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Using Sentinel-1 GRD SAR data for volcanic eruptions monitoring: the case-study of Fogo Volcano (Cabo Verde) in 2014/2015

Rafaela Tiengo*[1,2,3], José Manuel Rodrigues Pacheco[1], Jéssica Garcia Uchôa[1,2,3], Artur Gil[1]

[1] *Instituto de Investigação em Vulcanologia e Avaliação de Riscos (IVAR), Universidade dos Açores; Rua Mãe de Deus, Campus Universitário de Ponta Delgada, Edifício do Complexo Científico, 9500-321, Ponta Delgada, Portugal*
[2] *Universidade dos Açores, Faculdade de Ciência e Tecnologia, Universidade dos Açores; Rua Mãe de Deus, Campus Universitário de Ponta Delgada, Edifício do Complexo Científico, 9500-321, Ponta Delgada, Portugal*
[3] *cE3c: Centre for Ecology, Evolution and Environmental Changes & Azorean Biodiversity Group (cE3c-ABG), Faculdade de Ciências e Tecnologia da Universidade dos Açores; Rua Mãe de Deus, Campus Universitário de Ponta Delgada, Edifício do Complexo Científico, 9500-321, Ponta Delgada, Portugal*

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ABSTRACT

The last eruption in the Fogo Volcano, which began in November 2014, was the first eruptive event captured by the Sentinel-1 (S1) mission. The present work sought to complement previous research and explore the potential of utilizing data from the Synthetic Aperture Radar (SAR) S1 mission to better monitor active volcanic areas. S1 Ground Range Detected (GRD) data was used to analyze the changes that occurred in the area before, during, and after the eruptive event and was able to identify the progress of the lava flow and measure the affected area (3.89 km^2 in total). Using the GRD data on Google Earth Engine (GEE) platform demonstrated high potential in terms of response time to monitor and assess eruptive scenarios in near-real-time, which is fundamental to mitigate risks and to better support crisis management.

1. Introduction

The archipelago of Cabo Verde is located between latitudes 14º and 18º North and longitudes 22º and 26º West. Situated in the Atlantic, 1300 km from the Canary Islands, its territory has 10 islands and 13 islets and Fogo Island was the site of the last eruption (Fig. 1). Fogo Volcano is the most active volcano in this archipelago, with about 26 eruptions in the last 500 years.

After almost 20 years since the last eruption occurred in 1995, a new eruptive event with strombolian characteristics began in November 2014 and lasted approximately 78 days.

Fogo Island has an extensive eruptive history being the only island of the Archipelago of Cape Verde to have volcanic activity. The Fogo Volcano has a caldera with approximately 8 km in diameter that was formed from two collapses that occurred in the central part of the volcano and Pico do Fogo was formed in the sequence of collapses on the eastern flank of the island (Brum da Silveira et al., 1997).

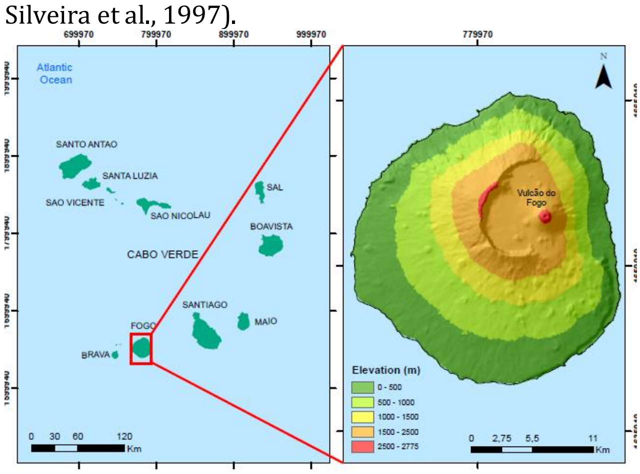

Figure 1. Map of Fogo Island, one of the ten volcanic islands of the Cabo Verde Archipelago. The Pico do Fogo (Fogo Volcano) constitutes the higher point of the island (2829m).

* **Corresponding Author**

*(rafaela.p.tiengo@azores.gov.pt) ORCID ID 0000-0002-9298-0178
(jose.mr.pacheco@azores.gov.pt) ORCID ID 0000-0002-9558-8868
(jessica.g.uchoa@azores.gov.pt) ORCID ID 0000–0002–5255-9207
(artur.jf.gil@uac.pt) ORCID ID 0000–0003–4450-8167

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Eruptive events may make it impossible to access affected areas and gather *in situ* data. Thus, the advancement of geospatial technologies proves critical in better understanding the genesis of these events remotely (Pyle et al., 2013; Jerram, 2018).

Mapping and updating the cartography of areas with active volcanism configures a fundamental task as it constitutes a tool to be used in the planning and crisis management process, as well as in the development of research, risk assessment, and crisis management (Fitz, 2008; Silva et al., 2018).

SAR data provides several advantages over other monitoring techniques due to the acquisition process of data in inaccessible and all-weather scenarios, by day or night. Besides that, S1 allows a relevant improvement for cost-effective monitoring and risk assessment of active volcanic areas. S1 pixel resolution is about 5x20 m in azimuth and range, respectively, with a revisiting cycle of 6 days. High spatial resolution SAR data is fundamental to allow the detection of unconformities in remote areas. SAR data is becoming essential in collecting relevant information about the dynamic processes by which an eruption can be generated (Fujira et al., 2017).

The GRD data from S1 mission was used in this study to identify the progress of the lava flow and measure the affected area, in order to assess its potential to monitor and assess eruptive scenarios in near-real-time, which is fundamental to mitigate risks and to better support crisis management.

2. Data and methods

This paper is focused on the application of S1 products in order to analyze eruptive scenarios. S1 GRD data was used to monitor the progression of the lava flows related to the 2014/15 eruption event through the detection of surface changes.

GRD is a S1 product that corresponds to SAR data detected, analyzed, and projected to the ground range taking into account the ellipsoidal Earth model, with separation capability in the object-target ratio of approximately 20 x 22m (ESA, 2016; ESA, 2021; Mullissa et al., 2021).

GRD consists in a product that presents the image amplitude values relative to backscattering, considering parameters such as surface roughness. These images require preprocessing to remove thermal noise. The workflow shown in Figure 2, suggested by Filipponi (2019), was applied to process this data in the SeNtinel Application Platform (SNAP) software.

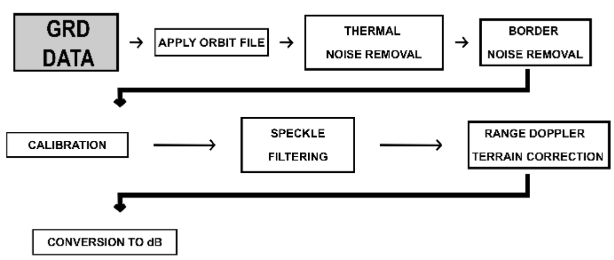

Figure 2. Workflow for removing thermal noise from S1 GRD data in SNAP software

The first stage of this procedure consists of the *Apply Orbit File* step, which corresponds to a refinement of the accuracy and the information referring to the position and speed of the satellite. Thenceforth, the *Thermal Noise Removal* step was applied in order to remove the thermal noise, thus normalizing the backscattering signal of the images. Subsequently, the *Border Noise Removal* procedure was used to compensate for the Earth's curvature levels, thus reducing the low-intensity noise contained in the images. *Calibration* step was then applied, ensuring that the image pixels were correlated with the backscattering that occurred during the information acquisition phase (ESA, 2021). Then, *Speckle Filtering* step was applied, which corresponds to the process of filtering speckles and noise. Afterward, *the* Range Doppler Terrain Correction step was undertaken to perform the geometric correction of the terrain to compensate for image distortions. The last step of this workflow consisted in converting the backscattering coefficient into decibels through a logarithmic transformation.

The GRD data acquired by the S1 mission is described in Table 1.

Table 1. S1 data used to generate the GRD of the area affected by lava flow

Image acquisition dates	Orbit
08 November 2014	Descending
27 November 2014	Ascending
09 December 2014	Ascending
21 December 2014	Ascending
02 January 2015	Ascending
07 February 2015	Ascending

To map the lava flow of the 2014/15 eruption, the GRD data was analyzed to identify the different paths that lava flow ran through day by day.

With the GRD data processed, the raster calculation tool of Arcmap 10.4 software was used to compute an Image Differencing Change Detection (Lu et al., 2004). In this procedure, each image after the start of the event is subtracted from a pre-event image. For this purpose, the value of an image referring to the last hours of the eruption was subtracted from an image prior to the beginning of the event. Very high ("change") and very low ("no change") values were thresholded in order to obtain the change detection map. To assess the accuracy and validate each change detection procedure, the Overall Accuracy was computed with independent validation datasets with 50 change/no change sampling points (Congalton and Green, 1999).

3. Results and discussion

In order to analyze the lava flow temporal progression, S1 GRD data was used to identify the affected area along the eruptive event. The successive change detection procedures showed Overall Accuracies ranging between 0.70 and 0.90. The surface changes that occurred during the 2014/15 eruption can be visualized in Figure 3. These changes are in line with the detailed description made by Cabral (2015) for this eruptive event.

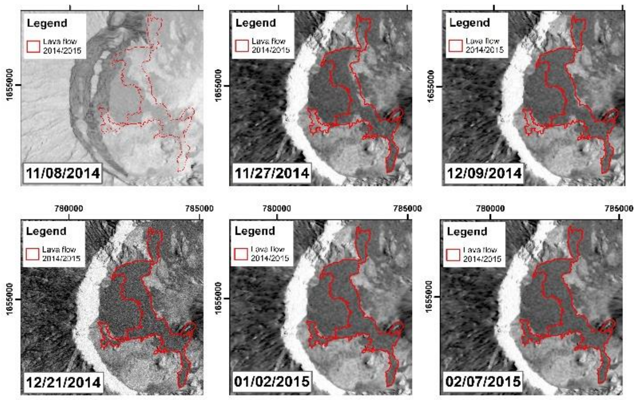

Figure 3. Level-1 GRD S1 multitemporal data used to illustrate the progression of the lava flow during the 2014/15 eruption.

In Figure 4, it is possible to note that some of the areas previously observed as affected by the 2014/15 lava flow were not identified in the change detection procedures with GRD data. It might be explained by the fact that there were no substantial roughness changes in the overlap area of 2014/15 lava flow with that of 1995 which occured at Chã das Caldeiras, as exposed by Bignami et al., (2020).

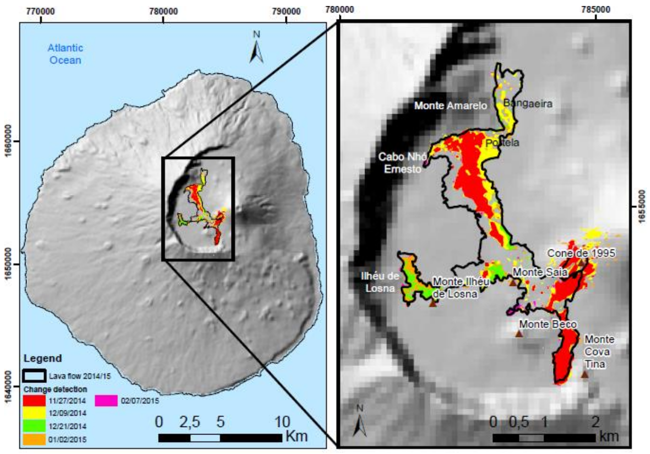

Figure 4. Changes detected with S1 GRD data throughout the 2014/15 eruptive event

The values of the total area affected by the lava flow were estimated to be approximately 3.89 km^2. The result is in relative agreement with other authors' findings when applying different techniques (Table 2).

Table 2. Total areas affected by the 2014/15 eruption, according to different authors

Area (km^2)	Reference
5,42	Cappello et al., (2016)
4,85	Richter et al., (2016)
4,97	Bignami et al., (2020)
4,8	Bagnardi et al., (2016)
4,53	Vieira et al., (2021)

The use of cloud-based platforms (e.g., GEE) allows their users to instantly access and analyze geospatial data through web interfaces (Gorelick et al., 2017). The user accesses all the cloud-hosted data without having to download the data of interest, in addition to the possibility of developing custom algorithms based on Python and JavaScript (JS) Application Programming Interfaces, which greatly reduces the computational constraint on the part of users (Navarro, 2017; Kumar & Mutanga, 2018; García et al., 2018).

A JS-based application was generated in GEE platform using a code by Google (2021) and adapted in order to compare the GRD images of S1 referring to the area affected by the lava flows resulting from the eruptive event. The data filtering parameters used in the JS script were applied to the GEE-based data collection entitled 'COPERNICUS/S1_GRD', with VV polarization corresponding to the IW mode.

The images in this application refer to the period from October 2014 to February 2015 (Fig. 5).

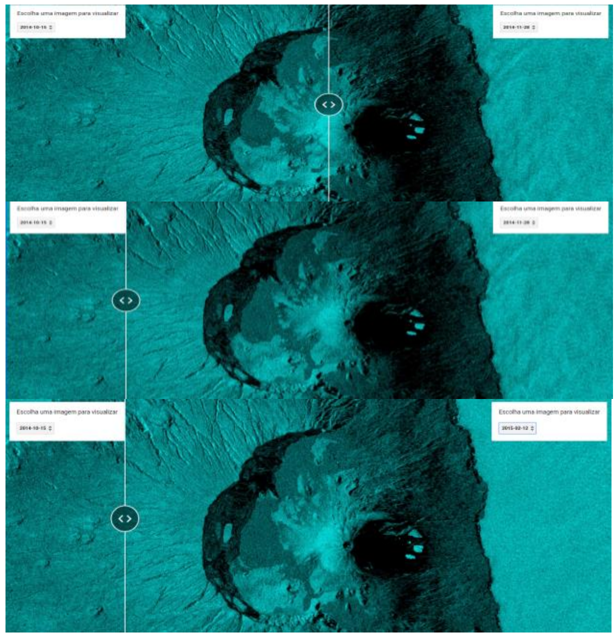

Figure 5. GEE-based application using S1 GRD data to observe the path of lava flows during the eruptive event. Above) Image from October 15th (2014) in a scenario prior to the eruption. Middle) Image from November 27th (2014) corresponding to the first hours of the eruptive event. Below) image from February 12th (2015) showing a post-eruption scenario. Application available at: <https://rafaelaptiengo.users.earthengine.app/view/fogocomparision>.

By selecting an image from before and after the eruptive event, the app is able to show the surface changes caused by the lava flow.

The use of GEE proves to be, therefore, a great asset to ensure greater speed of response, since it presents results in a matter of minutes after the script development.

4. Conclusion

Monitoring surface changes during eruptive events using S1 GRD data proved cost-effective in terms of data processing and analysis, with lower computational cost, and results consistent and coherent with those previously obtained with S1 SLC data or other types of

SAR data (including commercial high spatial resolution sensors). Therefore, this approach is pertinent and suitable for research but is especially valuable to integrate low-cost monitoring systems of active volcanic areas in near-real-time. The systematic use of GRD products can thus serve as the basis for event monitoring that confers greater agility in computation and analysis time for decision support. Furthermore, with the availability of the no-cost computing power provided by the GEE platform, and being GRD the only S1 data type currently available in the GEE catalog, this methodological approach can be considered as pertinent and cost-effective for supporting near-real-time monitoring and crisis management in active volcanic areas.

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