Biennial report for Permanent Supersite/Natural Laboratory

Vesuvius - Campi Flegrei Supersite

History	http://geo-gsnl.org/supersites/permanent-supersites/vesuvius-campi-flegrei-supersite/
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Abstract

Currently many studies are carried out in the Neapolitan Volcanic District (Vesuvius, Campi Flegrei and the Island of Ischia), thus demonstrating the interest by the Supersite science teams and the scientific community as a whole in this active volcanic area.

The aims of these studies by the science teams, though not limited to, are:

- research, by taking part into international research projects/activities and
- monitoring, focussed on the near real time surveillance of the volcanoes belonging to the Neapolitan Volcanic District, for benefit of the local and national Civil Protection agencies.

Such monitoring activities are mainly focussed on Campi Flegrei, currently at the *attention* (yellow) level according to the Campi Flegrei Emergency Plan issued by the Italian Civil Protection Department and, subordinately, the Island of Ischia, where a 3.9 magnitude earthquake occurred on August 21st, 2017.

Moreover, during the 2020-2022 biennium of the Supersite initiative, the improvement and fine-tuning of the MED-SUV (EC FP-7 Project) infrastructure (http://med-suv.essi-lab.eu/web/portal) continued, conceived for data dissemination within the scientific community. The infrastructure, to be exploited in the framework of EPOS (European Plate Observing System https://www.epos-ip.org/), allows the distribution of both satellite and in-situ data from the INGV (Istituto Nazionale di Geofisica e Vulcanologia) monitoring networks, according to the Space Agencies and the INGV data policies.

In this biennium, more activities supporting scientists involved in this Supersite took place, e.g. the provision of PLEIADES tri-stereo optical data over Campi Flegrei, jointly with the opportunity to get SAOCOM (L-band) InSAR data. The Supersite SAC is also exploring the possibility to get S-band InSAR data from the NovaSAR-S sensor over different areas in the World, including also our area of interest.

The exploited satellite data herein reported are from the SAR sensors on board the CSK constellation, TSX/TDX (monostatic) and S1-A/B. For the first time very preliminary results are shown on the use/integration of data from the Spanish PAZ sensor (X-band), a TSX/TDX twin, with data from these two satellites.

Also ASTER and LANDSAT8/9 data have been exploited over Campi Flegrei for monitoring purposes and herein presented.

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Science teams issues

Scientists and science teams from leading research and monitoring Institution in the field of geophysics, volcanology and earth observation take part in the activities of the Vesuvius-Campi Flegrei Supersite, namely:

- INGV (Istituto Nazionale di Geofisica e Vulcanologia, the Italian Institute of Geophysics and Volcanology) with the "Osservatorio Vesuviano" (INGV-OV), the "Osservatorio Etneo" (INGV-OE) and the "Osservatorio Nazionale Terremoti" (INGV-ONT) branches;
- IREA-CNR (Istituto per il Rilevamento Elettromagnetico dell'Ambiente, the Italian Institute for the Electromagnetic Sensing of the Environment from CNR, the National Research Council);
- Canada Centre for Mapping and Earth Observation, Ottawa (Canada);
- University of Naples "Federico II", Department of Earth Sciences, of the Environment and Resources (Italy);
- University of Rome 3, Sciences Department (Italy);
- Instituto de Geociencias, Universidad Complutense, Madrid (Spain);
- University of Colorado, Boulder (USA).

An interest as a whole by the national and international scientific community, besides by scientists from some Space Agencies, has been expressed in recent times in this active volcanic area, also with studies in other geo-fields complementing Earth Observation results.
Apart from the Sentinel Data Hub providing free-of-charge data, other data dissemination within the Supersite science teams is now a solved problem, through the exploitation of web platforms by Space Agencies, e.g. the *"ESA Geohazards Exploitation Platform"* (https://geohazards-tep.eu/#!) and the *"DLR Supersites Download Directory"* for TSX/TDX data (https://download.geoservice.dlr.de/supersites/files/Vesuv/).
Definitely, the Supersite coordinator finds no particular obstacles for the next biennial activities of this Supersite pointing out, on the contrary, the improvement due to the support provided by Space Agencies, through data dissemination and InSAR/Optical cloud-based processing services. The foreseen improvement of the MED-SUV/EPOS infrastructure for ground-based data dissemination must be taken into account as well.

In situ data

A general overview of the monitoring networks in the Neapolitan volcanic area is herein presented (pre covid-19 outbreak period, see fig.1 in the Annex):

INGV-OV monitoring networks (Vesuvius)

Seismic	Permanent:	19 stations	Mobile:	9 stations
GPS	Permanent:	9 3D vertices		
Levelling	Discrete:	325 benchmarks		
Tide gauge	Permanent:	2 stations		
Tiltmetric (permanent)	Surface:	3 stations	Borehole:	5 stations
Gravimetric	Discrete:	35 benchmarks	Permanent:	1 station
Geochemical	Permanent:	4 stations		
Thermal Infrared Imagery	Discrete:	3 stations	Permanent:	1 station

INGV-OV monitoring networks (Campi Flegrei)

Seismic	Permanent:	26 stations	Mobile:	19 stations
GPS	Permanent:	26 3D vertices		
Levelling	Discrete:	370 benchmarks		
Tide gauge	Permanent:	4 stations		
Tiltmetric (permanent)	Surface:	4 stations	Borehole:	6 stations
Gravimetric	Discrete:	37 benchmarks	Permanent:	1 station
Dilatometric	Permanent:	4 stations		
Geochemical	Permanent:	3 stations		
Thermal Infrared Imagery	Discrete:	11 stations	Permanent:	4 stations

Type of data	Data provider	How to access	Type of access
e.g. seismic waveforms, GPS time series, gas measurements, etc.	*……*	*Link to data repository or description of procedure for data access*	*E.g. unregistered public, registered public, limited to GSNL scientists, etc.*
Seismic waveform	*INGV*	*Link to Network Italian Seismic Network Web Service*	*Limited to MED-SUV Consortium - Registered*
Seismic events	*INGV*	*Link to Network Italian Seismic Network Web Service*	*Limited to MED-SUV Consortium - Registered*
GPS data	*INGV*	*Link to MED-SUV GSAC server*	*Limited to MED-SUV Consortium - Registered*

In situ data issues

As already mentioned, the in-situ data provided by INGV are discoverable and accessible through the e-Infrastructure implemented in the framework of the MED-SUV/EPOS activities, to be furtherly populated.

Some critical issues expected in a possible misalignment between the continuous availability of satellite data from Space Agencies and the data availability from the in-situ data provider, will be now overcome by the release of the INGV data policy.

Satellite data

Type of data	Data provider	How to access	Type of access
TerraSAR X. COSMO-SkyMed, Radarsat 2, ALOS-1/2, etc.	*DLR, ASI, CSA, JAXA, etc.*	*Link to data repository or description of procedure for data access*	*E.g. unregistered public, registered public, limited to GSNL scientists, etc.*
ERS-1/ERS-2	*ESA*	https://earth.esa.int/eogateway/missions/ers/data https://geohazards-tep.eu/#!	*Registered public*
ENVISAT	*ESA*	https://earth.esa.int/eogateway/missions/envisat/data https://geohazards-tep.eu/#!	*Registered public*
Sentinel	*ESA*	https://scihub.copernicus.eu/dhus/#/home https://geohazards-tep.eu/#!	*Registered public*
TerraSAR-X	*DLR*	https://download.geoservice.dlr.de/supersites/files	*Registered public*
PAZ	*HISDESAT*	*Through a dedicated AO*	*AO participants*
COSMO-SkyMed	*ASI*	https://geohazards-tep.eu/#! *Through an ASI FTP site for the Coordinator*	*Authorized GSNL scientists*
Landsat 8/9	*USGS*	http://earthexplorer.usgs.gov	*Registered public*
AVHRR	*NOAA*	http://earthexplorer.usgs.gov	*Registered public*
MODIS	*NASA*	http://modis.gsfc.nasa.gov/data/	*Open*

InSAR data availability

InSAR data provided through the Supersite initiative to date:

X-band data:

- COSMO-SkyMed (CSK, StripMap, SLC: SCS_B, **> 600** Ascending);
- TSX & TDX - monostatic (StripMap, SLC: SSC, **> 150** Ascending, Vesuvius);
- TSX & TDX - monostatic (StripMap, SLC: SSC, **> 200** Descending, Vesuvius);
- TSX & TDX - monostatic (StripMap, SLC: SSC, **> 200** Ascending, Campi Flegrei);
- TSX & TDX - monostatic (StripMap, SLC: SSC, **> 30** Descending, Campi Flegrei).

C-band data:

- RADARSAT-2 (RS-2, StripMap, SLC, Fine-Beam, **60** Ascending);
- ERS-1/2 & ENVISAT archive data available from the ESA web site;
- Sentinel archive and current data available from the Sentinel Data Hub.

Satellite data issues

As already outlined in a previous report, some satellite data issues still remain.
Shortly summarizing, they are:

- no way to trace scientists downloading ERS/ENVISAT and Sentinel data for the area of interest, potentially interested in interacting with the Supersite science teams (access registered public);
- same for TSX/TDX data (access registered public);
- TSX/TDX data download service could be improved, e.g. following the scheme pointed out after for CSK data provision to the Coordinator;
- alternatively (or jointly), direct upload of TSX/TDX data on the ESA GEP (Geohazards Exploitation Platform) platform.

As a general remark, apart from the issues outlined above, the Coordinator and the science teams feel completely satisfied with this data provision.
Moreover, the availability of geodetic data (cGNSS, levelling, etc.) from the ground-based monitoring networks of the Coordinator's Institution in the area, allows for regular comparison with InSAR data, as outlined in the research results paragraph.
No L-Band data (ALOS-2, SAOCOM) are currently available for the Vesuvius-Campi Flegrei Supersite, that would successfully complement the huge X- and C-band database for the area: this is a precise choice by the Coordinator, taking into account the current low deformation rate of Campi Flegrei (about 1 cm/month), resulting in a clear deformation signal with the L-band only after one year or more. Also very high-resolution data (spot, staring, etc.) have not been considered at present, as the Campi Flegrei deformation pattern is locally invariant without any relevant small deformation to be detected.
As anticipated, noteworthy is the excellent CSK data provision service to the Coordinator (via FTP), with data provided in near real time up to few hours after data acquisition, an added value in case of emergency. This data provision model should be kept as a reference by other Space Agencies, especially in terms of a possible crisis management.

Research results

Scientific achievements (figures in the Annex)

InSAR - A general overview on the Neapolitan Volcanic District (2021-2022)

In order to evaluate the ongoing ground deformations in the Neapolitan Volcanic District during the last biennium (2021.01.10-2022.06.30), the mean Line-of-Sight (LoS) velocity map from CSK data is shown in fig.2.
From the analysis of the figure, apart from the Campi Flegrei area (blu box, on the west), no noteworthy deformations can be pointed out in this time-span for Vesuvius, though potentially visible on longer (years) time series, considering their low deformation rates.

Campi Flegrei

Sentinel-1A/B data processing
(S. Borgstrom, P. De Martino - INGV-OV, M. Polcari - INGV-ONT)

The multitemporal interferometric monitoring of Campi Flegrei for 2021 (2021.01.03-2021.12.29) has been carried out starting from a dataset of 61 images from the S-1A/B sensors, which allowed to generate 177 interferograms, using as reference parameters for the interferometric pairs the values: temporal baseline (Btemp) max = 18 days (3 connections/scene) and perpendicular baseline (B⊥) max = 210 m.
Precise orbital state vectors for data processing were available on the relevant ESA web page, while the atmospheric delay correction has been carried out exploiting the ERA-5 global atmospheric model from the *European Centre for Medium-Range Weather Forecasts (ECMWF).*
The topographic contribution in the interferometric phase has been removed with a DEM from SRTMGL1 data (SRTM Global 1-arcsec), conveniently reduced to the WGS84 reference ellipsoid.
The processing results have allowed to generate both the ground deformation mean LoS velocity map from fig.3 (mean LoS velocity about +10 cm/year in the maximum deformation area) and the deformation time series on coherent targets.
These values are consistent with those measured by cGNSS stations in the area, though the absolute values are different, as the comparison is carried out on data from different geometries (LoS vs. vertical). In spite of this, for the only RITE (RIone TErra) cGNSS station, located on a place in which ground deformation is almost completely vertical, the reduction of the InSAR deformation to vertical was possible by means of the relation (1) where θ (39°) represents the mean value of the incidence angle:

$$\textbf{Vertical deformation} \sim \textbf{LoS deformation/cos}\ \theta \qquad (1)$$

The comparison between InSAR data reduced this way and the height variations from cGNSS measurements is shown in fig.4.

COSMO-SkyMED data processing
(S. Borgstrom - INGV-OV)

In addition to the S-1A/B data processing, a multitemporal interferometric analysis of Campi Flegrei for the period 2021-2022 (2021.01.10-2022.06.30) has been carried out on CSK data as well. This study was carried out starting from a dataset of 58 images from the CSK constellation, which allowed to generate 233 interferograms, using as reference parameters for the interferometric pairs the values: temporal baseline (Btemp) max = 119 days and perpendicular baseline (B⊥) max = 249 m.

The atmospheric delay correction has been carried out exploiting the ERA-5 global atmospheric model from the *European Centre for Medium-Range Weather Forecasts (ECMWF)*, while the topographic contribution in the interferometric phase has been removed with a DEM from SRTMGL1 data, conveniently reduced to the WGS84 reference ellipsoid.
The processing results have allowed to generate both the ground deformation mean LoS velocity map from fig.5 (mean LoS velocity about +10 cm/year in the maximum deformation area) and the deformation time series on coherent targets.
As outlined before, these values are consistent with those measured by cGNSS stations in the area, though the absolute values are different, as the comparison is carried out on data from different geometries (LoS vs. vertical). In spite of this, for the only RITE (RIone TErra) cGNSS station, located on a place in which ground deformation is almost completely vertical, the reduction of the InSAR deformation to vertical, as already done for S-1A/B data processing, was possible by means of the relation (1) where θ (49°) represents the mean value of the incidence angle:

$$\textbf{Vertical deformation} \sim \textbf{LoS deformation}/\cos\theta \qquad (1)$$

CSK data reduced this way for the cGNSS RITE station is shown in fig.6.

The TSX/TDX - PAZ experiment: an application to Campi Flegrei
(AO-003-021, PI S. Borgstrom - INGV-OV)

In 2021 the Coordinator applied for an AO *(AO-003-021_sven.borgstrom)* on the exploitation of data from the X-band Spanish PAZ sensor, a twin of TSX/TDX, focussed on the joint use of the 3 satellites, acting as a whole as a constellation.
Taking into account the closer revisit time (from 11 up to 4/7 days) combining TSX/TDX and PAZ data, the goal of this activity is to validate the scientific use of the experimental-campaign data for the development of a time-frequent and improved long term monitoring system, to be integrated with geodetic data from ground-based monitoring networks (cGNSS, others) belonging to the Coordinator's Institution.
The availability of a huge dataset (about 10 years, though not always fully populated) of TSX/TDX images acquired in the framework of Supersites for the AOI, will likely contribute to the success of this activity.
In this regard, the TSX/TDX-PAZ multitemporal interferometric analysis of Campi Flegrei (2021.01.10-2022.07.03) has been carried out starting from a dataset of 51 images which allowed to generate 396 interferograms, using as reference parameters for the interferometric pairs the values: temporal baseline (Btemp) max = 117 days and perpendicular baseline ($B\perp$) max = 250 m.
PAZ images (only 3, namely 2022.03.08, 2022.05.13, 2022.06.04) used in this study, perfectly integrated with the rest of the TSX/TDX dataset, have a revisit time with the previous images of only *4 days* and a revisit time with the next ones of only *7 days*, thus demonstrating the potentialities of an improved InSAR monitoring system of an active volcano while combining the two datasets.

The atmospheric delay correction has been carried out exploiting the ERA-5 global atmospheric model from the *European Centre for Medium-Range Weather Forecasts (ECMWF)*, while the topographic contribution in the interferometric phase has been removed with a DEM from SRTMGL1 data, conveniently reduced to the WGS84 reference ellipsoid.
The processing results have allowed to generate both the ground deformation mean LoS velocity map from fig.7 (mean LoS velocity about +10 cm/year in the maximum deformation area) and the deformation time series on coherent targets.
As already said, these values are consistent with those measured by cGNSS stations in the area, though the absolute values are different, as the comparison is carried out on data from different geometries (LoS vs. vertical). In spite of this, for the only RITE (RIone TErra) cGNSS station, located on a place in which ground deformation is almost completely vertical, the reduction of the InSAR deformation to vertical, as already done with previous InSAR data processing, was possible by means of the relation (1) where θ (43°) represents the mean value of the incidence angle:

$$\textbf{Vertical deformation} \sim \textbf{LoS deformation}/\cos\theta \qquad (1)$$

TSX/TDX-PAZ data reduced this way for the cGNSS RITE station is shown in fig.8.

IREA-CNR activities on the Napoli bay area
(M. Bonano, S. Buonanno, F. Casu, C. De Luca, A. Fusco, R. Lanari, M. Manunta, M. Manzo, F. Monterroso, G. Onorato, G. Zeni, I. Zinno - IREA-CNR)

In this report, some of the IREA-CNR activities performed over the Napoli Bay area, which have been carried out during the last years by exploiting DInSAR techniques, are presented. In particular, the ground displacements and the volcanism of the Campi Flegrei caldera, Vesuvius and Ischia Island, have been constantly monitored via Sentinel-1 data. The relevant DInSAR measurements are provided routinely to the Italian Civil Protection on a monthly basis. Indeed, as a Centre of Competence of the Italian Civil Protection Department, IREA-CNR is tasked to provide monthly updates on the ground deformation affecting the main active Italian volcanoes. Moreover, since January 2017, the ground displacement results generated by IREA-CNR over Campi Flegrei are included in the Surveillance Report periodically released by INGV. In the following, some of the DInSAR results obtained up to 2022 over the Napoli Bay area are presented.

Campi Flegrei

The surface deformation of Campi Flegrei is systematically analysed since 2015 by using the SAR data acquired by the Copernicus Sentinel-1 constellation. Both Sentinel-1A and Sentinel-1B satellites have operated almost continuously during the study period (March 2015 - May 2022). It is worth noting that since December 23rd 2021, the SAR sensor of Sentinel-1B has not been acquiring anymore due to some power issues. Since then, there is the availability of the Sentinel-1A data, only. Accordingly, the interferometric results presented below have been generated starting from two large sequences made of 369 and 368 SAR images acquired from ascending (Track 44) and descending orbits (Track 22), respectively. Table 1 summarizes the main characteristics of the used Sentinel-1 datasets. From these data, the displacement time series and the relevant mean deformation velocity maps have been generated by using the P-SBAS DInSAR technique [1,2].

Table 1: Sentinel-1 data sets used for the SBAS DInSAR analysis of Campi Flegrei

	ASCENDING	DESCENDING
Wavelength [cm]	5.5	
Average incidence angle [deg]	39	
Acquisition Mode	Terrain Observation by Progressive Scans	
Spatial resolution [m]	30x30	
Time Interval	2015.03.25 - 2022.05.11	2015.03.24 - 2022.05.10
SLC Images	369	368
Track	44	22

For the Interferometric processing, a 1 arcsec SRTM DEM of the area with a spatial resolution of 30 m has been used. Both the differential interferograms and the subsequent deformation maps and time series present a spatial resolution of about 30 m, which has been obtained via a multi-looking operation. Measurements are spatially referred to a point located within the city of Napoli.

The availability of SAR data acquired from both ascending and descending orbits makes possible to retrieve additional information related to the vertical and East-West components of the deformation, according to [3]. Accordingly, the mean velocity maps related to the vertical and East-West displacement components are reported in Figures 9a-b.

These maps reveal a radial spatial distribution of the vertical displacement whose centre, corresponding to the maximum deforming area, is approximately localized at the Rione Terra (see P2 in Figure 9a). The measured vertical displacement rates are of about 9 cm/year throughout the analysed period (March 2015 - May 2022). The East-West component has a maximum westward displacement in correspondence to the Arco Felice area (P3 in Figure 9b) and a maximum eastward displacement in the area between the “Accademia Aeronautica” and Bagnoli (P1 in Figure 9b): in both cases, the measured displacements are above 3.5 cm/year. This horizontal spatial distribution is consistent with the vertical maximum displacement measured at Rione Terra, where indeed the East-West component is negligible (P2 in Figure 9b).

Being the time difference between the ascending and descending passes of about 1 day, and assuming that the variation of deformation is almost negligible at a distance of one day, it is possible to combine the single ascending and descending acquisitions to generate the time series of both the Vertical and East-West deformation components [3]. This assumption is valid in case no sudden and large deformation (for example, in case of high magnitude earthquakes) occurs in the analysed period, as in this case.

Figure 9 also shows the plots of the time series of the vertical and East-West components of the deformation for the points indicated as P1, P2 and P3 in Figure 9a-b. In particular, the graphs of Figure 9c-9e-9g show how the vertical displacement has reached a maximum total uplift (Figure 9e) of about 66 cm, in the analysed time frame (March 2015 - May 2022). Plots of Figure 9 show the non-linear motion of the ground, which is indeed characterized by a not constant uplift rate. Since November 2021 the caldera is uplifting at a rate of about 14 cm/year.
The behaviour of the horizontal component of the displacements is consistent with the vertical one, as shown by the plots depicted in Figures 9d-9f-9h, relative to the previously identified points P1, P2 and P3 (Figure 9b). In particular, during the period under study, displacement values of approximately 30 cm towards East (Figure 9d) and 27 cm towards West (Figure 9h) have been measured, while no significant horizontal movement has been registered in the centre of the caldera (Figure 9f).

Vesuvius

Surface deformation of Vesuvius has also been studied by exploiting the same Sentinel-1 data sets used for the analysis of Campi Flegrei caldera. Mean deformation velocity maps (Figure 10) show a subsidence of the summit with rates that reach up to 2.5 cm/year. Time series testify that the subsidence is quite linear since 2015, showing a maximum cumulative displacement of about 16 cm (P4, Figure 10c).

Ischia Island

The same Sentinel-1 data sets used for the analysis of Campi Flegrei caldera and Vesuvius have been exploited to study the Ischia Island. Mean deformation velocity maps (Figure 11) show a general subsidence (Figure 11a) of the central part of the island (Mt. Epomeo), with rates that locally reach up to 2 cm/year. East-West motions (Figure 11b) are consistent with the observed subsidence and show rates of 2-3 mm/year. The temporal evolution of the subsidence is quite linear, as testified by the time series graphs shown in Figures 11c-h, which in the northern part of the island are interrupted by the Mw 3.9 earthquake occurred on August 21st, 2017 at Casamicciola Terme village.

Satellite thermal monitoring: ASTER and Landsat 8 (L8) data processing
(M. Silvestri, M.F. Buongiorno - INGV-ONT)

Satellite thermal monitoring of Campi Flegrei area is carried out on a regular basis by INGV, the INGV-ONT Rome branch.
In table 2 are reported the satellite data (ASTER and Landsat 8/9) analyzed in the years 2020-2022.

Month	Daytime ASTER			Nighttime ASTER		
	2020	2021	2022	2020	2021	2022
January	None	None	None	None	16	19,26
February	None	None	None	None	17, 24	None
March	9	28	15	None	28	8, 24
April	None	None	None	None	None	9, 25
May	28	None	18	21, 28	8	2, 18
June	None	None	3, 19	22	25	12
July	None	None	-	8, 15, 24	11	-
August	None	19	-	31	3	-
September	None	4	-	9, 25	None	-
October	None	None	-	1, 10, 17	None	-
November	None	None	-	None	None	-
December	None	None	-	None	18	-
				6		
Month	**Daytime Landsat 8**			**Nighttime Landsat 8 2021**		
	2020	**2021**	**2022**	**2020**	**2021**	**2022**
January	6,13, 22	None	11, 27	6, 22	8, 24	11, 18, 27
February	7	16, 25	12	7	25	3, 11, 12, 19, 20, 27, 28
March	10	4, 20, 29	8, 24	10	13, 29	16, 23, 24
April	2, 11, 18	5, 14, 30	9	11	14	24
May	27	7, 23	3, 19	None	None	2, 3, 10, 11, 19, 26
June	4, 13, 29	1, 17	4, 20, 28	30	1, 17	3, 4, 11, 12, 19, 20, 28
July	14, 21, 30	3, 10, 26	-	16	3	-
August	7, 16, 23	20, 11	-	None	20	-
September	1, 17, 24	27	-	18	5	-
October	9, 18	5, 12, 28	-	20	7	-
November	4, 20	14, 21	-	None	None	-
December	None	15	-	None	None	-
	14	17				

Moreover, Landsat 9 was successfully launched on Monday, Sept. 27, 2021. This second satellite system, whose data are available starting from January 2022, offers the possibility to increase the acquired number of Landsat data on the selected area.

With regard to ASTER data, it should be pointed out that their acquisition occurs *on demand* (differently from the worldwide coverage of Landsat 8 data), by a tasking plan in which monitoring of Campi Flegrei area has a lower priority with respect to other acquisitions on the same orbit or neighboring ones. For this reason, differently from Landsat 8 data, ASTER data acquisition is not regular.

Considering that diurnal satellite images are strongly affected by solar lighting, the estimated surface temperature value, mainly in areas with possible thermal anomalies, is unreliable. This is the reason why mainly data from night passes have been processed and analyzed. In this regard, night images detect with higher precision possible temperature variations in areas with thermal emission spots, due to a more uniform background temperature. In order to estimate the surface temperature by satellite data, the atmospheric effect has been also removed.

In the Figures 12 and 13 the maps of the night surface temperature estimation are shown, from Landsat and ASTER data. Data were acquired respectively on March 24 and April 25, 2022 on

Campi Flegrei area. In the maps, chosen as representative for the period 2020-2022, it is possible to check how the estimated surface temperature from ASTER and Landsat data does not exhibit in such a time interval meaningful variations in areas with higher thermal emission within the Solfatara Crater (Pozzuoli, Campi Flegrei).

Pléiades high-resolution tri-stereo optical data processing
(C. Spinetti, M. Polcari - INGV-ONT, S. Borgstrom - INGV-OV)

The object of the Pléiades tri-stereo survey is to reconstruct digitally the surface model of the Campi Flegrei caldera starting from optical high-resolution images. The Pléiades archive is poor of acquisitions on the area, thus the interaction between INGV and Airbus Defence and Space defining the area and acquisition angles, allowed new Pléiades images request and successful acquisitions. The proposed images were able to meet the needs of aerial coverage requested even though they do not exactly match initial specifications.

In the following table the proposed images from tri-stereo tasking mode are reported.

<table>
<tr><th rowspan="2">Acquired Strip Id.</th><th rowspan="2">Satellite</th><th rowspan="2">Date</th><th rowspan="2">QL</th><th colspan="3">Incidence angles</th><th rowspan="2">Cloud Cover</th><th rowspan="2">Status</th></tr>
<tr><th>Combined</th><th>Roll</th><th>Pitch</th></tr>
<tr><td rowspan="6">AS_FC_367306_1_7</td><td rowspan="6">PHR1A</td><td rowspan="6">2022-05-13</td><td rowspan="6">QL</td><td>13.59°</td><td>-0.48°</td><td>-13.58°</td><td>4.90%</td><td rowspan="6"></td></tr>
<tr><td colspan="4">DS_PHR1A_202205131003560_FR1_PX_E014N40_0421_01124</td></tr>
<tr><td>4.20°</td><td>-3.25°</td><td>-2.66°</td><td>5.14%</td></tr>
<tr><td colspan="4">DS_PHR1A_202205131004145_FR1_PX_E014N40_0421_01200</td></tr>
<tr><td>9.72°</td><td>-5.89°</td><td>7.78°</td><td>5.44%</td></tr>
<tr><td colspan="4">DS_PHR1A_202205131004320_FR1_PX_E014N40_0421_01183</td></tr>
<tr><td rowspan="6">AS_FC_367306_1_8</td><td rowspan="6">PHR1A</td><td rowspan="6">2022-05-13</td><td rowspan="6">QL</td><td>8.88°</td><td>-0.82°</td><td>-8.84°</td><td>5.37%</td><td rowspan="6"></td></tr>
<tr><td colspan="4">DS_PHR1A_202205131004041_FR1_PX_E014N40_0221_01636</td></tr>
<tr><td>4.26°</td><td>-3.61°</td><td>2.27°</td><td>4.89%</td></tr>
<tr><td colspan="4">DS_PHR1A_202205131004228_FR1_PX_E014N40_0221_01654</td></tr>
<tr><td>13.98°</td><td>-6.24°</td><td>12.61°</td><td>4.92%</td></tr>
<tr><td colspan="4">DS_PHR1A_202205131004403_FR1_PX_E014N40_0221_01654</td></tr>
</table>

Pléiades data acquired on tri-stereo tasking mode have been correctly delivered to INGV. Data processing started with the first step of the procedure in order to derive a digital elevation model of the Campi Flegrei caldera, consisting in finding the correct angles between the different images that allows the application of the SFM technique ASP (Palaseanu-Lovejoy et al., 2019).

Vesuvius

Sentinel-1A/B data processing
(S. Borgstrom, P. De Martino - INGV-OV, M. Polcari - INGV-ONT)

The multitemporal interferometric monitoring of Vesuvius for 2021 (2021.01.03-2021.12.29, see fig.14) is the workflow already shown for Campi Flegrei area, from which the reader can get the technical details.
From the analysis of fig.14, no noteworthy deformations in this time-span for the Vesuvius area related to volcano dynamics have been pointed out. This is likely due to a low/very low amount of the ongoing deformations, potentially detectable only by processing longer time series (years), besides considering the extended decorrelation due to the considerable vegetation coverage of the whole volcanic edifice and the presence of snow in some periods of the year.
The cGNSS network from INGV-OV (De Martino et al., 2021) shows for Vesuvius area ground deformations with a mean deformation rate of 1 mm/year, apart from the crater area (Gran Cono), characterized by a clear subsidence (6-7 mm/year).
The LoS ground deformation time series from S-1A/B data on coherent targets in the crater area (close or coincident with cGNSS BKNO and BKE1 stations) were reduced to vertical with the already shown relation (1) where θ (39°) represents the mean value of the incidence angle:

$$\textbf{Vertical deformation} \sim \textbf{LoS deformation/cos}\ \theta \qquad (1)$$

Time series reduced this way show mean subsidence values of about 6-7 mm/year (fig.15), comparable with those from cGNSS stations, due to compaction processes and/or gravitational slipping of low coherent soils, steeply sloping.

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Peer reviewed journal articles

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[2] Manunta, M., De Luca, C., Zinno I., Casu, F., Manzo, M., Bonano, M., Fusco, A., Pepe, A., Onorato, G., Berardino, P., De Martino, P., Lanari, R. (2019) "The Parallel SBAS Approach for Sentinel-1 Interferometric Wide Swath Deformation Time-Series Generation: Algorithm Description and Products Quality Assessment", IEEE Trans. Geosci. Remote Sens., doi: 10.1109/TGRS.2019.2904912

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Pappalardo, L., Caliro, S., Tramelli, A., and Trasatti, E. and the LOVE-CF team (2022) Linking surface Observables to sub-Volcanic plumbing-system:a multidisciplinary approach for Eruption forecasting at Campi Flegrei caldera (Italy). EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-6487, https://doi.org/10.5194/egusphere-egu22-6487, 2022

Bianco, F., Castellano, M. (2021) Il Monitoraggio dei Vulcani Campani

Research products

The main research products of this Supersite are the scientific publications (e.g. see the list above) and the surveillance reports to the national civil protection authorities.

Type of product	Product provider	How to access	Type of access
e.g. ground deformation time series, source model, etc.	*Name of scientist(s)*	*Link to publication, research product repository or description of procedure for access*	*E.g. public, registered, limited to GSNL scientists, etc.*
Research	*Supersite science teams*	*Scientific literature (national/international)*	*Public*
Surveillance	*Mainly INGV-OV, IREA-CNR*	*Surveillance reports*	*Restricted (Civil Protection Department)*

Research product issues

Access rules outlined above. New research products are expected from ongoing projects.

Dissemination and outreach

Dissemination and outreach activities went on, with publications and workshop presentations (mainly remotely due to the covid-19 outbreak still ongoing) addressed to the scientific community, besides reporting relevant results from the Supersite activities to the main stakeholder, the Italian Civil Protection Department in the form of surveillance reports.
These reports were primarily focussed on regular updates of the ongoing ground deformation in Campi Flegrei, currently at the *attention* (yellow) level according to the Emergency Plan issued by the Italian Civil Protection Department. Indeed, the area underwent an overall inflation, in the maximum deformation area close to the coast, of about 90 cm from 2011 to date (see "Bollettino Mensile Campi Flegrei 2022 06 at http://www.ov.ingv.it/index.php/monitoraggio-e-infrastrutture/bollettini-tutti/campi-flegrei/anno-2022-2).
Conversely, presentations of relevant results during conferences and public meetings with local authorities/citizens have been drastically reduced due to the ongoing covid-19 outbreak.

Funding

Currently no funding resources are officially available for the Vesuvius-Campi Flegrei Supersite, therefore any new funding opportunities must be investigated, with the submission of new project proposals to both European and National funding bodies.
At present, almost only in-kind contributions by the science teams are provided to support the Supersite activities, besides institutional funding resources.
For instance, a relevant financial support to INGV, the Coordinator's Institution, comes from the Italian Civil Protection Department for setting up and maintenance of the ground-based monitoring networks, whose data can be exploited for integration and validation with satellite data from this Supersite.
A limited financial support to the Supersite initiative is guaranteed by ongoing projects, e.g. nowadays the EPOS activities.

Societal benefits

The main stakeholders benefiting from the Vesuvius-Campi Flegrei Supersite activities are the Italian Civil Protection Department and, on a local scale, the Regional Civil Protection of the *Campania* Region, besides the different interested Municipalities.
In this regard, all the results from space-based studies (InSAR - conventional DInSAR processing, ground deformation velocity maps, time series on coherent targets - satellite thermal observations and recently high-resolution tri-stereo optical data, whose processing is ongoing),

besides other geophysical and geochemical studies, are reported on a regular basis to the Civil Protection Department for surveillance purposes and support to decision makers.
Nowadays, the societal benefits to be achieved through the outcomes of this Supersite can be summarized in a technical support to Civil Protection authorities in setting up the updates of the National Emergency Plan for Vesuvius and Campi Flegrei areas.
These plans are continuously evolving, depending on the contributions from the reference scientific community, in terms of new scientific knowledge of both areas.
Ultimately, the chance from remotely sensed data to extend investigations on large/wide areas, far beyond the measurements on single ground-based stations, is an added value in this case, where ground deformation patterns and/or thermal anomalies on large areas have to be considered for surveillance and civil protection purposes, addressed to risk mitigation.

Conclusive remarks and suggestions for improvement

As already highlighted in previous biennial reports, the Supersites initiative fits into a particularly favourable period for the scientific and the stakeholders communities. The availability of free-of-charge satellite data from some Space Agencies represents a big step forward in supporting research and surveillance in some areas in the World, prone to natural hazards.
A significant effort in this direction has been carried out by ESA with free-of-charge data provision, not only from currently operated missions like the Sentinel constellation, but from previous missions as well, e.g. ERS-1/2 & ENVISAT.
Same for DLR, whose TSX/TDX data for Supersite users are available from the "*DLR Supersites Download Directory"* after registration.
ASI is also sharing this data dissemination philosophy, making the CSK constellation data available through the ESA GEP platform for authorized users and, recently, also for other Institutional users.
Anyhow, the ESA GEP represents not only an opportunity for satellite data sharing, but also for data processing by means of cloud-based processing tools implemented in the platform, that continuously evolve in number and quality. Recently they became a pay-per-use service, though ESA is able to guarantee an economic support for scientific/institutional users. These extremely user-friendly cloud-based services result in a valuable tool for both scientific users and experienced stakeholders involved in land management issues.
In addition to cloud-based processing tools, a further support to the activities of the scientific users and the stakeholders is provided by the availability on the web of stand-alone and user-friendly software, like the ESA SNAP (the SeNtinel Application Platform https://step.esa.int/main/download/snap-download/), for an easy and well explained data processing.
However, the access to the aforesaid web services should be monitored, with a particular focus on the ESA GEP, to avoid the exploitation of processing tools by not expert stakeholders (e.g. not governmental), especially when they have no knowledge/experience to properly handle processing results.
As regard to the continuation of future activities, the provision of adequate funding resources is a key point, especially if mid-long term activities are foreseen.

The Covid-19 outbreak, still ongoing, has largely limited the Supersite activities, both as field activities and as office job, often carried out in "smart working" mode at home. This did not allowed (or partially allowing) the Coordinator and the members of the science teams to get in touch each other to get updates/information on the results of their scientific research/activity. In spite of this, the high quality of the scientific results achieved so far must be taken into account, thus demonstrating the efforts and the interest of the scientific community as a whole in this active volcanic district.
Definitely, apart from funding issues and minor problems outlined before and still to be fixed, the Supersite Coordinator finds no particular obstacles for the next biennial activities of the Vesuvius-Campi Flegrei Supersite.

Annex with dissemination material

Figures remain in the ownership of their Authors (see Credits). Any use must be previously authorized.

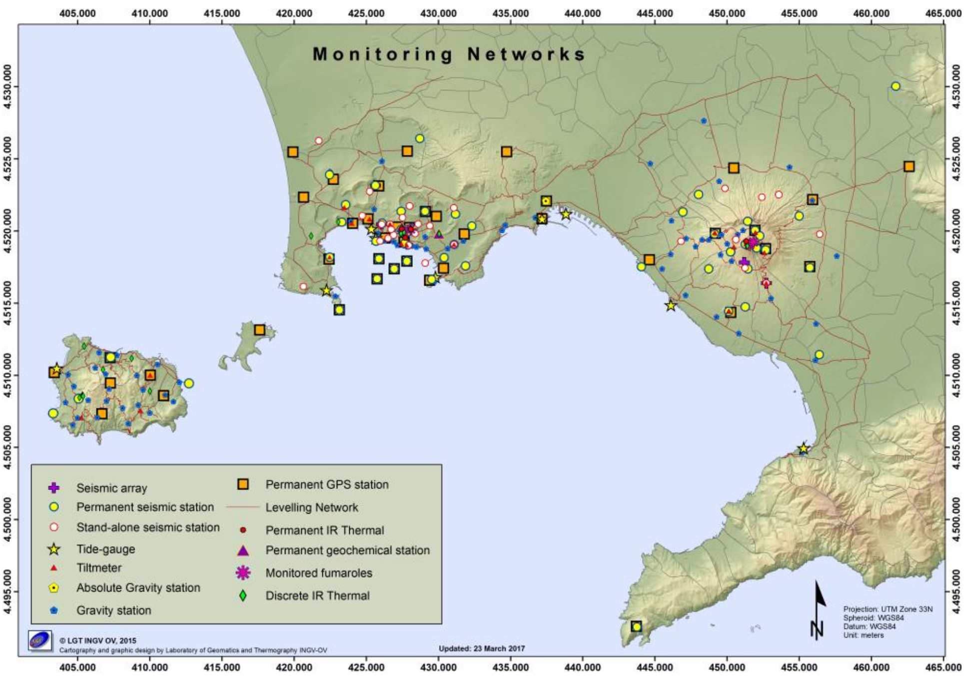

Figure 1 *- INGV-Osservatorio Vesuviano monitoring networks in the Neapolitan Volcanic District (Credits INGV-OV, Laboratory of Geomatics and Thermography)*

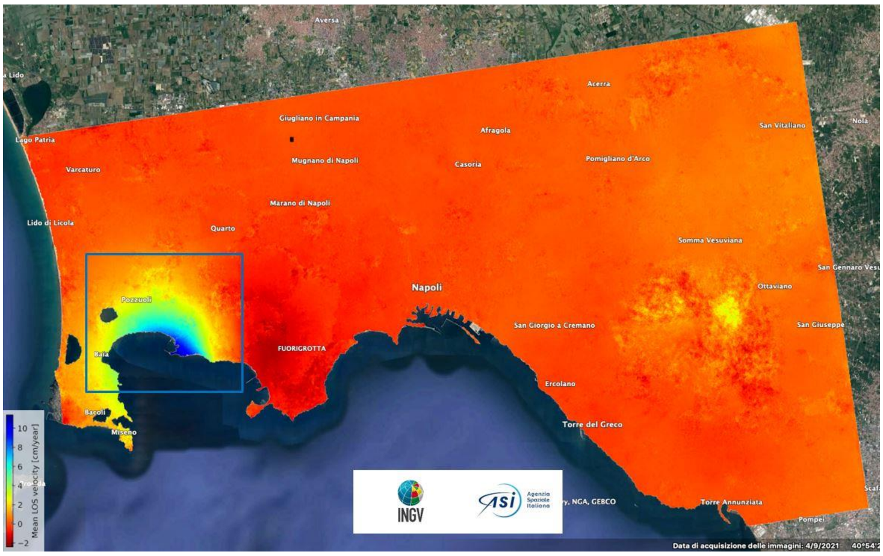

Figure 2 *- Ground deformation mean LoS velocity map (CSK, ascending track) (2021.01.10-2022.06.30) In the blu box the Campi Flegrei area (Credits INGV-OV)*

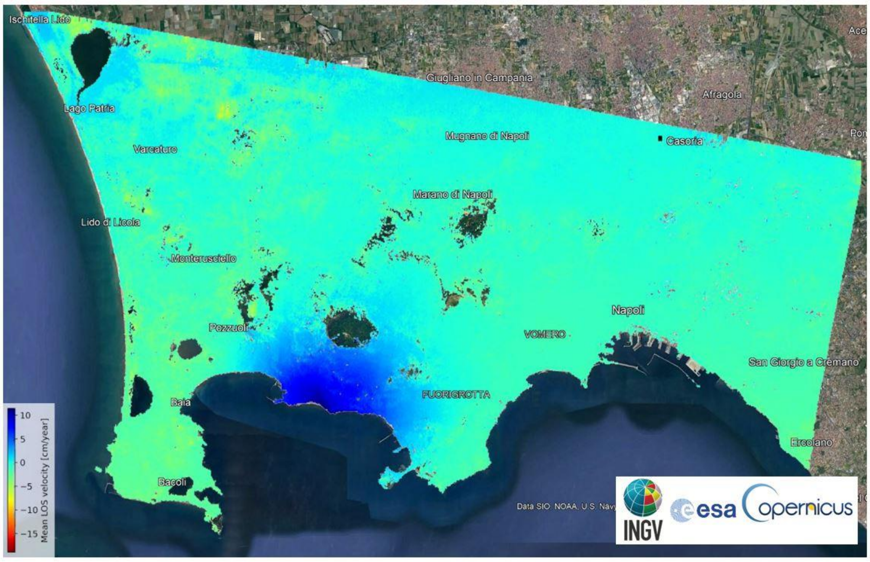

Figure 3 *- Ground deformation mean LoS velocity map (Sentinel-1A/B) (2021.01.03-2021.12.29) for Campi Flegrei. IWS data -TOPS mode, descending track (22), swath 1 (Credits INGV-OV)*

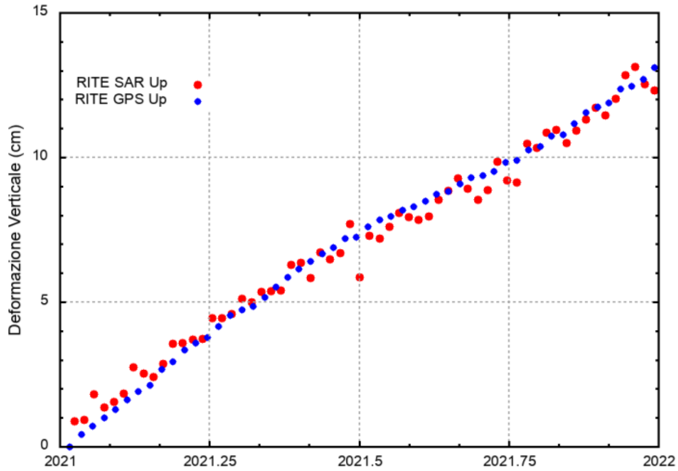

Figure 4 *- Time series (2021.01.03-2021.12.29) of the vertical deformation from InSAR data (red dots) and cGNSS data (blu dots, RITE station) in the maximum deformation area at* ***RI****one* ***TE****rra (Pozzuoli) (Credits INGV-OV)*

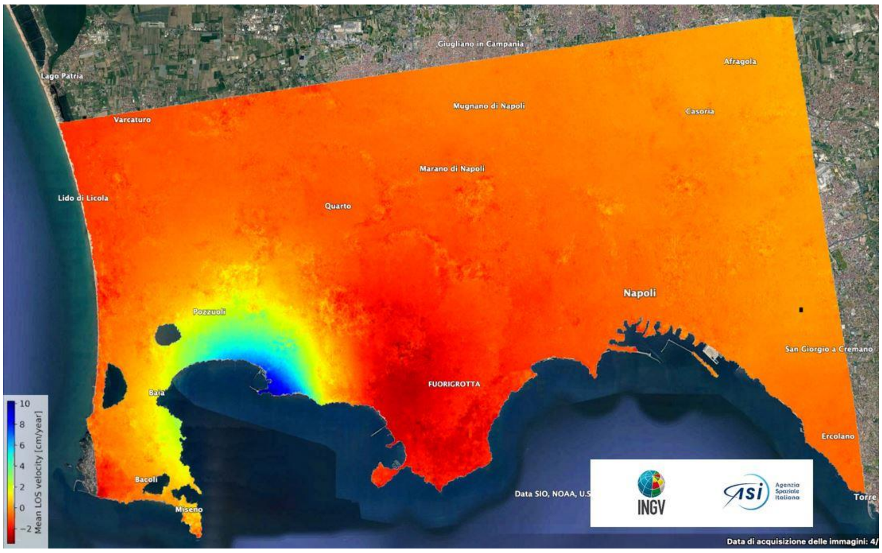

Figure 5 *- Ground deformation mean LoS velocity map (CSK, ascending track) (2021.01.10-2022.06.30) for Campi Flegrei (Credits INGV-OV)*

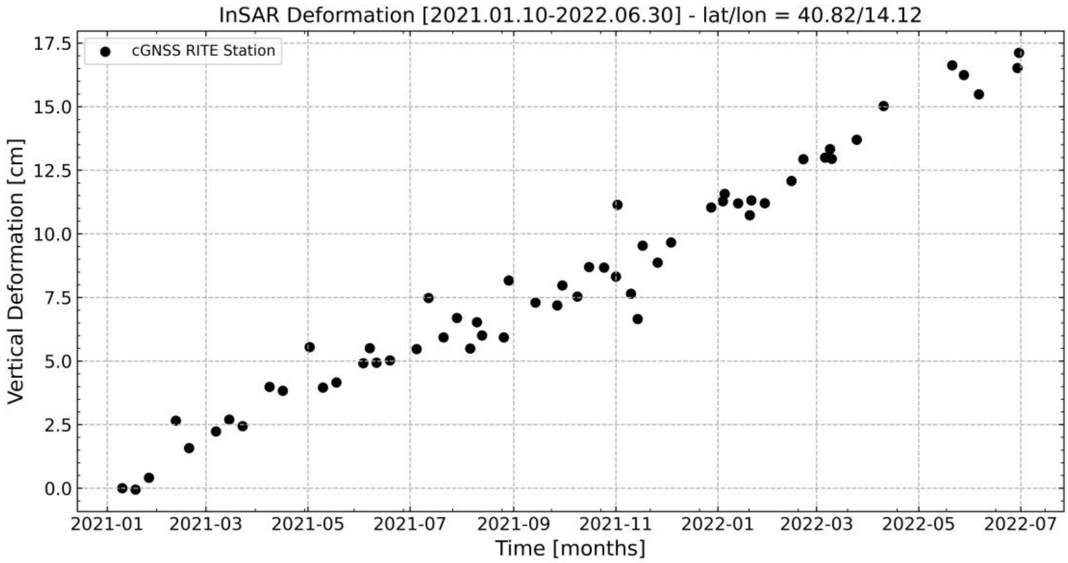

Figure 6 *- InSAR time series (vertical) (2021.01.10-2022.06.30) for a target located on RITE cGNSS station (Credits INGV-OV)*

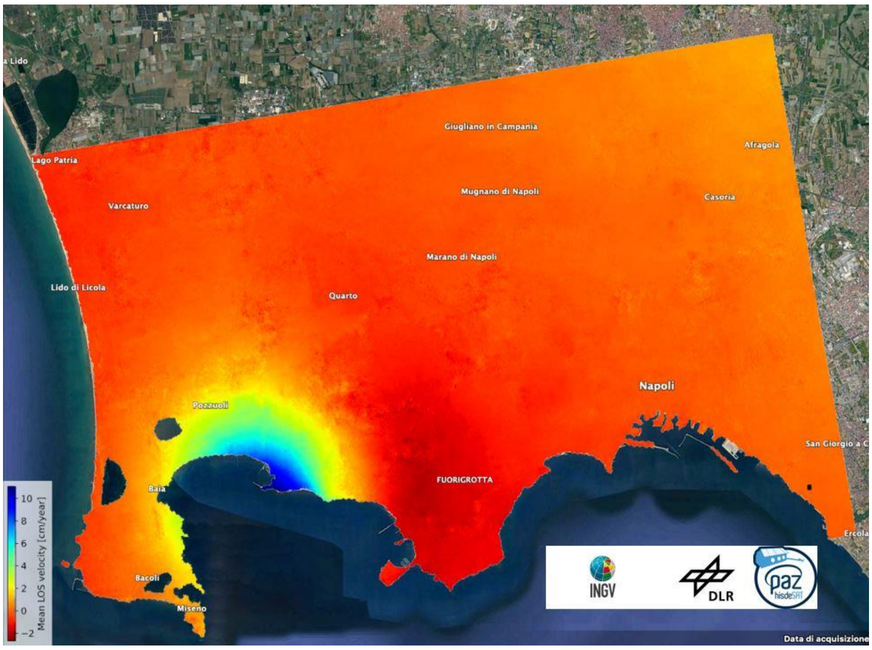

Figure 7 *- Ground deformation mean LoS velocity map (TSX/TDX-PAZ, ascending track) (2021.01.10-2022.07.03) for Campi Flegrei (Credits AO-003-021, PI S. Borgstrom - INGV-OV)*

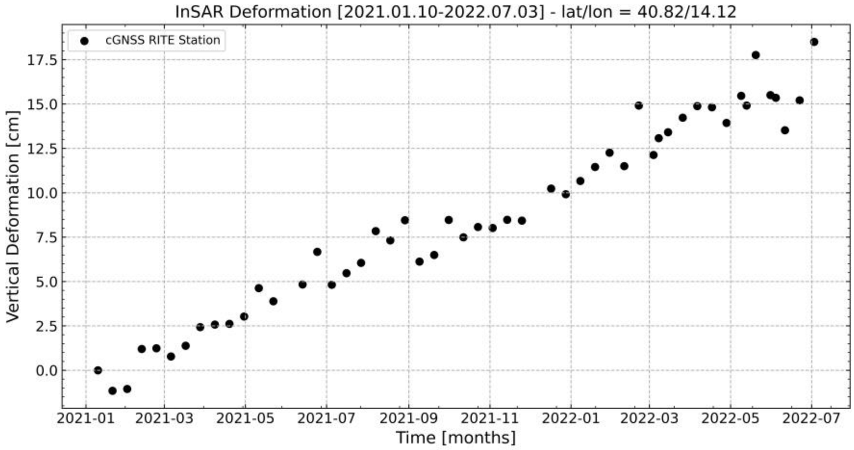

Figure 8 *- InSAR time series (vertical) (2021.01.10-2022.07.03) for a target located on RITE cGNSS station (Credits AO-003-021, PI S. Borgstrom - INGV-OV)*

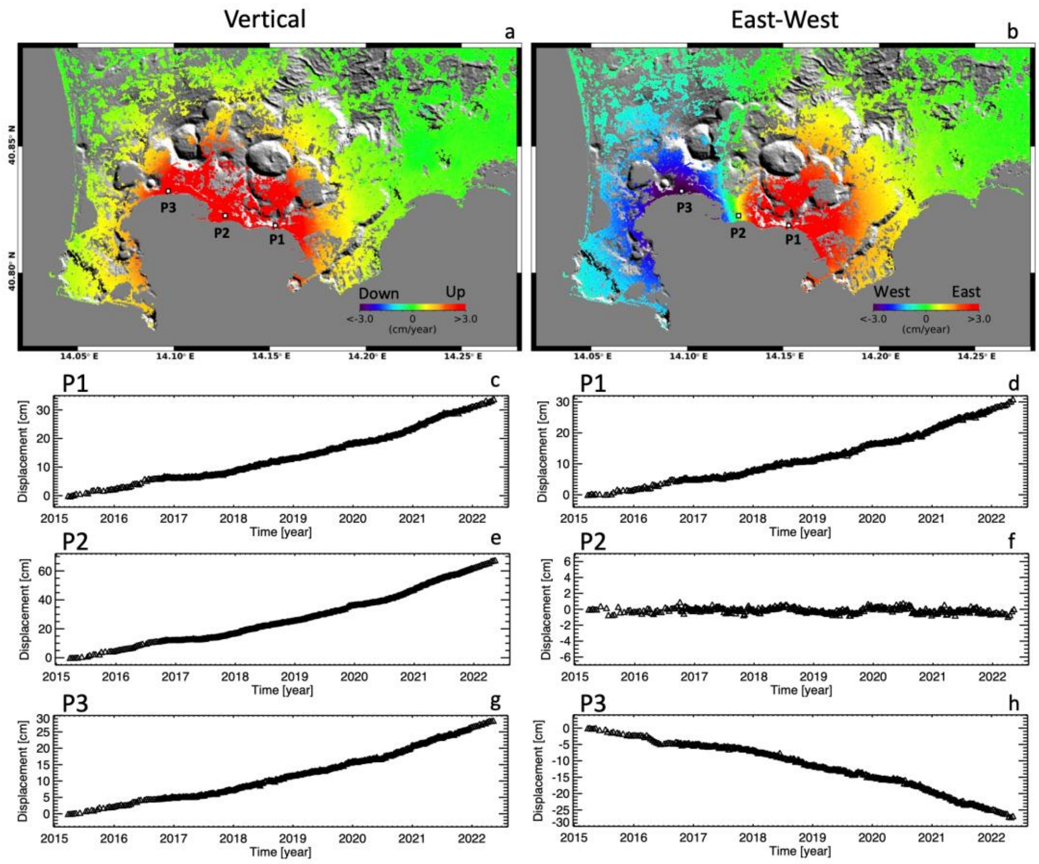

Figure 9 - *Campi Flegrei: mean velocity maps of the Vertical and East-West deformation components in the period March 2015 – May 2022, generated from Sentinel-1 data. a) Vertical Component. b) East-West component. c-h) Displacement time series along the Vertical (c) (e) (g) and East-West (d) (f) (h) directions of three points identified as P1, P2 and P3, respectively, in (a) - (b) (Credits IREA-CNR)*

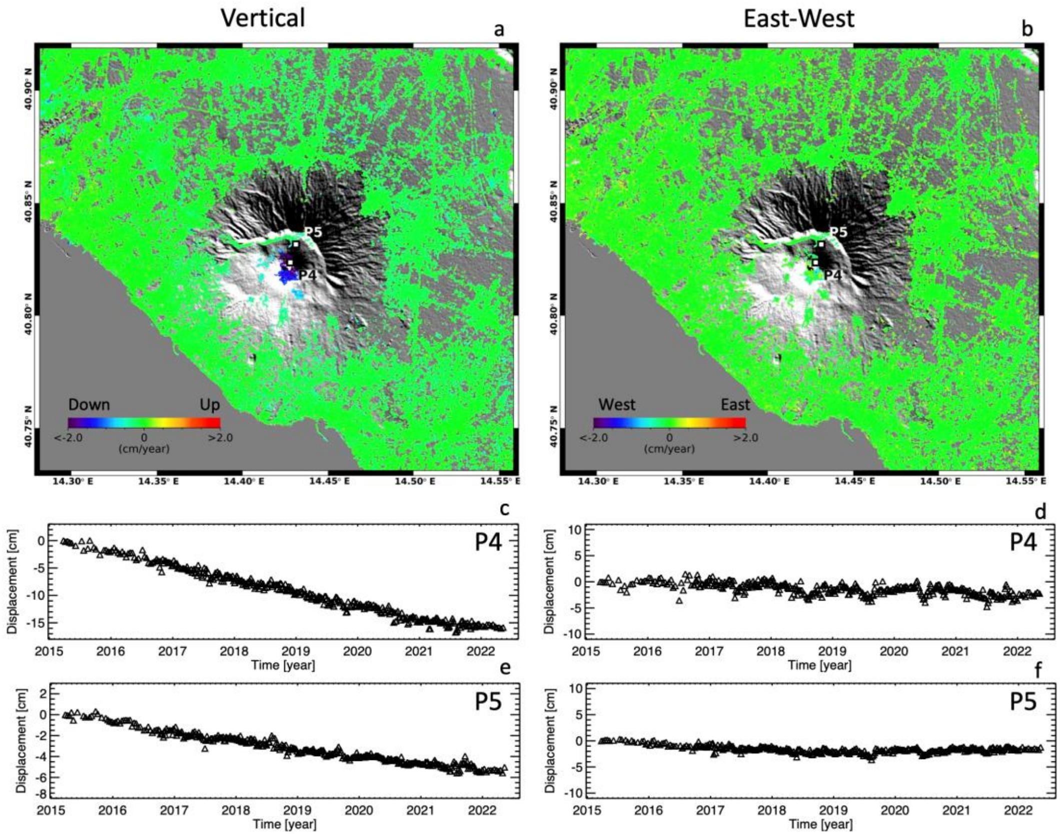

Figure 10 - *Vesuvius: mean velocity maps of the Vertical and East-West deformation components in the period March 2015 – May 2022, generated from Sentinel-1 data. a) Vertical Component. b) East-West component. c-f) Displacement time series along the Vertical (c) (e) and East-West (d) (f) directions of two points identified as P4, and P5, respectively, in (a) - (b) (Credits IREA-CNR)*

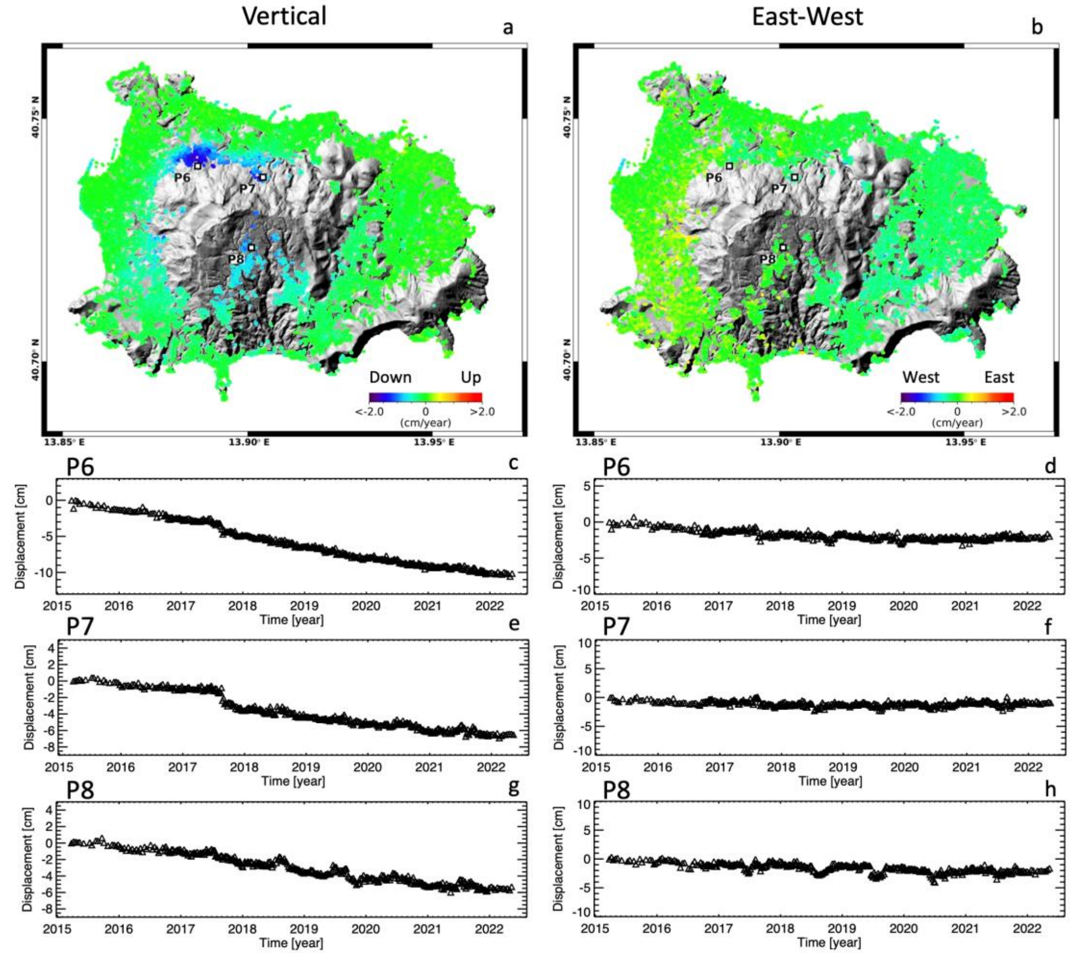

Figure 11 - *Ischia: mean velocity maps of the Vertical and East-West deformation components in the period March 2015 – May 2022, generated from Sentinel-1 data. a) Vertical Component. b) East-West component. c-h) Displacement time series along the Vertical (c) (e) (g) and East-West (d) (f) (h) directions of three points identified as P6, P7 and P8, respectively, in (a) - (b) (Credits IREA-CNR)*

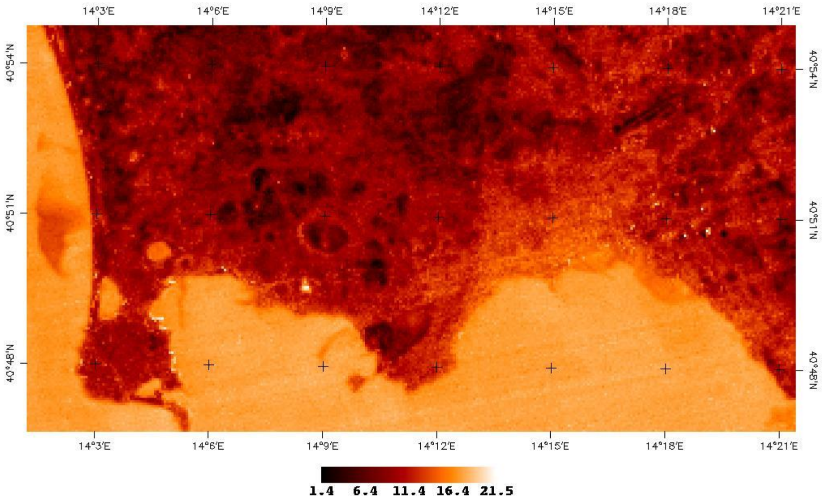

Figure 12 *- Surface temperature map from Landsat 8 data acquired at 20.46 UTC, March 24, 2022. Mean temperature inside Solfatara volcano estimated by satellite data is about 11 °C, while maximum temperature is 17 °C (Credits INGV-ONT)*

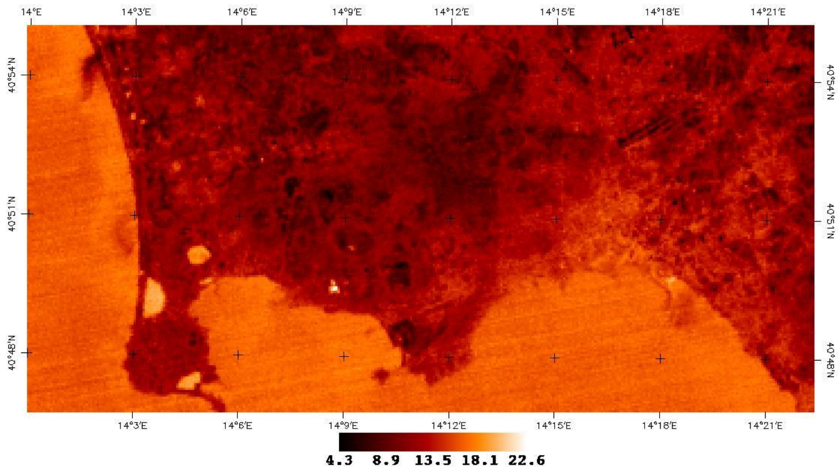

Figure 13 *- Surface temperature map from ASTER data acquired at 21.00 UTC, April 25, 2022. Mean temperature inside Solfatara volcano estimated by satellite data is about 16 °C, while maximum temperature is 22.6 °C (Credits INGV-ONT)*

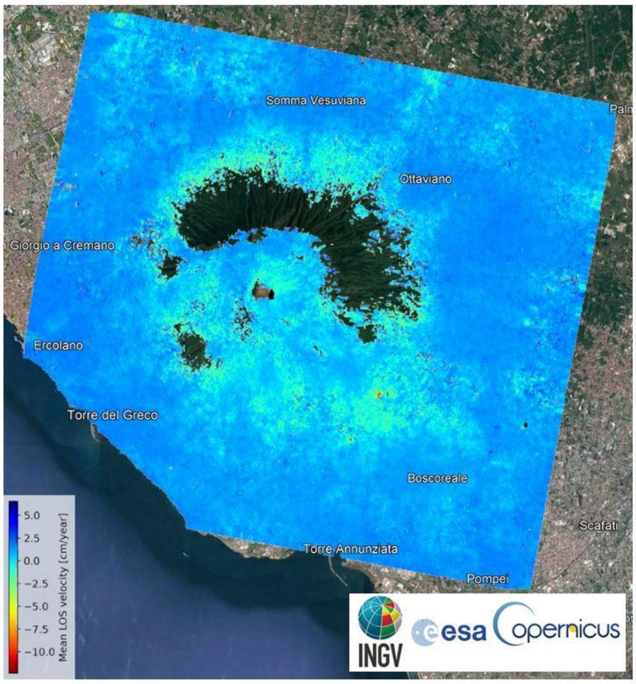

Figure 14 *- Ground deformation mean LoS velocity map (Sentinel-1A/B) (2021.01.03-2021.12.29) for Vesuvius. IWS data -TOPS mode, descending track (22), swath 1 (Credits INGV-OV)*

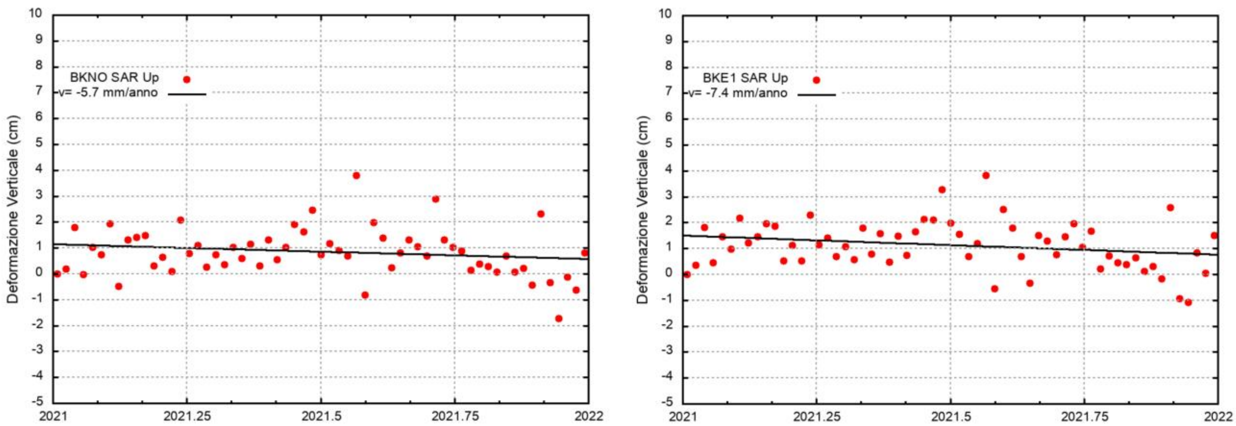

Figure 15 *- Time series (2021.01.03-2021.12.29) of the vertical deformation from S-1A/B data for the cGNSS BKNO and BKE1 stations in the crater area (Credits INGV-OV)*