The Role of Geospatial Technologies in Communicating a More Effective Hazard Assessment: Application of Remote Sensing Data

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Abstract

Remote sensing data and the application of geo-spatial technologies have progressively been built into real-time volcanic hazard assessment. Remote sensing of volcanic processes provides a unique synoptic view of the developing hazard, and provides insights into the ongoing activity without the need for direct, on-the-ground observations. Analysis and visualization of these data through the geospatial tools, like Geographical Information Systems (GIS) and new virtual globes, brings new perspectives into the decision support system. In this chapter, we provide examples of (i) how remote sensing has assisted in real-time analysis of active volcanoes; (ii) how by combining multiple sensors at different spatial, spectral and temporal resolutions one is able to better understand a given hazard, leading to better communication and decision making; and (iii) how visualizing this in a common platform, like a GIS tool or virtual globe, augments effective hazard assessment system. We will illustrate how useful remote sensing data can be for volcanic hazard assessment, including the benefits and challenges in real-time decision support, and how the geo-spatial tools can be useful to communicate the potential hazard through a common operation protocol.

List of Acronyms

AIRS	Airborne Infrared Remote Sounder
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer

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AVHRR	Advanced Very High Resolution Radiometer
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CNES	<i>Centre National d'Etudes Spatiale</i>
COMET	Centre for Observation and Modelling of Earthquakes, Volcanoes, and Tectonics
CONAE	Comision Nacional De Actividades Espaciales
EDS	Expedited Data Set
EM	Electromagnetic
ENVI	Environment for Visualizing Images
ERDAS	Earth Resources Data Analysis System
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GEOTIFF	Geostationary Earth Orbit Tagged Image File Format
GIS	Geographical Information Systems
GOES-R	Geostationary Operational Environmental Satellite-R
GOME-2	Global Ozone Monitoring Experiment-2
GPS	Global Positioning System
HDF	Hierarchical Data Format
IASI	Infrared Atmospheric Sounding Interferometer
ILWIS	Integrated Land and Water Information System
IMO	Icelandic Meteorological Office
KML	Keyhole Markup Language
KMZ	Keyhole Markup Zipped
KVERT	Kamchatka Volcanic Eruption Response Team
LANDSAT	Land Remote-Sensing Satellite (System)
MIR	Mid-Infrared
MODIS	Moderate Resolution Imaging Spectroradiometer
MTSAT	Multifunctional Transport Satellites
NASA	National Aeronautics and Space Administration
NERC	Natural Environment Research Council
NOAA	National Oceanic and Atmospheric Administration
NRT	Near Real-Time
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping Profiler Suite
ORFEO	Optical and Radar Federated Earth Observation
RADAR	Radio Detection and Ranging
RGB	Red, Green, Blue
ROI	Region of Interest
SACS	Support to Aviation Control Service
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SHP	Shape
SO2	Sulfur dioxide
SOP	Software de Procesamiento de Imágenes
SPIRITS	Software for the Processing and Interpretation of Remotely sensed Image Time Series
SWIR	Short Wave Infrared
TIR	Thermal Infrared

URP	Urgent Request Protocol
USGS	United States Geological Survey
UV	Ultraviolet
VEI	Volcano Explosivity Index
VIIRS	Visible Infrared Imaging Radiometer Suite
VLP	Very long Period
VNIR	Visible Near Infrared

1 Introduction

Timely analysis of volcanic activity makes for enhanced hazard assessment, and provides the best available information to both mitigate the hazard and reduce the risk it could pose. For example, seismic data can be collected and processed with sub-second acquisition frequency (McNutt 1996) to assess earthquake location and signal changes relating to volcanic tremor (Aki et al. 1977; McNutt 1986; Zuccarello et al. 2013), and very long period (VLP) earthquakes (Jousset et al. 2013). Global positioning system (GPS) data can produce time series of vertical and horizontal motion at similar frequencies (e.g. Owen et al. 2000). These two datasets provide point location information of volcanic activity and often require modeling of the volcanic edifice (e.g. Poland et al. 2006) to correlate the data to large changes in the volcanic system. While not having the sub-second periodicity of these geophysical data, satellite-based remote sensing data can be used to examine the large scale spatial changes at a volcano, before, during and after a volcanic event (Rothery et al. 1988; Prata et al. 1989; Guo et al. 2004; Bailey et al. 2010; Thomas et al. 2011; Webley et al. 2013).

Real-time satellite data and new data visualization techniques and software allow the decision maker to evaluate the local, regional, country-wide, continental, and global scales of the volcanic events and impending volcanic crises. Enhanced visualizations of the remote

sensing data can be critical to communicate the scale and impact of the volcanic events and connect with those most at risk. Satellite remote sensing data have been readily available for several decades, and while no sensor has been specifically designed for volcanoes only, there are a large number of satellite-based sensors used to analyze volcanoes and detect and map their associated hazards. While listing all past, current and future sensors is beyond this chapter, we discuss the different regions of the electromagnetic spectrum that can be useful for monitoring volcanoes and the tradeoffs between spectral, temporal and spatial resolutions when assessing the most appropriate sensor for the type of hazard assessment. Some satellites and their sensors are useful for mapping ground deposits and studying the volcano as it inflates and deflates under changing volcanic activity, while others are most applicable to detecting atmospheric emissions, such as volcanic ash and sulfur dioxide (SO₂).

2 Remote Sensing Basics

Lillesand et al. (2015) define remote sensing as “the science and art of obtaining information about an object, area or phenomena through the analysis of data acquired by a device that is not in contact with the object, area or phenomena under investigation”. Satellite remote sensors are either an active system, like RADAR (Radio Detection and Ranging), that sends a pulse and

Fig. 1 Electromagnetic spectrum highlighting the regions, UV, IR and microwave, where remote sensing analysis from space is possible; last viewed February 17, 2015 ([http://upload.wikimedia.org/wikipedia/commons/](http://upload.wikimedia.org/wikipedia/commons/thumb/d/d9/Atmospheric_window_EN.svg/2000px-Atmospheric_window_EN.svg.png)

[thumb/d/d9/Atmospheric_window_EN.svg/2000px-Atmospheric_window_EN.svg.png](http://upload.wikimedia.org/wikipedia/commons/thumb/d/d9/Atmospheric_window_EN.svg/2000px-Atmospheric_window_EN.svg.png)). Dashed line represents the scattering losses due to absorption across the full spectrum defined in the figure

waits for a return, or a passive system, that measures the response at a specific wavelength as radiation passes through the Earth's atmosphere. Wavelengths of emitted and reflected electromagnetic (EM) radiation, as measured by current satellite sensors, are divided into regions from ultraviolet (UV) to microwave (Fig. 1). Most, though not all observations, are made through 'atmospheric windows' where the absorption by the atmosphere is minimal. For some observations high opacity is useful such as infrared wavelengths around $7.3\ \mu\text{m}$ where the absorption features of SO_2 can be used to measure the amount of SO_2 released by a volcano (Thomas et al. 2009, 2011). In order to undertake a volcanic hazard assessment, the type of satellite sensor is therefore determined by the process being examined and the availability of atmospheric windows (Thomas and Watson 2010).

When describing remote sensing satellites and their sensors, the terms 'spectral', 'spatial' and 'temporal' resolutions are often used to assess if the available data can provide the required coverage for the hazardous event. Sensors can have low spectral resolution, such as the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) with three broad range

channels in the mid and thermal infrared wavelengths of the EM spectrum (Fig. 2a). This is compared to the low spectral resolution sensors, like NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) with 11 broad and narrow range channels across this portion of the EM spectrum. These are compared to multi- or hyperspectral sensors, like the NASA Airborne Infrared Remote Sounder (AIRS), which has over 2000 channels from 3.7 to $15.4\ \mu\text{m}$.

Trade-offs in the best sensor to use will occur between pixel size and detail level required (Fig. 2b). Finer spatial resolutions are often a function of a narrower swath width, i.e. coverage across the satellite track. Therefore, there is a trade-off between the spatial resolution and the repeat rate of measurements from the same sensor, i.e. its temporal resolution. Differences in temporal resolution generally relate to the chosen orbits of the different satellites (Fig. 2c). Sensors on satellites with a polar orbit, like AVHRR and MODIS, have a longer repeat period than those from a geostationary orbit, such as the Geostationary Operational Environmental Satellite (GOES-R). However, these geostationary satellites, which remain stationary at one point above the equator, have as a consequence a coarser spatial resolution than from a polar orbit. The

Fig. 2 **a** Varying spectral ranges of satellite channels for AIRS, AVHRR and MODIS (NASA 2003)—note that AIRS data represents multispectral data with narrow bands while AVHRR and MODIS represent individual broad band channels; **b** Changes in image resolution ‘smooths’ out useful data (the same image is shown at

5 × 5, 40 × 40 and 80 × 80 m pixels to illustrate the data smoothing at coarser resolutions); and **c** differences in polar and geostationary orbits for repeat coverage (adapted from http://www.meted.ucar.edu/satmet/npp/media/graphics/geo_leo_satellites.jpg)

spectral resolution is limited by available energy, and hence, as larger footprints provide more energy there is a trade-off with spatial resolution. The chosen applications of the satellite sensor inform the decisions around the spectral, spatial and temporal resolutions of the data available. NOAA (2015a) and JPL (2015) provide an overview of the NOAA and NASA satellite missions currently in operation, while WMO (2013) provide information on different satellites and their sensors specifically for detecting volcanic ash and SO₂ clouds. In the following section, we highlight some of the online tools currently available that routinely process satellite data and provide derived products for volcanic hazard assessment and decision support.

3 Accessing Real-Time Data

Gaining timely access to remote sensing for hazard assessment is essential for rapid analysis. Users can download available data from online sites provided by the satellite data providers (Table 1). To fully analyze the available data often requires access to expensive software, such as ENVI® (Environment for Visualizing Images), as well as proficiency in remote sensing image analysis (Table 2). Other projects and agencies

have provided online access to products from available polar, geostationary/geosynchronous satellite data (Table 3). These online services are often designed by specific groups or organizations for their own monitoring capabilities and so may not be optimally designed for others to use in their hazard assessment and mitigation. However, they do provide excellent routinely processed products that can be used in real-time to assess the hazardous events and mitigate their impact.

Other groups have set up their own receiving stations (Kaneko et al. 2002; Webley et al. 2008) for local access to data to reduce the time delay between acquisition and data processing. Again, as with accessing data from the services listed in Table 1, there is need for either a local remote sensing expert or a fully automated system and online tool for all to use the derived data during a volcanic event.

4 Applications During Volcanic Eruptions

To illustrate how remote sensing data have been successfully used during volcanic eruptions, the following section focuses on three different eruptive events (Fig. 3) with examples from

Table 1 Some of the available online tools available for accessing the multispectral and high spatial resolution remote sensing data

Primary Org.	Website/Tool name	Capabilities for the user
NASA	https://earthdata.nasa.gov/data/data-tools/search-and-order-tools	Lists all possible online tools for search and ordering of data from NASA sensors
USGS	EarthExplorer http://earthexplorer.usgs.gov/	Search for data from archival and NRT data, view premade images, download data in HDF form
NASA	Reverb http://reverb.echo.nasa.gov/	Can search any data from NASA or affiliate agencies; download data in HDF form
USGS/NASA	ASTER EDS data https://astereds.cr.usgs.gov/	View all newly acquired ASTER data from urgent request, premade browse images, download HDF data
USGS	GloVis http://glovis.usgs.gov/	Java based interface for viewing archival data, premade browse images, request data in HDF format.
EUMETSAT	Earth Observation Portal https://eoportal.eumetsat.int/	Requires account, can view all EUMETSAT data, need specific agreement to download data

ASTER Advanced Spaceborne Thermal Emission and Reflection Radiometer, *EDS* Expedited Data Sets, *NRT* Near Real-Time and *EUMETSAT* European Organisation for the Exploitation of Meteorological Satellites

Table 2 Example of remote sensing software that can be used to analyze spaceborne data and produce two-dimensional datasets and imagery per channel and satellite overpass

Software	Manufacturer	Platform	Capabilities for the user
BEAM/SNAP	ESA	Unix	Display, basic image processing, band arithmetic, rectification, ROI statistics
ENVI	Harris	Unix, Windows, MacOSX	Display, band arithmetic, rectification, ROI statistics, advanced algorithms for image processing
ILWIS	52 North	Windows	Digitizing, editing, display, GIS, basic analysis
Imagine	ERDAS	Unix, Windows, MacOSX	Display, band arithmetic, rectification, ROI statistics, advanced algorithms for image processing
ORFEO	CNES	Unix, Windows, MacOSX	Display, band arithmetic, rectification, ROI statistics
Opticks	BATC	Unix, Windows	Display, image manipulation, statistics
Geomatica	PCI	Unix, Windows, MacOSX	Display, Mosaics, DEM extraction, rectification
REMOTE-VIEW	Textron	Windows	Display, multispectral analysis, calibration
SOPI	CONAE	Unix, Windows	Display, basic image processing, rectification
SPIRITS	JRC	Windows	Display, basic image processing, band arithmetic, rectification

Table 3 Sample list of online resources, specifically designed for volcanoes, for access to derived products from satellite data

Name	Website/Tool name	Sensor/Satellite analyze	Focus/Details
Volcview	http://volcview.wr.usgs.gov/	AVHRR/MODIS/MTSAT/GOES	Access to a number of satellites in near real time for the North Pacific region
Volcanic Cloud Monitoring	http://volcano.ssec.wisc.edu/	AVHRR/MODIS/MTSAT GOES/SEVIRI/VIIRS	NOAA-CIMSS satellite imagery pages. Includes a range of single, two and multi-channel products
ASTER Volcano Archive	http://ava.jpl.nasa.gov/	ASTER	Provides users access to search for all ASTER data for volcanoes
SACS	http://sacs.aeronomie.be/nrt/	GOME-2, IASI, OMI, OMP, AIRS	Near real time SO ₂ and ash alert notification and imagery
NASA SO ₂	http://so2.gsfc.nasa.gov/	OMI, OMPS	NASA Global SO ₂ monitoring page

SEVIRI Spinning Enhanced Visible and Infrared Imager, *IASI* Infrared Atmospheric Sounding Interferometer, *MTSAT* Multifunctional Transport Satellites, *VIIRS* Visible Infrared Imaging Radiometer Suite and *OMI* Ozone Monitoring Instrument

Fig. 3 a Indonesia and its volcanoes, highlighting Merapi volcano (modified from Gertisser and Keller 2003); b The volcanoes of Kamchatka emphasizing the location

of Plosky Tolbachik (adapted from Kirianov et al. 2002); and c Icelandic volcanoes and associated geology showing the site of Bárðarbunga volcano (GVP 2011)

across the EM spectrum. Through these case studies, we show examples of available online data as well as post-processed data and imagery that encapsulate multiple sources (Table 4) and different types of analyses.

4.1 Merapi Volcano and Its 2010 Eruption

Merapi Volcano in Indonesia (Fig. 3a) has, since 1900, typical recurrence intervals of 4–6 years with lava dome generation that collapse to

generate pyroclastic flows and lahars (Surono et al. 2012). In 2010, the volcano erupted explosively with the main explosive events on October 26, 29, 31 and November 1, 3, and 4. Surono et al. (2012) along with Jousset et al. (2013) provide an excellent overview of the eruption. Here, however, we focus on the use of radar data, as this provided a spectacular view of the growing dome and was essential in aiding forecasting of the eruptive crisis in terms of predicting the impact that could be generated if (or when) the dome collapsed. After the first phreatomagmatic explosive phase on October 26,

Table 4 All sensors described in chapter, for full names of sensors and agencies see descriptions within the chapter

Sensor (Agency)	Spatial ^a	Spectral	Temporal ^b	References
SEVIRI (EUMETSAT)	1–3 km	0.635–12.4 μm	15 min	EUMETSAT (2015a)
MTSAT (JMA)	1–4 km	0.55–12.5 μm	30 min	BOM (2015)
IASI (EUMETSAT)	25 km	3.6–15.5 μm	Twice a day	EUMETSAT (2015b)
OMI (NASA)	13 $\times$ 24 km (nadir)	0.27–0.5 μm	Daily	Krotkov et al. (2006)
AIRS (NASA)	13.5 km	3.7–15.4 μm	16 days	NASA (2003)
GOME-2	40 km (nadir)	0.25–0.79 μm	29 days ^c	EUMETSAT (2014)
OMPS (NOAA)	50 km (nadir)	0.3–0.38 μm	16 days	NASA (2015a)
ALI (NASA)	10–30 m	0.48–2.35 μm	16 days	NASA (2011a)
HYPERION (NASA)	30 m	0.4–2.5 μm	16 days	NASA (2011b)
ASTER (NASA)	15–90 m	0.52–11.65 μm	16 days ^d	USGS (2014a)
AVHRR (NOAA)	1 km	0.58–12.5 μm	Multiple a day	NOAA (2013)
MODIS (NASA)	250 m–1 km	0.459–14.3 μm	Twice a day	NASA (2015b)
GOES-R (NOAA)	500 m–2 km	0.47–13.3 μm	15 min	NOAA (2014)
TerraSAR (Astrium)	1–18 m	3.1 cm	2.5 days	Astrium (2015)
RadarSAT-2 (CSA)	1–8 m	5.6 cm	24 days	CSA (2015)
VIIRS (NOAA/NASA)	375 m (nadir)	0.412–12.013 μm	Twice a day	NOAA (2015b)
LANDSAT-8 (USGS/NASA)	15–100 m	0.43–12.5 μm	16 days	USGS (2014b)

^aSpatial resolution is defined as the range across swath unless specified

^bTHIS is the orbital repeat time, rather than the time it takes to view the same point on the earth. Also, note that for several sensors, such as AVHRR, MODIS and GOME-2, the time is specified per sensor and there are multiple sensors in orbit on different satellites

^cGOME-2 images the same location more than once every 29 days but at different locations within the swath

^dASTER sensor can be tasked and data can be requested to view specific locations more frequently than the 16 day orbit repeat time

remote sensing data became a critical tool in monitoring and guiding those in crisis management (Pallister et al. 2013). The availability of commercial satellite radar data from RADARSAT-2 and TerraSAR-X, at 0.5–3 m pixel resolution, provided a unique view of the summit activity and the data to analyze the dome growth occurring at the summit between each explosive event (Fig. 4).

Pallister et al. (2013) stated that the speed of availability for these data was critical in providing the best available analysis of the growing

dome for life-saving crisis response. For example, estimates based on radar data suggest that the dome grew 5 million m^3 between October 26 (Fig. 4a) and November 4 and by the early hours of November 6, the dome was gone (Fig. 4b). However, a new dome of approx. 1.6 million m^3 grew in the space of 11 h that same day (Fig. 4 c). The fact that local volcanologists and emergency managers were able to examine the activity at the summit of Merapi at sub 3 m resolution enabled them to make short term assessments on the dome's stability. By

Fig. 4 Merapi RADARSAT-2 and TerraSAR data, adapted from Pallister et al. (2013) showing data from **a** October 11 and 26, 2010; **b** November 4 and 6, 2010; and **c** November 6, 2010 at 11:08 and 22:07 UTC where *PF* pyroclastic flow, *K* Kali Kuning, *Kj* Kinorejo, *C* empty crater, *D* lava dome, and *S* surge deposits. On October 11 and 26, 2010, the red arrow highlights the 2006 dome while 'G' indicates the location of Kali Gendo, where a pyroclastic density current flowed down. The 1 and 2 km distances are equivalent to the length of the arrow line segment

measuring the extrusion rate of the dome as it grew between explosive events volcanologists were able to assess the likelihood of dome destabilization.

Radar data were just one form of remote sensing data that were available during the eruption. High temporal frequency visible and infrared data (see Sect. 5) were available to detect and analyze the location of the dispersing ash clouds for aviation safety. Time series analysis of the dome growth and its potential to destabilize provided the inputs to build probabilistic scenarios of the likelihood for an eruption (Pallister et al. 2013) and for a significant dome collapse that could impact the surrounding population centers.

4.2 Tolbachik Volcano and Its 2012–2013 Eruption

Tolbachik or Plosky Tolbachik volcano, situated on the Kamchatka Peninsula, is a massive basaltic volcano sitting at the southern end of the Klyuchevskaya volcano group. GVP (2017) state that the majority of its activity is relatively low level with volcano explosivity indices (VEI) of 1 and 2 (see Newhall and Self (1982) for explanation of VEI). However, it had a major fissure eruption in 1975–1976 (Fedotov et al. 1980) that was classified as a VEI 4. Tolbachik was quiet until late 2012, when the local volcano monitoring group, Kamchatka Volcanic Eruption Response Team (KVERT), reported that an eruption had begun on November 27.

We examine the mid and thermal infrared wavelength data from both high temporal (multi views a day), low spatial (one [1] km in IR) data and low temporal (one overpass every few days), high spatial (<100 m in IR). Figure 5a shows images from the NASA Advanced Land Imager (ALI) sensor, where differences in the extent of the fissure can be seen from choice of band combinations. Bands 3, 2, 1 represent a true color image. Switch the combination to bands 5', 4', and 4, and the red color in the RGB composite is enhanced. Finally, with the composite of Bands 7, 5', and 5 the thermal signals from the fissures

at Band 7, 2.35 μm , are close to saturation and therefore a 'red glow' effect occurs. These ALI data (Figs. 5a–d) illustrate that by using different band combinations and comparing signals at different wavelengths it is possible to determine the hottest part of the eruptive feature.

For example, Fig. 5b shows ALI data from December 1, five days after the first reported activity. The visible data show the steaming flows as they interact with the surrounding snow and ice, while the SWIR, right-hand side of Fig. 5b, shows the thermal signals being emitted from the flows. Combining visible and SWIR imagery, the ALI data is able to capture the location and intensity of thermal signals from the fissure eruption. Figure 5c shows visible and thermal infrared (TIR) data from the NASA Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor on February 13, 2013 'tasked' using the ASTER Urgent Request Protocol (URP), see Ramsey and Dehn (2004). The TIR data shows the hottest part of the flow on the eastern side, noting the earlier western erupted flows are still warmer than the surrounding region. Compare to this to SWIR from the ALI data on December 1, 2012, Fig. 5b. This cooler material on February 13 corresponds to the hot active flows six weeks earlier. With its 10.6 μm data, the ASTER URP data could be used to determine the effusion rates from the fissure eruption and assess if the activity was increasing or waning.

With the chosen channels for the RGB composite (Fig. 5d), it is possible to differentiate the higher radiances at 2.193 μm , indicating warmer temperatures. This composite analysis for HYPERION shows how with hyperspectral data it is possible to assess subtle variations in the thermal signals of active flows. Additional analyses can include examining the full suite of 220 channels to determine the surface characteristics, such as rock type and mineral composition (see Hubbard et al. 2003).

The high spatial resolution imagery from ASTER, ALI and HYPERION were not the only thermal infrared data to capture the activity at Tolbachik volcano. The high temporal, lower spatial resolution data from the NOAA AVHRR

Fig. 5 Different sensors over time for Tolbachik volcano in 2012–2013 where differences in the extent of the fissure can be seen based on the choice of band combinations. **a** NASA ALI on February 14, 2013 of Bands 3, 2, 1 (0.63–0.69 μm ; 0.525–0.605 μm ; 0.45–0.515 μm) showing a true color image; Bands 5', 4' and 4 (1.1–1.3 μm ; 0.845–0.89 μm ; 0.775–0.805 μm) and Bands 7, 5, and 5' (2.08–2.35 μm ; 1.55–1.75 μm ; 1.2–1.3 μm); **b** NASA visible and SWIR ALI from December

1, 2012; **c** NASA ASTER Urgent Request Protocol (URP) data (visible and TIR) from February 13, 2013 with subset in the *red box* showing a thermal signal from the most active part of the fissure as the *red color* is elevated; and **d** NASA HYPERION RGB composite with Channels 204, 150 and 93 at 2.193, 1.649 and 1.074 μm from February 14, 2013 data showing the most active portion of the flows (*red and yellow regions in the inset*)

and NASA MODIS sensors provided a vital tool in monitoring the fissure eruption. March 2, 2013 provided an ideal opportunity to compare the thermal signals available from the three different sensors (Fig. 6). The ASTER data resolution allows finer details in the flow pattern to be captured and therefore is closer to the actual spatial extent of the flow. The MODIS and AVHRR data have much larger pixels, 1.1 km^2 at nadir that grows in size towards the swath edge impacting the ability to detect small scale (spatial and thermal output) thermal events.

The timely data from the MODIS and AVHRR sensor meant that they could be used to

assess relative changes from one overpass to the next, given the sub-daily temporal frequency of the available data. The ASTER data, while more accurate given its pixel size, is one point in time. Therefore, for enhanced hazard assessment the MODIS and AVHRR data, coupled to the finer spatial resolution ASTER for comparison, became a critical tool in the daily monitoring of the ongoing hazard. The MODIS and AVHRR data (Fig. 6) were routinely collected by KVERT for analysis of the ongoing hazard, while the ASTER data were acquired by NASA URP and the ALI/HYPERION data were available via the online tools from satellite providers. This satellite

Fig. 6 Intercomparison of sensors on the same date: **a** ASTER Band 13 at 00:32 UTC; **b** AVHRR Band 4 at 01:18 UTC; and **c** MODIS Band 31 at 00:30 UTC on March 2, 2013. Here ASTER Band 13 data, 9.1 μm , is compared to AVHRR Band 4, 10.6 μm , and MODIS

Band 31, 11.02 μm . ASTER with 90 m spatial resolution captures more of the flow's details, and shows an area of 30 km^2 . Compare this with the MODIS data with an area of 54.8 km^2 and AVHRR with 47.3 km^2

remote sensing data was useful to analyze the relative change in the fissure eruption and showed how, by coupling multi resolution data, one could assess if the eruption was over or if it was increasing towards a new level of heightened activity.

4.3 Bárðarbunga Volcano and Its 2014–2015 Eruption

Bárðarbunga volcano is situated beneath the northwestern part of Vatnajökull ice cap in south-eastern Iceland. In August 2014, the Icelandic Meteorological Office (IMO) reported increased seismicity at the volcano. By August 23, this activity had developed into a 150–400 m long dyke beneath the Dyngjufjökull glacier, prompting a change in the aviation color code to red (GVP 2014). By August 29, IMO reported that a small fissure eruption had started in Holuhraun and lava started to erupt on August 31 along a 1.5 km long fissure (GVP 2014).

Following the eruptions from Eyjafjallajökull 2010 (Gudmundsson et al. 2010, 2012) and Grimsvötn 2011 (GVP 2011), there had been a lot of focus on the potential impact of another Icelandic eruption on Europe and its transportation infrastructure. Routine satellite remote sensing data were collected and processed to build derived products from ultraviolet data with Ozone Mapping Profiler Suite (OMPS) and Global Ozone Monitoring Experiment-2 (GOME-2) sensors, in addition to infrared data from VIIRS, AIRS and other geosynchronous/polar-orbiting sensors.

IMO provided daily online updates on the ongoing eruption from Bárðarbunga volcano (Holuhraun fissure) (IMO 2015), including any field observations and notes from meetings of the Scientific Advisory board. Satellite remote sensing data was an integral part of this monitoring and daily reporting of volcanic activity. For example, IMO used LANDSAT-8 (Land Remote-Sensing Satellite (System)-8) data to analyze the spatial footprint of lava flows,

Fig. 7 Data from the Icelandic Meteorological Office (IMO) website **a** LANDSAT data as RGB composite of the flows on January 3, 2015; **b** as GIS layer see http://en.vedur.is/media/jar/myndsafn/full/20150115_afstodukort_ornefni_300dpi.png; and **c** ALI thermal from January 16, 2015 using the same geographical projection to allow comparison to the LANDSAT-8 data from January 3

determine the most active portion (Fig. 7a) and develop a map of the ongoing activity for decision making (Fig. 7b). The combined images (Fig. 7a–c) show how IMO and other local authorities were able to use the high spatial resolution data to map out the full flow extent and also generate GIS data layers for use in comparison to other data from field observations and or seismic activity.

The activity from Bárðarbunga volcano along the Holuhraun fissure generated more satellite derived SO_2 imagery than for volcanic ash (Fig. 8). Figure 8a for AIRS on September 1 shows less detectable SO_2 than from GOME-2, Fig. 8b, and OMPS, Fig. 8c. Figure 8d–f, illustrate the influence of the sunlight on deriving UV satellite based measurements. For the OMPS sensor, Fig. 8f, the derived SO_2 is cut off as a result of the lack of sunlight. This impact can be significant for any northerly drift of the SO_2 cloud from the Holuhraun fissure.

Figure 8 shows the usefulness of using common spatial domains and temporal averaging of

satellite data to analyze for relative change. However, the background information on local infrastructure, populated locations, and transportation links as well as the ability to overlay multi satellite data together is limited. Often Geographical Information Systems (GIS) are used to display different datasets together or to generate maps for hazard assessment. The need to compare different data sources and include supplementary information has led to the use of Virtual Globes.

5 Geo-Spatial Tools and Virtual Globe Applications

Satellite remote sensing has become an integral part of daily monitoring of volcanic activity (Webley et al. 2008) and is part of a suite of geophysical data utilized by volcano observatories (Webley et al. 2013). To combine all of these datasets together requires a Geospatial tool, remote sensing processing software or a virtual

Fig. 8 Real-time daily Support to Aviation Control Service (SACS, <http://sacs.aeronomie.be/>) products, AIRS, GOME-2 and OMPS on September 1 (a, b, c) and October 1, 2014 (d, e, f) from Bárðarbunga/Holuhraun volcanic activity. Note these are daily composites given the polar orbiting nature of the satellites and that

SACS (2015) have set both common geographical domains and measurement scales to ensure quick comparisons. These common geographical regions and temporal periods allow those in hazard assessment to compare the relative change in the SO_2 output without the need to process and/or re-project the data

globe. These Geospatial or Virtual Globe tools allow the user to overlay many different datasets and add in other geophysical data such as earthquake locations or GPS point data. To display remote sensing data within a Geospatial tool, the satellite imagery (often in Hierarchical Data Format [HDF], or Geostationary Earth Orbit Tagged Image File Format [GEOTIFF]) needs to be converted into shape (SHP) files with associated metadata. These files can be displayed along with other GIS data layers to produce hazard maps which can be used to assess the risk and mitigate impacts.

It is possible to use Virtual Globes to display the imagery and make rapid assessments of the hazard and its potential impact. Recently, Google Earth has been used for visualizing geospatial data (Webley et al. 2009; Prata and Prata 2012) but it requires the user to generate a Keyhole Markup Language (KML) or Keyhole Markup Zipped (KMZ) file of their own satellite imagery (Bailey et al. 2010). In early 2015, the ability for all to use Google Earth Pro was made possible (Google 2015) as it was publically available free of charge. This has the added advantage of being able to read in GEOTIFF and GIS SHP files, but there are still some limitations. Google Earth Pro will open automatically to its pre-defined start up. The user is then able to simply drag and drop their GEOTIFF or SHP file and Google Earth Pro will fly to the center location from the geospatial information in the associated file (Fig. 9). If the GEOTIFF file is too large in size or the SHP file has a large number of entries, the software will request the user to choose the desired image resolution. Once chosen, it will display the data, but as Fig. 9 shows, the scaling of the GEOTIFF data may lead to no useful information being shown in the overlay. By generating a GEOTIFF *image* file from ENVI or similar software rather than the default GEOTIFF *data* file, the user can display their data in Google Earth Pro with a more useful scaling for visualization. ENVI® is a geospatial product (see Table 2 for list) provided by Harris Geospatial (Harris Geospatial 2016) that combines advanced image processing and geospatial technology to allow the user to extract

useful information from remote sensing data and make better informed decisions.

Once the data are available in either a Geospatial tool or Virtual Globe, users can map the hazard and measure its spatial extent and potential for further impacts. Virtual Globes like Google Earth Pro bring a new mapping capability not available in Google Earth. Figure 10 shows how a hazard manager would load the data into ENVI or a similar image processing tool, and then map out a region of interest (ROI) using either points (red) or as a polygon (green). This can also be done in Google Earth Pro where the imagery is loaded and displayed as an overlay. Using the polygon tool, the hazard manager can map out the edge of the flow. Comparing the area from ENVI with its ROI tool and a pixel by pixel analysis to the results from Google Earth Pro with its polygon tool, the total mapped area for this flow was calculated as 76.13 and 76 km² respectively. The relative difference was 0.13 km² or 0.02% difference, thus highlighting that Google Earth Pro allows those in hazard assessment and mitigation to quickly and accurately map out volcanic features, without the need for access to specific and often expensive remote sensing software.

Virtual Globes also allow for the intercomparison of satellite data from different sensors and across different spectral ranges with the same sensor. Figure 11 shows the ALI data, from Fig. 10, by displaying Band 1 (0.48–0.69 µm and 10 m spatial resolution panchromatic data) and a set of RGB composites using the VNIR, SWIR and MIR channels (0.43–2.35 µm and 30 m spatial resolution data). Note that the black area in the image overlay is a result of the satellite overpass and therefore no data is recorded in this region. It is important information for the decision maker as it shows that there is no satellite data but the flow could still exist in this location. More data is needed in this region to confirm the lack of lava flow. As the data are geolocated, the relative differences between channels can be easily compared and used to assess the location of the hottest part of the flow. Small, hot targets will produce the strongest

Fig. 9 How to display GEOTIFF data in Google Earth Pro, using example from ALI Band 1 on January 16, 2015. Google Earth Pro allows the use of 'drag and drop', where the user can simply drop the GEOTIFF file into software. © 2016 Google Inc. All rights reserved. Google and the Google Logo are registered trademarks of Google Inc.

Fig. 10 ENVI® and Google Earth Pro workflow to analyze the spatial footprint of the flow from Band 1 ALI data on January 16, 2015. ENVI® analyzed area was 761,359 points or area of 76.13 km², Google Earth Polygon was 76 km². © 2016 Google Inc. All rights reserved. Google and the Google Logo are registered trademarks of Google Inc.

Fig. 11 ALI data from January 16, 2015 displayed in Google Earth Pro®. **a** Band 1; **b** RGB Bands 432; **c** RGB Bands 543; **d** RGB Bands 654; **e** RGB Bands 765; and **f** RGB Bands 876. © 2016 Google Inc. All rights reserved. Google and the Google Logo are registered trademarks of Google Inc.

radiant signal in the SWIR and MIR data and by comparing the RGB data from the VNIR to the SWIR, operational hazard managers can assess the most hazardous parts of the flow and thus where to prioritize resources.

For some of the shorter wavelengths, the resultant satellite data may be saturated so longer wavelength data, greater than 2–3 μm , may be needed to assess subtle changes (see use of thermal infrared data (10 μm) over mid-infrared

data ($3.7\ \mu\text{m}$) in Webley et al. (2013)). By combining the data together (both across different satellite sensors and across different spectral ranges), hazard managers can make a quick assessment that can assist those in the field and reduce the potential impact to local population or infrastructure.

Virtual Globes, like Google Earth Pro highlighted here, and GIS tools (see Fig. 7b) can be used as the interfaces for those in hazard assessment to visualize and analyze the available satellite data. From the analysis in Figs. 10 and 11, KMZ and KML data files can be generated for comparison to other geophysical data along with georeferenced maps, with associated data such as latitude/longitudinal grids, distance scale bars, population centers and transportation links (Fig. 12). As with Fig. 11, the black area highlights the region of no data due to the swath edges from the satellite data.

The insert in Fig. 12 shows how a user is able to define site visit locations using the place marker option in Google Earth Pro. The latitude and longitude location can be extracted and used for fieldwork planning and logistics. With more real-time geophysical data being developed for the Virtual Globe market, as well as the development of online geospatial tools, such as the Google Earth Engine and Google Maps Engine,

the use of the tool will continue to increase among the real-time hazard assessment community.

6 Summary

There has been an integration of remote sensing data and geospatial tools into day-to-day operations for volcano monitoring. They are used to perform a more effective hazard assessment of ongoing volcanic activity. Remote sensing data are now available from ultraviolet to microwave wavelengths (spectral); from m's to km resolutions (spatial) and from daily to weekly repeat times (temporal). There is a trade-off between the spectral, spatial and temporal and it has been the combination of all available data that has increased the uptake of the remote sensing data into routine volcano monitoring. Satellite data provides an overview of the local, regional, country-wide, continental, and global scale of the volcanic eruptive events. Effective visualization of these data can then significantly help decision makers to communicate the impact to those at risk in an effective and efficient manner.

This chapter highlights examples where satellite remote sensing was used during volcanic eruptions to: (1) improve the assessment of

Fig. 12 ALI data from January 16, 2015 map as generated from Google Earth Pro. Map shows latitude and longitude grid, scale bar to show distances in km, North arrow to align image N-S, the locations of all the volcanoes, airports, roads (yellow lines) and also any

population centers. *Inset* shows area zoomed in on the flow with user defined locations for site visits of Flow edge-North and Flow edge-South. © 2016 Google Inc. All rights reserved. Google and the Google Logo are registered trademarks of Google Inc.

potential for dome collapse using meter resolution radar data (Merapi 2010); (2) examine the changing shape and thermal properties of a large fissure eruption using multi wavelength and resolution data (Tolbachik 2012–2013); and (3) map the spatial extent of thermal activity from volcanic flows using high resolution data and routinely available volcanic gas measurements (Bardarbunga/Holuhraun 2014–2015). Additionally, the chapter shows how Virtual Globes have become an integral tool for hazard assessment and new developments will lead to a greater use of these in real-time assessments.

Remote sensing data and geospatial technologies are now critical parts of the monitoring toolbox. To be used in a real-time event, the data needs to be collected, processed and displayed routinely, i.e. for every possible satellite overpass and using the same geographical domain. Satellite data providers have created several online tools to undertake the initial hazard assessment. To combine all the data together, they need to be on common projections and have associated metadata on the spectral, spatial and temporal resolutions. Then the choice is on the best geospatial technology for the application and/or assessment required. This can be a GIS tool where ancillary data is already in a GIS format, or it could be a Virtual Globe where other data is in a KML/KMZ format. Using the new geospatial technologies to display, visualize and analyze the routinely (automatically) acquired and processed remote sensing data will provide the best tools for real-time hazard assessment, in essence building a system ready if an eruption occurs, rather than building the system as it is developing.

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