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Data Descriptor

Satellite-Based Reconstruction of the Volcanic Deposits during the December 2015 Etna Eruption

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Abstract: Satellite-derived data, including an estimation of the eruption rate, proximal volcanic deposits and lava flow morphometric parameters (area, maximum length, thickness, and volume) are provided for the eruption that occurred at Mt Etna on 6–8 December 2015. This eruption took place at the New Southeast Crater (NSEC), the youngest of the summit craters of Etna, shortly after a sequence of four violent paroxysmal events took place in 65 h (3–5 December) at "Voragine", the oldest summit crater. Multispectral SEVIRI images at 15 min sampling time have been used to compute time-averaged eruption rate curves, while tri-stereo Pléiades images, at 50 cm spatial resolution, provided the pre-eruptive topography and topographic changes due to volcanic deposits. In addition to the two types of satellite data, other parameters have been inferred, such as probable vesicularity and pyroclastic deposits.

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Keywords: Etna volcano; satellite remote sensing; SEVIRI; Pléiades imagery; digital elevation model

1. Summary

The increased availability of a multitude of satellite data opens new frontiers for volcano monitoring [1]. Nowadays, thanks to infrared satellite data, such as the ones acquired by most satellites for weather forecasting, it is possible to detect and characterize thermal anomalies on active volcanoes worldwide. Owing to middle infrared bands, extreme thermal events, such as volcanic eruptions, can be detected and analyzed. By using multiple bands, i.e., multiple wavelengths, it is possible to characterize a single pixel by retrieving subpixel portions at different temperatures and hence computing the radiant heat flux associated with a thermal event [2]. This radiant heat flux, if related to a lava flow, can be converted in time averaged discharge rate (TADR), i.e., an estimation of the rate of emission of the flow [3].

Optical satellite imagery, especially at sub-meter spatial resolution, has also recently been a useful tool to produce digital topographic data [4]. The new generation of Earth observation satellites has the ability to increase acquisition capacity, allowing nearby areas to be acquired during the same orbit at multiple views, i.e., from different incidence angles [5]. This aspect greatly improves the 3D mapping of the Earth surface from optical satellite images allowing the generation of very high-resolution digital elevation models [6].

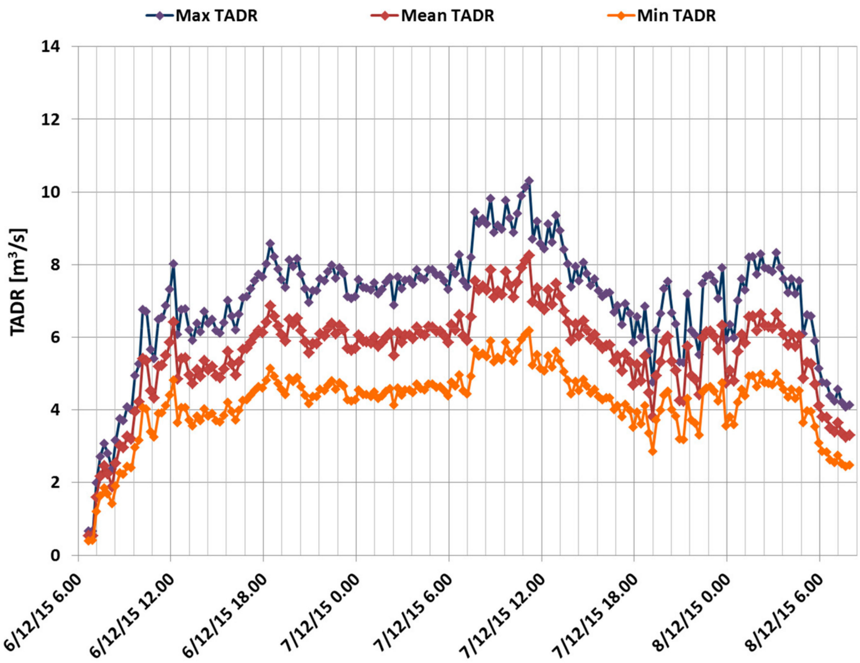
Here we combine high spatial resolution visible data with high temporal resolution infrared data to produce a complete characterization of volcanic deposits. We employ the HOTSAT thermal monitoring system [7,8] in order to retrieve TADR and lava flow volumes that erupted on 6–8 December 2015 at Mt Etna.

Moreover, we use the MicMac code (http://micmac.ensg.eu) to process Pléiades data and obtain pre- and post-eruptive digital elevation models, from which we derive bulk volumes. We thus provide DEMs, TADR curves and volumes estimates to be used to control lava flow morphological parameters, infer a minimum magma supply rate, and assist computer simulations of lava flow paths for hazard assessment studies.

2. Data Description

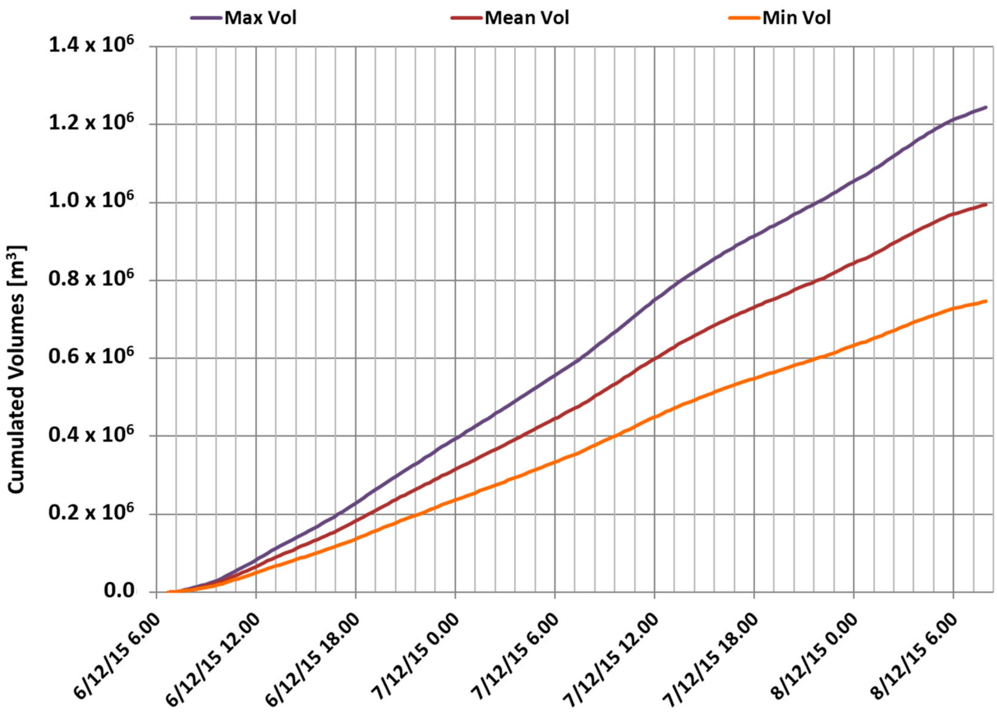
TADR curves are provided as tab delimited text file (Supplementary Material, TADR&Volume.txt), with the following format: date expressed in Greenwich Mean Time (GMT) as dd/mm/yy hh.mm; minimum, mean and maximum value for TADR expressed in m^3/s; minimum, mean and maximum value for cumulative volume in m^3.

We found a nearly constant TADR with a maximum value of 10.3 m^3/s that occurred on 7 December at 11:12 GMT. By integrating TADR curves, we found a dense rock equivalent (DRE) volume of $0.99 \pm 0.25 \times 10^6$ m^3 (Figure 1).



(**a**)

Figure 1. *Cont.*

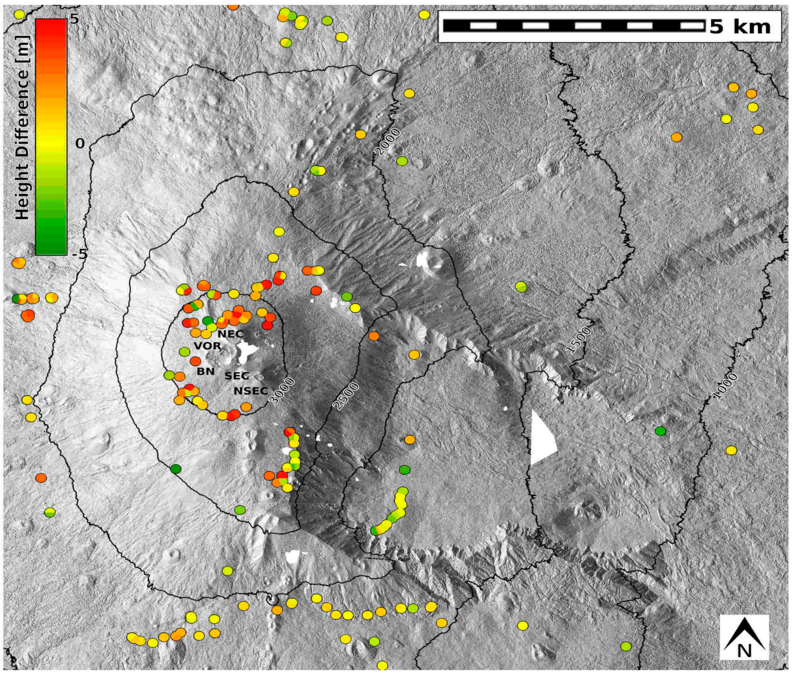


(**b**)

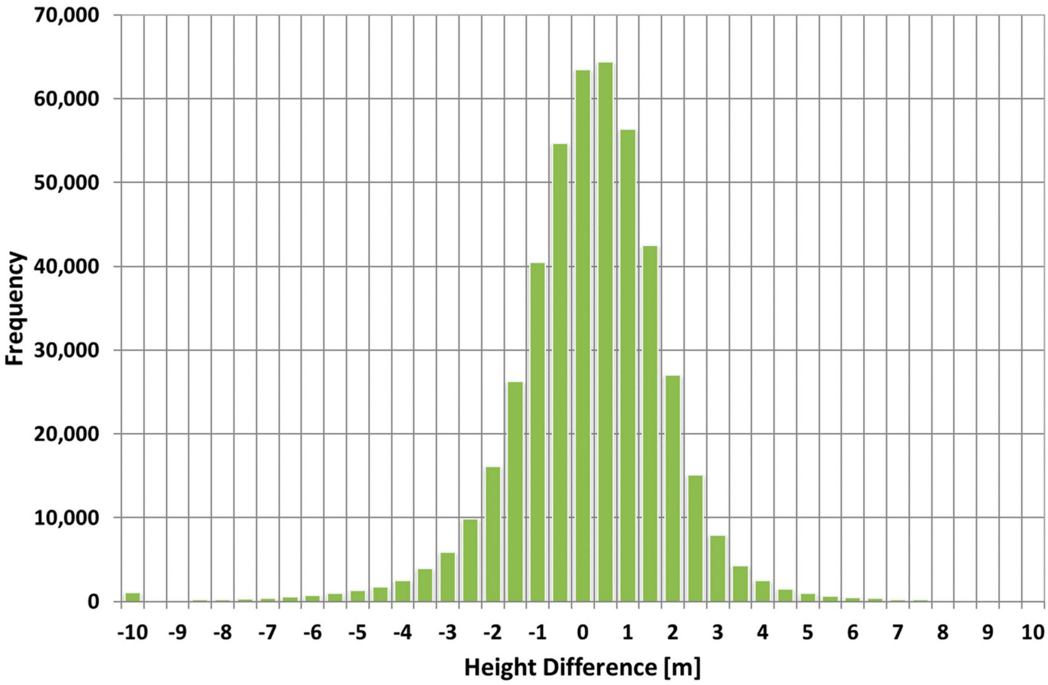
Figure 1. Minimum (orange), medium (dark red) and maximum (violet) estimates for (**a**) TADR and (**b**) cumulative volume computed from 6 to 8 December 2015 by HOTSAT using SEVIRI data.

Pre-eruptive DEM is provided as GEOTIFF (Supplementary Material, Pre-eruptive_DEM.tiff), with elevations in meters relative to the UTM 33North projection, WGS84 Datum (EPSG: 32633). It has a spatial resolution of 2 m spanning an area of about 15 × 15 km, which covers the summit craters area and a portion of the south-east flank of the volcano, including the Valle del Bove depression. The highest point of 3359 m is on the south rim of the North East Crater (NEC), while the South East Crater (SEC) and New South East Crater (NSEC) reach an elevation of 3335 m and 3322 m, respectively.

The residuals between the pre-eruptive DEM and GPS Ground Control Points (GPCs) (more than 200) available on Etna volcano (Figure 2) are provided in a tab delimited text file (Supplementary Material, Residuals_GPC&DEM.txt), in the following format: Easting, Northing expressed in meters in UTM 33 North projection, WGS84 Datum (EPSG: 32633) and elevation difference in meters.



(**a**)



(**b**)

Figure 2. (**a**) Spatial distribution of the GPS GCPs used to validate the Pleiades-derived pre-eruptive DEM. Colors represent the height difference between the GCPs and the corresponding pixels of the DEM. The five summit craters of Etna are highlighted: NEC (North-East Crater), VOR (Voragine), BN (Bocca Nuova), SEC (South-East Crater) and NSEC, (New South-East Crater); (**b**) Histogram of the residuals, peaking at 0.94 m, with a standard deviation of 1.63 m, representing the vertical accuracy of the DEM.

The 3D mapping of volcanic deposits is provided as GEOTIFF (Supplementary Material, 3D_deposits.tiff), with elevations in meters relative to the UTM 33 North projection, WGS84 Datum

(EPSG: 32633). The deposits due to the lava flow emplacement of the NSEC eruption that started on 6 December cover an area of about 514×10^3 m^2, with a maximum length of 3.9 km (Figure 3). The minimum, median, and average thicknesses, computed from DEMs difference, are 1.00 m, 4.81 m, and 5.31 m, respectively. The lava flows represent most of the emplacement (435×10^3 m^2), accounting for 86% of the volume of the total deposit, with a bulk volume of $2.35 \pm 0.85 \times 10^6$ m^3. The deposits proximal to the NSEC, including both lava and loose materials, reach maximum thickness of 20.39 m, with a bulk volume of $0.38 \pm 0.08 \times 10^6$ m^3.

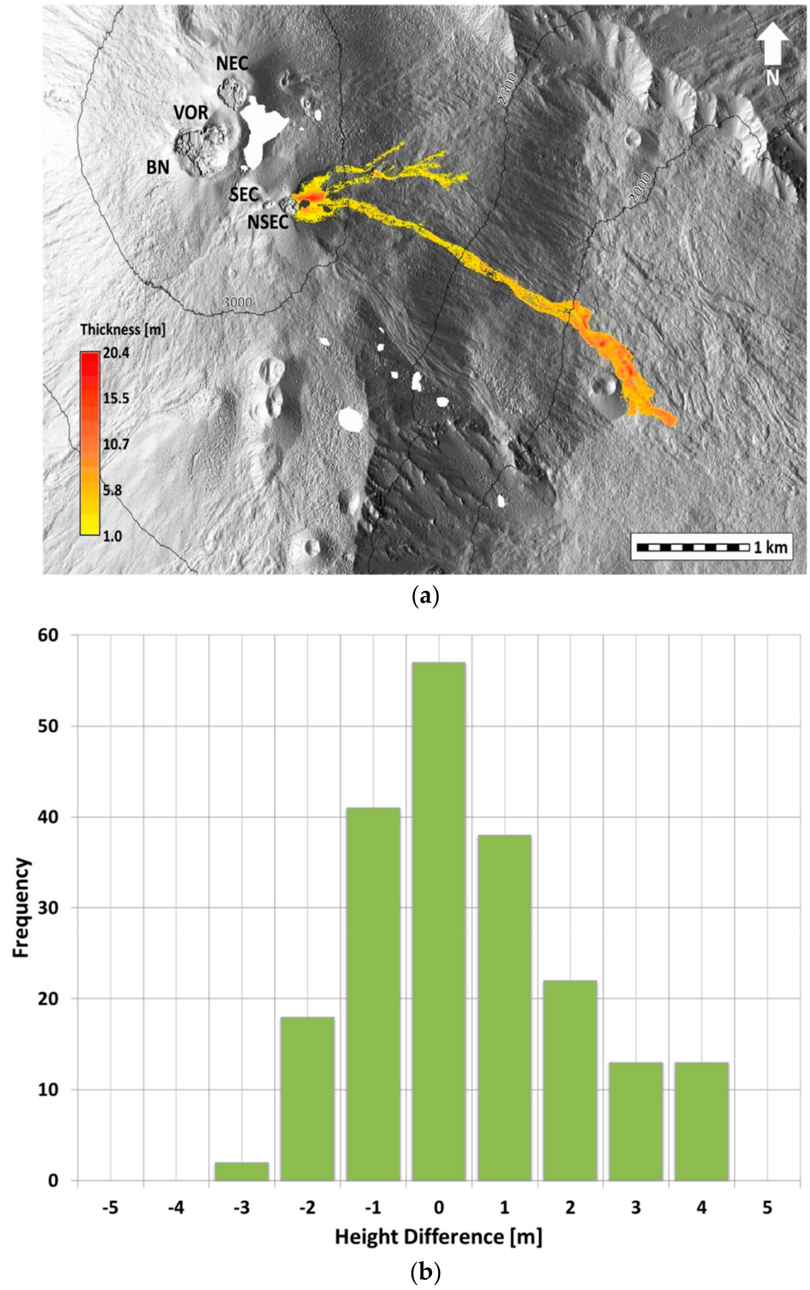


Figure 3. (**a**) Elevation change obtained by differencing the two DEMs derived from Pleiades images acquired before and after the December 2015 Etna eruptions. The colors indicate flow thickness in meters inside the lava flow fields. The five summit craters of Etna are highlighted: NEC (North-East Crater), VOR (Voragine), BN (Bocca Nuova), SEC (South-East Crater) and NSEC, (New South-East Crater); (**b**) The zero-peaked histogram of the terrain residuals, proving that the two DEMs are properly aligned.

The main volcanological quantities (thickness, area and volume) for the proximal deposits around the cone and the lava flows are reported in Table 1.

Table 1. Thickness, area and bulk volume of the cone and the lava flows identified from the difference between post- and pre-eruptive DEMs. The uncertainty ranges for the estimation of the minimum and maximum volumes was estimated as the product between each area and the standard deviation calculated outside the area of the deposits (i.e., 1.96 m).

Deposit	Thickness [m]		Area [m^2]	Volume [$\times 10^6$ m^3]		
	Mean	Max		Min	Mean	Max
Cone	4.81	20.39	79,024	0.23	0.38	0.53
Flows	5.40	20.09	435,276	1.50	2.35	3.20
Total	5.31	20.39	514,300	1.73	2.73	3.73

SEVIRI data processing provides an estimation of the radiating portion of the volcanic deposits, while DEM difference provides an estimation of the whole deposit expressed as bulk. From a comparison between the DRE volumes found from SEVIRI data and the bulk volumes obtained from DEM difference, it is possible to infer as probable estimate of the DRE lava flow volume the maximum value of the TADR, i.e., 1.2×10^6 m^3 and as for the bulk the minimum value obtained from DEM difference, i.e., 1.5×10^6.

Comparing these values, we obtain a vesicularity of 18–20% for the lava.

3. Methods

SEVIRI data were processed using the HOTSAT satellite thermal monitoring system [7,8]. The HOTSAT system was designed to ingest multispectral satellite data in order to retrieve thermal anomalies (hotspot) associated with the volcanic activity. The system finds the thermally anomalous pixels relying on a two-step contextual algorithm, which means that it finds a threshold inside the image in an area considered as "Non Volcanic". Whether a hotspot is found, the system provides information about the magnitude of the thermal anomaly in terms of radiant heat flux, by using the MIR radiance approach [9]. Adding up the radiant heat flux obtained from each pixel, a total radiant heat flux is found. In case of effusive eruptions, the radiant heat flux can be converted to TADR [2].

Here, the HOTSAT system is applied to imagery acquired by the Spinning Enhanced Visible and Infrared Imager (SEVIRI) flown on the Meteosat Second Generation satellites, which provides data every 15 min at a spatial resolution of 3 km at nadir. SEVIRI data are recorded in twelve wavebands, including one in the mid-infrared and two in the thermal infrared particularly useful in detecting and tracking hot spots associated with effusive activity.

The 3D processing of the tri-stereo Pléiades imagery was performed using the free and open source MicMac photogrammetric library [10] developed by the French IGN (Institut Géographique National). The pre-eruptive DEM was derived from two triplet of Pleaides images acquired on 28 July and 5 September 2015. Since these two images have different occluded areas with cloudy pixels, we combined the processing of the two triplets by averaging the resulting heights of corresponding pixels in order to fill-in holes and discard possible blunders and errors present in the initial data.

The height accuracy of the pre-eruptive DEM was estimated by using extensive GPS Ground Control Points (GPCs) (more than 200) available on Etna volcano (Figure 2a). We compared the elevation of the pre-eruptive DEM and each of the 209 GPS points, finding residuals ranging between −2.47 and 4.68 m, with a mean value of 0.94 m and a standard deviation of 1.63 m, which represents the vertical accuracy of the DEM (Figure 2b).

By differencing the pre-eruptive DEM and post-eruptive DEM, obtained from tri-stereo Pléiades images acquired on 24 December 2015 [11], we obtained the topographic changes due to the volcanic deposits emplaced during the eruptive activity of Etna between 6 and 8 December 2015.

Furthermore, we retrieved areas, volumes and thickness distribution of the deposit emplaced out of the summit craters on 3–8 December 2015. It is worth noting that before computing their difference, we co-registered the two DEMs by applying the Nuth and Kääb algorithm [12–14], in order to minimize the errors due to misalignment. This algorithm first finds iteratively the horizontal shift between two DEMs, based on a slope-aspect method, and removes it. Then, a potential elevation-dependent error is checked and removed. Finally, higher-order biases are checked and corrected, by rotating the coordinate axis, if necessary (e.g., along/cross track corrections). Corresponding corrections, which result in a polynomial function, can then be applied.

The total volume of products, calculated by integration of the thickness distribution over the area covered by the deposit, is 2.73×10^6 m^3, with an uncertainty of 1.00×10^6 m^3, i.e., 37% of the entire volume. The uncertainty is given by the product of the area and the standard deviation of terrain residuals outside of the deposit, which is 1.96 m (Figure 3b).

Supplementary Materials: The following are available online at https://zenodo.org/record/3362925#.XUvw7I4zaUk. TADR&Volume.txt—TADR and Volume curves; Pre-eruptive_DEM.tiff—Pre-eruptive DEM; Residuals_GCP&DEM.txt—Terrain Residuals between GCP and DEM; 3D_deposits.tiff—3D Mapping of volcanic deposits.

Author Contributions: G.G. processed SEVIRI data and extracted the topography from Pléiades images. A.C. computed DEM differences and performed statistics on it. G.B. computed DEM accuracy and performed the statistical analysis on the comparison with GPS ground control points with the contribution of C.C., C.D.N. coordinated the research.

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Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the collection and analysis of satellite data, and in the writing of the manuscript.

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