such as those occurring at Pu’u ’O’o over the past 20 years. It is expected that spatial resolution and the number of satellites will continue to increase, providing more surface details and better temporal resolution. Despite these expected improvements, limiting factors to routine use of these ultra-high resolution instruments are still expected. The first is the prohibitive cost of these commercial data sets, which is especially critical where monitoring is concerned. The second constraint is the technology, which requires very accurate targeting due to the small swath widths (e.g., an IKONOS image is only 11 km wide).

3.4. Uncooled thermal infrared detectors

Thermal infrared (TIR) imaging has been limited in the past, with ASTER being the only instrument to provide moderate spectral and moderately high spatial resolution in the TIR. This past dearth in TIR data was in part caused by the expense of launching and

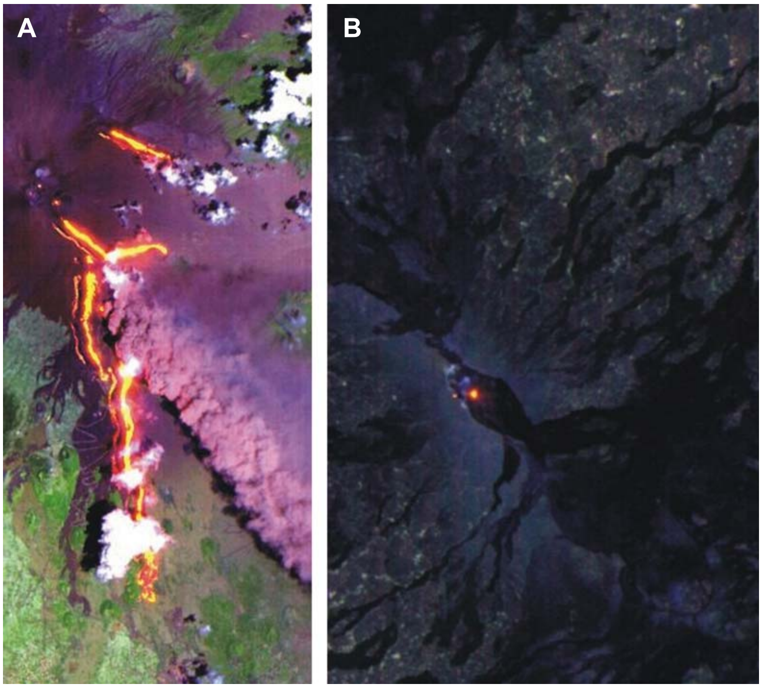

Fig. 4. The hyperspectral Hyperion instrument offers 220 spectral bands between 0.4 and 2.5 μm, but over a narrow image swath width of ~ 7.5 km. Two types of volcanic activity are shown in RGB combinations of bands 213, 152, and 32. In both cases, the activity was radiant enough to saturate some of the Hyperion detectors causing a shadow anomaly 11 pixels to the left and one pixel below the original saturated pixel. (A) A July 22, 2001 image showing the advancement of lava flows of the Mt. Etna, Sicily eruption. (B) An April 12, 2001 image showing the persistently active Erta Ale lava lake in Ethiopia. Each image is a full Hyperion swath width (7.5 km) across.

maintaining large, actively cooled TIR detector arrays. Larger arrays are more expensive to fabricate, increase the complexity of calibration, and have a higher probability of failure of one or more detectors. Further, whereas the active cooling of these arrays produces good signal to noise, it also consumes large amounts of power. A new advance in technology is the use of uncooled thermal infrared microbolometer detectors with acceptable signal to noise. The use of microbolometers allows for the production of smaller, less-expensive instruments, and eliminates the need for coolers. This technology is currently being used to collect orbital TIR data of the Martian surface (Christensen et al., 2003).

3.5. Automated acquisition requests

Automated remote detection of volcanic eruptions is not new. A variety of geophysical systems including seismic networks with alarms and precision GPS instruments can be used to warn of impending eruptions. However, the harsh environment surrounding an active volcano is a very inhospitable place for expensive field equipment. Moreover, the number of potentially active volcanoes that have to be covered in large regions such as the Aleutians and Kamchatka precludes deployment of field equipment in all locations. The Alaska Volcano Observatory and the University of Alaska Fairbanks have led the way with an operational, remote sensing and geophysics-based system for monitoring active volcanoes. The semi-automated Okmok algorithm has been used by AVO/UAF for years to search AVHRR data for volcanic hot spots (Dean et al., 2002). Positive correlations trigger an alert that warns of volcanic activity. In the near future, volcano monitoring will be taken a step further. Large data-processing algorithms such as the MODIS Thermal Alert (Wright et al., 2004-this issue) ingest and process two entire global 1-km data sets every day to search for volcanic and other hot spots. Out of this large volume, only the fraction of pixels that are positively identified as hot spots by the algorithm are mined and reserved in alert files. The center point latitude and longitude of the alert file entries are accurate to within 200 m of their actual location, meaning that the thermal alert files are well within operational parameters to be able to accurately task other higher spatial resolution acquisitions of Landsat 7 ETM+ (185 km swath), ASTER (60 km swath), ALI (37 km swath), IKONOS (11 km swath), and even Hyperion (7.5 km swath). For several remote yet active volcanoes, such as Michael Volcano in the South Sandwich Islands and Big Ben Volcano on Heard Island, the MODIS Thermal Alert system provides the most accurate location information for the current eruptions. Such a system has also been proposed for the monitoring of the northern Pacific volcanoes (Ramsey and Dehn, 2002). This would take advantage of the ASTER scheduling pathway by utilizing the current AVHRR monitoring as a virtual trigger for ASTER data collection. It is clear that the tools now exist to completely automate the acquisition of high spatial resolution active volcano imagery using satellite data and could serve as low-cost test beds for future satellite monitoring arrays.

In addition to examining new technology and recent trends in spaceborne data collection for earth science processes, one can look to recently published reports for clues to possible future directions. One such document is the NASA Solid Earth Science Working Group report (Solomon, 2002). This group was commissioned by NASA to formulate a 25-year vision with the ultimate goal of understanding solid earth science processes in sufficient detail to predict outcomes, consequences and impacts. Although the report is heavily dominated by geopotential field research, inner planet processes, and an emphasis on SAR (especially InSAR), it does not completely abandon NASA's long-standing data collection programs that focus on surface processes using optical remote sensing. The report focuses on synoptic, spaceborne observations and describes how measurements from future instruments can be used to address six important questions, one of which focuses on volcanology directly: "How do magmatic systems evolve and under what conditions do volcanoes erupt?"

How might volcanic observations from space differ two decades from now? Several possibilities are detailed in the SESWG report, each with the overarching goal of, "a more complete integration of field and remote sensing data sets in order to have a robust volcanic warning system for forecasting at progressively longer time scales". To achieve this the report calls for, among other things, a global comprehensive compilation of observations of all major land volca-

Table 1
NASA Solid Earth Science Working Group (SESWG) summary highlighting recommendations applicable to volcanology

Observational strategies	Immediate (1–5 years)	Near term (5–10 years)	Long term (10–25 years)
Surface deformation	Single dedicated InSAR satellite L-band, left/right looking capability weekly access 1 mm/year surface displacement	Constellation of InSAR satellites daily temporal frequency submillimeter accuracy 1 m spatial resolution	Constellation of InSAR satellites in low-Earth orbit hourly global access increased density of ground/seafloor geodetic observations
Variability of Earth's gravity field	GRACE mission monthly estimation to within a few mm at a few-hundred-km spatial resolution	GRACE follow-on demonstration of satellite-to-satellite laser interferometry technology	Measurement improved by two to three orders of magnitude satellite-to-satellite laser interferometry spaceborne quantum gradiometer
Imaging spectroscopy of Earth's changing surface	Continued imaging in the solar reflected spectrum hyperspectral airborne capability in the TIR (3–5 and 8–12 μm)	Improved spaceborne imaging spectrometer hyperspectral VNIR, 30 m spatial resolution demonstration of 30 m spaceborne TIR imaging spectrometer	Continuous full-spectrum spaceborne imaging global access, across multiple wavelengths repeat frequency of hours to years

noes. This data set would ideally be updated on weekly time scales and include deformation changes using InSAR, surface composition changes using imaging spectroscopy, and thermal/plume anomaly detection using advanced radiometers. The report also documents a systematic road map for development over 5-, 10-, and 25-year increments. Parts of this roadmap specific to volcanology (technology expansion in InSAR, spaceborne gravity, and imaging spectrometers) are summarized in Table 1.

A significant obstacle facing scientists in the EOS-era is navigating and analyzing the enormous data volume that has become available. Clearly, this volume will only expand in the decades to come and therefore there is a great need for new and innovative ways to query, visualize and reduce these huge data sets. The SESWG report also recognizes this growing need and calls for a focusing of modeling and computation priorities, with the development of distributed storage and processing infrastructure. One suggestion documented in the report is to develop thousands of storage sites that each contain volumes greater than 1 Terabyte and allow users access to files greater than 100 Gigabytes in several minutes. Realization of this level of information storage and access is a daunting task, but it is critical for use in analyzing dynamic volcanic crisis situations.

4. Summary

This volume illustrates a number of uses for remotely sensed data for volcanological applications. We have presented examples in separated sections for three types of investigations: (1) global monitoring; (2) volcanic ash and aerosols; and (3) volcanic flows, domes, and surfaces. These examples show the great progress afforded by advances in satellite instrument technology as well as data availability both in terms of global coverage and the dramatic shortening of time required to acquire the data sets. In remote locations such as Alaska and Kamchatka, operational volcano monitoring systems have been developed to include pre-EOS era satellite data out of necessity (Dean et al., 2002). EOS instruments now offer global coverage and the opportunity for worldwide hazard mitigation. Increasingly common use of the Internet as well as easier Internet access for even distant locations have sped the distribution of these complex data products. The advances in spatial, spectral, and temporal resolution outlined in this special issue are only the start. Rapid dissemination of information will always be of crucial importance. As the response time to order an acquisition and receive a data product has lessened, the number of volcanological applications has increased. Getting an interpreted data product into the hands of volcanologists and disaster management officials dealing with a volcanic crisis is a key issue for hazard monitoring and rapid response.

Acknowledgements

The authors served as co-conveners of the special session at the Fall 2001 AGU meeting on this topic in addition to acting as the co-editors of this special journal issue. The process of going from the initial concept for a meeting session to a dedicated volcanological journal issue on this topic will have taken more than 2 years and a great deal of hard work. We wish to thank everyone involved in the process, especially the authors and co-authors of the original talks and posters and the papers herein. Clearly, this process would have been impossible without their dedication and hard work. In addition, our thanks to the Volcanology, Geochemistry, and Petrology Section (VGP) section of AGU for sponsoring the special session and Elsevier Press for agreeing to dedicate a special issue of JVGR to this topic. We are also greatly appreciative of those who dealt with the manuscript review logistics, as well as the those who served as manuscript reviewers: Michael Abrams, Steve Anderson, Jeff Byrnes, Ken Dean, Jonathan Dehn, Lori Glaze, Jonathan Fink, Andy Harris, Peter Mouginis-Mark, David Pieri, Clive Oppenheimer, Bill Rose, Dave Rothery, Scott Rowland, Dave Schneider, Dave Sherrod, Ian Watson, and Martin Wooster. MSR support comes from the NASA Solid Earth and Natural Hazard Program (NAG5-9439); the support for LPF is derived from the Hawaii Space Grant Consortium and NASA grant number NGT5-40076. This manuscript was improved with the helpful reviews of Scott Rowland and Jeff Byrnes.

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