Version 1.2
23 March 2018

www.geo-gsnl.org

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 Supersite science teams, though not limited to, are:

- research, by taking part into international research projects/activities and
- monitoring, focused 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 is mainly focused on Campi Flegrei, currently at the *attention* (yellow) level according to the Campi Flegrei Emergency Plan issued by the Italian Civil Protection Department, and the Island of Ischia, where a seismic activity is ongoing, starting from the 4.0 magnitude earthquake occurred on August 21st, 2017.
Moreover, during the 2018-2020 biennium of the Supersite initiative, the improvement and fine-tuning of the MED-SUV (EC FP-7 Project) infrastructure (http://medsuv_portal.ct.ingv.it/) continued, conceived for data dissemination within the scientific community. The infrastructure, to be exploited in the frame of EPOS (European Plate Observing System https://www.epos-ip.org/), allows the distribution of both satellite and in-situ data from the INGV monitoring networks, according to the Space Agencies and the recently released INGV data policies.
Similarly, besides the release of high resolution DEMs (12 m + 30 m pixel posting) in response to the DLR *Announcement of Opportunity* for TDX DEM products request (http://www.earthobservations.org/documents/gsnl/201701_tdx_dem_campi_flegrei_vesuvius_mt_etna.pdf), in these years more support activities to facilitate scientists involved in this Supersite were planned and should be implemented in a near future, like the request for PLEIADES stereo data over Campi Flegrei and the request - though to be confirmed - for InSAR data from the recently launched NovaSAR-S S-band SAR sensor over 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. The availability of a recently improved RS-2 dataset has allowed the production of mean velocity maps and ground deformation histories

(time series) over coherent targets on both Campi Flegrei and Vesuvius. Also ASTER and LANDSAT8 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 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).

With respect to the international participation in this Supersite, some variations were made with respect to the first science teams in 2014, including also scientists from outside Europe, actively involved in different research activities on the Neapolitan Volcanic District (e.g. Tiampo et al., 2017). Also an interest from ASI and ESA scientists was recently expressed in the exploitation of SAR data of this active volcanic district. This was a precise choice from the Supersite coordinator, in order to improve the results not only in terms of InSAR and thermal studies but also to include new outcomes from modelling of the deformation source in the area of interest.

With regard to data dissemination within the Supersite science teams, apart from the Sentinel data hub, the set up in these years of web platforms by some Space Agencies, e.g. the *ESA Geohazards Exploitation Platform* (https://geohazards-tep.eu/#!), the *ESA Virtual Archive, vers.4,* (https://va4h02.esa.int/) and the *TSX Supersites Download Service* (https://download.geoservice.dlr.de/supersites/files/) is now overcoming this initial problem, allowing also near real time data dissemination.

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 above-mentioned support provided by Space Agencies, besides the foreseen improvement of the MED-SUV/EPOS infrastructure for ground-based data dissemination.

In situ data

A general overview of the monitoring networks in the Neapolitan volcanic area is presented (up to 2018, 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 (CF)

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 frame of the EC FP-7 MED-SUV project, to be furtherly populated.

As also mentioned, improvements of the infrastructure continued, in the perspective of its exploitation in EPOS (Freda et al., 2017).
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, should be now overcome by the recent release of the INGV data policy.

Satellite data

Type of data	Data provider	How to access	Type of access
ERS-1/ERS-2	ESA	http://eo-virtual-archive4.esa.int/?q=Vesuvius	Registered public
ENVISAT	ESA	http://eo-virtual-archive4.esa.int/?q=Vesuvius	Registered public
Sentinel	ESA	https://scihub.copernicus.eu/dhus/#/home	Registered public
TerraSAR-X	DLR	https://download.geoservice.dlr.de/supersites/files/	Registered public
COSMO-SkyMed	ASI	Coordinator requests access to ASI for individual users	Authorized GSNL scientists
RADARSAT-2	CSA	Coordinator requests access to CSA for individual users	Authorized GSNL scientists
Landsat 8	USGS	http://earthexplorer.usgs.gov	Registered public
AVHRR	NOAA	http://earthexplorer.usgs.gov	Registered public
MODIS	NASA	http://modis.gsfc.nasa.gov/data/	Open

Current availability of InSAR data provided through the Vesuvius-Campi Flegrei Supersite initiative:

X-band data:

- COSMO-SkyMed (CSK, StripMap, SLC: SCS_B)
  Ascending: 555 scenes in the time span 2011.01.07 to 2020.04.29;

Descending: 10 scenes in the time span 2011.11.25 to 2013.05.13.

- TerraSAR-X & TanDEM-X - monostatic (TSX/TDX, StripMap, SLC: SSC)
  Ascending (Vesuvius): **132** scenes in the time span 2008.02.15 to 2020.04.16;
  Descending (Vesuvius): **173** scenes in the time span 2008.02.13 to 2020.04.08;
  Ascending (Campi Flegrei): **174** scenes in the time span 2009.03.11 to 2020.03.30;
  Descending (Campi Flegrei): **24** scenes in the time span 2010.07.12 to 2020.04.14.

C-band data:

- RADARSAT-2 (RS-2, StripMap, SLC, Fine-Beam)
  Ascending: **60** scenes in the time span 2011.09.09 to 2016.02.27.
- ERS1/2 & ENVISAT archive data available from the ESA Virtual Archive.
- Sentinel archive and current data available from the Sentinels Scientific Data Hub.

Currently, no L-Band data available for the Vesuvius-Campi Flegrei Supersite.

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 (access registered public);
- TSX/TDX data ordering service could be improved, as future data can be tasked/ordered based on two options: (i) the repetition of previously ordered data (same product type, sensor mode, pass direction, etc.) only one at a time or (ii) the ordering of more data at once, but the user will get data only after the last acquisition, which is not a viable solution in the event of a sudden crisis, when near real time data are needed.
- RS-2 data ordering, only from Windows through the APT tool, still remains a not user-friendly procedure: a web-based ordering solution would represent an improvement, allowing a smoother way to get data;
- no ALOS-2 data available for this Supersite: these data would successfully complement the huge X- and C-band database for the area;
- no high/very high resolution data (e.g. spotlight/staring-spotlight) available for this Supersite, apart from (few) TSX spot data acquired after the 2017 Ischia earthquake; the integration with ground-based geodetic data would result in a better knowledge of the deformation pattern for some critical areas.

A valuable service is the one offered by ESA to provide data from both the ESA sensors (currently operated + archive missions) and SAR systems from other Space Agencies through the GEP (Geohazards Exploitation Platform), by linking the platform to their repositories. Excellent CSK data provision service to the coordinator (via FTP) and members of the science teams (through the ESA Virtual Archive), with data dissemination 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 (2019)
(S. Borgstrom - INGV-OV)

In order to evaluate the ongoing ground deformations in the Neapolitan Volcanic District during 2019 (2019/01/02-2019/12/16), the mean Line-of-Sight (LoS) velocity map from S-1A/B data is shown in fig.2.
From the analysis of the figure, apart from the Campi Flegrei area (red box), no noteworthy deformations can be pointed out in this time span, though potentially visible on longer (years) time series, considering their low deformation rates.

Campi Flegrei area

TerraSAR-X data processing (classical DInSAR)
(S. Borgstrom - INGV-OV)

The analysis of ground deformation (second half of 2019) in Campi Flegrei was carried out exploiting TSX data (Stipmap mode), resulting in the deformation map from the differential interferogram 2019/07/03-2020/01/06 (fig.3). In the figure each color cycle corresponds to 1 cm of deformation in LoS.
From the analysis of the deformation map, the uplift acting along the coast line (the area within the red oval) is in the order of about 5 cm, though this value is not very clear due to the decorrelation in the inland. Such a result is confirmed from the comparison with the height variations of a continuous GPS (cGPS) station located in the maximum deformation area, for the same time interval.
Though the deformation map in fig.3 has been obtained by a single interferogram, potentially affected by atmospheric artefacts, note that ground deformation highlighted along the coast line remains well defined/unchanged.
The phase component of topography has been removed using a DEM from SRTMGL1 (SRTM Global 1arcsec) data, with a pixel spacing of about 30 m, whose geodetic heights have been reduced to the reference ellipsoid (WGS84) starting from the EGM96 geoid.

Sentinel-1A/B data processing

(S. Borgstrom - INGV-OV)

The multitemporal interferometric monitoring of Campi Flegrei for 2019 (2019/01/02-2019/12/16, see fig.2) has been carried out starting from a dataset of 54 images from the ESA S-1A/B sensors, which allowed to generate 255 interferograms, using as reference parameters for the interferometric pairs the values: Btemp max = 30 days and B⊥ max = 171 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, conveniently reduced to the WGS84 reference ellipsoid.
The processing result has allowed to generate both the ground deformation mean LoS velocity map from fig.2 (mean LoS velocity about +8 cm/year in the maximum deformation area) and the deformation time series on coherent targets, shown in fig.4.
These values are consistent with those measured by cGPS stations (fig.5), 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) cGPS station, located on a place in which ground deformation is completely vertical, the reduction of the InSAR deformation to vertical was possible by means of the relation (1) where θ represents 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 cGPS measurements is shown in figures 6a, 6b.

COSMO-SkyMED data processing

(M. Polcari - INGV-ONT)

With regard to the multitemporal satellite monitoring of the Campi Flegrei area, a dataset of 462 images from the ASI CSK data has been processed over a time span of more than 8 years, from January 2011 to June 2019.
For the speckle reduction, multilook factors were chosen in order to have the dimension of the ground pixel of about 30 m both in range and in azimuth. For the removal of the topographic contribution in the interferometric phase a 12 m resolution DEM has been used, provided by the DLR TandenDEM-X mission, conveniently sub-sampled to 30 m.
Based on the parameters chosen for the interferometric pairs (Btemp max = 120 days and B⊥ max = 250 m), a network of 3203 interferograms has been obtained, afterwards filtered and unwrapped.
The result in terms of ground deformation mean LoS velocity map is shown in fig.7.
The volcanic inflation in the Campi Flegrei caldera is clearly visible with deformation values of more than +4 cm/year in the Pozzuoli harbor area. On the contrary, negative values are detectable on the east side of the caldera, due to the horizontal component of ground deformation that, considering the acquisition geometry of the SAR sensor, is subtracted from the vertical component.

In fig.8 InSAR ground deformation time series of some targets located inside the Campi Flegrei caldera are shown. Time series obtained on points close to RITE and STRZ cGPS stations are in a good agreement with the height measurements from cGPS. It should be pointed out that InSAR time series are evaluated along the LoS therefore, taking into account the acquisition geometry and particularly the low incidence angle (about 49°) of the SAR sensor, the vertical component of deformation is significantly higher, in accordance with the aforementioned relation (1).
In this regard, considering for instance the RITE InSAR time series, the maximum LoS uplift of about 33 cm (January 2011-June 2019) corresponds to a vertical deformation of about 51 cm, as also confirmed from the height variations of the RITE cGPS station for the same time interval (fig.9). The InSAR time series obtained close to the cGPS IPPO station is affected, on the contrary, by a strong horizontal component in the east direction, resulting in a negative velocity.
The maximum uplift in the Campi Flegrei caldera has been measured close to the Pozzuoli Cathedral (DUOMO time series), in the historical area of Rione Terra.

RadarSat-2 data processing
(S. Borgstrom - INGV-OV)

RS-2 full frames over the Neapolitan Volcanic District have been conveniently cropped in order to analyze ground deformations in time (2011/09/09-2016/02/27) for both Campi Flegrei and Vesuvius areas.
The multitemporal interferometric processing of Campi Flegrei for this period has been carried out starting from a dataset of 60 fine-beam images, which allowed to generate 321 interferograms, using as reference parameters for the interferometric pairs the values: Btemp max = 192 days and $B_\perp$ max = 250 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.
Processing results have allowed to generate both the ground deformation mean LoS velocity map from fig.10 (mean LoS velocity about +4 cm/year in the maximum deformation area) and the deformation time series on coherent targets, where the RITE cGPS location is shown (fig.11).
This latter value of the InSAR cumulative displacement (17.4 cm) is consistent with the one measured by the RITE cGPS station in the same period (fig.12, the box with red dashed lines), 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 cGPS station, located on a place in which ground deformation is completely vertical, the reduction of the InSAR deformation to vertical was possible by means of the aforementioned relation (1) where the incidence angle θ is now 47.5°. The comparison between InSAR data reduced this way and the height variations from cGPS measurements is in a good agreement, with a value of about 25 cm (2011/09/09-2016/02/27), which can be pointed out also from fig.12.

SNAP COSMO-SkyMed DInSAR service for ground displacement mapping available on GEP
(M. Foumelis - BRGM, the French Geological Survey)

The SNAP GEP service has been fully tested on the Naples area (fig.13), exploiting CSK data provided in the frame of the GEO-GSNL international activities.
The SNAP COSMO-SkyMed DInSAR service for ground displacement mapping is the first service available on GEP that processes ASI COSMO-SkyMed radar data. The service is based on ESA's open source toolbox, SentiNel Application Platform (SNAP).
The service uses as input pairs (master and slave) COSMO-SkyMed Level-1A Stripmap Single Look Complex (SLC) products and runs with a processing scheme that utilizes both SNAP command-line functionalities and Jupiter Notebooks. The majority of the processing parameters are fixed, with user defined parameters kept at the minimum. This serves optimum manipulation of data for most of the cases.
The outputs of the SNAP COSMO-Sky-Med DInSAR service include the geocoded wrapped differential interferogram and the corresponding coherence levels both in geographic lat/lon projection.
SNAP COSMO-SkyMed DInSAR service is developed by the French Geological Survey (BRGM) and Terradue Srl in the frame of the CEOS Working Group Disasters Geohazards Lab activities. The service is accessible to users via GEP.
Currently, the COSMO-SkyMed data collections available on GEP are accessible for the authorized user teams of the CEOS Working Group Disasters and the GSNL, while upload and usage of private archives is also supported.

IREA-CNR activities on the Naples Bay area
(M. Bonano, R. Castaldo, F. Casu, C. De Luca, V. De Novellis, M. Manunta, M.R. Manzo, G. Onorato, S. Pepe, G. Solaro, P. Tizzani, E. Valerio, I. Zinno - IREA-CNR)

In this report, some of the IREA-CNR activities on the Naples 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 Campi Flegrei caldera, Vesuvius an Ischia Island, have been constantly monitored via both COSMO-SkyMed and 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 IREA-CNR displacement results over Campi Flegrei are included in the Surveillance Report released every 6 months by INGV. In the following, some of the DInSAR results obtained up to 2020 in the Naples Bay area are presented.

COSMO-SkyMed DInSAR results
The processing of the CSK data has been carried out using the Small BAseline Subset (SBAS) DInSAR algorithm on the data acquired from ascending orbits in the time interval 12 July 2009 - 23 December 2019. Table 1 shows the main characteristics of the data used for the CSK interferometric analysis.

Table 1: CSK data set used for the SBAS DInSAR analysis of Campi Flegrei

Sensor	COSMO-SkyMed
Wavelength [cm]	3.1 cm
Orbit	Ascending
Average incidence angle [deg]	44
Spatial Coverage [km]	40x40
Time Interval	12 July 2009 – 23 December 2019
SLC Images	645
DEM	SRTM (30 m)

In Figure 14, the map of the mean deformation velocity in the sensor LoS relevant to the analysed area, which includes the Campi Flegrei caldera (on the left) and the city of Naples (on the right), is presented. The information of average deformation velocity (in false colours) has been geocoded and superimposed to an optical image of the area (in grey); the areas where the deformation measurement is affected by decorrelation noise are excluded from false colour map; the spatial reference with respect to which the deformation measures were calculated is located near the Naples harbour.

Figure 14a shows a radial deformation pattern (the surface is moving towards the sensor) of the caldera, whose centre can be identified within the city of Pozzuoli (i.e. Rione Terra area). In particular, a maximum displacement (in LoS) of about 46 cm in the whole analysed period (12 July 2009 - 23 December 2019) has been measured. Accordingly, Figure 14 shows the temporal evolution of the displacement in LoS for a point located in the area of maximum deformation of the caldera (Rione Terra, Pozzuoli). Assuming that in this area the movement is purely vertical, the measured entity corresponds to about 64 cm of uplift.

From the analysis of Figure 14b, it is evident that since 2011 the caldera has been interested by a positive deformation rate, which is characterized by an alternation of accelerations and slowdowns. In particular, during the April 2012-January 2013 time interval, the caldera has shown a rapid uplift of about 11 cm, with a peak rate of about 3 cm/month during December 2012.

More recently, starting approximately from July 2017, the caldera is experiencing a nearly constant uplift (Figure 14c).

By exploiting part of the data generated in the framework of monitoring activities, we studied the 2012-2013 uplift crisis with the use of potential field techniques. To this aim, we processed the SAR data acquired from the COSMO-SkyMed constellation along ascending and descending orbits. Specifically, we processed 215 ascending and 46 descending SAR data relevant to the February 2011–January 2014 time-interval, and computed about 750 interferograms from the ascending orbits and 102 from the descending ones, with maximum perpendicular and temporal baseline values of 800 m and 400 days, respectively. The interferograms were inverted by applying the SBAS-DInSAR technique to generate mean deformation velocity maps and the corresponding time series. All the achieved results are referred to a pixel located in the city of Naples.

The availability of DInSAR measurements for both the ascending and descending orbits allows discriminating the Vertical (V) and East–West (E-W) mean velocity components. In addition, in

order to uniform temporal sampling, the two passes were resampled to 11 days by using a linear interpolation. This allowed the computation of time series representing the temporal evolution of the E-W and Vertical deformation components (Figure 15). The analysis of the generated maps reveals an extended deformation pattern that involves the whole caldera. The vertical component shows a maximum located in correspondence to Pozzuoli harbour, while the horizontal one testifies the presence of a region of very low E-W velocity that separates the eastern and western sides of the caldera. In addition, three pixels were selected to show the temporal evolution of the Vertical and E-W components in correspondence to their respective maxima. Accordingly, Figure 15g emphasizes that the vertical component of the ground deformation reaches a maximum value of about 18 cm, while the horizontal displacements towards East and West reach maximum values of 8 cm and about 6 cm, respectively (Figure 15h–i).
Pepe S. et al, 2019 apply the Total Horizontal Derivative (THD) technique (Figure 15l) to perform a basic detection of the deformation source boundaries. Specifically, the THD technique is an edge detection filter commonly employed for analysing potential field data and it is based on analysing the maxima of the horizontal gradient magnitude, as computed from the first order x- and y-derivatives of the field; their distribution depends on the source geometry since the maxima occur where the physical property has the greatest variation, that is at the boundaries of the sources. Despite some limitations in its applicability and accuracy, THD is a powerful boundary analysis technique. The use of this innovative potential field analysis allowed us to detected the geometrical asymmetry in the ground deformation field and highlighted the regions of caldera affected by major dynamics that represent the area where are present major fumarolic and seismic activity.

Sentinel-1 DInSAR results
The surface deformation of Campi Flegrei is also constantly 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 2020). In order to generate the interferometric results presented below, 258 and 256 SAR images have been acquired from ascending (Track 44) and descending orbits (Track 22), respectively. Table 2 summarizes the main characteristics of the Sentinel-1 data used. From these data, the displacement time series and the relevant mean deformation velocity maps have been generated by using the SBAS-DInSAR technique. For the Interferometric processing, a 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 was obtained via a multilooking operation. Measurements are spatially referred to a point located in the city of Naples.

Table 2: Sentinel-1 data set 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	25/03/2015 – 03/05/2020	24/03/2015 – 02/05/2020
SLC Images	258	256
Track	44	22

The availability of SAR data acquired from both ascending and descending orbits allows to retrieve the Vertical and East-West components of the deformation.

Accordingly, the mean velocity maps related to the Vertical and East-West displacement components are reported in Figures 16a-b. These maps reveal a radial spatial distribution of the vertical displacement whose centre, corresponding to the maximum deforming area, is approximately localized in the Rione Terra (P2 in Figure 16a). The measured vertical displacement rates are of about 7 cm/year throughout the analysed period (March 2015 - May 2020). The East-West component has a maximum westward displacement in the Arco Felice area (P3 in Figure 16b) and a maximum eastward displacement in the area between the "Accademia Aeronautica" and Bagnoli (P1 in Figure 16b): in both cases, the measured displacements are about 3 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 16b).

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

Figure 16 also shows the plot 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 16a-b. In particular, the graphs of Figure 16c-16e-16g show how the vertical displacement has reached a maximum total uplift (Figure 16e) of about 37 cm, in the analysed time frame (March 2015 – May 2020). Since July 2017 the caldera is experiencing an almost constant uplift at a rate of about 8.5 cm/year.

The behaviour of the horizontal component of the displacement is consistent with the vertical one, as shown by the plots of Figure 16d-16f-16h, relative to the previously identified points P1, P2 and P3 (Figure 16b). In particular, during the period under study, positive (eastward, Figure 16d) and negative (westward, Figure 16h) displacement values of approximately 15 cm have been measured, while no significant horizontal movement have been registered in the centre of the caldera (Figure 16f).

Satellite thermal monitoring: ASTER and LANDSAT8 (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.
Below, an example of the exploitation of satellite data (ASTER and LANDSAT8) in the second half year 2019 (July-December 2019) has been reported.
Satellite optical data acquired in this period are:

ASTER (Diurnal) July: no data August: no data September: 8, 15 October: no data November: no data December: no data	ASTER (Night) July: 13, 22 August: 7, 30 September: 8, 24 October: 17 November: no data December: 4, 13
LANDSAT8 (Diurnal) July: 5, 14, 21, 30 August: 6, 15, 22, 31 September: 7, 16 October: 9, 18 November: 26 December: 28	LANDSAT8 (Night) July: 30 August: 15 September: 16 October: 18 November: no data December: 5

Therefore, these data have been processed:

N° 2 ASTER (diurnal)
N° 9 ASTER (night)

N° 14 LANDSAT8 (diurnal)
N° 5 LANDSAT8 (night)

With regard to ASTER data, it should be pointed out that their acquisition occurs *on demand* (differently from the worldwide coverage of L8 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.
Therefore, differently from L8 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 the figures 17, 18 the maps of the night surface temperature estimation are shown, from ASTER and L8 data. Data were acquired respectively on October 17 and 18, 2019 on Campi Flegrei area.
In those maps, chosen as representative for the period July-December 2019, it is possible to check how the estimated surface temperature from ASTER and L8 data does not exhibit in such a time interval meaningful variations in areas with higher thermal emission within the Solfatara Crater (Pozzuoli, Campi Flegrei).

Vesuvius area

Sentinel-1A/B data processing
(S. Borgstrom - INGV-OV)

The multitemporal interferometric monitoring of Vesuvius for 2019 (2019/01/02-2019/12/16, see fig.19) is the workflow already shown for Campi Flegrei area, from which the reader can get the technical details.
From the analysis of fig.19, no noteworthy deformations in this time interval for the Vesuvius area are 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.

COSMO-SkyMED data processing
(M. Polcari - INGV-ONT)

The multitemporal interferometric monitoring of Vesuvius for the time span January 2011-June 2019 (see fig.7) is the workflow already shown for Campi Flegrei area, from which the reader can get the technical details. From the analysis of fig.7, negative velocities in the Great Cone area have been pointed out.
In fig.20 the ground deformation time series (2011/01-2019/06) for a target located in the aforementioned Great Cone area is shown. The subsidence pointed out here from the interferometric processing is about -7 cm, likely due to gravitational and natural compaction phenomena.

RadarSat-2 data processing
(S. Borgstrom - INGV-OV)

The multitemporal interferometric processing for Vesuvius (2011/09/09-2016/02/27) is the workflow already shown for Campi Flegrei area, from which the reader can get the technical details.

Processing results has allowed to generate both the ground deformation mean LoS velocity map from fig.21 and the deformation time series on coherent targets, where a point located in Great Cone area is shown as an example (fig.22).
As already highlighted from CSK multitemporal analysis over the Vesuvius area, also from RS-2 interferometric processing (2011/09/09-2016/02/27) negative velocities are detectable in the Great Cone area, with a mean LoS velocity of about -1.5 cm/year and a cumulative displacement of about -9 cm.

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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, e.g. the H2020 EUROVOLC (2018-2021) (EUROpean Network of Observatories and Research Infrastructures for VOLCanology) infrastructure project (Vogfjörd et al., 2018).

Dissemination and outreach

Dissemination and outreach activities went on, with publications and workshop presentations 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 focused 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 more than 60 cm from 2011 to date (see http://www.ov.ingv.it/ov/bollettini-campi-flegrei/Bollettino_Flegrei_2020_04_28.pdf)
Relevant results were also presented during conferences and public meetings with local authorities/citizens.

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 comes from the Italian Civil Protection Department for setting up and maintenance of the ground-based monitoring networks, whose data can be exploited for the integration with satellite data from this Supersite.
A limited financial support to the Supersite activities is now guaranteed by ongoing projects, like the EC H2020 EUROVOLC project, besides 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 - and satellite thermal observations), 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 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 was carried out by ESA for data dissemination not only from currently operated missions like the Sentinel constellation, but from previous missions as well, e.g. ERS/ENVISAT, available through the ESA Virtual Archive (VA4).

Same for DLR, whose TSX/TDX data for Supersite users are available from the *TSX Supersites Download Service* after registration.

ASI is also sharing this data dissemination philosophy, making the CSK constellation data available through the ESA GEP platform for authorized users.

Anyhow, the ESA GEP represents not only an opportunity for satellite data sharing, by linking to web portals from other Space Agencies, but also for data processing by means of cloud-based processing services implemented in the platform. These extremely user-friendly services result in a valuable tool for both scientific users and experienced stakeholders involved in land management issues.

In addition to cloud-based processing services, 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 http://step.esa.int/main/toolboxes/snap/), for an easy and well explained data processing, available not only in the frame of the GEP platform.

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 services 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.

A desirable availability of high/very high resolution data by Space Agencies would result in a strong improvement in the knowledge of some restricted and critical areas of interest (e.g. the Solfatara-Pisciarelli volcanic district in Campi Flegrei), especially in combination with in-situ data from monitoring networks; this possibility has been greatly increased through the availability of new very high resolution sensors (e.g. TSX staring-spotlight, CSK second generation).

Definitely, the Supersite coordinator finds no particular obstacles for the next biennial activities of the Vesuvius-Campi Flegrei Supersite, although some issues mentioned before still need to be fixed. Anyway, the high quality of the scientific results achieved so far must be taken into account, thus demonstrating the interest of the scientific community in this active volcanic area.

Side notes

Some notes to be kindly considered by the evaluation committee.
This report lacks in some parts for two main reasons, namely:

- serious health problems of the Supersite coordinator, resulting in his absence from the job/office for a period of about one year, ended in 2018; this resulted in a training period after his return - partially still in progress - in which he had to restart all the activities, also in direction of Supersites;
- in recent times the Covid outbreak, resulting in the current smart working home activity of the coordinator, which did not allow (or partially allowing) him to get in touch with the other colleagues from the Supersite science teams to fully get updates/information on the results of their scientific research/activity.

The coordinator tried to do his best to get an acceptable result in such an unfavourable context.

Annex with dissemination material

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

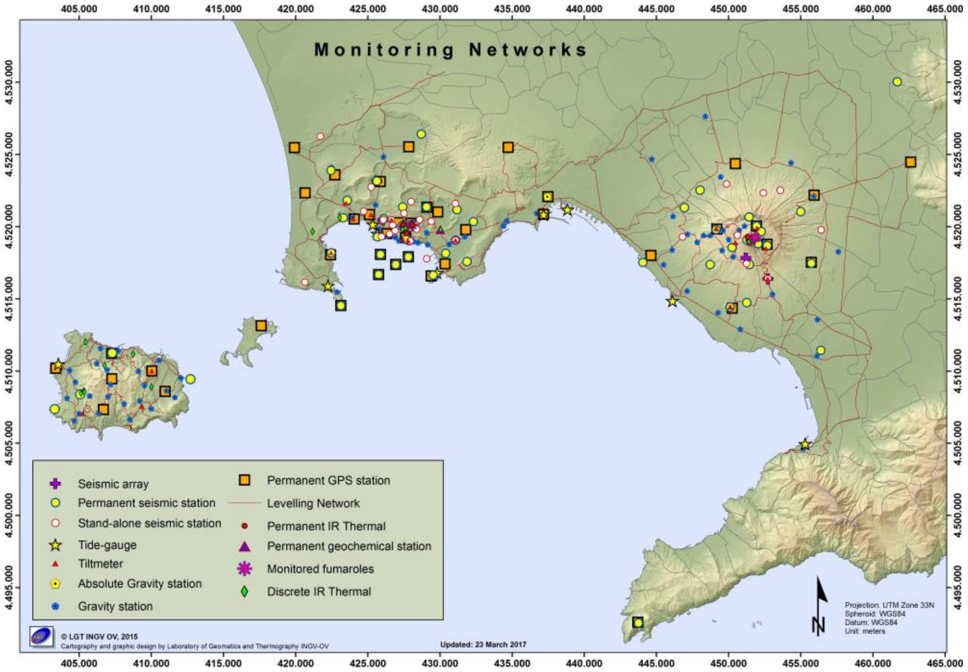

Figure 1 *- INGV-Osservatorio Vesuviano monitoring networks in the Neapolitan Volcanic District (Credits INGV-OV, Laboratory of Geomatics and Thermography)*

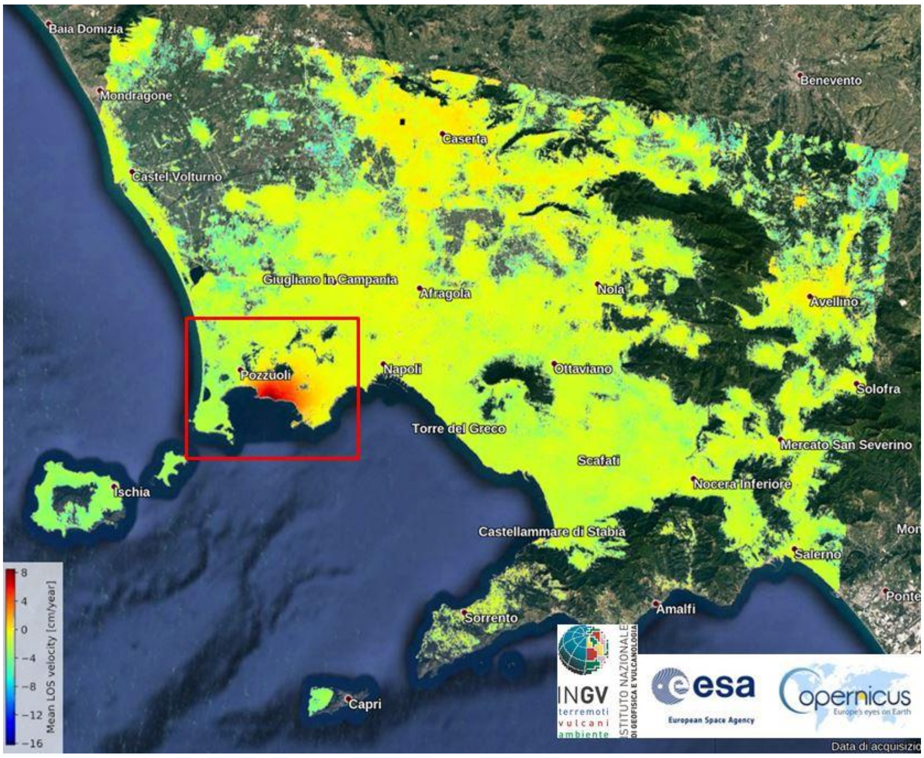

Figure 2 *- Ground deformation mean LoS velocity map (Sentinel-1A/B) (2019/01/02-2019/12/16)*
In the red box the Campi Flegrei area - IWS data, TOPS mode, Descending orbits (22), Swath 1
(Credits INGV-OV)

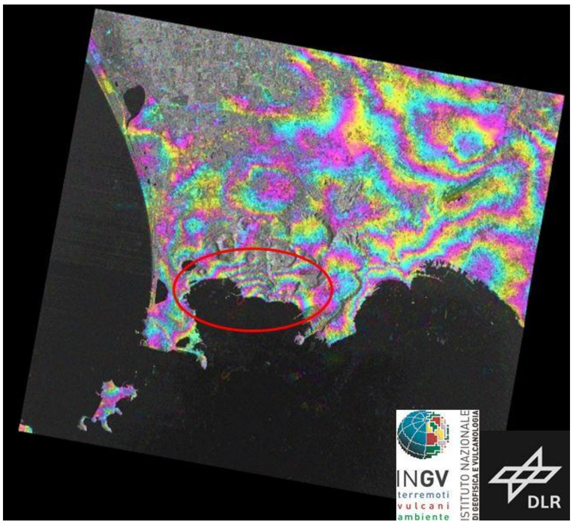

Figure 3 *- Ground deformation map (LoS) (TerraSAR-X) (2019/07/03-2020/01/06)*
In the red oval the maximum deformation area
(1 cm/color cycle, Stripmap data, Descending orbits, B⊥ = 27 m) (Credits INGV-OV)

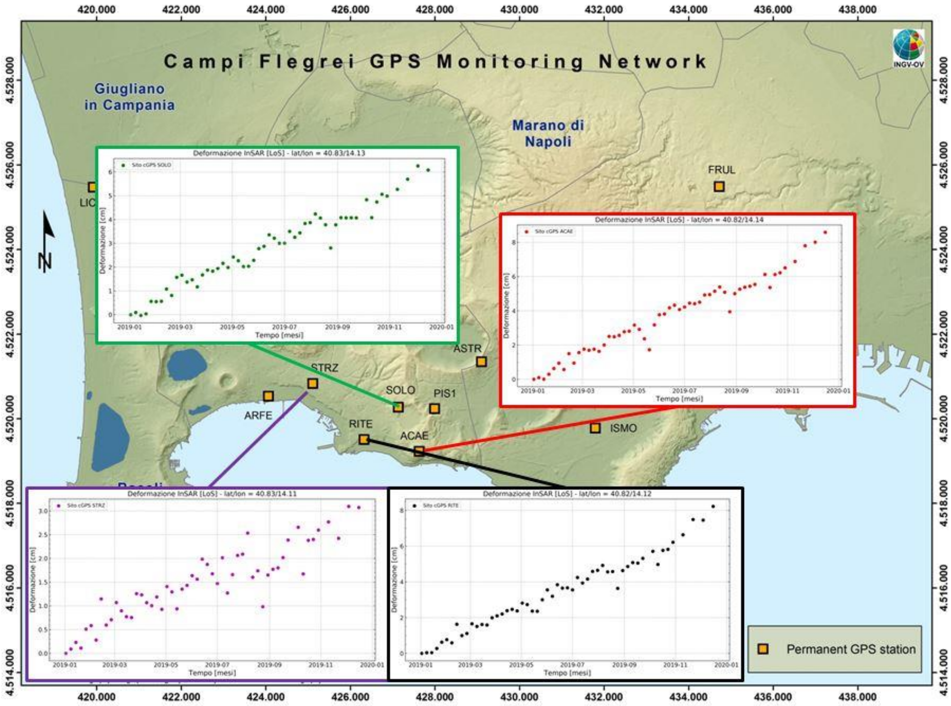

Figure 4 *- InSAR LoS time series (2019/01/02-2019/12/16) for targets located on cGPS stations (RITE, ACAE, SOLO, STRZ) (Credits INGV-OV)*

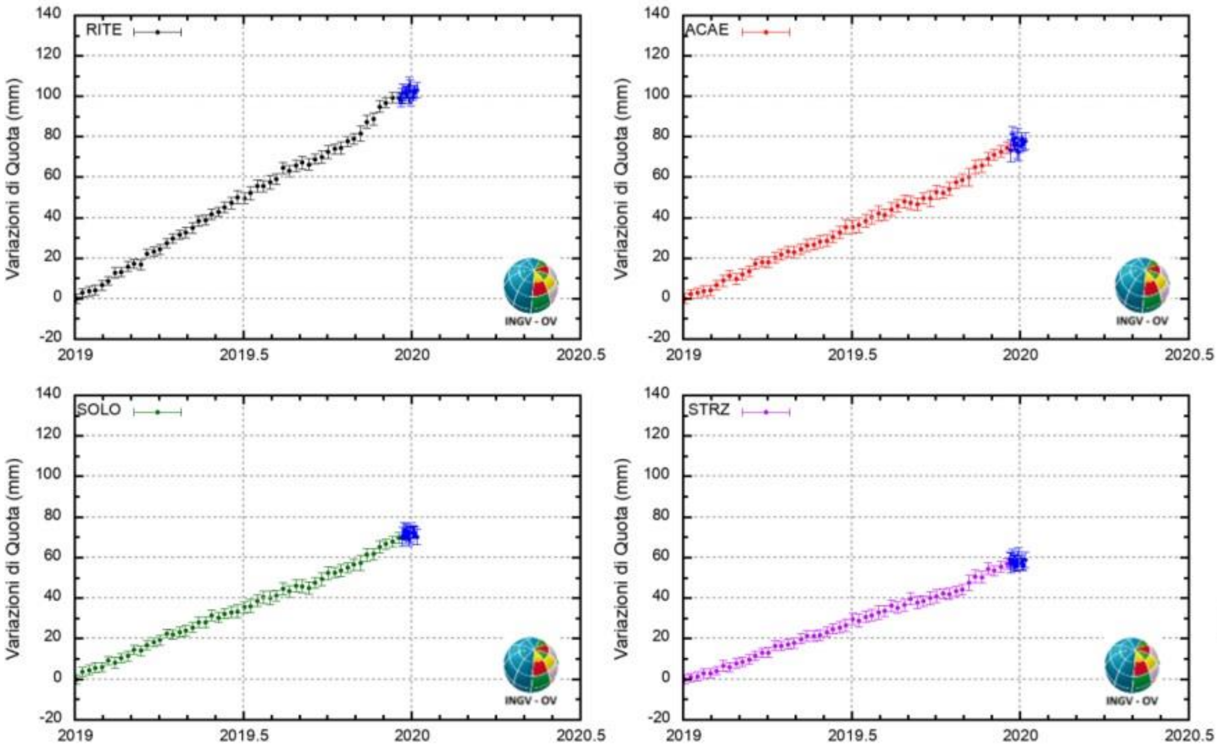

Figure 5 *- Height variations (2019/01/01-2020/01/06) for cGPS stations from Figure 4. Blu dots represent daily variations obtained with raw IGS products (Credits INGV-OV, Courtesy P. De Martino)*

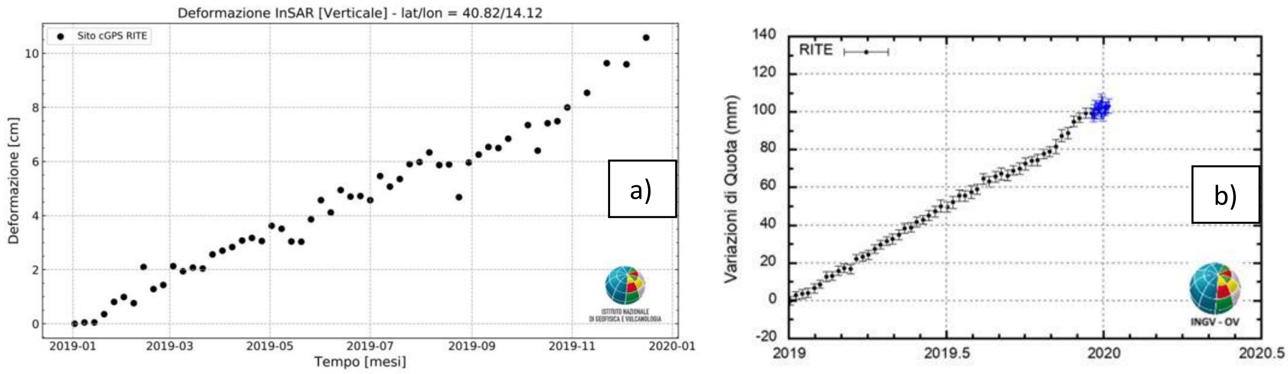

Figure 6 *- a) InSAR time series (vertical) (2019/01/02-2019/12/16) for a target located on RITE cGPS station; b) Height variations (2019/01/01-2020/01/06) for RITE cGPS station (Credits INGV-OV, cGPS image courtesy P. De Martino)*

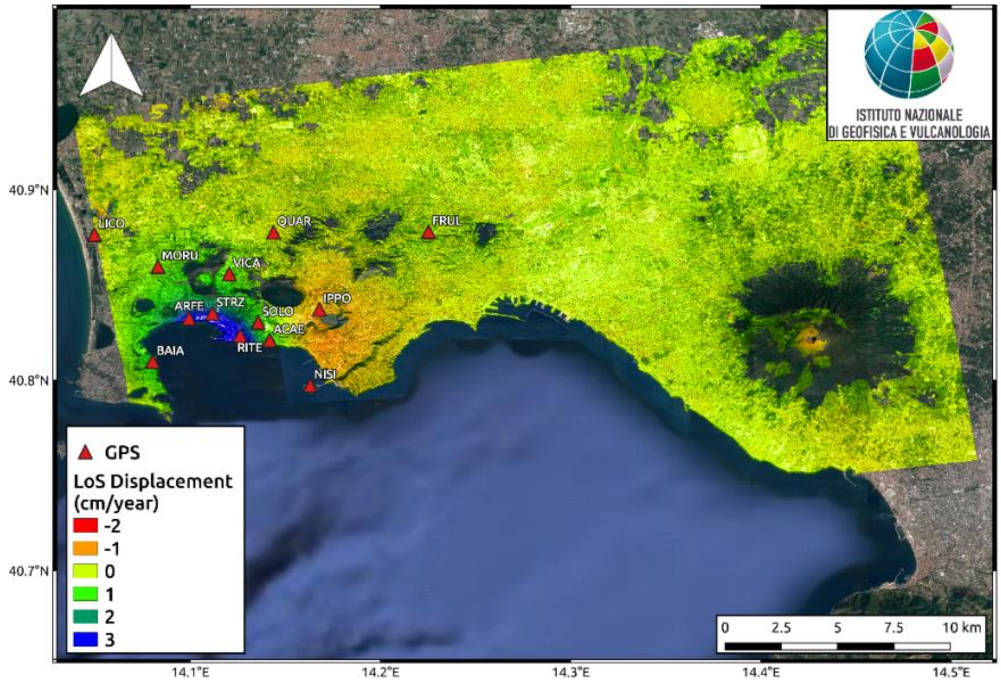

Figure 7 *- Ground deformation mean LoS velocity map (COSMO-SkyMed) (2011/01-2019/06) (Credits INGV-ONT)*

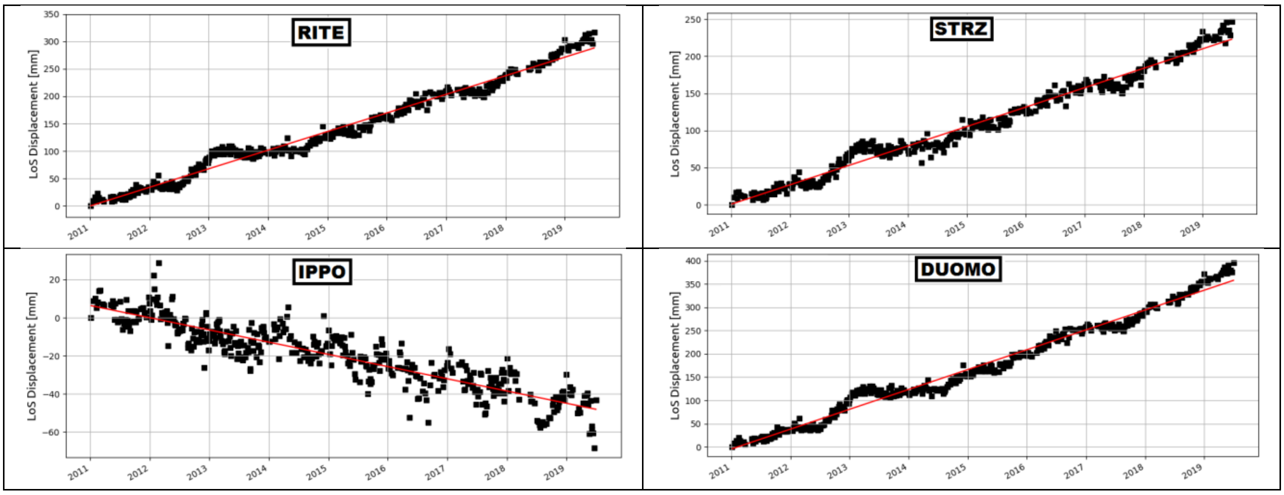

Figure 8 *- InSAR LoS time series (2011/01-2019/06) for targets located on cGPS stations (RITE, STRZ, IPPO) and DUOMO site (Pozzuoli) (Credits INGV-ONT)*

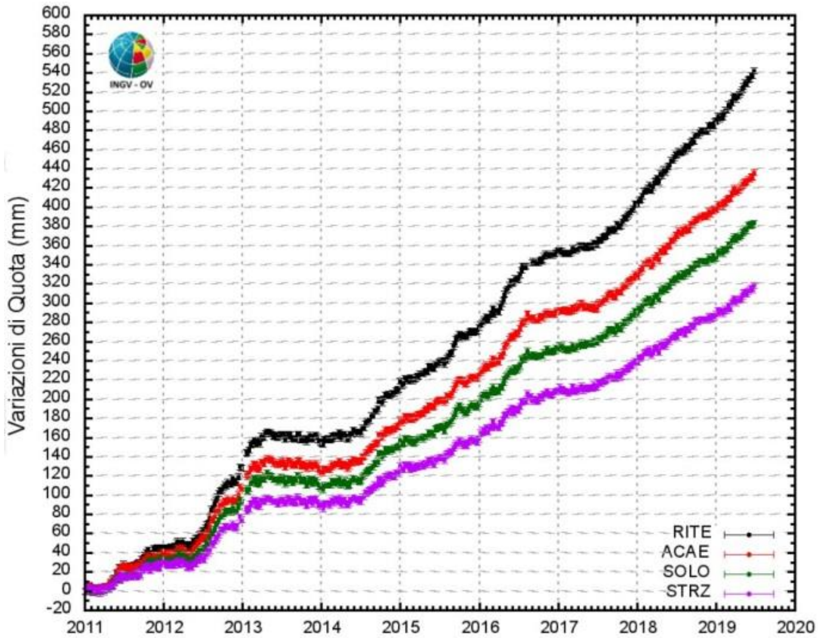

Figure 9 *- Height variations for cGPS stations (RITE, ACAE, SOLO, STRZ) belonging to the Campi Flegrei geodetical networks (2011/01/01-2019/06/29)*
(Credits INGV-OV, Courtesy P. De Martino)

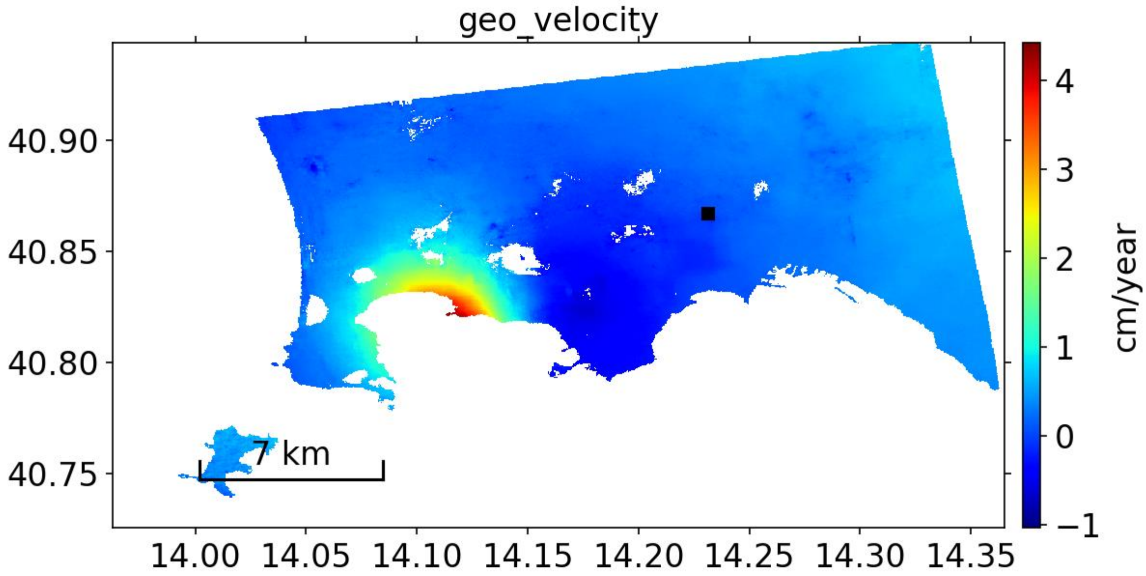

Figure 10 *- Ground deformation mean LoS velocity map (RadarSat-2) (2011/09/09-2016/02/27) (Credits INGV-OV)*

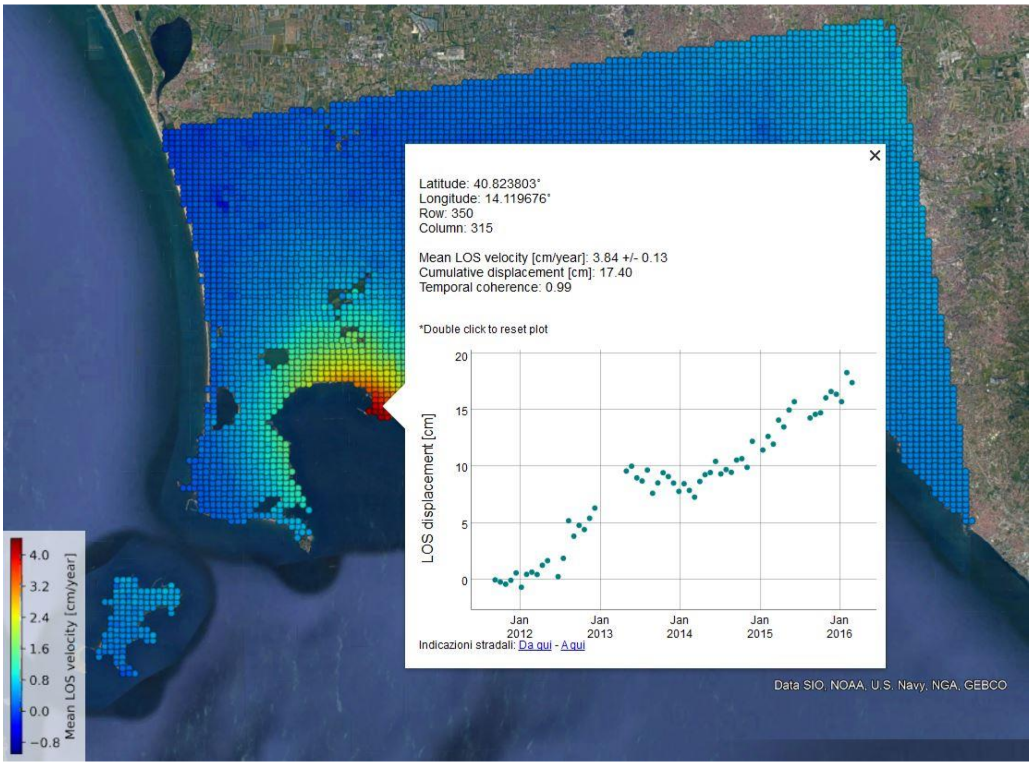

Figure 11 *- InSAR LoS time series (2011/09/09-2016/02/27) for a target located on RITE cGPS station (Credits INGV-OV)*

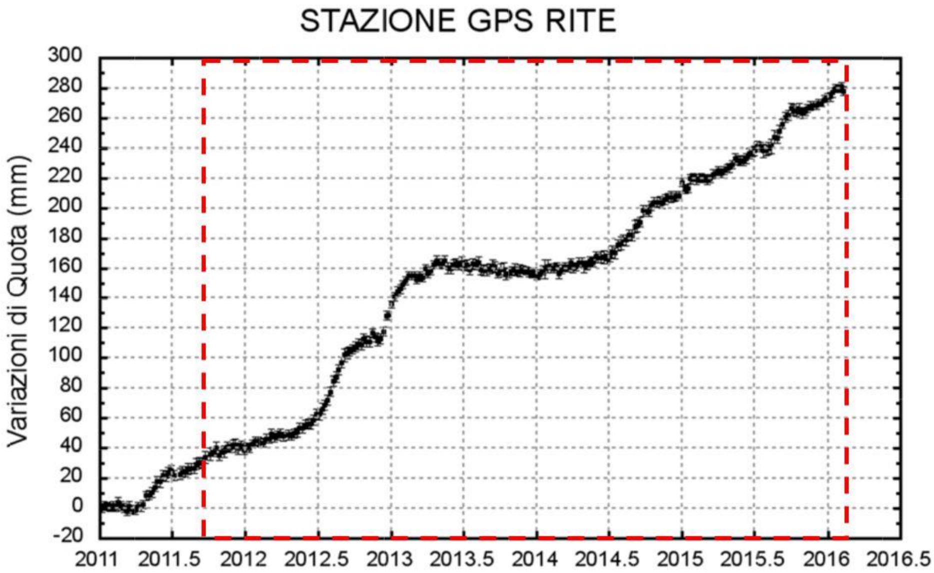

Figure 12 *- Height variations for RITE cGPS station*
The box with red dashed lines corresponds to the interval (2011/09/09-2016/02/27) of the RS-2 time series (Credits INGV-OV, Courtesy P. De Martino)

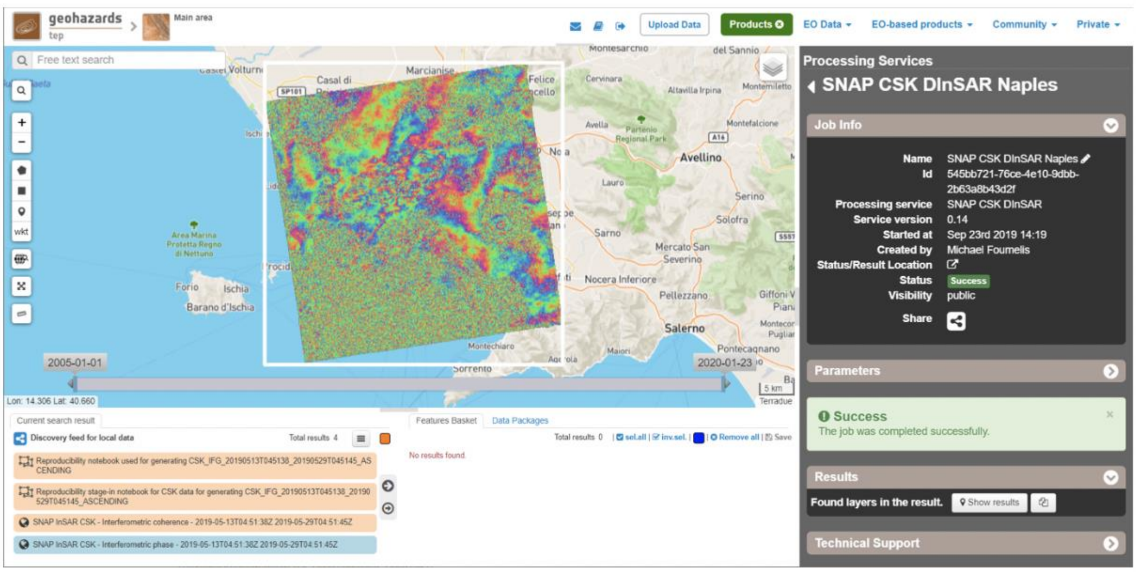

Figure 13 *- GEP SNAP COSMO-SkyMed DInSAR service - Interferometric phase results over a period of 16 days (2019/05/13-2019/05/29) over the Naples area (Credits BRGM)*

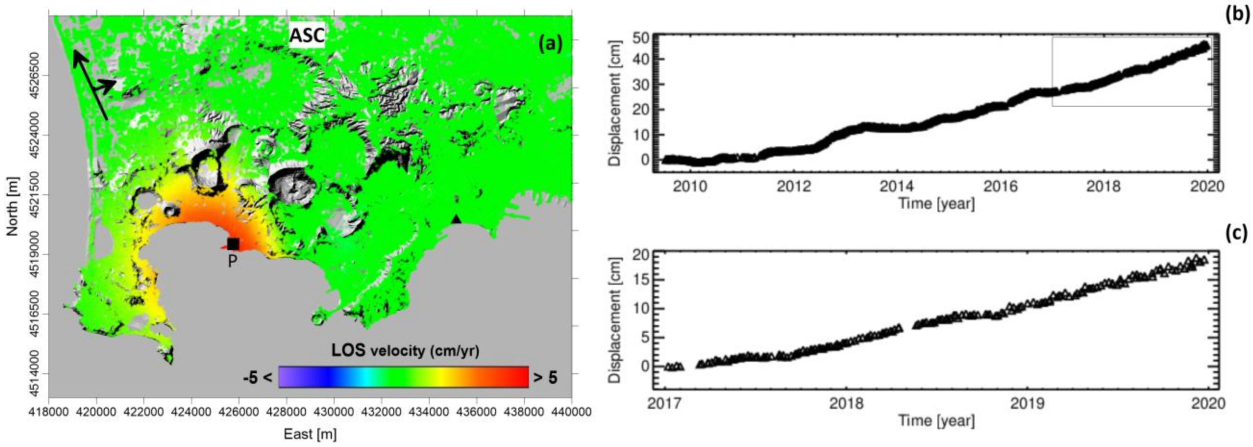

Figure 14 *- a) Geocoded map (in false colours) of the average deformation rate in LoS for the area of Campi Flegrei. The map is superimposed to the DEM of the area (in grey). b) displacement LoS time series of a point, marked as P in (a), located in the area of maximum deformation (Rione Terra, Pozzuoli) for the 12 July 2009 – 23 December 2019 period. c) Same as in (b) but relevant to the 7 January 2017 – 23 December 2019 time span (Credits IREA-CNR)*

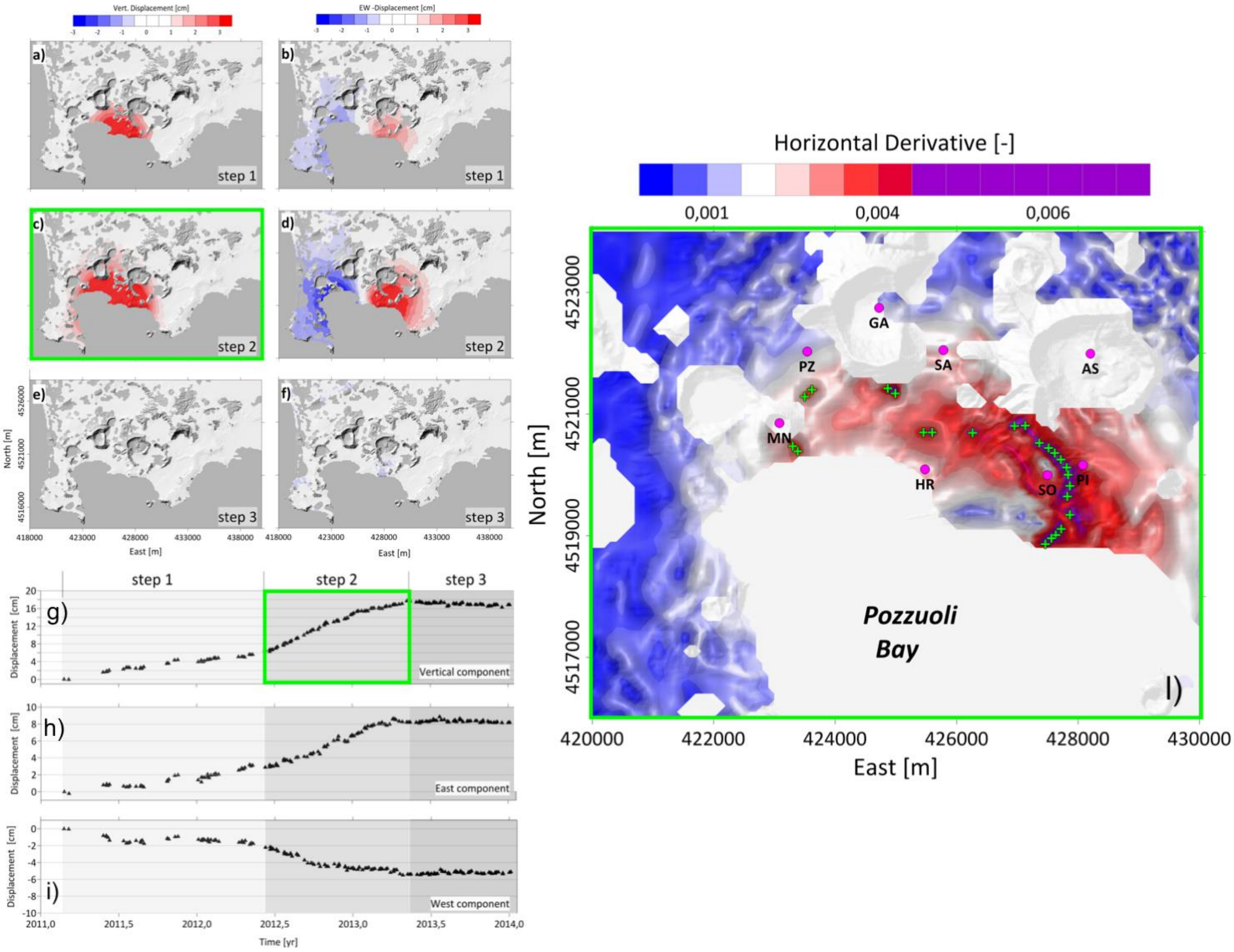

Figure 15 *- SAR Interferometry analysis for the period 2011-2014 at Campi Flegrei. (a, b) Map of the Vertical and EW displacements, respectively, measured during step 1, between February 2011 - May 2012, (c, d) step 2, between May 2012 - April 2013 and (e, f) step 3, between April 2013 and January 2014. (g-i), time series of vertical and east-west displacements are shown. The period of time analysed is divided into three phases (grey regions) characterized by periods of homogeneous linear deformation. (l) THD analysis (total horizontal derivatives) of the vertical deformation component relevant to step 2 (May 2012 - April 2013), highlighted in green in the whole image. Green crosses identify THD peaks. The magenta circles represent the location of the Pozzuoli (PZ) site, the city of Naples (NA), Monte Nuovo (MN), the port of Pozzuoli (HR), the crater of Astroni (AS), the crater Solfatara (SO), from the fumarole source Pisciarelli (PI), from Monte Gauro (GA) and San Vito (SA). The green box indicates the analysis period (Credits IREA-CNR)*

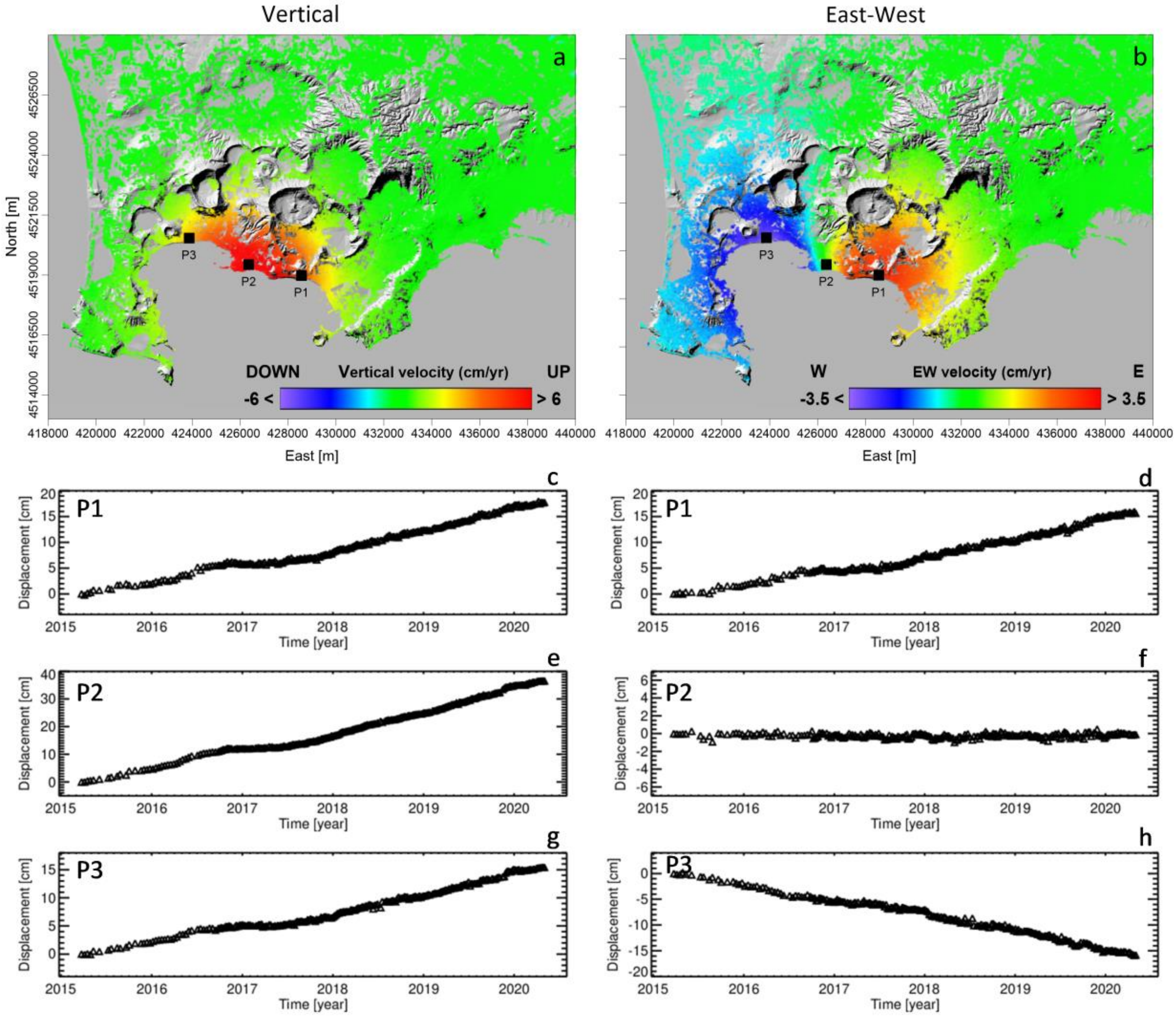

Figure 16 *- Mean velocity maps of the Vertical and East-West deformation components in the period March 2015 – May 2020, generated from Sentinel-1 data. a) Vertical Component. b) East-West component. c-h) Displacement time series along the Vertical (c) (e) (g) and East-West (d) (f) (h) directions of three points identified as P1, P2 and P3, respectively, in (a) - (b) (Credits IREA-CNR)*

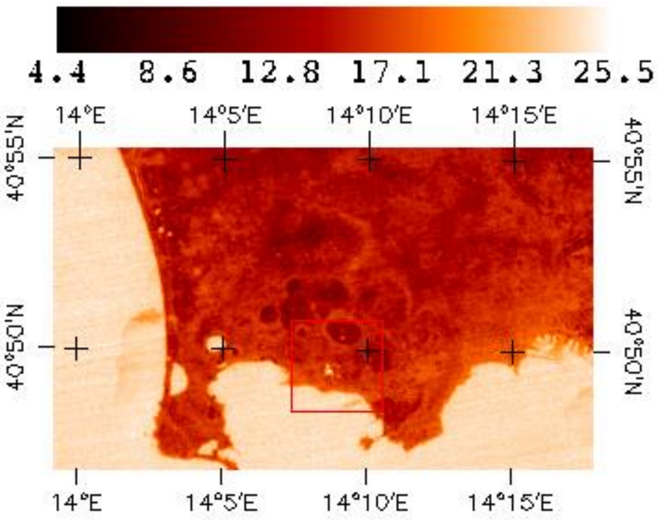

Figure 17 *- Surface temperature map from ASTER data acquired at 21.10 UTC, October 17, 2019 (Credits INGV-ONT)*

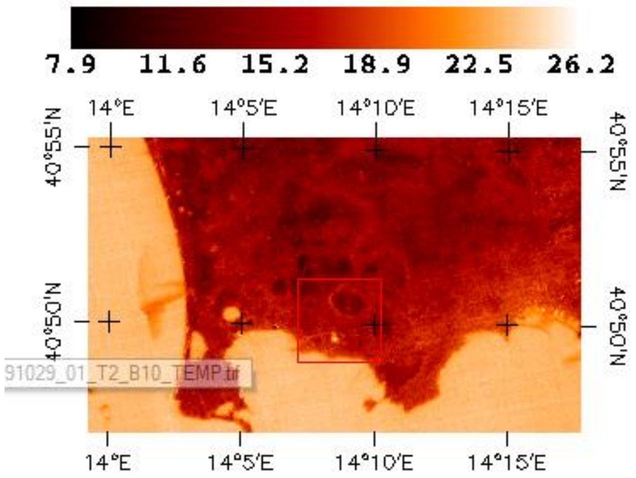

Figure 18 *- Surface temperature map from LANDSAT8 data acquired at 20.46 UTC, October 18, 2019 (Credits INGV-ONT)*

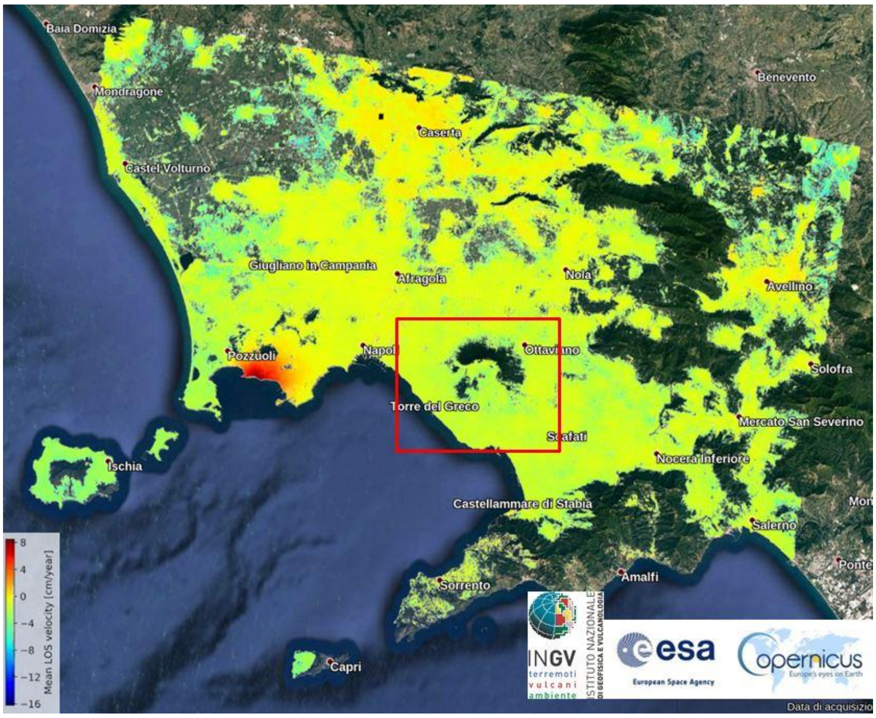

__Figure 19__ - Ground deformation mean LoS velocity map (Sentinel-1A/B) (2019/01/02-2019/12/16)
In the red box the Vesuvius area - IWS data, TOPS mode, Descending orbits (22), Swath 1
(Credits INGV-OV)

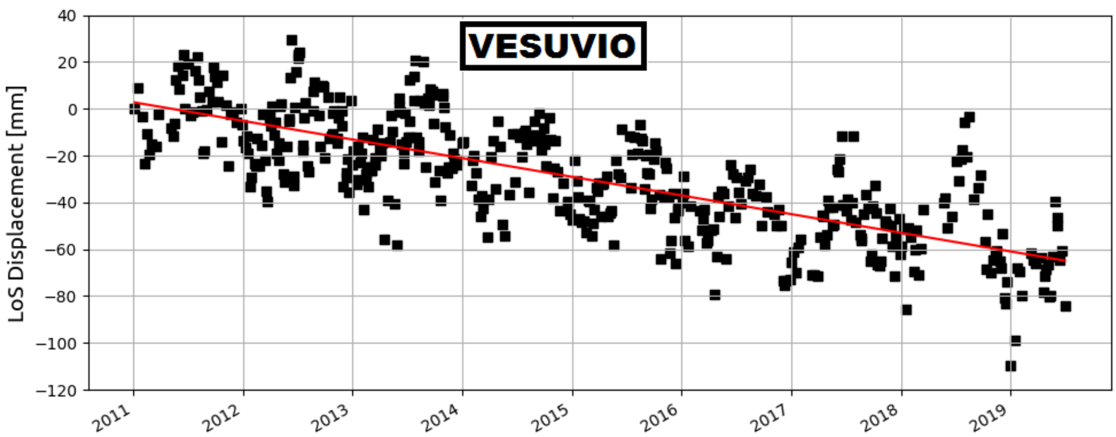

__Figura 20__ - InSAR LoS time series (2011/01-2019/06) for a target located in the Great Cone area
(Credits INGV-ONT)

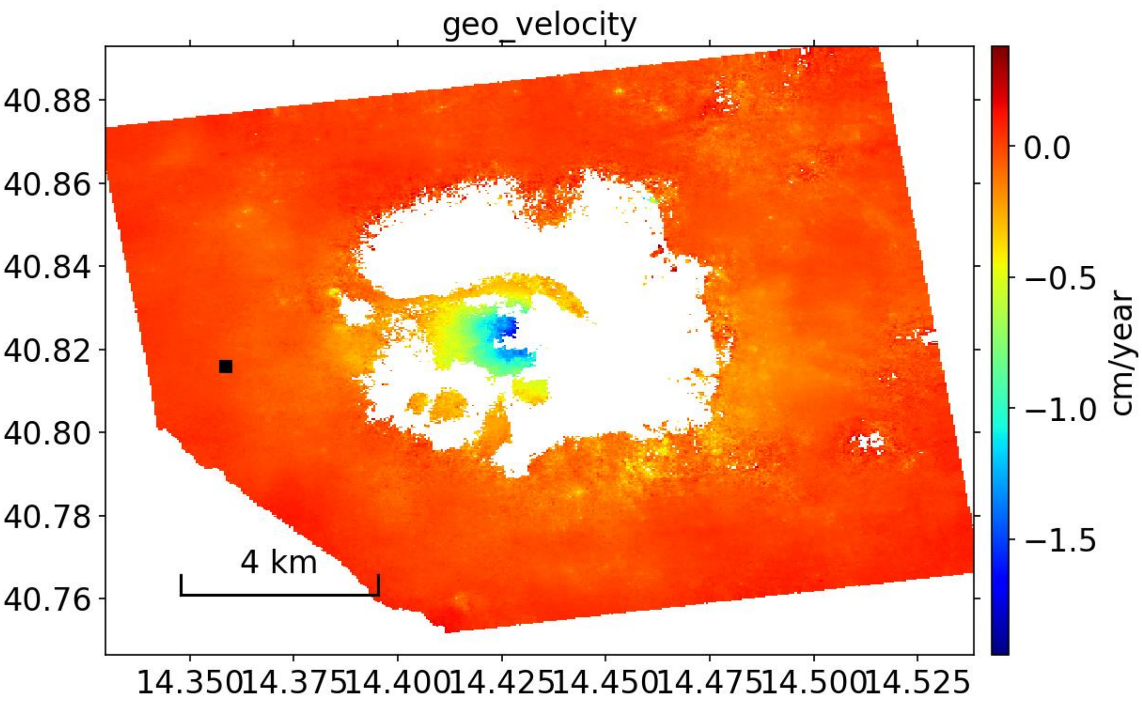

Figure 21 *- Ground deformation mean LoS velocity map (RadarSat-2) (2011/09/09-2016/02/27) (Credits INGV-OV)*

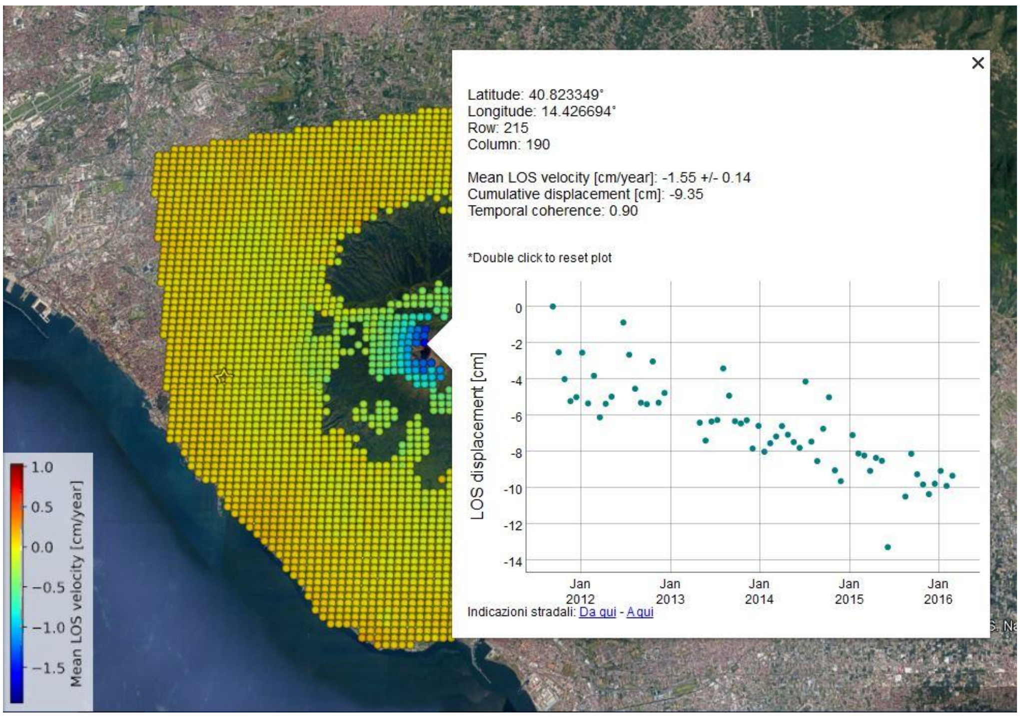

Figure 22 *- InSAR LoS time series (2011/09/09-2016/02/27) for a target located in the Great Cone area (Credits INGV-OV)*