Biennial report for Permanent Supersite/Natural Laboratory

Mt. Etna Supersite: June 2020 – June 2022

History	***https://geo-gsnl.org/supersites/permanent-supersites/mt-etna-volcano-supersite/***
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1. Abstract

Mt. Etna is one of the most active volcanoes on Earth that in the past few decades has erupted virtually every year. The current Etnean volcanism results from the interaction between magma ascent in the rather complex plumbing feeding system and the local tectonic regime controlled by the volcano edifice's eastern flank instability, whose driving conditions (e.g., structural setting, tectonic forces) and cause-effect relationships are not completely understood yet. At the surface, the combination of the two factors produces eruptions along fissures that open on the flanks (e.g., in 2001, 2002-03, 2004-05, 2018) or at the one or more of the four summit craters (e.g., in 2011-'13; 2015; 2021-'22). Eruptions might be either strongly explosive (e.g., in 2002; 2011-'13; 2015; 2021-'22) or quietly effusive (e.g., in 2004-05). Explosive eruptions have produced volcanic ash plumes, sometime reaching also the stratosphere, that likely disrupt air traffic for hours to weeks (e.g., 5 January 2012), whereas effusive eruptions have fed lava flows capable of invading the populated areas of the volcano edifice, thus threating human property and vital infrastructures. Flank eruptions are often linked to seismic swarms with thousands of earthquakes having maximum magnitude of medium intensity (Mw = 4-5) and local severe damages to artifacts.

During the reporting period, the dynamic of the volcano was dominated by the activity at the summit craters. In particular, more than sixty paroxysmal episodes occurred at the New South East Crater (NSEC) characterized by lava flows, strombolian explosions, often evolving to lava fountains and forming sustained volcanic plumes. Furthermore, a few very small effusive events occurred in the Valle del Bove.

In this context the scientific production was focused on the analysis and interpretation of EO data related to these events and their effects (e.g. the morphological variation in the summit area). Beside the scientific objective, Mt. Etna Supersite data (both EO and in-situ) were largely used to support the volcano surveillance and the activity of the Italian Civil Protection (both at local and regional level).

During the reporting period, the management of the Etna Supersite suffered from the limitations due to the pandemic COVID-19. Despite that, the working group managed the evolution of the data portal (see Section 3) and the participation to the GEO-GSNL initiative. Furthermore, some focused actions have been activated to encourage the participation of the Mt, Etna Supersite in new national and European projects.

2. Scientists/science teams

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Scientists/science teams issues

The science team is largely a legacy of the EC-FP7 MEditerranean SUpersite Volcanoes (MED-SUV) project. Indeed, most of the participants listed above had declared the interest in using the Supersite data and thus, they are registered users of the MED-SUV portal, as well as of the EO data sets that require proper registration (e.g. CSK or TSX data). The main issue concerns the capacity to maintain an adequate level of cooperation and scientific benefit in the future, and possibly to enlarge the number of users, although the lack of steady financial support. To face this issue, the team has encouraged the exploitation of the Mt. Etna Supersite resources and the use of the MED-SUV data portal in the framework of international and national projects and initiatives. This is the case of EUROVOLC project, just finished, as well as the EPOS and ENVRI infrastructures and related projects. This point will be detailed in section 7 of this report.

3. Data Portal

During the biennial reporting period, it was necessary to re-structure the web and data portals implemented in the MED-SUV project as the agreement among the institutions managing the portals expired. From 2020 to 2022 the IT Team planned actions concerning porting of contents and data belong to the MED-SUV Supersite project into the EPOS Volcano Observations Gateway (http://vo-tcs.ct.ingv.it/), currently under development. The actual state of the art is the following:

- The MED-SUV Data Search web portal is still running at the following link (http://med-suv.essi-lab.eu/web/portal), but this site, managed by CNR, will be dismissed at the end of August 2022. The data portal is actually hosted by the staging version of the EPOS Volcano Observations Gateway Data Hub. At the moment, part of the in situ data described in the previous report have been moved to the new platform, because the idea is to move present services into new REST services, fully compliant with EPOS requirements. For this purposes, actual services, present in the Volcano Gateway Data Hub have been realized having in mind Volcanological domains and in order to host data and metadata from different active volcanoes.
- The BRGM definitively dismissed the daily management of the MED-SUV project web portal; however the main information of the project is still available through a dedicated static web page kindly provided by BRGM (https://www.brgm.fr/en/reference-completed-project/med-suv-project-mediterranean-supersite-volcanoes). A specific section dedicated to MED-SUV Supersite portal is implemented in the Volcano Observations Gateway; all useful information concerning the Supersite project is already present into the new structure, starting from the one collected by BRGM (e.g. MED-SUV list of partners, related publications, experiments, etc.).

4. In-situ data

The in situ data are recorded from the INGV monitoring networks of Mt. Etna, which are listed below.

Seismic	Permanent:	29 stations	Mobile:	12 stations
Accelerometric	Permanent:	6 stations		
Infrasonic	Permanent:	11 stations		
GPS	Permanent:	38 stations	Periodic surveys:	80 benchm.
Leveling			Periodic surveys:	38 benchm.
Tilt & strainmetric	Permanent:	13+2 stations		
Gravimetric	Permanent:	4 stations	Periodic surveys:	106 stations
Magnetic and SP	Permanent:	9 + 3 stations		
Dilatometric	Permanent:	4 stations		
Geochemical	Permanent:	25 stations		
Visible & Thermal IR Imagery	Permanent:	14 stations		

The table below shows the in-situ available data and the access is offered through Web Rest Services. Metadata are available in the most common data format

Type of data	Data provider	How to access	Type of access
Seismic waveform	*INGV*	*Link to Network Italian Seismic Network Web Service through the Gateway Portal and EPOS Data Portal*	*Public*
Seismic events	*INGV*	*Link to Network Italian Seismic Network Web Service.* *A dedicated catalogue on Mt. Etna is provided through the Gateway Portal and EPOS Data Portal*	*Public*
GPS data	*INGV*	*Not available at the moment.* *A migration into a GLASS server is mandatory to be compliant with EPOS*	*Public*
GPS data survey (1994- 2013)	*INGV*	*provided through the Gateway Portal*	*Public*
GPS coordinates / displacement vectors	*INGV*	*Not available at the moment.* *A migration into a GLASS server is mandatory to be compliant with EPOS*	*Limited to registered users*
Hydrophone / OBS waveform	*INGV*	*Not available at the moment*	*Limited to registered users*

Thermal cameras	*INGV*	*Not available at the moment*	*Limited to registered users*
Tilt	*INGV*	*Under testing*	*Public*
Geochemical Bulk Rock Data	*INGV*	*provided through the Gateway Portal and EPOS Data Portal*	*Public*

In-situ data issues

The in-situ data are provided by INGV. They are discoverable and accessible through the e-infrastructure implemented in the framework of EC-FP MED-SUV. During the biennial reporting period it was deeply re-structured as the agreement among the institutions managing the web and data portals implemented in the MED-SUV project expired. This evolution mostly impacted on the in-situ data provision. To this aim, from 2020 to 2022 the IT Team planned actions concerning porting of contents and data belong to the MED-SUV Supersite project into the EPOS Volcano Observations Gateway (http://vo-tcs.ct.ingv.it/), currently under development. At the time of writing this report, the MED-SUV Data Search web portal is still running at the following link (http://med-suv.essi-lab.eu/web/portal), but this site, managed by CNR, will be dismissed at the end of August 2022. The data portal is actually hosted by the staging version of the EPOS Volcano Observations Gateway Data Hub. At the moment, part of the in situ data described in the previous report have been moved to the new platform, because the idea is to move present services into new REST services, fully compliant with EPOS requirements. An example of this evolution is the provision of the catalogue Mt. Etna Earthquake Parameters (2000-2019) and geochemical database, this last recently added as a new service in the Supersite portfolio. For this purposes, actual services, present in the Volcano Gateway Data Hub have been realized having in mind Volcanological domains and in order to host data and metadata from different active volcanoes.

5. Satellite data

<In the table below please list all satellite data types available for the Supersite>

Type of data	Data provider	How to access	Type of access
ERS-1/ERS-2	ESA	Direct link to http://eo-virtual-archive4.esa.int/?q=Etna or through the MED-SUV Portal	Registered public
ENVISAT	ESA	Direct link to http://eo-virtual-archive4.esa.int/?q=Etna or through the MED-SUV Portal	Registered public
Sentinel	ESA	Direct link to https://scihub.copernicus.eu or through the MED-SUV Portal	Registered public
TerraSAR-X	DLR	Direct link to https://supersites.eoc.dlr.de or through the MED-SUV Portal	GSNL scientists
COSMO-SkyMed	ASI	Through the ASI server of the MED-SUV Portal	GSNL scientists
PLEIADES	CNRS	PoC requests access from CNRS for individual users;	GSNL scientists
Landsat 8	USGS	Direct link to https://earth.esa.int/eogateway/missions/landsat-8	Registered public
AVHRR	NOAA	Direct link to http://earthexplorer.usgs.gov	Registered public
MODIS	NASA	Direct link to http://modis.gsfc.nasa.gov/data/	Open

Satellite data issues

During the reporting period, the main efforts have concerned the consolidation of the e-infrastructure to manage the data (both EO and in situ); about this activity details are in Section 3. Due to ongoing activity on the e-infrastructure, some severe issues occurred in the update of the databases, e.g., the TSX data, as well as in the addition of new type of EO data, e.g., optical data. These issues will be solved in the future as the e-infrastructure will be fully operational. A further issue was encountered in acquiring Radarsat-2 data, owing the difficulties to finalize the update of the agreement with CSA .

Furthermore, during the biennial period, some users express interest in using Pleiades data. Considering the continuous volcanic activity of the volcano, Mt. Etna Supersite is interested to include in the EO provision also one Pleiades tri-stereo acquisition / year (at minimum), of an area 20x20 Km, centered to the summit craters. Ideally, it would be more than appropriate to have a new acquisition after each main volcanic event (i.e. causing large morphological changes, as lava flow eruptions or major explosive activity).

MED- SUV Data portal described at the section "In-situ data issue", also provided a subsection of satellite data. In the recent years the agreement between ASI and ESA to distribute CSK data through the portal (https://geo-gsnl.org/access-to-cosmo-skymed-supersite-sar-imagery).

6. Research results

After a sort summary of the Mt. Etna volcanic activity, we report below recent research results based on the use of Mt. Etna Supersite data.
Additionally, here are also briefly reported results of researches carried out in the framework of national and international projects that explicitly declared their interest to scientifically support the Etna Supersites; these ancillary projects are both national (ATTEMPT) and international (EUROVOLC, e-SHAPE).

6.1. Summary of the Volcanic Activity.

During the biennial reporting period, Mt. Etna's volcanic activity consisted mostly in summit eruptions with a few small flank eruptions. From July to December 2020 the activity at the four Summit Craters was mainly degassing with short periods of strombolian activity at Bocca Nuova Crater (BNC), Nord East Crater (NEC) or New South East Crater (NSEC). On 13 December 2020, started a sequence of paroxysmal episodes at NSEC that lasted until February 2022. In the sequence may be identified two clusters of paroxysms: from February to April 2021 and from May to August 2021, characterized by very short intervals between two successive episodes (in the order of hours to days). Each paroxysmal episode is characterized by a sudden unrest of strombolian activity at NSEC, often anticipated or accompanied by emission of short lava flows from the crater, that in a few hours (at maximum one day) evolves in sustained lava fountain. For this period Calvari and Nunnari (2022) report 66 lava fountain episodes with an average duration of each episode of 2 hours (120 min) with a height of the sustained column ranging from 0,8 to 1,8 km and an average volume of magma ejected during each episode of about 1 10^6 m^3. The sustained columns form volcanic plumes that may reach stratospheric altitudes (10-12 km) during the most energetic episodes. After each lava fountain episode, usually lava flows continue to pour out from the crater or vents opened nearby the crater, for some hours or days; this phenomenon concludes the paroxysm. The sequence of paroxysms modified significantly the morphology of the NSEC and the summit area of the volcano as a whole. During the sequence of paroxysm and after it, we recorded effusion of lava flows from new vents opened in the western wall of the Valle del Bove, at different elevation, without explosive activity at the vents. The effusive episodes were modest in term of duration and volume of emitted lava. The Figure 1 summarize the activity during the biennial period.

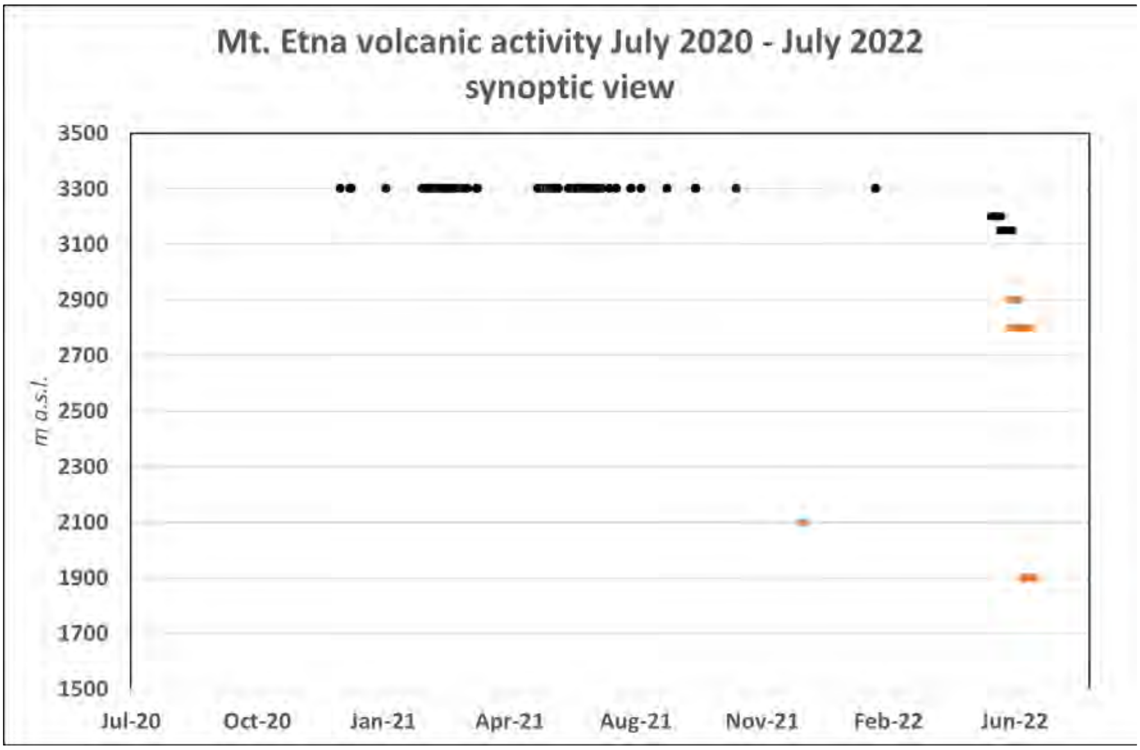


Figure 1. Summary of the volcanic activity at Mt. Etna, from July 2020 to July 2021. Black dots show the paroxysmal episodes at the NSEC; orange line shows the lava flows in the Valle del Bove area

6.2. Ground Deformations

The results of scientific researches aimed at studying the ground deformations were carried out in the framework of institutional activities of INGV and European projects.

Sentinel 1A/1B have been routinely processed in the framework of institutional activities of INGV to monitor the ground deformation related to the intense volcanic activity observed at Mt. Etna from 2020 to 2022.
For the pre-event phase, the 2020-2021 Sentinel-1A and B SAR data, acquired in descending geometry, was processed with the GAMMA-IPTA package processed using conventional PSI A-DInSAR tecnique.

The obtained mean LOS (Line Of Sigth) velocity map and the relative Time Series are reported in Figure 2, and show that the 2021 eruptive phase was anticipated by a rather continuous period of "inflation", involving the entire volcano briefly interrupted in July 2020.

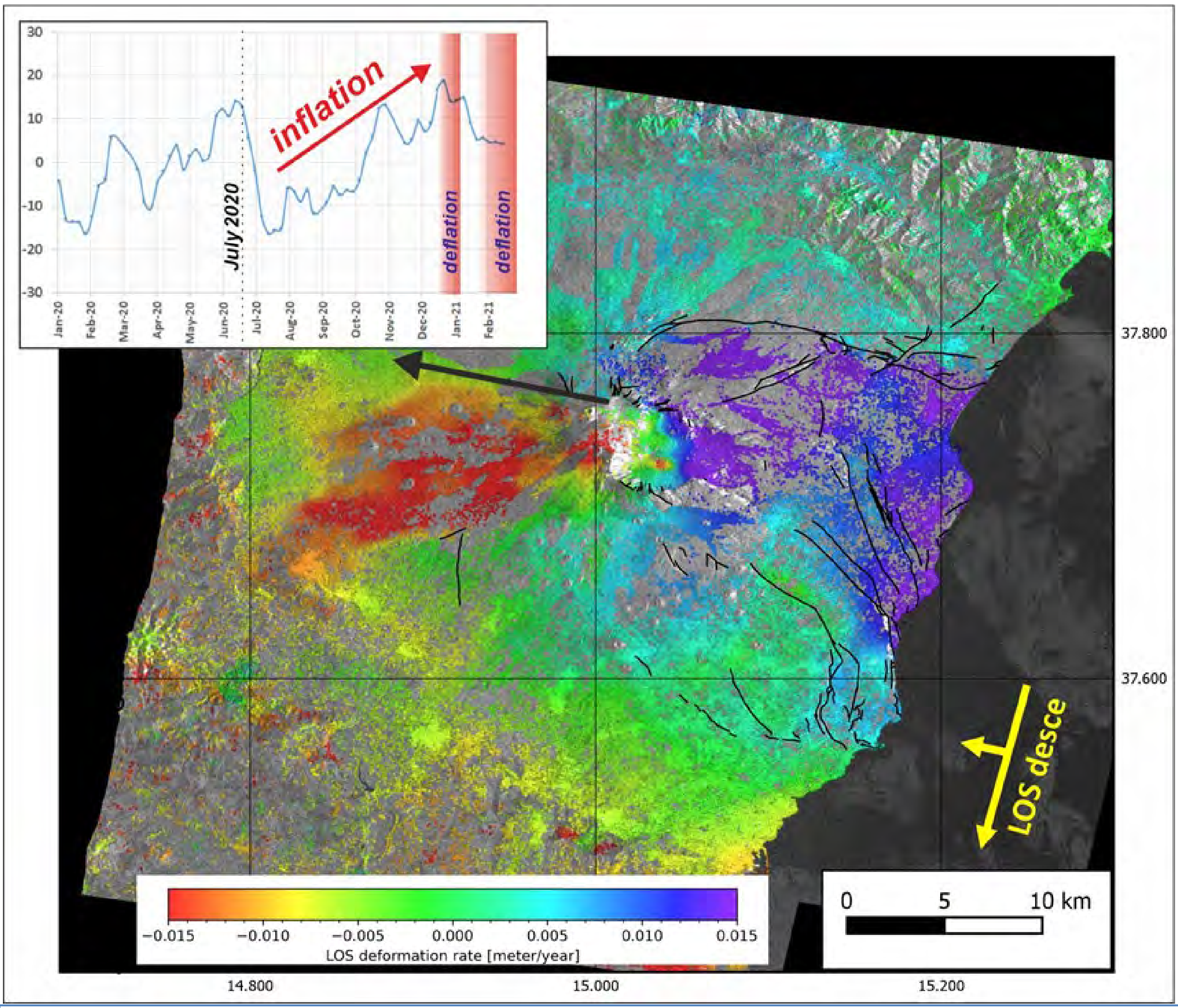


Figure 2. SENTINEL 1 A/B IPTA Advanced DInSAR Analysis. Descending Mean LOS velocity Map & Time series relevant to 2020/01/04-2021/02/21 time span. Details of the time evolution of the inflation is reported in the plot. The East flank shows the deformation related to the persistent flank motion (green-purple area).

From the end of December 2020 to March 2021 a deflation phase accompanied the start of the 2021 paroxysms of mt Etna, with about 2 fringes in moving away from the satellite. The relevant interferogram (Figure 3) imaged the cumulated deformation produced by the entire paroxysm sequence, with a strong deflation of about 6 centimeters, centered on the uppermost-western flank of the volcano.

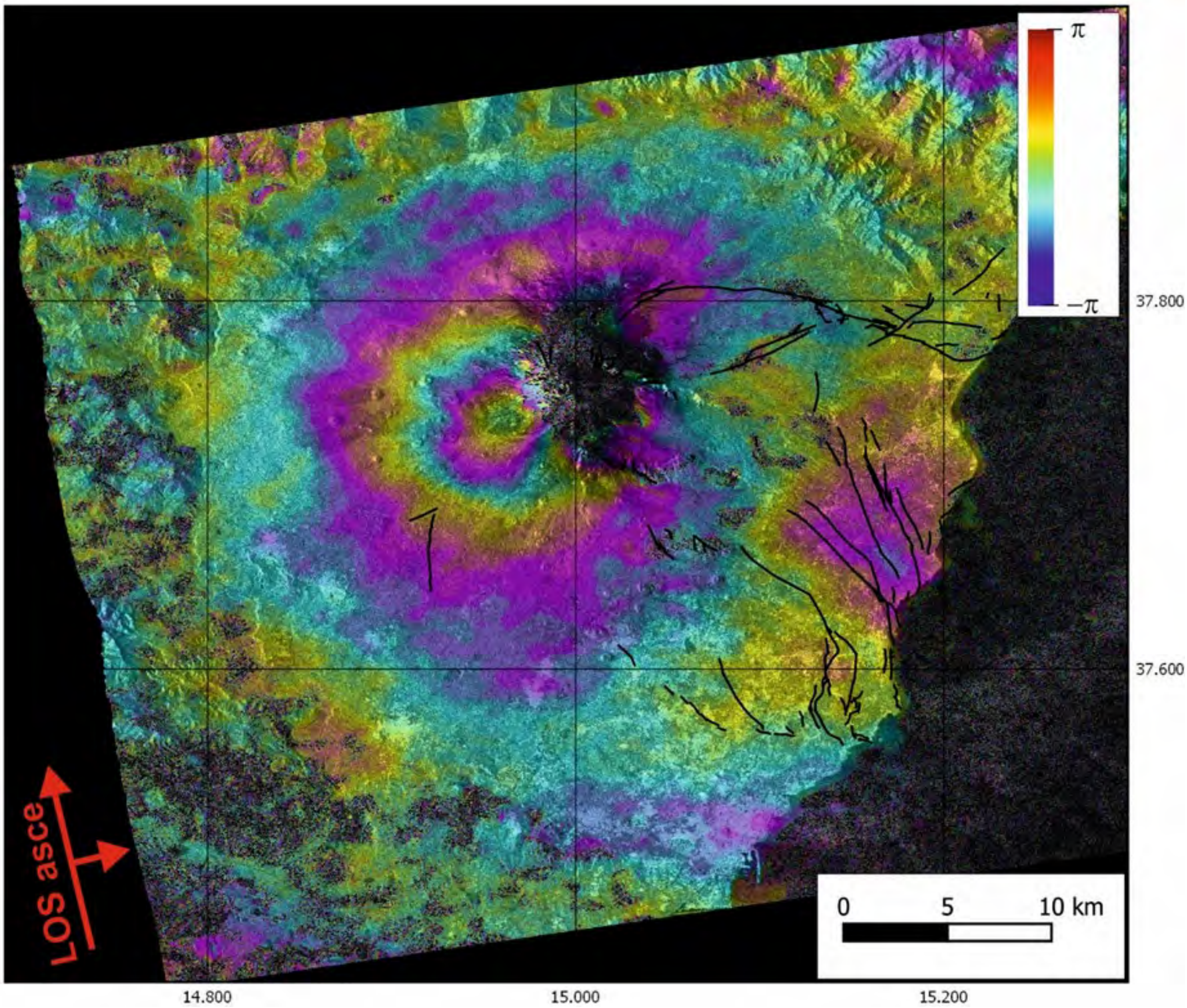


Figure 3. Sentinel 1 A/B ascending phase interferogram relative to December 23th 2020 –March 29th 2021. The volcanic edifice is affected by a diffuse deflation of about 2 fringes.

This dynamic is coherent with the model suggested by Bonforte et al. (2021), which performed a multi-temporal-scale analysis of ground deformation data (tilt, GNSS and DInSAR) acquired on Mt. Etna during the during the 2015 “Voragine paroxisms”, and the final results suggested a machine-gun-like mechanism comprising a middle-depth reservoir continuously charging a shallower one that works as a firing chamber triggering (Figure 4).

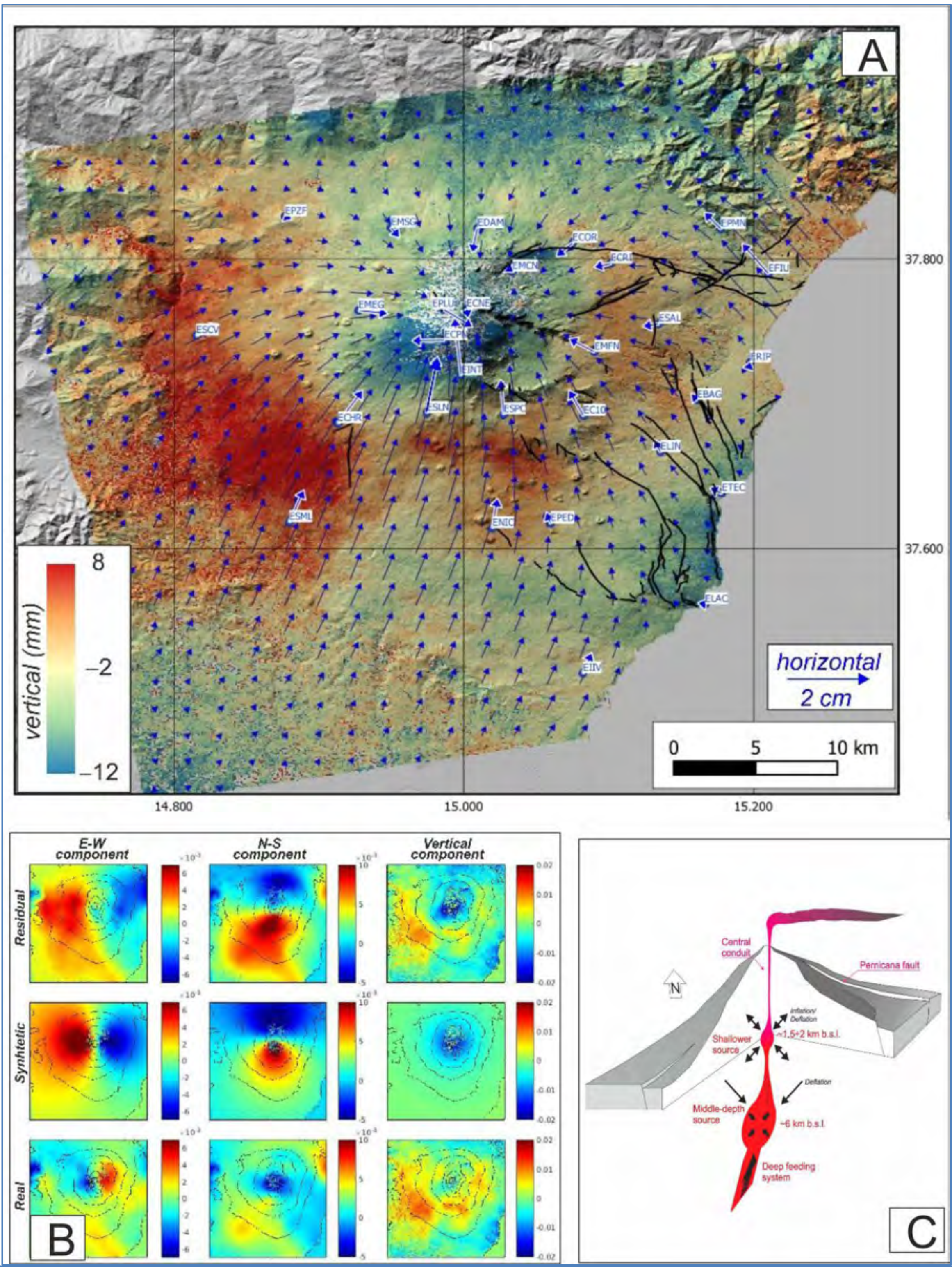


Figure 4. Bonforte et al. 2021 summary. A) 3D displacement map obtained by SISTEM algorithm over the 2015 Dec 2 to 14 - B) SISTEM inversion results; C) Sketch of the feeding system resulting from High Rate data and SISTEM modelling

In order to investigate the long-term ground deformation, a A-DINSAR analysis of the Sentinel ascending dataset was performed. The obtained mean LOS (Line Of Sigth) velocity map and the relative Time Series are reported in Figure 5, and show that the 2021 eruptive phase was anticipated by a rather continuous period of "inflation", involving the entire volcano, which started after the end of December 2018's eruption (Bonforte et al, 2019), briefly interrupted in 2019 (May and July) and in 2020 (May and December), in coincidence with episodes of volcanic activities at the summit craters.
Furthermore, the time series relative to South-eastern flank (along the Pernicana Fault and Fiandaca Fault) are shown. The historical series of displacements measured along the Pernicana fault and along the Fiandaca fault show the non-linear behavior of the deformation during the investigated period, with an increase after the 2018 flank eruption.

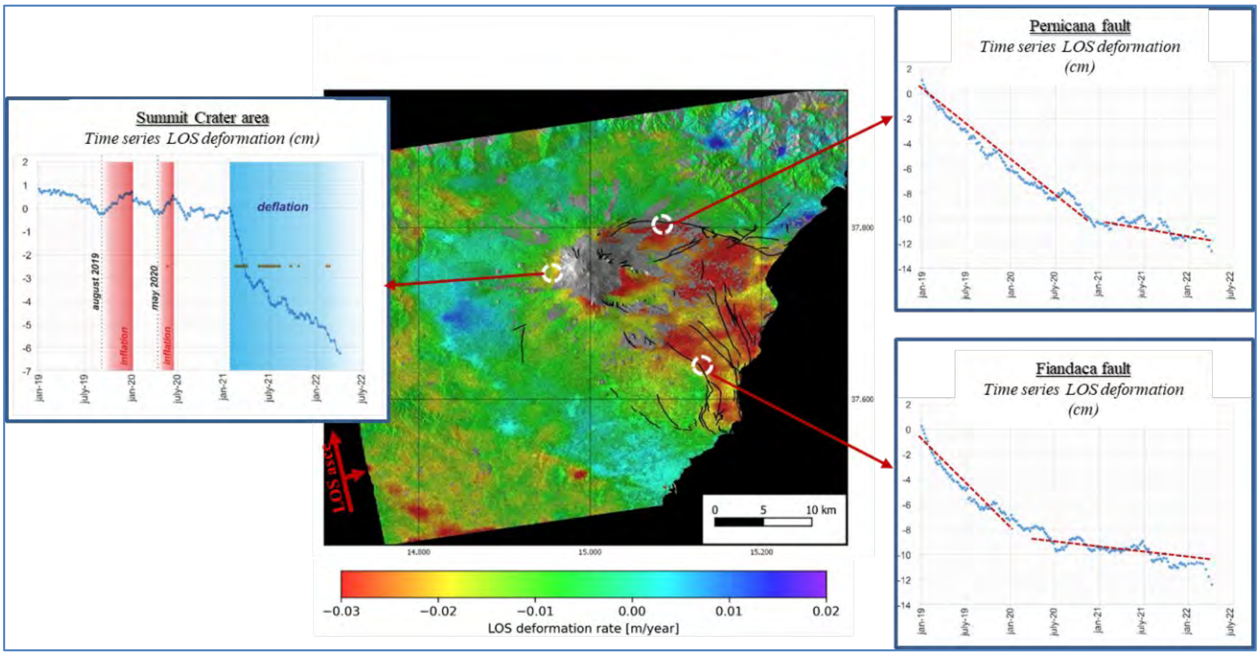


Figure 5. A-DInSAR analysis 2019-2022. Ascending mean LOS velocity and time series of LOS displacement of selected points.

A methodological research aimed at improving the SAR interferometric analysis by integrating satellite and ground-based information about the atmosphere, has carried out in the frame of two European projects (MED-SUV and EVER-EST) (Aranzulla et al., 2021). Thanks to the prominent orography and the high spatial and temporal variability of weather conditions, Mt. Etna is particularly suitable to carry out research aimed at estimating and filtering atmospheric effects on GPS and InSAR ground deformation measurements. To this end, data from the permanent GPS monitoring network and MODIS multispectral satellite data series are used to reproduce the tropospheric delays affecting interferograms. A tomography algorithm has been developed to reproduce the wet refractivity field over Mt. Etna in 3D, starting from the slant tropospheric delays calculated by GPS in all the stations of the network. With the aim of applying this algorithm to real cases, we introduce the water vapor content measured by the MODIS instrument on board the Terra and Aqua satellites.

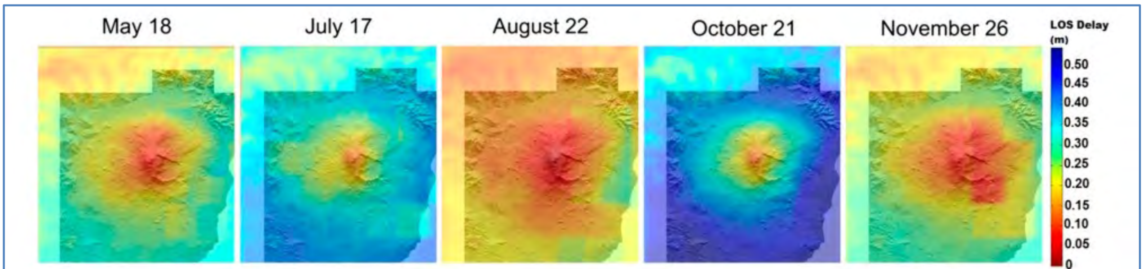


Figure 6. Wet delay line of sight maps referred to the five actual cases selected according to Sentinel-1A descending orbit acquisitions.

The tomography algorithm was applied on selected real cases to correct the Sentinel-1 DInSAR interferograms acquired over Mt. Etna during 2015 (Fugure 6). The corrected interferograms show that the differential path delay (i.e. the difference in tropospheric delay between the two SAR acquisitions used for the interferograms) in the extreme case, reaches 0.1 m, i.e. 3 C-band fringes, in ground deformation, demonstrating how the atmospheric anomaly affects precision and reliability of InSAR space-based techniques (Figure 7). The real cases show that in most cases the tomography is able to capture the atmospheric effect at the large scale and correct the Sentinel-1 interferograms. Furthermore, the introduction of MODIS data significantly improves the voxel resolution at the critical layer (1 km). These results encourage future studies aimed at overcoming the main limit of the method (consisting in the large voxel dimensions) and to improve its effectiveness, also by including other GNSS constellation data.

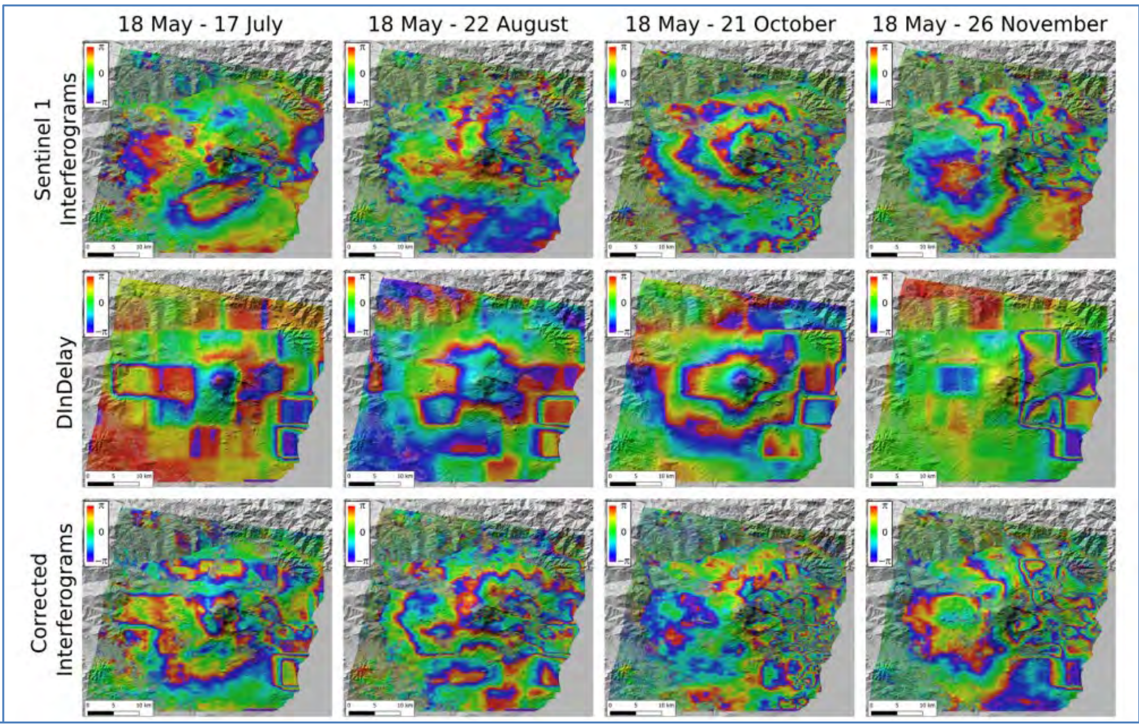


Figure 7. Sentinel-1 interferograms, DInDelay (Differential Interferograms Delay) and Sentinel-1 corrected interferograms. On the first row the DInSAR data are shown, on the second and third rows the corresponding DInDelay and corrected interferograms. All the images are shown in phase ($-\pi$, π ; 2 π phase corresponds to 28 mm). In the 18 May – 26 November interferogram the high-frequency atmospheric perturbation is in the NE flank.

6.3. Morphological changes

Pleiades images were acquired in tristereo configuration from 2021 at Etna volcano in the framework of the GEO-GSNL Supersite. At the Osservatorio Etneo INGV Catania a semi-automatic procedure was developed in order to obtain updated digital surface models from very high spatial resolution satellite images acquired in stereo, tri-stereo or multiview configuration (Ganci et al., 2018; 2019).
A triplet was acquired on 26 February 2021 at 9:57 GMT by the Pleiades 1B sensor as pansharpened images at 0.5 m resolution. These primary products were processed by using the MicMac open source library (http://micmac.ensg.eu Rupnik et al.,2017) in order to obtain a digital surface model (DSM Fig.8a) of Mt Etna. The DSM was coregistered with the previous available DSM from August 2020 and the difference was computed in order to evaluate the emplaced lava flow field and the growth of the SEC cone (Fig. 8b).

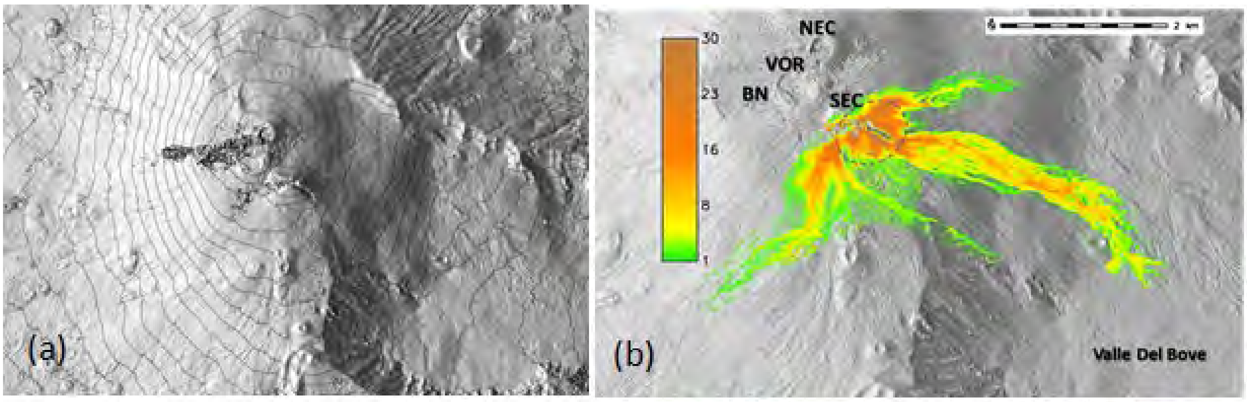


Figure 8. a) DSM of Etna volcano obtained from the Pleiades triplet acquired on 26 February 2021; b) Thickness of deposits emplaced from December 2020 to 26 February 2021.

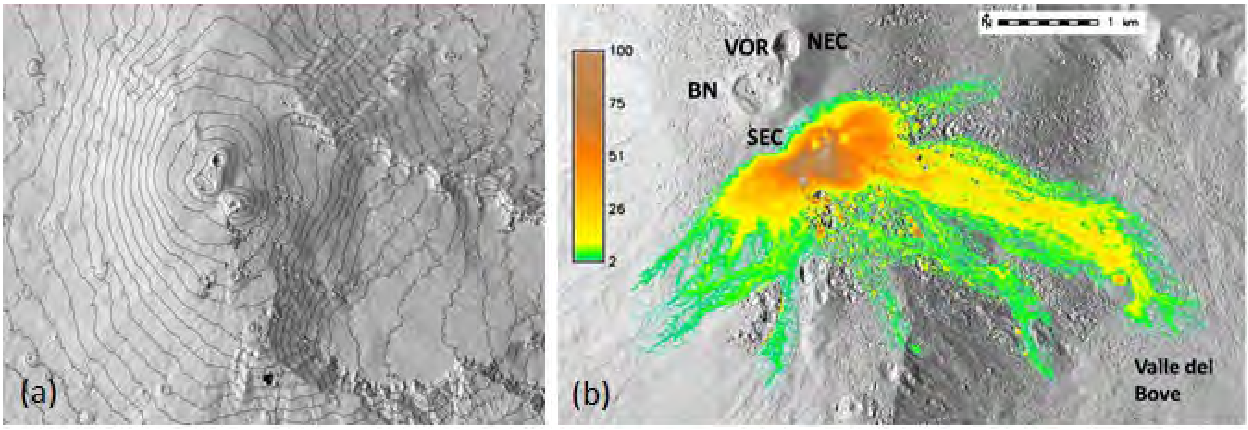


Figure 9. a) DSM of Etna volcano obtained from the Pleiades triplets acquired on 13 and 25 July 2021; b)Thickness of deposits emplaced from December 2020 to 25 July 2021.

The same methodology was successively applied to two Pleiades triplets acquired on 13 and 25 July 2021. In this case, because of partial cloud coverage and presence of volcanic plumes, two DSM were produced for each triplet and the results were integrated into a merged DSM (Figure 9a). Results from thickness of deposits emplaced from August 2020 to 25
July 2021 are shown in Figure 9b.
Results from thickness of deposits emplaced from August 2020 to 25 July 2021 are shown in figure 2b. This last DSM was extremely useful because it allowed us to infer the new Etna summit at the SEC crater that reached about 3350 m a.s.l..

6.4. Thermal Anomalies

ATTEMPT is a project funded in the frame of the INGV "Pianeta Dinamico - Working Earth" coordinated project (https://progetti.ingv.it/it/pianeta-dinamico). ATTEMPT is aimed at realizing a demonstrator of an integrated system capable of collecting multi-parametric space borne data to monitor different natural hazards over Mediterranean. Mt. Etna Supersite is the test site for the volcanic hazard. WP3's objective is to evaluate the volcanic unrest by integrating warning indices obtained from SAR and Infrared (IR) sensors. In particular, here is reported the study the sensitivity of an index based on infrared remotely sensed data that can be used to evaluate the surface thermal state of active volcanoes, by using as test case the 13 December 2021 event occurred in Valle del Bove.
Because the spectral radiance emitted by hot spots reaches its maximum in the region of Mid Infra-Red (MIR), the early detection of an impending eruption has been highlighted by exploiting the SEVIRI 3.9 μm channel. Despite its spatial resolution (3x3 sqkm at nadir), the presence of a high temperature source, even affecting only a small portion of one large pixel, causes a dramatic increase of the emitted MIR radiance easily detectable also at 4x5 sqKm (mid latitude).

The procedure named MS2RWS (MeteoSat to Rapid Response Web Service) allowed us to identify the Mt Etna summit area eruption since February 2010, when it was developed to detects the beginning and to estimates the duration of an eruption (Musacchio et al., 2011, 2012) (Figure 10). The procedure starts from the assumption that in a remote sensing image a pixel may assume a limited number of radiance values ranging from 0 up to the saturation.

The radiance of a given pixel, in clear sky condition and no eruption ongoing, follows a characteristic Gaussian trend related to the Sun elevation and this trend varies during an

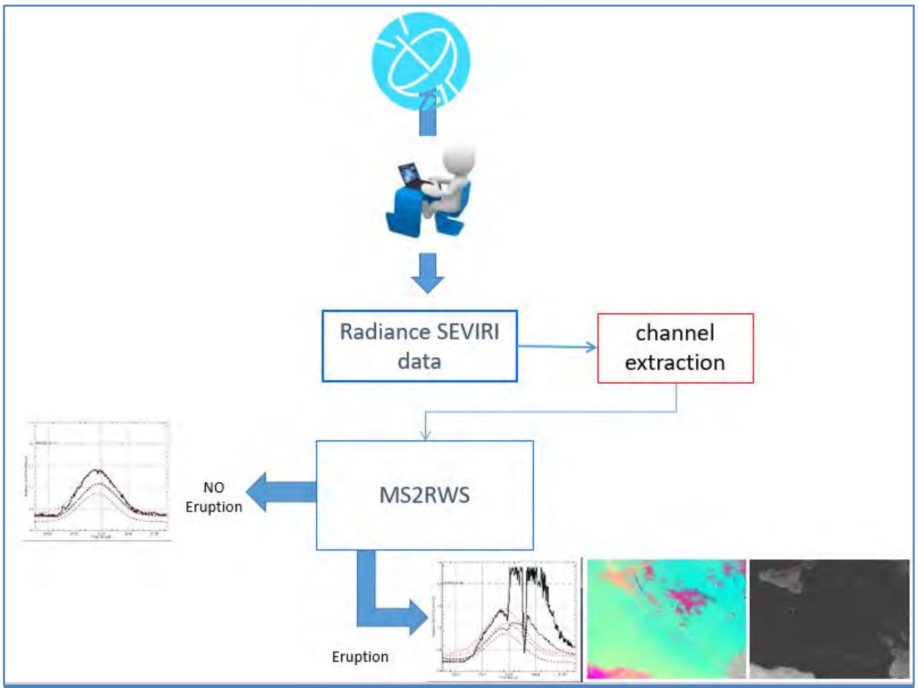


Figure 10. Flowchart of the MS2RWS (MeteoSat to Rapid Response Web Service).

eruption affecting, in particular, the pixel centred over the summit Mt. Etna craters (Corradini et al., 2018) (Figure 11).

Mt. Etna is characterized by several types of eruptive style located mainly on the summit area and secondary on the flank. One of the most common activity is represented by lava fountain that may inflate ash in the atmosphere impacting on e.g. the activities of the close international airport. For such a reason we developed an automatic procedure to identify the hotspot and to detect the presence of volcanic ASH / SO2 in the eruptive plume. Since 2010 this system analyses the thermal state of the ETNA summit area making a contemporaneous space and time domain analysis on 25 pixels distributed on the Etna area and covering both the summit and the flank areas (Figure 11). All the information on the developed algorithm has been presented on Musacchio et al., 2011, 2012 and Corradini et al. 2018, 2019, Lombardo et al., 2019 , Scollo 2020. Since 2010 up to now almost all events are occurred in pixel n°13 corresponding to the summit craters area. In the last dozens of year, the fountains have had a duration ranging from a few hours up to one day, rarely more. Indeed, in a very few case we had the opportunity to follow for more than one day an eruption. The 2021 has been characterized by a huge number of event occurred on t Etna with a behaviour similar to those described above, small duration lava fountain, lava flows from the central area.

On 13th December 2021 an eruptive vent opened in the eastern flank of Mt. Etna volcano, at an elevation of 2100 m a.s.l., about 3.5 km far from the summit craters. This eruption lasted only one day and produced a small lava flow (less than 1 km length). For this effusive activity; no earthquakes or ground deformations were measured before or during the eruption and the erupted volume was in the order of 10^4 m^3 (the smallest flank eruptions are larger than 10^6 m^3; smallest summit eruptions are in the order of 10^5 - 10^6 m^3).

Thus it might be considered as a "punctual event" in the eruptive history of the volcano and it has been used to test a procedure performed for summit area located events. It is ideal for validating the capability of the MS2RWS procedure in detecting flank eruptions since their beginning. We followed this event from the very beginning that was recognized at the same time reported in the bulletin published for civil protection use.

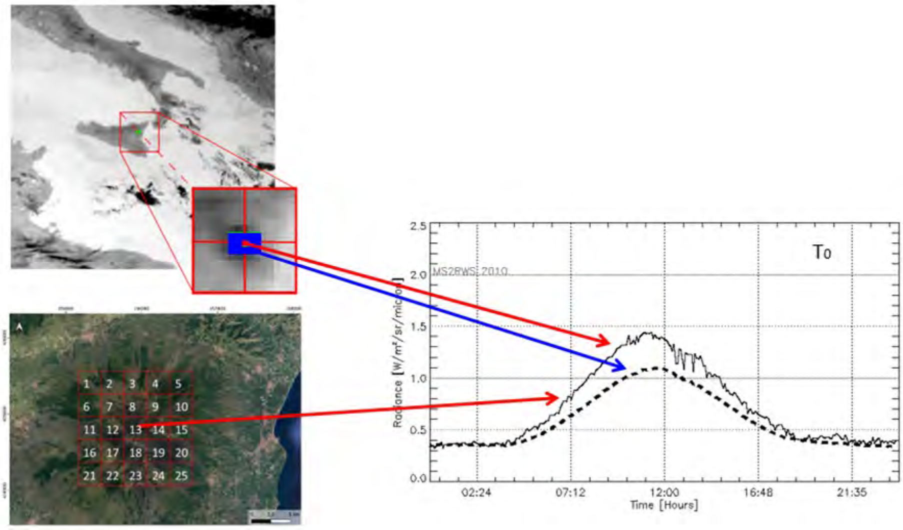


Figure 12. Radiance distribution of the pixels during the 13-14 December 2021 volcanic event.

We localized this event in the very lower right part of the used kernel/matrix in the area covered by the pixels 24 and 25 (Figure 12, 13). Of course, due to the pixel resolution of MSG that at this latitude is about 4x5 sqkm it cannot be use to map the flow but it properly works for the hotspot detection.

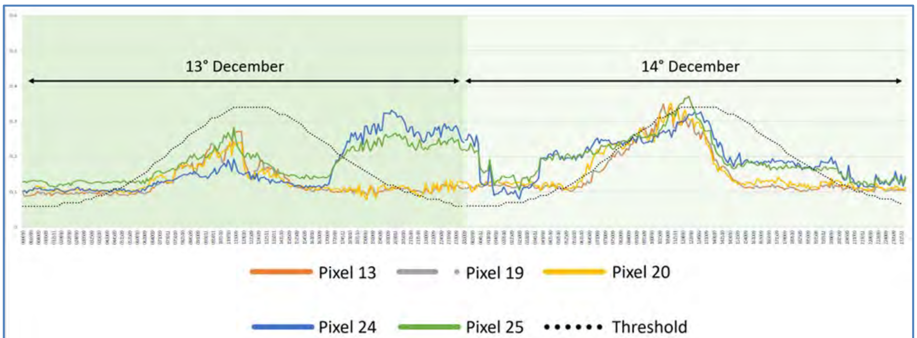


Figure 11. Configuration of the pixels analysed by MS2RWS on Mt. Etna (left side) and example of the actual Gaussian distribution of the radiance for the central pixel and relevant threshold (right side)

In the case of this event to demonstrate the applicability of this procedure we have benefit of two factors occurred: 1) no precursors were recorded 2) despite this event occurred during winter time the wheatear condition was good for the period of the eruption and no clouds occurred.

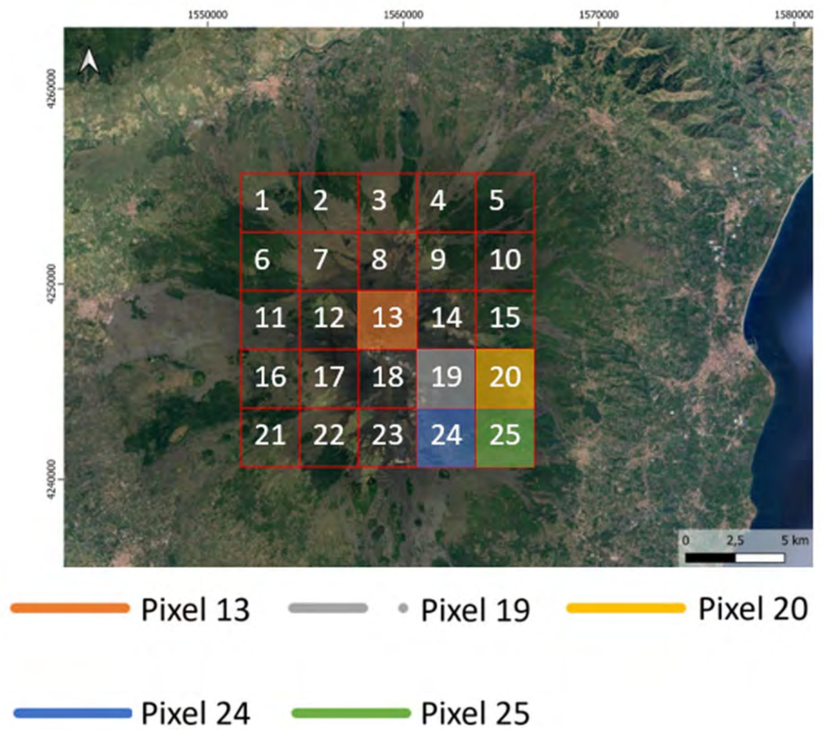


Figure 13. Location of the pixels “activated” during the 13-14 December 2021 event.

This experiment succeeds, demonstrating that the MS2RWS procedure has the capability to detect also lateral eruptions, as this was, giving a further contribute on the monitoring of volcanic activity by space.

6.5. Volcanic plumes

In the frame of two European projects (EUROVOLC and e-Shape) some relevant results concerning the detection and modelling of volcanic plumes.
In fact, several studies were carried out with the aim to have a better characterization of the eruption source parameters at the volcanic source. Those parameters are essential for characterizing the eruptive style (intensity and magnitude) and prevent risks due to the volcanic ash dispersal and fallout (eruption source parameters could be included in near real time within volcanic ash dispersal models to have more reliable forecasts of volcanic plume dispersal and fallout far from the volcanic source). Recent studies concern the analysis of the eruption source parameters using remote sensing techniques which span from ground (e.g. radar, lidar, cameras) to satellite (SEVIRI, MODIS) sensors. In fact, using different sensors installed at Etna, Freret-Lorgeril et al. (2021, 2022) characterized some lava fountains. The in fact analysed data acquired by two Doppler radars, satellite-based infrared sensors, one infrasound array, visible and thermal INGV-OE cameras as well as data from tephra-fallout deposits, and found that different sensors are complementary and

that, if they are well combined, can provide comprehensive estimates of the event duration, plume heights (Figure 14), total erupted mass, mass eruption rate and, moreover, a first approximation of total grain-size distribution of volcanic particles at the volcanic source.
Figure 14 from Feret-Lorgeril et al. (2021) shows the plume height estimates of Etna lava fountains occurred in 10 April 2011 (a) and in 23 November 2013 (b) from X-band radar (MWR, black line), MODIS at 12:30 UTC (green cross), SEVIRI (blue line), and ECV (red line). Red dashed line corresponds to data from the visible camera ECV of INGV-OE. Error bars are also shown for all sensors.

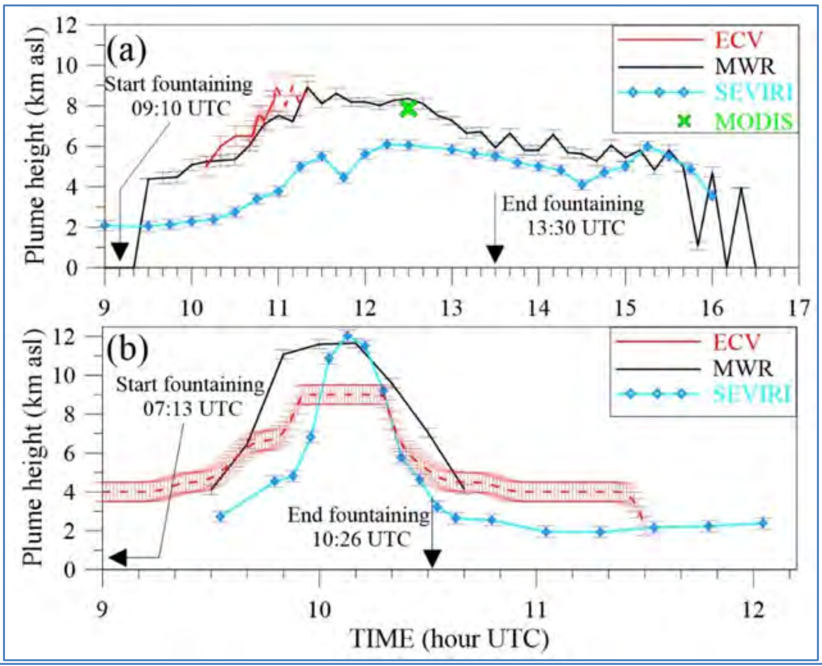


Figure 14. Plume height evolution during the lava fountain of Etna occurred in in 10 April 2011 (a) and in 23 November 2013 (b). The figure is from Feret-Lorgeril et al.

Mereu et al. (2022) investigated the analysis of mass eruption rate and its uncertainty using microwave radar techniques at L- and/or X-bands and images from the thermal camera of INGV-OE. The Etna lava fountains of 3–5 December 2015 were taken as test cases. Authors developed different methodologies (Figure 15) finding that a method, entirely based on the X-band radar data and named MCA, is able to give the better estimations of mass eruption rate with an error of only 22.3%, whereas other approaches exhibit a higher uncertainty (between 26.4% and 31.6%).

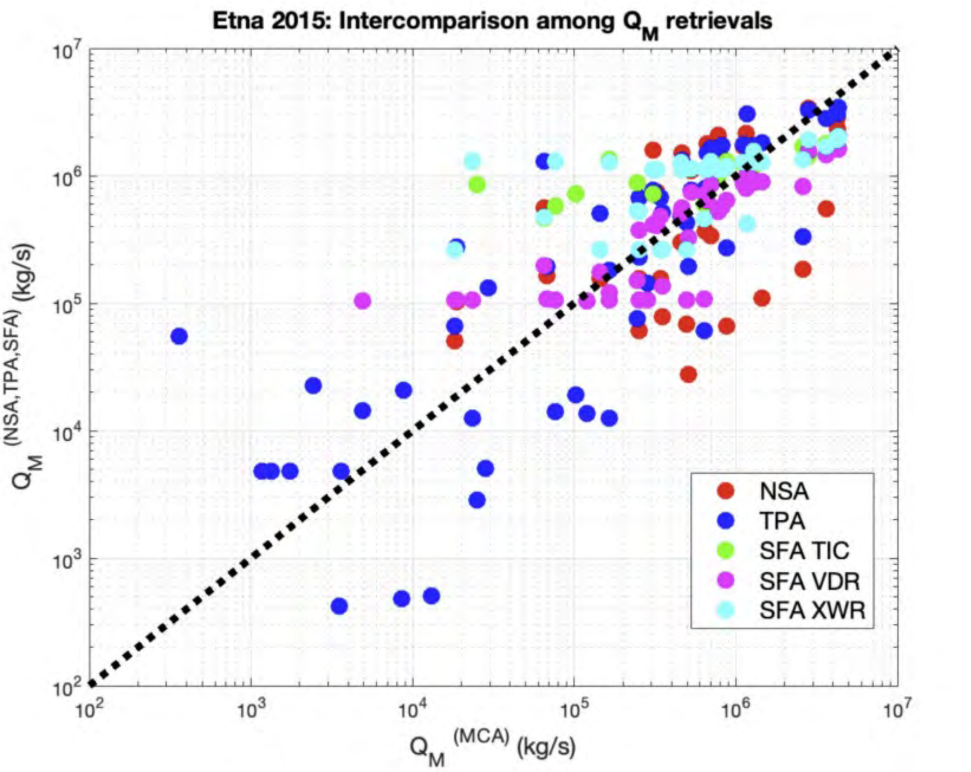


Figure 15. Plot showing on the x-axis the mass eruption rate (QM) derived from the MCA method and on the y-axis the QM retrieved from other sensors (e.g. the VOLDORAD radar and INGV-OE thermal camera). Plot from Mereu et al. (2022).

Finally, another important parameter is the total grain-size distribution. Although this parameter is the most difficult to retrieve using remote sensing systems as the particle size retrieved by the sensor depend on its wavelengths, a recent study (Feret-Lorgeril et al., 2022) has demonstrated the possibility to have a good characterization of this parameter through a combination of field and satellite data (Figure 15).

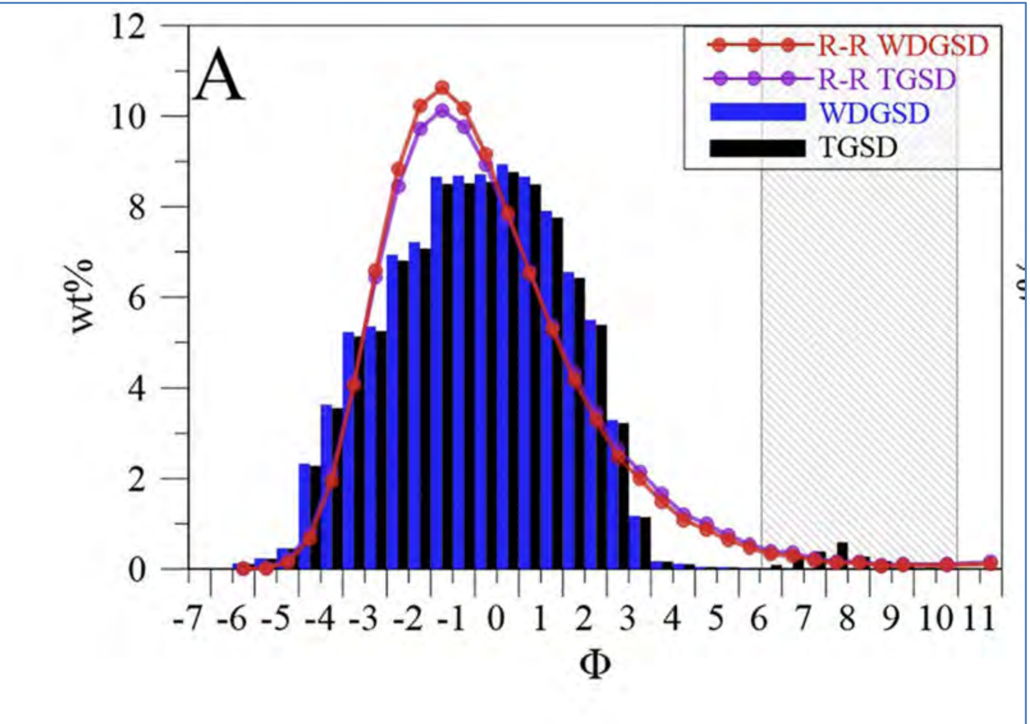


Figure 16.) Total Grain-size distribution (blue histograms) and associated Rosin-Rammler best fit (red line) which combined field and satellite data of the 29 August 2011 weak paroxysm at Etna (Italy). Plot and details can be found in Freret-Lorgeril (2021b).

6.6. Publications

Peer reviewed journal articles

Aranzulla M, Spinetti C, Cannavò F, Romaniello V, Guglielmino F, Puglisi G and Briole P (2021) Water Vapor Tomography of the Lower Atmosphere from Multiparametric Inversion: the Mt. Etna Volcano Test Case. Front. Earth Sci. 8:510514.doi: 10.3389/feart.2020.510514

Bonforte, A.; Cannavò, F.; Gambino, S.; Guglielmino, (2021). F. Combining High- and Low-Rate Geodetic Data Analysis for Unveiling Rapid Magma Transfer Feeding a Sequence of Violent Summit Paroxysms at Etna in Late 2015. Appl. Sci. 2021, 11, 4630. https://doi.org/10.3390/app11104630

Freret-Lorgeril V, Bonadonna C, Scollo S, Guerrieri L, Corradini S, Donnadieu F., Mereu L, Marzano FS, Lacanna G., Ripepe M., Merucci L, Stelitano D (2021) Examples of Multi-Sensor Determination of Eruptive Source Parameters of Explosive Events at Mount Etna. Remote Sensing https://doi.org/10.3390/rs13112097.

Freret-Lorgeril V, Bonadonna C, Corradini S, Guerrieri L, Lemus J., Donnadieu F., Scollo S, Gurioli L, Mereu L, Rossi E (2021). Tephra characterization and multi-disciplinary determination of Eruptive Source Parameters of a weak paroxysm at Mount Etna (Italy). Journal of Volcanology and Geothermal Research. https://doi.org/10.1016/j.jvolgeores.2021.107431.

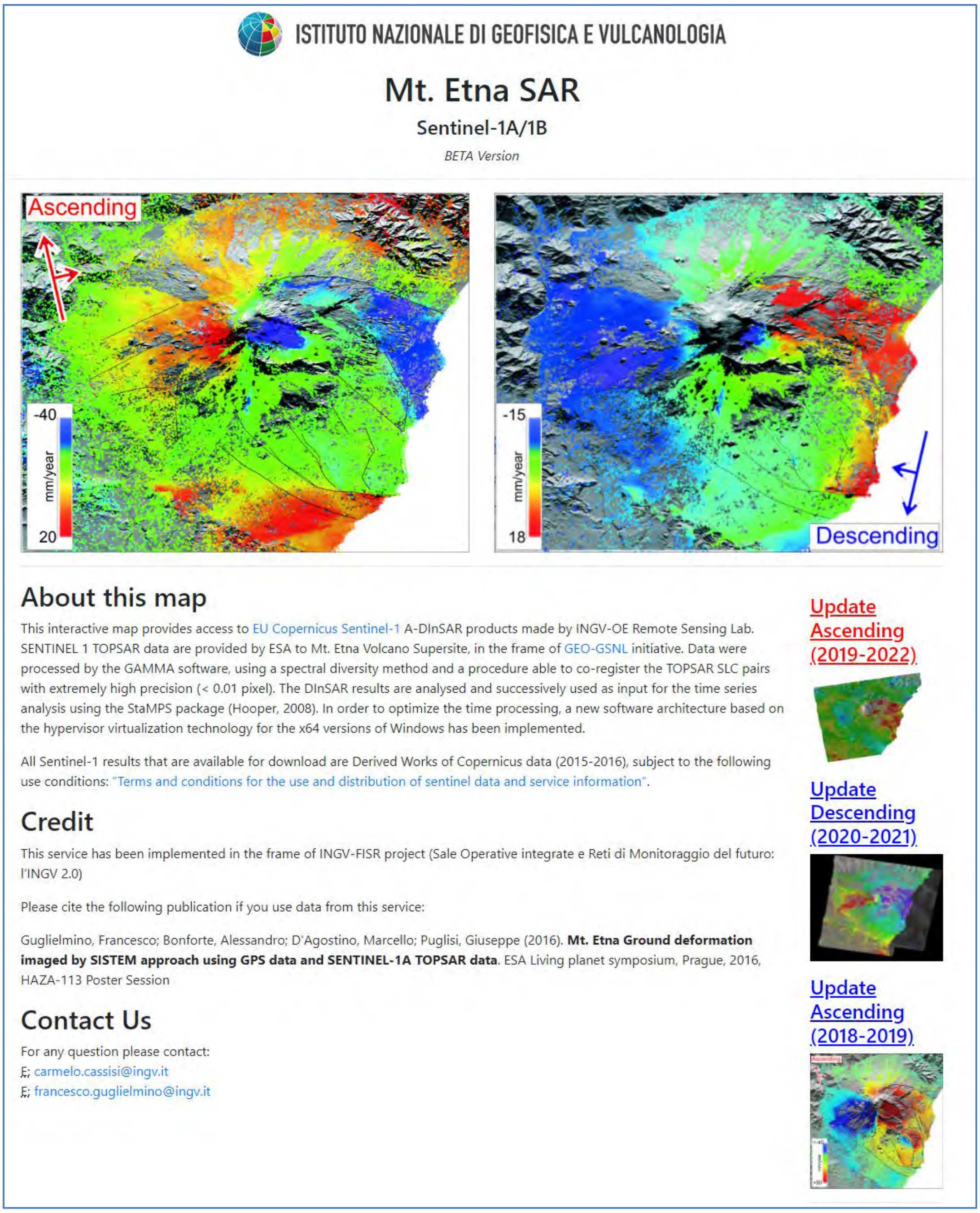
Mereu, L., Scollo, S., Bonadonna, C., Donnadieu F., Freret-Lorgeril, V., Marzano, F.S. Ground-Based Remote Sensing and Uncertainty Analysis of the Mass Eruption Rate Associated with the 3-5 December 2015 Paroxysms of Mt. Etna, IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING, VOL. 15, 2022

Conference presentations/proceedings
Carnemolla, F., Bonforte A., Brighenti F., Briole P, De Guid, G., Guglielmino F, Puglisi, G.; ,Joint GNSS-InSAR analysis of ground deformation on the eastern flank of Mount Etna,,Copernicus Meetings
Gambino S., Aiesi G., Bonforte A., Brandi G., Calvagna F., Consoli S., Distefano G., Falzone G., Ferro A., Guglielmino F. Laudani G., Marsala G., Obrizzo F., Privitera L., Puglisi G., Russo S., Saraceno B., Velardita R. (2020). Dynamics of the 1989 fracture system and relations with the Etna eruptive activity of the last 30 years, EGU General Assembly Conference Abstracts,1938, ,
Guglielmino F., Aiesi G., Bonforte .A., Brandi G., Calvagna, F,. Consol, S,. De Guid, G,. Distefano, G., Falzone G., Ferro A, Gambino S., Laudani G., Marsala G., Obrizzo F., Privitera L., Puglisi G., Russo S., Saraceno B.. (2020). "Multidisciplinary study of the Trecastagni fault (Mt. Etna volcano, Sicily)",EGU General Assembly Conference Abstracts,1988,
Musacchio, M., Silvestri M., Puglis, G., Buongiorno M. F. (2022).,ETNA 2021 13th December eruption: does SEVIRI data contribute to the early detection of lateral event?,2022,Copernicus Meetings
Bonforte A. , Guglielmino F., Puglisi G.(2022) Structural assessment of Mt. Etna from twenty-five years of SAR interferometry. DRT-2022 - 23rd International Conference on Deformation Mechanisms, Rheology and Tectonics – Catania 4-10 July 2022

6.7. Research products

A part from the papers and presentations listed above, it has been recently updated the data set of the INGV-OE Remote Sensing Lab service to visualise the interferogram products obtained from the Sentinel-1A/1B data acquired at Mt. Etna (Figure 17). The products consist in the ascending and descending mean LOS (line-of-sight) velocity maps, The data sets have been updated with the velocity maps of ascending orbits 2018-2019 and 2019 2022, and descending orbits 2020-2021. The service allows to display the time-series of the displacements (positive toward the sensors) and comparison between time series that can be get by clicking the individual maps (Figure 18).

Type of product	Product provider	How to access	Type of access
Ground Deformation Time series	*Francesco Gugliemino (INGV)*	http://tsd.ct.ingv.it/tsdws/sar	*public*



ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

Mt. Etna SAR

Sentinel-1A/1B

BETA Version

About this map

This interactive map provides access to EU Copernicus Sentinel-1 A-DInSAR products made by INGV-OE Remote Sensing Lab. SENTINEL 1 TOPSAR data are provided by ESA to Mt. Etna Volcano Supersite, in the frame of GEO-GSNL initiative. Data were processed by the GAMMA software, using a spectral diversity method and a procedure able to co-register the TOPSAR SLC pairs with extremely high precision (< 0.01 pixel). The DInSAR results are analysed and successively used as input for the time series analysis using the StaMPS package (Hooper, 2008). In order to optimize the time processing, a new software architecture based on the hypervisor virtualization technology for the x64 versions of Windows has been implemented.

All Sentinel-1 results that are available for download are Derived Works of Copernicus data (2015-2016), subject to the following use conditions: "Terms and conditions for the use and distribution of sentinel data and service information".

Credit

This service has been implemented in the frame of INGV-FISR project (Sale Operative integrate e Reti di Monitoraggio del futuro: l'INGV 2.0)

Please cite the following publication if you use data from this service:

Guglielmino, Francesco; Bonforte, Alessandro; D'Agostino, Marcello; Puglisi, Giuseppe (2016). **Mt. Etna Ground deformation imaged by SISTEM approach using GPS data and SENTINEL-1A TOPSAR data**. ESA Living planet symposium, Prague, 2016, HAZA-113 Poster Session

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Update Ascending (2019-2022)

Update Descending (2020-2021)

Update Ascending (2018-2019)

Figure 17. WEB-Gis home page

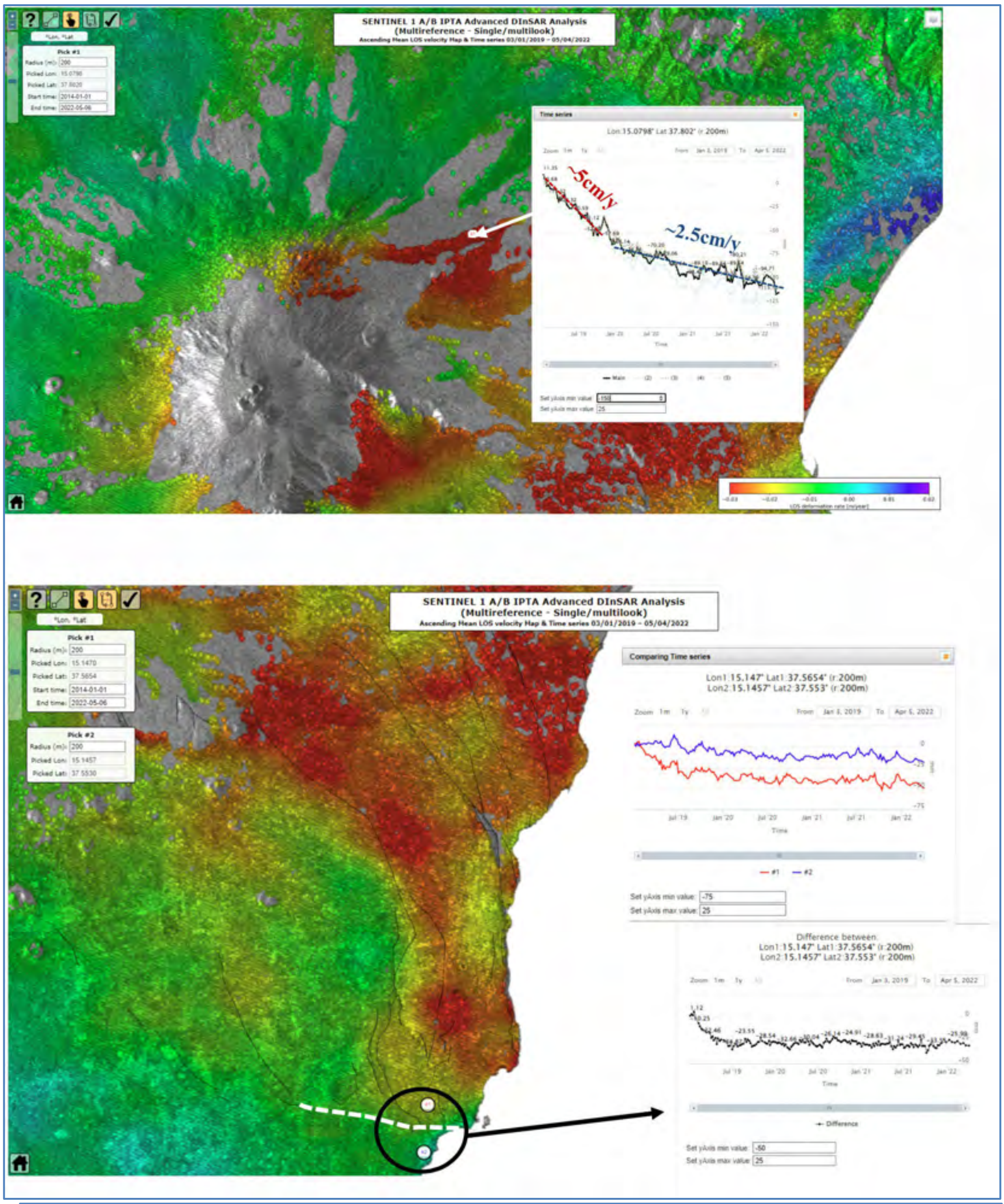

Figure 18. (upper part) Single Time Series Visualization; (lower part) Snapshot of Comparing Time Series tool

7. Dissemination and outreach

The COVID-19 pandemic dramatically reduced the activity of the dissemination and outreach activities and in particular the work plan of the project funded by the National Civil Service (Servizio Civile Nazionale), mentioned in the previous biennial reporting period and aimed at the implementation of specific dissemination and outreach initiatives (e.g. the Supersite Day), which were cancelled.

8. Funding

The analysis of the economic support to the Etna Supersite should be distinguished between the support to the scientific activities and the management.

Considering the absence of specific financial support for scientific researches on the Supersite, the scientific results relevant to the Mt. Etna Supersite during the biennial period has come from institutional activities of the INGV and national and international project, as summarized in Section 6. This positive experience encouraged to continue to promote the support to the Supersite in preparing scientific proposals. Indeed, there are three European projects, just started or forthcoming, which explicitly plan researches focused on the Mt. Etna Supersite. In particular the IMPROVE MCSE ITN project (https://www.improve-etn.eu/), started in September 2021, supports the scientific coordinated projects of five Early Stage Researchers (ESRs) on Mt. Etna to investigate the phenomena in the range of frequencies between the seismic and quasi-static deformations, by integrating ground-based and satellite data. The summer school planned on Mt. Etna in 2023, will see the participation of ESA to foster the use of satellite data in the next generation of researchers. This project will give a significant contribution also from the infrastructural point of view, because it is planned the implementation of a database for the project results fully compliant with EPOS. In the forthcoming months, two Horizon Europe projects will start, which include Mt. Etna supersite as privileged location for their activity: Geo-INQUIRE and DT-GEO. The former is aimed at improving the offer of scientific data and foster the advanced use of the research infrastructure. In this frame Mt. Etna Supersite will benefit from the implementation of updated datasets (relevant to geophysical and volcanological data), new tools to analyse the data and specific training activities. The second is aimed at designing and experimenting the concept of "Digital Twins" in different contexts, among which there are the volcanoes; Mt Etna will be the volcano test site of this project. Both projects will encourage the trans-domain use of the research infrastructure; with regard to this objective, the Mt. Etna Supersite will have the opportunity to confirm its potentiality already exploited in the past years (see the biennial report 2018-2020). In order to promote the infrastructural value of the Mt. Etna Supersite and considering the positive experience in offering physical access to volcanological research infrastructure at Mt. Etna, gained in the previous biennial period, we participated to a national infrastructural proposal (MEET) to update the Open Access facilities at Mt. Etna volcanological observatory at Pizzi Deneri (2800 m a.s.l.).

The management of Mt. Etna Supersite is largely based on the in-kind contribution of the INGV, through the personnel efforts and a little financial support to maintain the MED-SUV portal. During the previous biennial period we paved the way to structure the management of the Supersite by appointing a specific working group at the Etna Observatory the INGV branch in Catania and by opening a new position to support the technical activity related to the Mt. Etna supersite portal in the framework of the EPOS Italia Joint Research Unit activity. The COVID19 pandemic limited the daily activity of the working group and delayed the selection procedures for the new position that, in the end, was unfruitful. However, thanks to the restore of the normal working condition, the Mt. Etna Supersite management will renew the request for hiring IT personnel to maintain and upgrade the data portal.

9. Societal benefits

The main benefitting no-scientific stakeholders are the national and regional (Sicilian) departments of Civil Protections, which take advantage of the possibility of INGV to use the remote sensing data provided in the framework of the Supersite. Indeed, INGV is an official "Centre of Expertise" (Centro di Competenza) of the national Civil Protection system, which assignment is to scientifically support the National and Regional departments in disaster risk management activities. Such a benefit is proved by several contributions based on satellite data included in the periodic reports to and meetings with the Civil Protections departments provided by INGV.

10. Conclusive remarks and suggestions for improvement

During the 2020-2022 period of activity of the Mt. Etna Supersite, the main scientific achievements referred to the use of the EO data for investigating the dynamic of the volcano associated to the paroxysmal events occurred from December 2020 to February 2022. This activity had also an important impact for the society, as these results have been exploited in the framework of surveillance activity for Civil Defence purposes. Furthermore, a few relevant scientific achievements resulted from some national or international projects that foresee Mt. Etna Supersite as a reference site for their activities.

Despite the limitations due to the pandemic and the end of the agreement among the institutions involved in the maintenance of the MED-SUV web sites, we pursued the objective of the consolidation of the data infrastructure in the framework of the EPOS European infrastructure. The re-structuring of the data portal, still ongoing, is benefitting also from the enrichment of the in-situ datasets thanks to the outcomes of the H2020 EUROVOLC project.

The positive experience gained in promoting the Mt. Etna Supersite in the framework of national and international projects encourage continuing in this direction for the future activity of the Supersite.

Overall, the management of the Supersite is continuing along the strategic guidelines depicted in the previous biennial report, i.e., to strengthen the link with national and international initiatives aimed at implementing the system of the research infrastructures in Europe and worldwide, to attract research projects to use Mt. Etna Supersite data to carry out advanced researches, to expand toward research domains different from that of the study of the volcano internal dynamics and to foster access modalities different from those linked to the virtual access to the data sets.

11. Cited References

Andronico D., Cannata A., Di Grazia G., Ferrai F. (2021). The 1986 – 2021 paroxysmal episodes at the summit craters of Mt. Etna: Insights into volcano dynamics and hazard. Earth-Science Reviews 220, 103686. https://doi.org/10.1016/j.earscirev.2021.103686.

Bonforte A., Guglielmino F., Puglisi G., (2019). Large dyke intrusion and small eruption: The December 24, 2018 Mt. Etna eruption imaged by Sentinel-1 data. Terra Nova, 31, 4, 405-412. 10.1111/ter.12403

Calvari, S.; Nunnari, G. (2022). Comparison between Automated and Manual Detection of Lava Fountains from Fixed Monitoring Thermal Cameras at Etna Volcano, Italy. Remote Sens. 14, 2392. https://doi.org/10.3390/rs14102392

Corradini, S., Guerrieri, L., Lombardo, V., Merucci, L., Musacchio, M., Prestifilippo, M., Scollo S., Silvestri, M., Spata, G., Stelitano, D. (2018). Proximal monitoring of the 2011–2015 Etna lava fountains using MSG-SEVIRI data. Geosciences, 8(4), 14.

Ganci, G. et al., (2018). Mapping Volcanic Deposits of the 2011–2015 Etna Eruptive Events Using Satellite Remote Sensing, Front. Earth Sci., doi: 10.3389/feart.2018.00083

Ganci, G. et al., (2019). Satellite-Based Reconstruction of the Volcanic Deposits during the December 2015 Etna Eruption, Data, 4(3), 120; doi: 10.3390/data4030120

Musacchio M., M. Silvestri, and M.F. Buongiorno (2011). Use of radiance value from MSG SEVIRI and MTSAT data: application for the monitoring on volcanic area 2011 EUMETSAT Meteorological Satellite Conference OSLO, NORWAY 5 – 9 SEPTEMBER 2011

Musacchio M., M. Silvestri, and M.F. Buongiorno (2012). RT Monitoring of active volcanoes: MT Etna, SeaSpace International Remote Sensing 21-24 October 2012 Conference, Seaspace Corporation, San Diego.

Rupnik, E.; Daakir, M.; Pierrot Deseilligny, M. (2019). MicMac—A free, open-source solution for photogrammetry. Open Geospat. Data, Softw. Stand. 2017, 14.