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Forecasting of thermal behavior of lava fountains with the synergic use of multi-sensor satellite data

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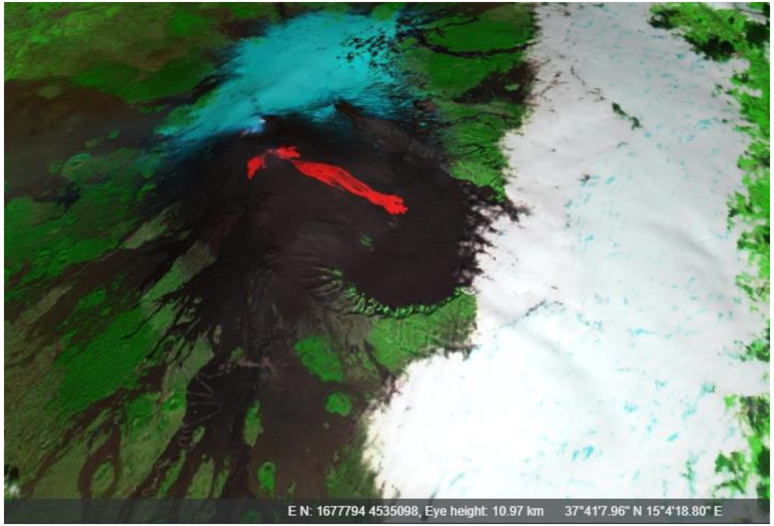
MOTIVATIONS

Infrared radiometers on-board of **geostationary and polar satellites** orbiting around the Earth are increasingly used to measure radiance from high-temperature volcanic features worldwide, whose released energetic content is quantified by the **volcanic radiative power (VRP).**

- **Geostationary** satellite sensors offer high temporal resolution → **accurate temporal information** of the monitored volcanic phenomena, such as the exponential decay factor of a lava fountain cooling curve.
- **Polar** satellite sensors offer mid-high spatial resolution → **accurate spatial information** such as the areal extent of the volcanic thermal anomaly.

Our goal is **forecasting the thermal behavior** of the long sequence of lava fountains occurred at Mt. Etna between February and March 2021 by combining the temporal and spatial features provided by geostationary and polar satellite sensors respectively.



INTRODUCTION

Infrared radiometers on-board of **geostationary and polar satellites** orbiting around the Earth are increasingly used to measure radiance from high-temperature volcanic features, whose released energetic content is quantified by the **volcanic radiative power (VRP).**

HOTSPOT DETECTION
identification of pixels occupied by volcanic thermal anomalies.

- **Spatial-based (or contextual) algorithm**
- **Temporal-based algorithm**
- **Spectral-based algorithm**
- **Machine Learning algorithm**

VRP RETRIEVAL

For each hotspot pixel, the VRP is calculated using the **MIR radiance approach** of Wooster [2003]

$$VRP_{TOT} = \frac{\sigma \cdot \varepsilon \cdot A}{a \cdot \varepsilon_{MIR}} \sum \left(L_{MIR} - L_{\mathrm{MIR,bg}} \right)$$

σ: Stefan-Boltzmann constant
ε: emissivity
A: pixel ground sampling area (m^2)
a: constant derived from empirical best-fit relationships
L_{MIR}: spectral radiance in the MIR band
L_{MIR}, bg: spectral radiance in the MIR band of background

INTRODUCTION

SUN-SYNCHRONOUS POLAR-ORBITING SATELLITES

A polar-orbiting satellite pass over both poles of Earth, from north to south. Polar orbits are a type of low Earth orbit, as they are at low altitudes between 200 to 1000 km.

Sun-synchronous orbit is a particular kind of polar orbit which allows the satellite to be synchronous with the Sun, this means that the satellite always visits the same spot at the same local time.

GEOSTATIONARY SATELLITES

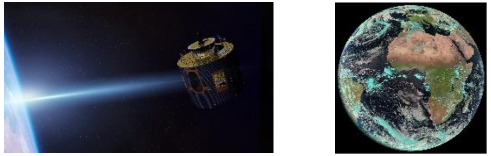
A geostationary satellite is located in an equatorial position and, unlike the polar one, it always observe the same area and revolves in the same direction the earth rotates (west to east). It is placed at an altitude of approximately 35800 km and, at this altitude, one orbit takes 24 hours.

Sentinel-3

Suomi-NPP

NOAA-20

Meteosat Second Generation (MSG)



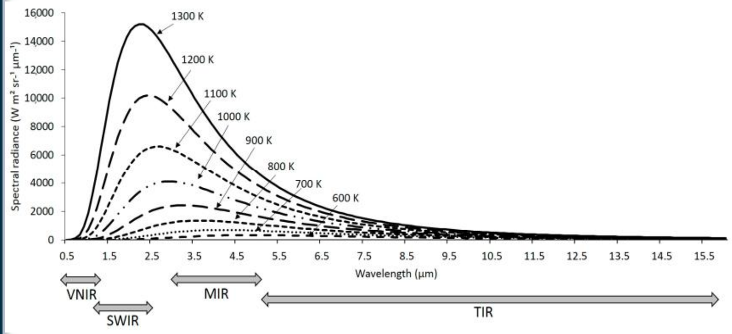
GET ACCURATE SPATIAL INFORMATION

Areal extent of the volcanic thermal anomaly

GET ACCURATE TEMPORAL INFORMATION

Exponential decay factor of a lava fountain cooling curve

SATELLITE DATA SOURCE



Nowadays, space agencies make available processed satellite data free of charge. In particular, specific geophysical parameter values are usually derived using models and auxiliary datasets, these are named **Level-2 products**.

The **Fire Radiative Power (FRP) Level-2 Products** measure the rate at which a thermally active area is emitting radiative energy.

SENSOR	SATELLITE	CHARACTERISTICS	DATA TYPE
Spinning Enhanced Visible and Infrared Imager (**SEVIRI**)	ESA Meteosat Second Generation geostationary satellite	12 bands: VNIR-TIR Resolutions: 1000 - 3000 m	Radiative power from LAV@HAZARD
Moderate Resolution Imaging Spectroradiometer (**MODIS**)	NASA Terra and Aqua satellites polar satellites	32 bands: VNIR-MIR-TIR Resolutions 250, 500 and 1000 m	Radiative power from LAV@HAZARD
Visible Infrared Imaging Radiometer Suite (**VIIRS**)	NASA Suomi-NPP and NOAA-20 polar satellites	22 bands: VNIR-SWIR-TIR Resolutions: 375 - 750 m	Level-2 FRP Product from LANCE/FIRMS
Sea and Land Surface Temperature Radiometer (**SLSTR**)	Sentinel-3A and Sentinel-3B polar satellites	11 bands: VNIR-SWIR-TIR Resolutions: 500 – 1000 m	Level-2 FRP Product from Copernicus Open Access Hub

METHODS: FastVRP platform

GRAPHIC INTERFACE

start_date: 2021 / 02 / 16

end_date: 2021 / 04 / 01

latitude_min: 37.64

latitude_max: 37.835

longitude_min: 14.87

longitude_max: 15.069

SLSTR_Sentinel3: ☑

VIIRS_Suomi: ☑

VIIRS_Noaa20: ☑

output_filename: "results_Etna.xlsx

MAIN

Set the time interval and the coordinates in the graphic interface

Use the **API to send a request** to remote web server for retrieving active fire data

Check the interval time choosen by the user

VIIRS	SLSTR
- **Download** Level-2 FRP Products	- **Check** the Coordinates choosen by the user
- **Check** the Coordinates choosen by the user	- **Download** Level-2 FRP Products

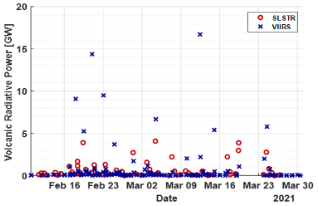
Sum the filtered values, in order to obtain a final and unique VRP value for each acquisition

RESULTS

Excel File

	A	B	C	D
1	Data	SLSTR S-3 [GW]	VIIRS-Suomi [GW	VIIRS-Noaa20 [GW
121	01/02/2020 01:00		0,0478	
122	01/02/2020 01:48			0,1303
123	01/02/2020 11:30			0,0543
124	01/02/2020 23:48			0,0205
125	02/02/2020 00:42		0,0792	
126	02/02/2020 01:30			0,142
127	02/02/2020 11:12			0,0178
128	02/02/2020 12:00		0,115	
129	02/02/2020 12:54			0,1006
130	03/02/2020 00:24		0,0496	
131	03/02/2020 01:12			0,0782
132	03/02/2020 12:36			0,1024
133	04/02/2020 00:00		0,0134	
134	04/02/2020 00:54			0,074

Graphic Plot



FastVRP is an entry-level, cloud-based platform developed in **Google Colab** that leads to an automatic and fast retrieve and process of Level-2 FRP Products to detect and measure the heat radiation released during volcanic activity.

VRP values are retrieved by using Level-2 FRP Products derived from VIIRS and SLSTR.

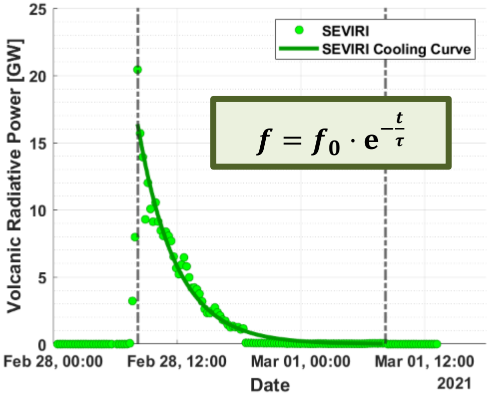
SENSOR	FIRE DETECTION BANDS		ACTIVE FIRE DETECTION ALGORITHM	CONSTANT FOR THE VRP CALCULATION $[W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1} \cdot K^{-4}]$	REFERENCE
	MIR	TIR			
VIIRS	I4→saturation: 367K, resolution: 375 m M13→saturation: 634K, resolution: 750 m	I5→saturation: 380K, resolution: 375 m M15→saturation: 330K, resolution: 750 m	VIIRS active fire detection algorithm	VIIRS-I: $a = 3.21 \cdot 10^{-9}$ VIIRS-M: $a = 2.88 \cdot 10^{-9}$	[Zhang et al., 2017]
SLSTR	S7→saturation: 323 K, resolution: 1000 m F1→saturation: 500 K, resolution: 1000 m	S8→saturation: 321 K, resolution: 1000 m F2→saturation: 400 K, resolution: 1000 m	SLSTR active fire detection algorithm	$a = 3.327 \cdot 10^{-9}$	[Xu et al., 2021; Wooster et al., 2012]

METHODS: Forecasting of thermal behavior of lava fountains

The thermal waveform during a lava fountain is made by an initial phase of sharp increase in heat fluxes, which reach a peak corresponding to the main fountaining activity, and a subsequent phase characterized by waning heat flux associated with the slow cooling of the lava overflowed from the crater rim. This thermal behavior is described by the so called **cooling curve** [Ganci et al., 2012]. High temporal resolution thermal data, like SEVIRI data, are well suited to characterize these cooling curves, which follow a fountaining event and decay within a few hours.

Forecasting of thermal behavior of lava fountains

1 **Fitting** of SEVIRI radiative power values and calculation of the exponential decay time constant τ



2 **Reconstruction** of the cooling curves related to VIIRS and SLSTR VRP values exploiting the constant τ and two (or one) VRP values for each sensor.

3 **Validation** of the procedure comparing the results with MODIS radiative power values, since this sensor has characteristics very similar to those of VIIRS and SLSTR.

Taking:

- 2 SLSTR VRP values ($f_{(1,SLSTR)}$, $f_{(2,SLSTR)}$),
- their acquisition time ($t_{(1,SLSTR)}$, $t_{(2,SLSTR)}$)
- τ provided by SEVIRI

we can estimate the initial value $f_{(0,SLSTR)}$

$$f_{(0,SLSTR)} = \frac{f_{(1,SLSTR)} + f_{(2,SLSTR)}}{e^{-\frac{t_{(1,SLSTR)}}{\tau}} + e^{-\frac{t_{(2,SLSTR)}}{\tau}}}$$

The same procedure is applied to VIIRS data

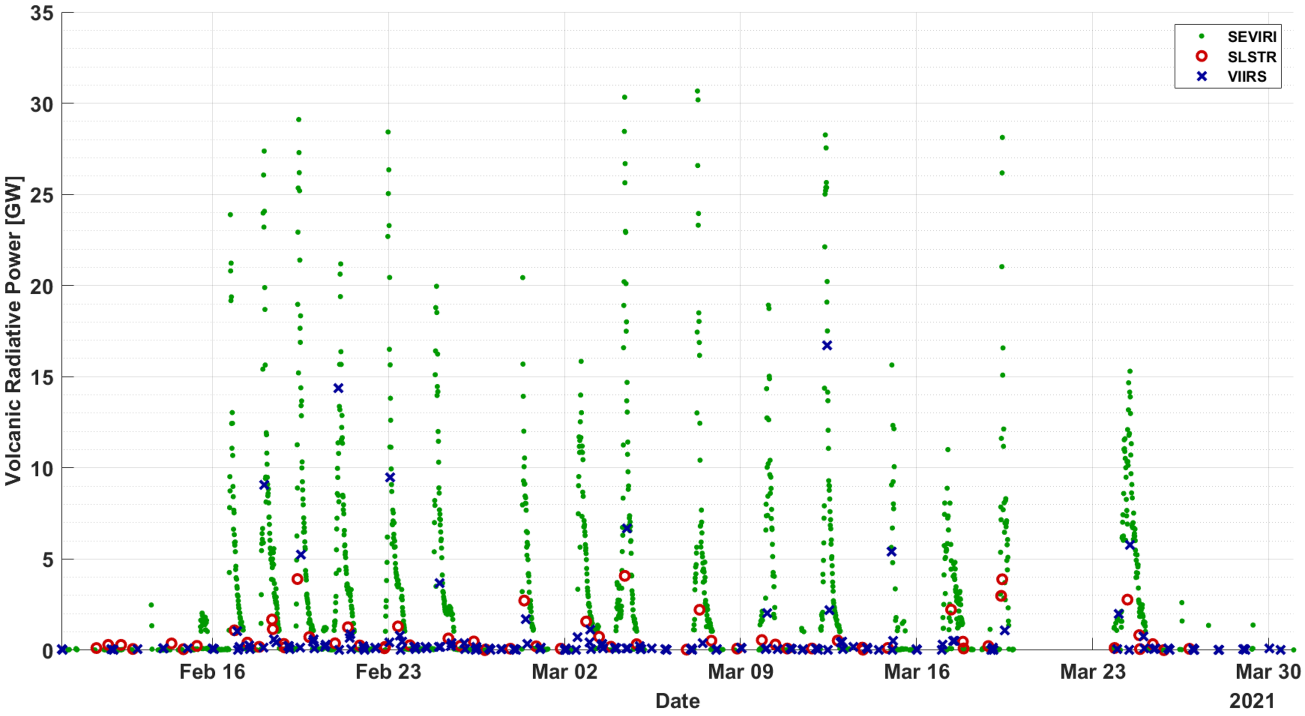
$$f_{(0,VIIRS)} = \frac{f_{(1,VIIRS)} + f_{(2,VIIRS)}}{e^{-\frac{t_{(1,VIIRS)}}{\tau}} + e^{-\frac{t_{(2,VIIRS)}}{\tau}}}$$

Moreover, taking into account the first VIIRS and the first SLSTR acquisition, we calculate the initial value $f_{(0,S\&V)}$ as follows:

$$f_{(0,S\&V)} = \frac{f_{(1,S\&V)} + f_{(2,S\&V)}}{e^{-\frac{t_{(1,S\&V)}}{\tau}} + e^{-\frac{t_{(2,S\&V)}}{\tau}}}$$

RESULTS

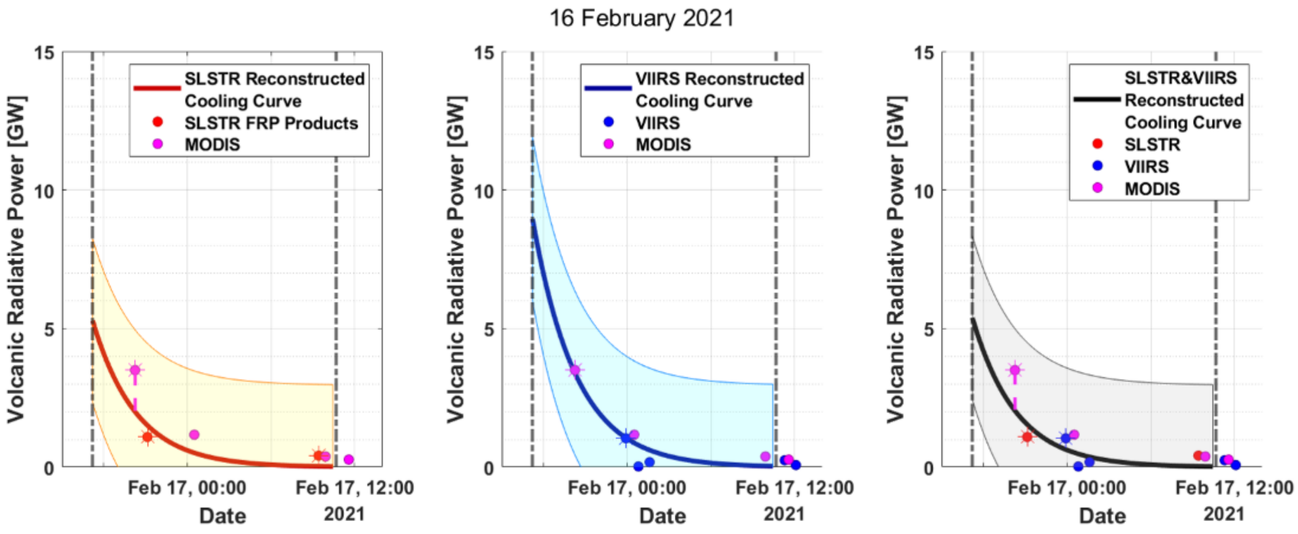
Sequence of lava fountains occurred between February and March 2021



The period of time between February and March 2021 was characterized by a sequence of **16 paroxysms** of short duration (a few hours) and high intensity, occurred with a certain regular frequency (every about 30 hours from each other).

RESULTS: 16 February 2021

Interval time fitting SEVIRI [h]	17.25
τ from fitting SEVIRI (·10⁴)	1.13
$f_{(0,SEVIRI)}$ from fitting SEVIRI [GW]	22.85
Estimation of $f_{(0,SLSTR)}$ [GW]	5.28
Estimation of $f_{(0,VIIRS)}$ [GW]	8.96
Estimation of $f_{(0,SLSTR\&VIIRS)}$ [GW]	5.39

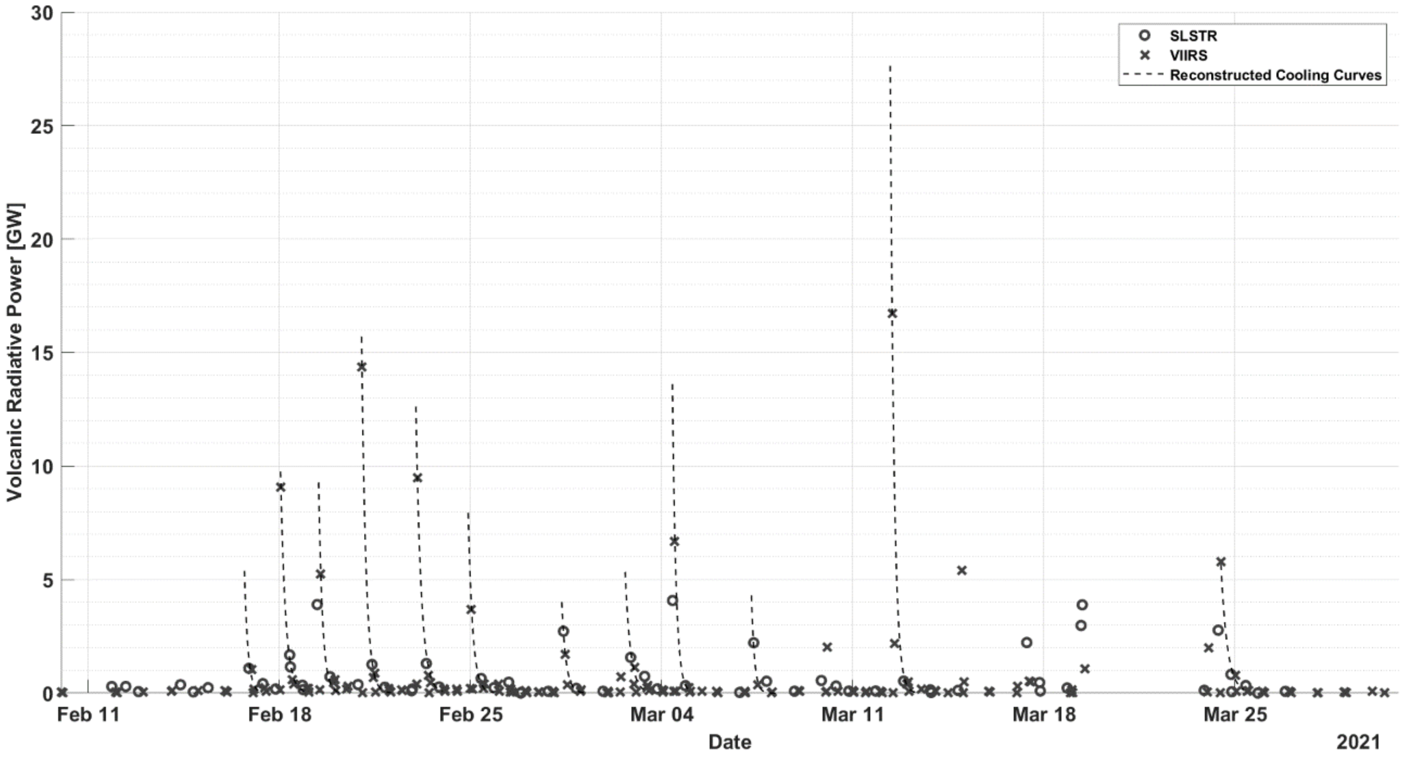


MODIS		SLSTR		VIIRS		SLSTR&VIIRS	
Acquisition time	**VRP value [GW]**	**VRP reconstructed value [GW]**	**Distance from MODIS [GW]**	**VRP reconstructed value [GW]**	**Distance from MODIS [GW]**	**VRP reconstructed value [GW]**	**Distance from MODIS [GW]**
16/02/2021 16:15	3,50	2,03	1,47	3,44	0,06	2,07	1,43

RESULTS

The **reconstruction procedure** considering both VIIRS and SLSTR polar sensors permitted to **forecast the cooling curves** of the overall sequence of the lava fountains occurred at Etna between February-March 2021.

VIIRS and SLSTR VRP values retrieved by FastVRP are exploited together with the SEVIRI data to apply the fitting procedure and then to reconstruct the cooling curves of the lava fountains sequence thanks to the **retrieved synthetic data.**

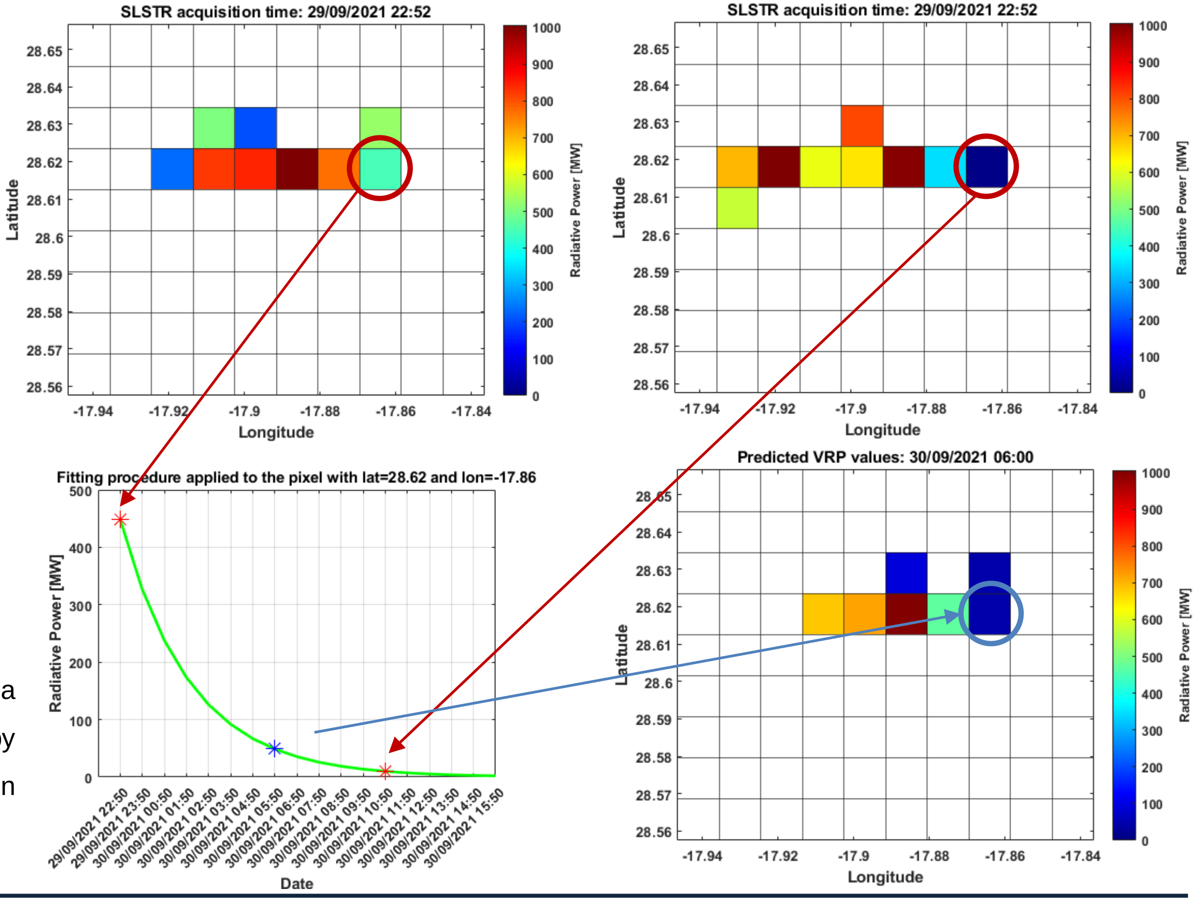


FUTURE WORKS

Goal: the reconstruction of the spatial map of the hotspots pixels using the fitting procedure and exploiting the good spatial resolution of polar sensors.

Sentinel-2 L2A 30/09/2021 12:00

Cumbre Veija volcano is situated in La Palma Island and in 2021 was characterized by different volcanic eruptions, which began on 19 September and ended on 13 December.



CONCLUSIONS

- A novel approach to forecast the thermal behavior of a lava fountain with the synergic use of multi-sensor satellite data was proposed. In particular, we combined the **accurate spatial features provided by the polar satellite sensors VIIRS and SLSTR** and the **temporal features provided by the geostationary satellite sensor SEVIRI**.

- The synthetic data obtained from VIIRS and SLSTR were used to reconstruct the cooling curves of each lava fountain, starting from the SEVIRI exponential decay calculated for each of these.

- This approach wants to improve and make more accurate the quality of the radiative power estimates.

- Future steps will be in exploiting the good spatial resolution of polar sensors so as to predict not only the total radiant power emitted, but also to locally predict the VRP and thus reconstruct the spatial map of hot spots.


Thanks for your attention
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