

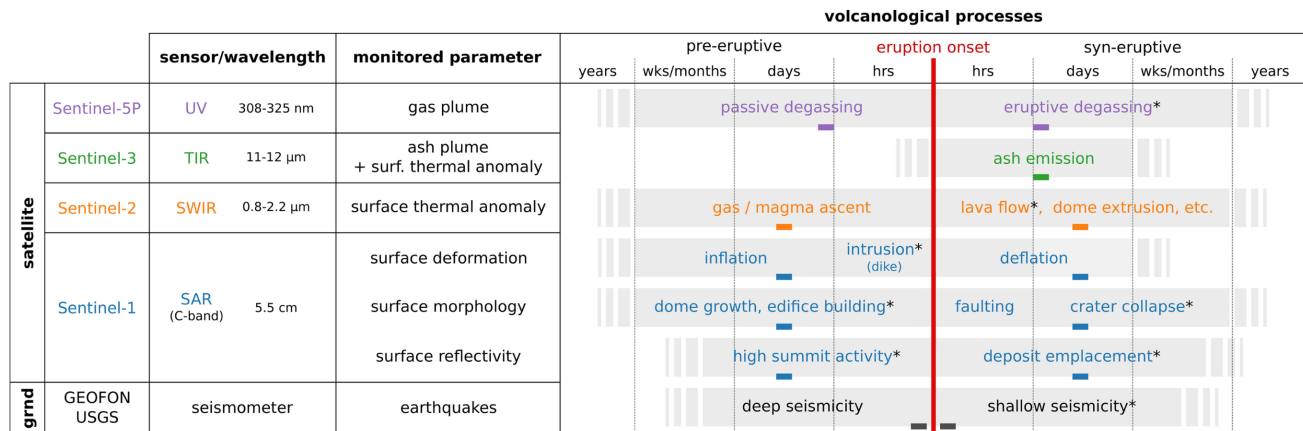
# Forecasting volcano eruption activity

Stefan Ehehalt

2010837484@stud.fh-kufstein.ac.at

FH Kufstein Tirol

Kufstein, Austria



**Figure 1: Utility of different sensor types, both orbital and ground-based, used by MOUNTS to monitor various volcanic processes. [12]**

## ABSTRACT

Volcanic activity monitoring typically are based on gas emissions, seismic activity, thermal anomalies, deformation and surface change. These events can be extracted by globally tracked observation data that span the electromagnetic spectrum. Orbital earth observation is generated by sensors focusing on different wavelength. Earth bases systems used for earthquake monitoring can also be used to monitor volcanic activity. Eruptions are often forgone by a number of indicators that can be detected by the available orbital and earth based measurement systems. Already a lot of projects provide free access to specific measurement data bases. Challenges in combining and exploiting the different data sources include ensuring regular data acquisitions over interesting areas and the robust automation of the analysis of the vast amount of multi-sensor signals. Processing and extract the relevant information from the available satellite images and time series brings the need of Machine Learning algorithms.

## KEYWORDS

natural science, satellite monitoring, volcano monitoring, eruption forecasting, machine learning

## 1 INTRODUCTION

The recent Cumbre Vieja eruption on Las Palmas (Canary Islands, Spain) beginning on the 19 September 2021 and lasting for more than two month, lead to lava flows destroying more than a hundred properties on their way to the sea [7]. Luckily nobody was injured gravely as the eruption produced mild explosive activity and lava flows. The last eruption on Las Palmas was recorded in

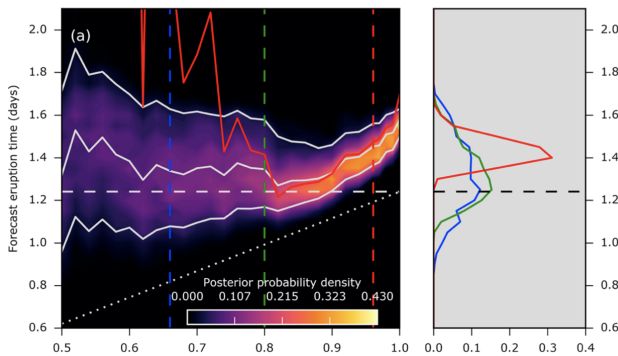
1971. However, this eruption had relatively mild effects, the eruption of the Anak Krakatau (Indonesia) in 2018 had more dramatic consequences. The volcanic tremor caused underwater landslide and generated a tsunami wave hitting the Indonesian coast line. Based on authorities, the tsunami has caused more than 400 death [6]. The fact that more than 1500 active volcanoes are recorded and lead to around 50-85 eruptions each year [10] lead to the need of a global early warning system in order to better react to the hazardous eruption consequences. The most active volcanoes are not properly instrumentally monitored, as ground-based monitoring is limited or lacking, due to remote environments and/or limited resources [12]. In such cases, satellite sensing can provide crucial monitoring data. The interaction of available ground-based monitoring systems and satellite monitoring data can lead to eruption early warnings. Volcanic eruptions are often forgone by prior activity signals indicating a possible state of unrest (see 1). Mainly data for the four types of observation is collected:

- seismicity
- deformation and surface change
- gas emissions
- thermal activity

Seismic data can only be monitored by ground-based stations. All other can be collected from space by exploiting various wavelengths across the electromagnetic spectrum. A ever growing number of earth observation satellites are already providing freely available data to access the required information. The high amount of data leads to the need of data reduction and new ways to interpret this data. Machine Learning algorithms can help handling this data and bring new insights.

## 2 SEISMIC DATA

Seismic activity like magma migration, hydrothermal activity or fracturing generate a variety of measurable signals. The precursory seismic activity shows patterns of acceleration that can be used - in most cases - as a robust precursor of volcanic eruptions. Seismometers are able to measure this seismic activity. However, the closer the instrument is located to the seismic edifice the better the signals can be monitored, but high magnitude activity can still be measured several kilometers away. As only a few of the active volcanoes are monitored closely, freely available ground-based earthquakes information systems like the Global Earthquake Catalogues GE-OFON and USGS can be used to access this seismic data. Locally installed ground-based monitoring instrumentation can be used additionally to gather a better database for the interpretation of the signals. A researcher team monitored the unrest at Domuyo Volcano in Argentina by a network of several local seismometers [3]. They used an automatic event detection algorithm based on short-term and long-term averages, which was controlled by visual observations in order to eradicate false positives. An analysis at the Tungurahua volcano in Ecuador used a Bayesian approach based on material Failure Forecast Method (FFM) theory in order to investigate a retrospective forecast. They have seen that the evaluation of seismic events are able to contribute to improve forecasts of volcano eruption [4]. FFM consists in adjusting an empirical power law on precursory patterns of seismicity and is a well known attempt for deterministic forecasting of eruptions. Figure 2 shows the forecast likelihood of the eruption, which steadily increases during the considered time sequence.

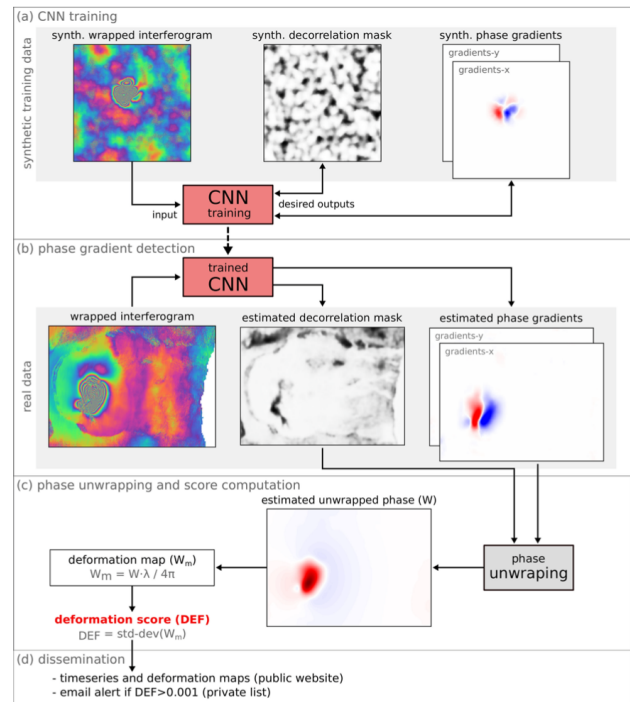


**Figure 2: Evolution of posterior distribution of eruption time and posterior probability density distribution at times indicated by correspondingly colored dashed lines [4]**

Most Failure Forecast Method implementation utilize the method for analyzing complete precursors time series. However, FFM is not optimized to handle real time analysis which is necessary for automated forecasting systems. Boué et. al show some improvements of the material Failure Forecast Method. They efficiently make use of Hidden Markov Models to automatically classify the seismic event patterns in order to have real time precursors available [5].

## 3 GROUND DEFORMATION

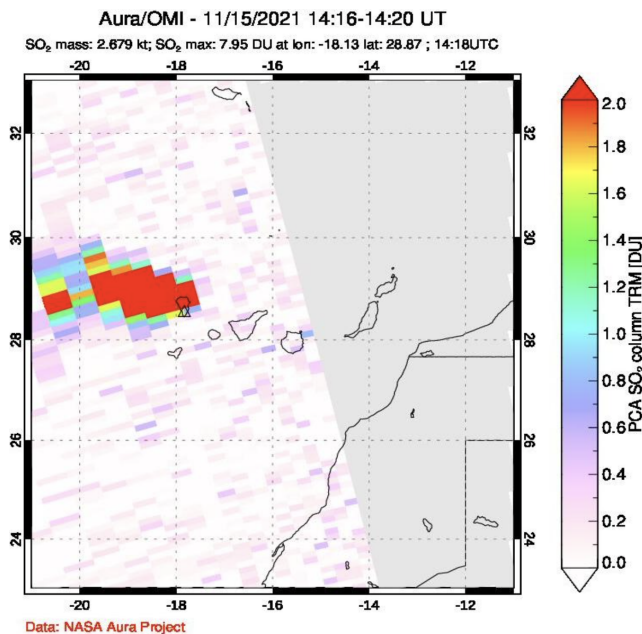
Interferometric Synthetic Aperture Radar (InSAR) can be used to quantify ground-surface deformation. Not only the Sentinel missions of the European Space Agency provide free InSAR data of digital elevation maps with different resolutions worldwide. InSAR uses radar wavelength which are mostly unaffected by weather clouds and operates during day and night. This is especially advantageous as the revisit period is up to twelve days, depending on the location and satellite. COMET (Centre for Observation and Modelling Earthquakes, Volcanoes and Tectonics) provides a open database for interferograms for several hundred volcano's (<https://comet.nerc.ac.uk/volcanoes/>). The difference between two data acquisitions of the same ground-area retrieves the surface deformation, which is known as Differential InSAR (DInSAR). Typically only two images are exploit to retrieve the deformation, but also multiple images could be exploited with time series processing to gain a more advanced insight. The MOUNTS project currently only focus on two-images-processing, as multi-image-processing is too computation-intensive [12]. They use a with synthetic data pre-trained CNN in order to automatically generate deformation time series and maps (see figure 3). The advantage of using a CNN is the already included filtering and noise detection. This leads to a rather simple method to treat decorrelated areas [12].



**Figure 3: Workflow to detect ground deformation using a pre-trained convolutional network [12]**

## 4 GAS EMISSIONS

Gas emissions are often a characteristic of an volcanic unrest [2]. Outgassing is caused due to magma flux which is escalating towards the surface. The pressure decrease leads to volatiles which can escape through existing pathways into the atmosphere. An increased gas concentration therefore can be a important eruption indicator. Especially  $SO_2$  is commonly used, as the background concentration is relatively low and the gas concentration is already be measured from satellites [8].  $SO_2$  absorbs ultraviolet (UV) and infrared (IR) radiation and are measured by UV and IR spectrometer. The Infrared Atmospheric Infrared Sounder (IASI) and Ozone Monitoring Instrument (OMI) satellites are only a few of the currently available systems. The Global Sulfur Dioxide Monitoring Home Page brings together  $SO_2$  emission data from various monitoring systems (<https://so2.gsfc.nasa.gov>) and opens the data to the public. Figure 4 shows the increased  $SO_2$  concentration above Las Palmas several days before the Cumbre Vieja eruption. However, due to



**Figure 4: Increased  $SO_2$  mass over Canary Island on the 15 November 2021, captured by the OMI satellite [1]**

the  $SO_2$  emission sensor capabilities the generated data is based on relatively low frequency and low resolution measurements.

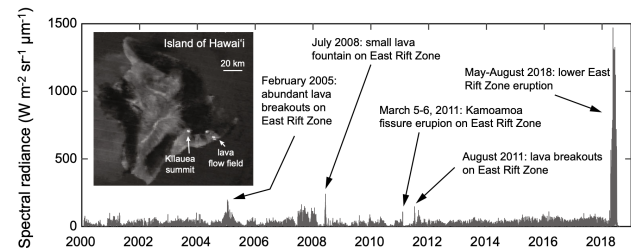
## 5 THERMAL INFORMATION

A rising surface temperature of a volcano can also be an precursor for an upcoming eruption. Anomalous temperatures can be caused by hydrothermal systems like crater lakes caused by the arrival of magma at shallow depths or the magma arrival at the surface. A time series analysis of the thermal data can help to detect eruptions. Quite a lot of operating satellites include sensors for measuring thermal emissions like Sentinel-2. These sensors differ in their used spectral bands, the resolution and the revisit period. The difficulty

in generating and interpreting the data is the interference with different other factors:

- clouds
- Reflected sunlight during the day
- temperature range of ambient surface
- Ratio between point of interest and capturing resolution

The combination of different wavelength sensors can face these problems. Existing thermal monitoring systems like MODIS, MODVOLC or MODLEN already provide reliable nearly real-time data. Figure 5 shows the thermal activity time series of the Kilauea Volcano on Hawaii. Different eruptions and lava breakouts can be seen in the data. The smaller breakouts are not always lead by an continuous rising temperature, they happened most likely abrupt. The big eruption however was clearly preceded by an tremendous rise of the temperature.



**Figure 5: Time series of thermal unrest at Kilauea Volcano, Hawaii, recorded by MODIS [8]**

## 6 SUMMARY

As we have seen the seismic events, surface deformation, thermal anomalies and gas emission are good precursors for volcanic eruptions. The near-real-time availability of measurement data for these indicators is already provided by a lot of independent monitoring projects. However, the available data is scattered over different data bases with different quality, depending on temporal, environmental, spatial and spectral resolution factors. Ground-based measurement systems generate only local, but high frequency data. Orbit measurement systems provide only low-frequency data but generate data globally. The monitoring of these data has provided already a lot of insights into volcanic dynamics and some projects already put effort in combining and analyzing the free available multi-sensor data:

- GlobVolcano project
- European Volcano Observatory Space Services EVOSS
- Disaster Risk Management (DRM) led by the Committee on Earth Observation Satellites CEOS
- Monitoring Unrest from Space (MOUNTS) [11]

The MOUNTS project [11] currently monitors 66 global volcanoes and you can register to receive automatic alerts on specific events. They are already using Machine Learning algorithms and time series analysis to support their automatic forecast processes in order to handle the vast amount of available data. However, MOUNTS only uses the data of three Sentinel missions for their predictions.

## 7 CONCLUSION AND OUTLOOK

We have seen that a vast amount of monitoring data is already publicly available but can hardly be automatically utilized by systems for automatic eruption prediction, especially in real time. The combination of the different data sources and automatic preprocessing of the different data sources is the key for improved eruption forecasting in future. We have seen already some support of machine learning algorithms in this field, but there is more capability to support the forecasts in the future:

- Automated processes in order to have robust precursors available in real-time as the delay for civil protection to act needs to be long enough.
- Improved algorithms to better recognize subtle changes compared to the background noise, Convolutional Neuronal Networks have been seen in this field to help handling this problem, especially for processing the satellite based image data.
- Robust change detection to be able to exclude changes non related to volcanic activity. Also CNN could help here to filter the data with environmental disturbance.
- Alignment of different satellite sensor data to extract more robust and frequent monitoring data as the resolution of the sensors differ. A interesting approach here could be the segmentation with the use of CNN-encoders suggested by Rudner et. al. They segmented flooded buildings via Fusion of multiresolution, multisensor, and multitemporal satellite imagery [9]. This could also be used to automatically identify the volcano area of interest.
- Make use of the already available monitoring data to improve existing machine learning models and make them more robust.

However, the insights indicate that machine learning algorithms combined with automated processing systems have the potential to form an alert system for volcanic unrest especially in remote and inaccessible regions.

## REFERENCES

- [1] NASA National Aeronautics and Space Administration. 2022. *Global Sulfur Dioxide Monitoring Home Page*. <https://so2.gsfc.nasa.gov>
- [2] Alessandro Aiuppa, Roberto Moretti, Cinzia Federico, Gaetano Giudice, Sergio Gurrieri, Marco Liuzzo, Paolo Papale, Hiroshi Shinohara, and Mariano Valenza. 2007. Forecasting Etna eruptions by real-time observation of volcanic gas composition. *Geology* 35, 12 (12 2007), 1115–1118. <https://doi.org/10.1130/G24149A.1> arXiv:<https://pubs.geoscienceworld.org/gsa/geology/article-pdf/35/12/1115/3532987/i0091-7613-35-12-1115.pdf>
- [3] Ana Astort, Thomas R. Walter, Francisco Ruiz, Lucía Sagripanti, Andrés Nacif, Gemma Acosta, and Andrés Folguera. 2019. Unrest at Domuyo Volcano, Argentina, Detected by Geophysical and Geodetic Data and Morphometric Analysis. *Remote Sensing* 11, 18 (2019). <https://doi.org/10.3390/rs11182175>
- [4] A. F. Bell, M. Naylor, S. Hernandez, I. G. Main, H. E. Gaunt, and M. Mothes, P. a d Ruiz. 2018. Volcanic Eruption Forecasts From Accelerating Rates of Drumbeat Long-Period Earthquakes. *Geophysical Research Letters* 45 (2018). <https://doi.org/10.1002/2017GL076429>
- [5] A. Boué, P. Lesage, G. Cortés, B. Valette, and G. Reyes-Dávila. 2015. Real-time eruption forecasting using the material Failure Forecast Method with a Bayesian approach. *Journal of Geophysical Research: Solid Earth* 120, 4 (2015), 2143–2161. <https://doi.org/10.1002/2014JB011637> arXiv:<https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2014JB011637>
- [6] Agencia Guatemalteca de Noticias. 2019. *Indonesia: Earthquakes and Tsunami – Sunda Straits Tsunami*. <https://reliefweb.int/report/indonesia/indonesia-earthquakes-and-tsunami-sunda-straits-tsunami-mdrid013-epoa-update-n-15-n>
- [7] A.E. Global Volcanism Program (Crafford and eds.) Venzke, E. 2021. *Report on La Palma (Spain) – October 2021*. <https://volcano.si.edu/showreport.cfm?doi=10.5479/si.GVP.BGVN202110-383010>
- [8] Michael P. Poland, Taryn Lopez, Robert Wright, and Michael J. Pavolonis. 2020. Forecasting, Detecting, and Tracking Volcanic Eruptions from Space. *Remote Sensing in Earth Systems Sciences* 3, 1 (01 Jun 2020), 55–94. <https://doi.org/10.1007/s41976-020-00034-x>
- [9] Tim G. J. Rudner, Marc Rußwurm, Jakub Fil, Ramona Pelich, Benjamin Bischke, Veronika Kopačková, and Piotr Biliński. 2019. Multi3Net: Segmenting Flooded Buildings via Fusion of Multiresolution, Multisensor, and Multitemporal Satellite Imagery. *Proceedings of the AAAI Conference on Artificial Intelligence* 33, 01 (Jul. 2019), 702–709. <https://doi.org/10.1609/aaai.v33i01.3301702>
- [10] L. Siebert, T. Simkin, and P. Kimberly. 2011. *Volcanoes of the World: Third Edition*. University of California Press. [https://books.google.de/books?id=0DZrflL9\\_DMC](https://books.google.de/books?id=0DZrflL9_DMC)
- [11] Sébastien Valade. 2017. *Volcano Monitoring System powered by Sentinel satellites*. [www.mounts-project.com](http://www.mounts-project.com)
- [12] Sébastien Valade, Andreas Ley, Francesco Massimetti, Olivier D'Hondt, Marco Laiolo, Diego Coppola, David Loibl, Olaf Hellwich, and Thomas R. Walter. 2019. Towards Global Volcano Monitoring Using Multisensor Sentinel Missions and Artificial Intelligence: The MOUNTS Monitoring System. *Remote Sensing* 11, 13 (2019). <https://doi.org/10.3390/rs11131528>