Monitoring the Thermal Activity of Volcano

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1. Introduction

Volcanic unrest and volcanic eruptions are one of the major natural hazards next to earthquakes, floods, and storms. A great majority of the world's potentially active volcanoes are unmonitored. Less than twenty-five percent of the volcanoes that are known to have had eruptions in historical times are monitored. Moreover, seventy-five percent of the largest explosive eruptions since 1800 occurred at volcanoes that had no previous historical eruptions (Simkin et al., 1994). Being able to quickly react to volcanic unrest at so far not well or unmonitored volcanoes is therefore a social challenge because the danger associated with volcanoes is not only restricted to their eruption, but also includes earthquakes, dangerous gases, flank movement and other deformation, tsunamis, landslides, and even climatic changes. Defining criteria by which to forecast volcanic eruptions is therefore the most fundamental goal of volcanological research and it is a mandatory prerequisite for any successful hazard mitigation strategy associated with volcanic activity and critically depends on a full understanding of volcanic systems.

One of the keys to understand the eruptive potential of a volcanic system is our ability to characterize the actual state of stress of a volcanic system that involves proper monitoring strategies. In the framework of the Geotechnologien project financed by the BMBF in Germany (BMBF, 2008) we are developing the core of a mobile Volcano Fast Response System (VFRS) that can be quickly deployed in case of a volcanic crisis or volcanic unrest. The core of the system builds on established volcanic monitoring techniques such as seismicity, ground deformation, and remote sensing tools. The raw data collected by the VFRS will be further analyzed and fed into different models to constrain the actual state of activity at the volcano and to set alert levels which are presented within GIS. A major novelty of this mobile system is the attempt of a direct inclusion of satellite based observations to deduce ground deformation, to detect hazardous gas emissions and to monitor thermal activity.

As the research is still in progress the article concentrates merely on the thermal activity monitoring – detecting and characterizing so called hot spots (their temperature is at least 100 K higher than the temperature of the background) that can be considered as one of eruption precursors. The article presents the physical background of hot spots remote sensing, available data and the monitoring hot spots strategy that will be applied in the near future into VFRS.

2. Remote sensing of volcano thermal anomalies

2.1 Physical background

Land surface temperature can be retrieved by remote sensing that is based on the interpretation of radiance measurements of a distant body. According to Planck’s law the measurements of the black body spectral radiance at a certain wavelength in the thermal infrared spectra are correlated with the kinetic temperature

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of the radiating body. Volcano hot spots (lava lakes and lava flows) have typical temperatures in the range of 400 K to 1000 K (Simkin et al., 1994). According to Wien’s Displacement Law (the wavelength of the peak of the emission of a black body and its temperature are in an inverse relationship), the peak emission of radiance for blackbody surfaces of such temperatures is between 3 and 5 μm (this part of spectra belongs to medium infra red – MIR; figure 1). For a temperature of 300 K, which is the expected temperature to be measured by Earth orbiting radiometers, the peak of radiance emission is located at approximately 10 μm (this wavelength belongs to thermal infra red spectra – TIR; figure 1).

![Graph showing the relationship between the spectral radiance and the wavelength for blackbodies at different temperatures.](image)

Fig. 1: Graph showing the relationship between the spectral radiance and the wavelength for blackbodies at different temperatures.

Hot spot detection algorithms from remote sensing use this behaviour to detect hot spots that usually cover only a small part of the sensor pixel area. For example, given a lava lake at 700–1200 K that covers less than a percent of the pixel area, an observation in the MIR spectra would result in a temperature of around 320–370 K. TIR observation would in contrast be just a degree or two above 270 K (given that the background temperature equals 270 K). The sensitivity of the MIR spectra to hot spots is so high that it reveals small (even smaller than 0.1% of the pixel area) sub-pixel anomalies that do not have any significant impact upon the TIR temperature. The temperature difference (MIR – TIR) of usually 50–100 K is the basis for hot spots detection.

The problem arises during the daytime because of the sunlight glints that might cause anomalies in the MIR. Solar heated anomalies can be eliminated using refined techniques based on spectral or spatial comparison. The solar heated anomalies are not the only problem – the range of appropriate temperature differences at volcano hot spots is quite large and their characteristics are sometimes for example similar to the characteristics of MIR – TIR differences of cold clouds. A solution to distinguish volcano hot spots from other phenomena is normalizing the temperature difference by the sum of MIR and TIR temperatures. This kind of normalized thermal index NTI = (MIR – TIR) / (MIR + TIR), which was introduced by Wright et al. (2002), offers a possibility to automatically discriminate hot spots from the background on
the basis of NTI threshold. Other algorithms based on temporal comparison or contextual analyses are also available to automatically detect hotspots but NTI is often used because of its simplicity.

Once the hotspots are finally detected they should be characterized by physical parameters as kinetic temperature, area, radiant flux and effusion rate. The thermal anomaly area is as already mentioned typically smaller than the sensor pixel area. Therefore, the radiance observed by the sensor is within a pixel marked as a hot spot a mixture of the radiance emitted by the hot feature with that emitted by the cooler region surrounding the feature. Dozier (1981) described this radiance mixture and used it to estimate the temperature and the area part of thermal anomalies; the approach is today known as dual-band technique, which was in a volcano case study first tested in 1988 by Rothery et al.. The dual-band technique is based on a system of two equations (rad is measured radiance in channels 1 and 2, \( p \) is part of the area covered by a hot spot, \( R_{\lambda i} \) is Planck’s function of a given wavelength \( \lambda \) and background temperature \( T_B \) or hot spot temperature \( T_H \)).

\[
\begin{align*}
\text{rad}_1 &= p \cdot R(\lambda_1, T_H) + (1 - p) \cdot R(\lambda_1, T_B) \\
\text{rad}_2 &= p \cdot R(\lambda_2, T_H) + (1 - p) \cdot R(\lambda_2, T_B)
\end{align*}
\]

The system contains three variables (\( p, T_H, T_B \)) and it is not linear because of the Planck’s function characteristics. It can be solved numerically if one of the variables is estimated from other data (the background temperature is often estimated from the temperatures in the vicinity of a hot spot). The problem arises if one of the measured radiances is saturated, which is not unusual in the case of areas at temperatures 350 K or higher (most radiometers were designed to observe the ground surface at temperatures near 300 K) when the hot spot covers most the pixel area. Dual-band solution then provides merely a lower limit to the hot spot temperature and a lower limit to fraction of the hot spot area.

In addition to the temperature and area of the hot spot, radiant flux and effusion rate provide interesting information too. Radiant flux can be easily estimated if the area and effective radiant temperature is known (assuming that lava emissivity can be estimated) according to Stefan-Boltzmann’s law. The effusion rate is more difficult to determine because lava flow densities can be very heterogeneous, other petro-physical parameters have to be estimated from appropriate data, thus errors as large as twice the eruption rate are not unusual.

### 2.2 Difficulties of hot spots remote sensing

One has to be aware of all the issues by monitoring thermal anomalies by remote sensing. During the last decade most volcano monitoring was carried out using AVHRR, GOES, MODIS, ASTER, and Landsat TM/ETM+ sensors that differ in spatial resolution ranging from 4 km for GOES all the way down to 30 m pixels for ASTER. Availability of similar scenes varies also strongly, with geostationary systems sending images every 15 min and ASTER every 16 days, which makes it liable to miss events of less than several hours duration.

An important issue is the transmissivity of the atmosphere – unless it is particularly thin and transparent it is unlikely for a sensor to see through ash- or meteorologic-cloud that contains mainly water vapour. Therefore, it is important to mask at least thick clouds. Some parts of the spectra are absorbed also by gases like CO\(_2\), O\(_3\), etc. thus only a few atmospheric windows are appropriate for thermal anomalies monitoring: 2–2.5 \( \mu \)m (SWIR), 3.5–4 \( \mu \)m (MIR) and 9–11 \( \mu \)m (TIR). The first window in the SWIR spectra is appropriate for detecting the hotspots of temperatures of 1000 K or even more, the second one in the MIR spectra is the most suitable for temperatures of 500 K and the last one in the TIR spectra suits the background temperatures of 300 K. The use of daytime images in the SWIR and MIR spectra is often limited because the spectra coming from the sun extends into the MIR spectra (figure 2).
Fig. 2: A comparison between day (left; land in the light and sea in the dark colours, area of Etna within the black rectangle – enlarged in the small image) and night MODIS image (right; land in the dark and sea in the light colours, area of Etna within the white rectangle – enlarged in the small image) for the July 18 2002 for the Etna volcano (Sicily). It can be seen how the thermal activity can be easily seen in the night image (hot spot in white, marked by the circle within the enlarged image; the anomaly lower left from Etna is the city of Catania) but not in the day image because of the sun glint, thus the daytime hot spot monitoring is limited to only intensive thermal anomalies (area or temperature wise).

In order to estimate the temperature with a high accuracy the emissivity of the lava has to be known. It is usual to either anticipate that the lava acts like a black body or to work with the emissivity value of around 0.95. The problem is that the emissivity decreases even to 0.6 for molten lava. Furthermore, the emissivity is a function of temperature, thus using a predefined value leads into errors that can be even 100 K.

Point spread function (PSF – a function that defines, how the sensor sees a point object) is an issue that is usually not considered in the case of low resolution sensors. However, when sensors of spatial resolution of around 100 m or less are being used then the PSF cannot be neglected; more pixels are “contaminated” by the hot spot even in the case of a single hot spot that is situated only in one sensor pixel. This means, that the hot spot covers larger area than it actually is. If the sensors’ PSF is known (usually Gaussian form assumed) then its affect can be reduced. The PSF affect can be additionally reduced characterizing a huge spot as a cluster of pixels and not each pixel separately (Zhukov et al., 2005).

3. Available data overview

Table 1 presents important characteristics of sensors appropriate for volcano thermal activity monitoring. The first three presented sensor have been already often used in the volcanologic studies. The last one, SEVIRI, is aboard MSG that is a geostationary meteorological satellite. It is presented because of the general characteristics of the geostationary satellites – they have much better temporal resolution than polar orbiting satellites. Some other sensors (listed below) might be appropriate for volcano thermal anomaly monitoring but they have some major limitations that do not make them a perfect choice for a continuous volcano monitoring.

- AATSR (similar characteristics as AVHRR or MODIS) on board Envisat is primarily intended for detecting the sea surface temperature, thus it is often saturated in the case of hot spots. Its swath width is narrow (512 km), thus its revisit time equals 3 days. An advantage of this sensor is a channel working in the NIR spectra during night-time if the channel in the MIR spectra is saturated (most other sensor turn off the NIR channel during night-time) – this is useful to characterize hot spots with temperatures over 1000 K.
• TM / ETM+ on board Landsat 5 / 7 has only one TIR channel in 120 / 60 m spatial resolution and two SWIR channels; all of them are only 8-bit channels, thus the acquired data is often saturated. ETM+ has a malfunction since 2004. It can be used to detect and characterize fumaroles that are often present next to volcano and have a temperature of 50–100 K above the background temperature.

• MTI on board the MTI satellite has 11 IR channels with a 20 m spatial resolution but this is an US military satellite that is no longer operational (launched in 2000; 3 year lifespan).

• HRS aboard BIRD satellite (German test satellite for fire detection) is not functioning since 2003. Its swath is narrow (190 km) but it has a good spatial resolution (370 m) with an innovative system based on double sampling that prevents channel saturation in most cases (Zhukov et al., 2005; figure 2).

• Imager on board geostationary GOES satellites that cover North and South America and Pacific ocean have already been used in the volcanologist studies (Harris et al., 2001). Its major disadvantage is its poor spatial resolution (4 km in nadir) that limits its use to only large volcanic thermal anomalies.

<table>
<thead>
<tr>
<th>Spatial resolution in nadir</th>
<th>AVHRR</th>
<th>MODIS</th>
<th>ASTER</th>
<th>SEVIRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>VISIBLE &amp; INFRARED: 1090 m</td>
<td></td>
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<tr>
<td>SWIR: 250 m</td>
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<tr>
<td>MIR: 500 m</td>
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<tr>
<td>TIR: 1000 m</td>
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Some appropriate channels:

- 3A (1.58–1.64 μm)
- 3B (3.55–3.93 μm)
- 4 (10.3–11.3 μm)
- 5 (11.5–12.5 μm)

- 7 (2.10–2.16 μm)
- 21 (3.93–3.99 μm)
- 31 (10.8–11.3 μm)
- 32 (11.8–12.3 μm)

- 9 (2.36–2.43 μm)
- 13 (10.3–11.0 μm)
- 14 (11.0–11.6 μm)
- 5 (3.48–4.36 μm)

- 10 (9.8–11.8 μm)

Swath width:

- AVHRR: 3000 km
- MODIS: 2330 km
- ASTER: 60 km
- SEVIRI: whole hemisphere (el.>10°)

Aboard satellite:

- NOAA 15–18, MetOP
- Terra, Aqua
- Terra
- MSG

Time of equator crossing:

- 9:30 (MetOP)
- 10.30 (Terra), 13.30 (Aqua)

Shortest revisit time (on equator):

- 1 day
- 1–2 days
- 16 days
- 15 min

Tab. 1: Interesting characteristics of some sensors appropriate to monitor volcano thermal anomaly. Additional important characteristic is the saturation temperature but it varies with each sensors channel (in general the saturation temperature on the MODIS aboard Terra are the highest).
Fig. 3: HRS (BIRD) images from the MIR channel for the July 18, 19 and 20 2002 for the Etna volcano (Sicily). It can be seen how the thermal activity (hot spot in white) was decreasing over these three days ($T_{18} = 560$ K, $A_{18} = 0.4$ ha, $E_{18} = 12$ MW; $T_{19} = 400$ K, $A_{19} = 1.4$ ha, $E_{19} = 8$ MW; no hot spot on July 20).

4. Strategy of minimising error

More requirements have to be fulfilled in order to successfully detect and characterize a hot spot: the right assumptions about atmosphere transmissivity, surface emissivity and sensor PSF have to be made. Furthermore, the hot spots remote sensing can be successfully used as an eruption precursor merely when the observations are frequent and have an appropriate spatial resolution. Polar orbiting satellites, which usually cannot provide more than two images per day, are usually used in volcano hot spot detection. However, using more satellites can provide coverage of perhaps 10 images per day or even more, which is less than 96 images per day provided by latest geostationary meteorological satellites (image every 15 minutes) but the polar orbiting satellites provide better spatial resolution. The appropriate sensors on polar orbiting satellites have a spatial resolution of around one kilometre. Sensors with better spatial resolution can be used too but their temporal coverage is too poor for a continuous volcano monitoring and they get saturated easily.

Because of these facts we decided to perform further tests in the combination of AVHRR and MODIS data. The AVHRR sensor is situated on five still operational satellites: NOAA 15, 16, 17, 18 and METOP-A. This means that 10 images can be acquired by AVHRR every day. In addition, MODIS is situated on Terra and Aqua satellite that can provide additional 4 images per day. Because all MODIS overpasses takes place approximately as the same time as the some AVHRR overpasses, merely 10 acquisitions per day can be obtained. They are not equally distributed through the day but their amount makes it still possible to use all the data for a continuous volcano monitoring. The MODIS has a better signal to noise ratio and it saturates at higher temperatures as AVHRR, thus it makes sense to use AVHRR merely when MODIS data are not available.

All the measurements contain some noise that together with the errors built into the assumptions used to simplify the hot spot characterization lead to even larger gross errors. Therefore, it is important that all the used data is assimilated together according to its accuracy into an estimate of the hot spots characteristics that has the minimised error. Data assimilation is the technique that combines observations with data from a numerical forecast model to produce an “optimal” estimate (according to some criterion) of the evolving system state. It functions like a filter (one of Kalman filters) and moreover, it can also include a sophisticated physical model. In order to minimize the error and estimate its value we are going to use a Kalman filter at the first stage and at the second stage we will try to implement the model of lava cooling.
5. Discussion

Volcanoes are a threat to at least its closest environment although they have sometimes a significant influence also on the global level. It is therefore important to continuously monitor their activity. The direct measurement of the surface temperature of volcanic features is usually expensive, time consuming and unsafe, thus remote sensing of surface temperatures is an important alternative to direct measurements. Remote sensing capabilities, however, might be reduced in the near future because MODIS on board Terra has already functioned longer than expected (a lifetime of six years was anticipated). In the case of its malfunction only MODIS on board Aqua will provide some “luxury” comparing to AVHRR or AASTR. The situation should improve in 2013 when NPOESS program will start. The new satellite system will bring also an improved resolution which will allow us to detect thermal anomalies 10 times smaller than it is possible by using MODIS today.

Although the described research is still in progress we can draw some conclusions. The first comparison between AVHRR and MODIS data showed that the datasets are similar enough to integrate all the available data into a data assimilation scheme that will provide data about the volcano thermal anomaly temperature, area and radiant flux of relatively high temporal and spatial resolution with minimised level of error. In the future, we will also consider the data from geostationary satellites in the case of major thermal activities in order to improve the temporal resolution of the volcano monitoring.

The proposed procedure has not been tested as a tool for an eruption precursor so far but it has itself at least proven to be a valuable tool to describe already existing eruptions and moreover, a similar procedure can be used for fire monitoring. The fire temperatures are in general even higher than the temperatures detected by volcanic anomalies and anomalies are more widespread. The examples of oil-burning in Iraq acquired by BIRD also showed that the NIR spectra has a huge potential in the fire characterizing as the MIR spectra is often saturated in the case of high temperature anomalies (Zhukov et al., 2005). A similar technology can be therefore used for volcano thermal anomalies and fire detection but their characterization might differ somewhat.

6. Acknowledgement

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Bibliography