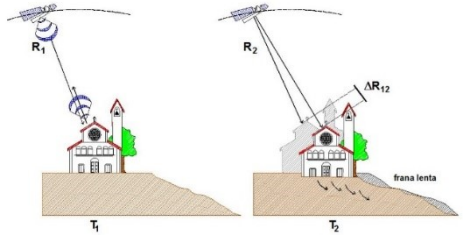
GROUND MOTION MONITORING

InSAR & in-situ data interpretation



OUTLINE

- Methodology
- Geohazard assessment
- EO & in-situ monitoring
- PS InSAR analysis
- PSI data interpretation

METHODOLOGY

similarity and differences in different monuments and sites, timeline approach

Background → Diagnosis of Current conditions → Monitoring Processes → Conservation policies and management

UNESCO

LINKING KNOWLEDGE AND TECHNOLOGY WITH LOCAL COMMUNITY

Background (desk and field study): investigating the origin, typology, construction techniques, restoration history, evolution in time, etc.

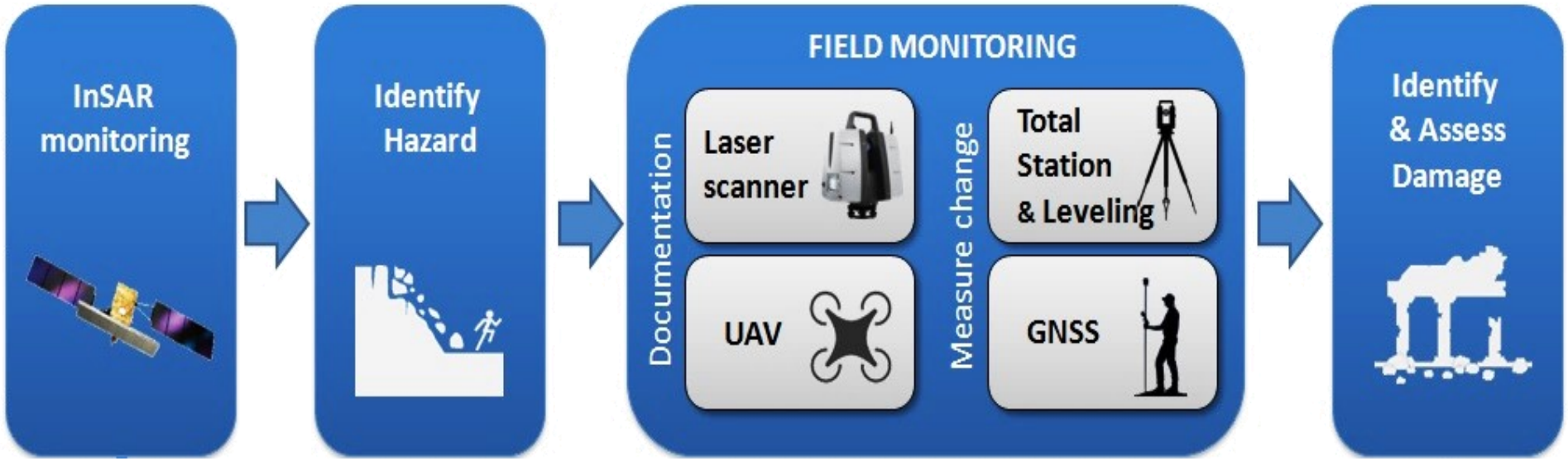
Diagnosis of current conditions field study): Non-invasive and non-destructive investigations.

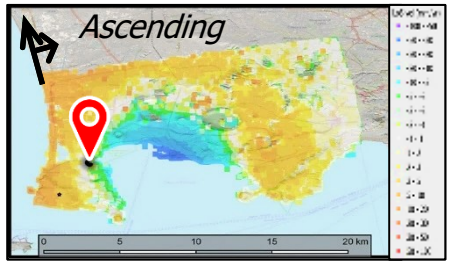
Monitoring processes (field study): Remote and in situ monitoring with low environmental impact.

Conservation policies and management (desk and field study): An Eco-friendly strategy to enhance sustainability and local conservation practices

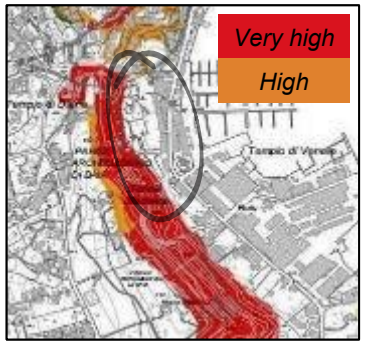
Integrated Assessment

Combining EO monitoring with field survey to calibrate and implement in situ monitoring systems and identify and assess potential damages.





S1 PS InSAR analysis



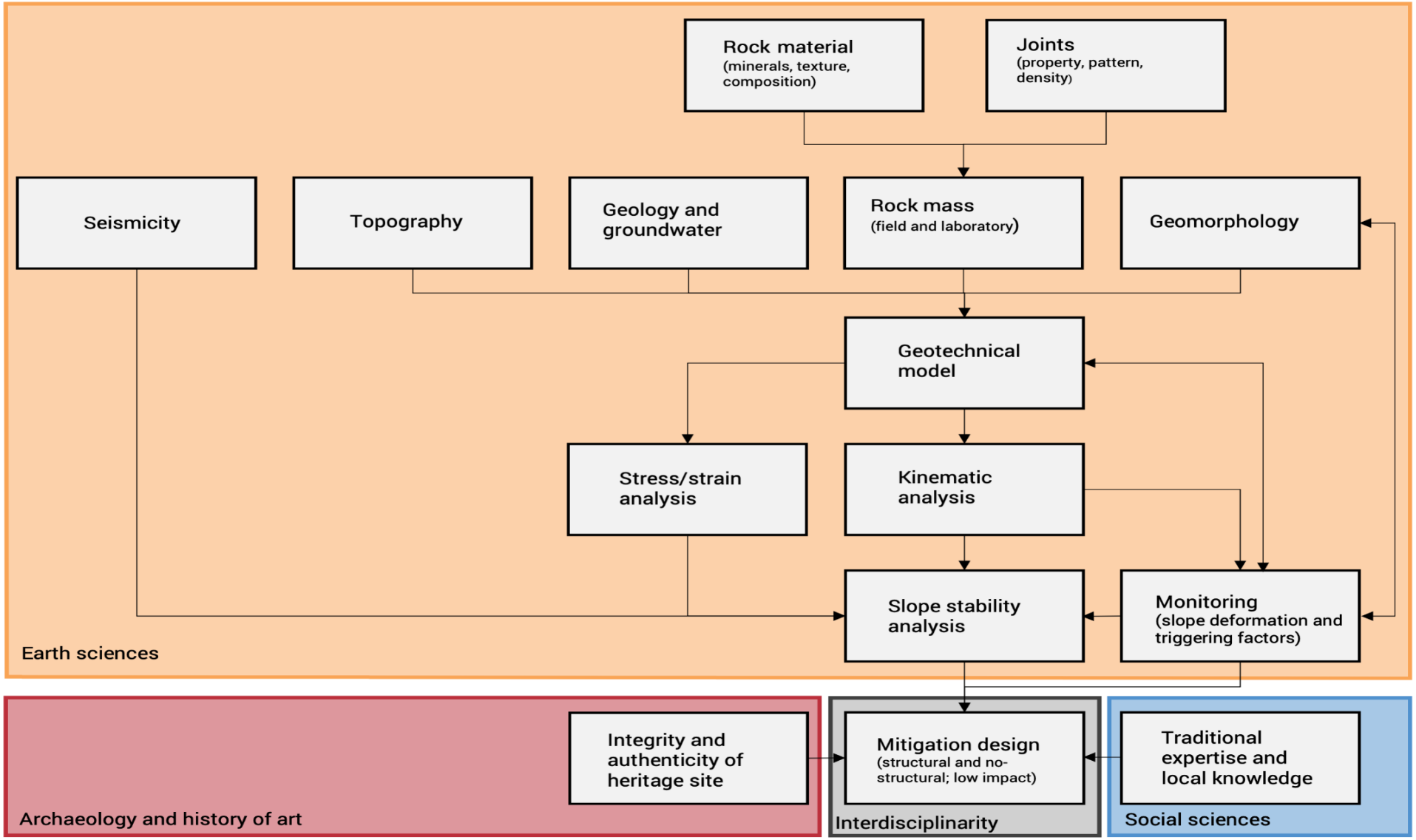
LANDSLIDE RISK

UAV 3D MODELING

FIELD SURVEY

Engineering geology for CH hazard assessment

Site engineering geology approach to weak rock slope instabilities in archaeological sites.



[From: Margottini & Spizzichino, 2021]

OUTLINE

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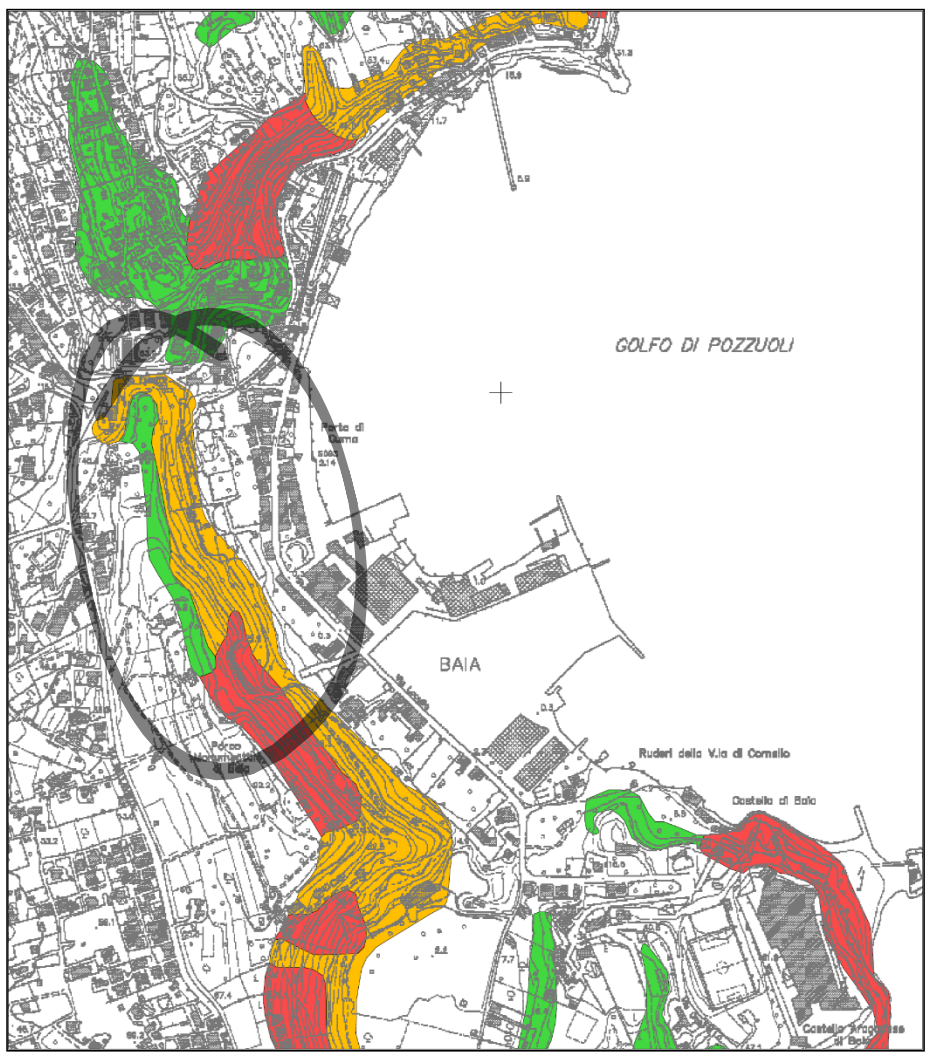
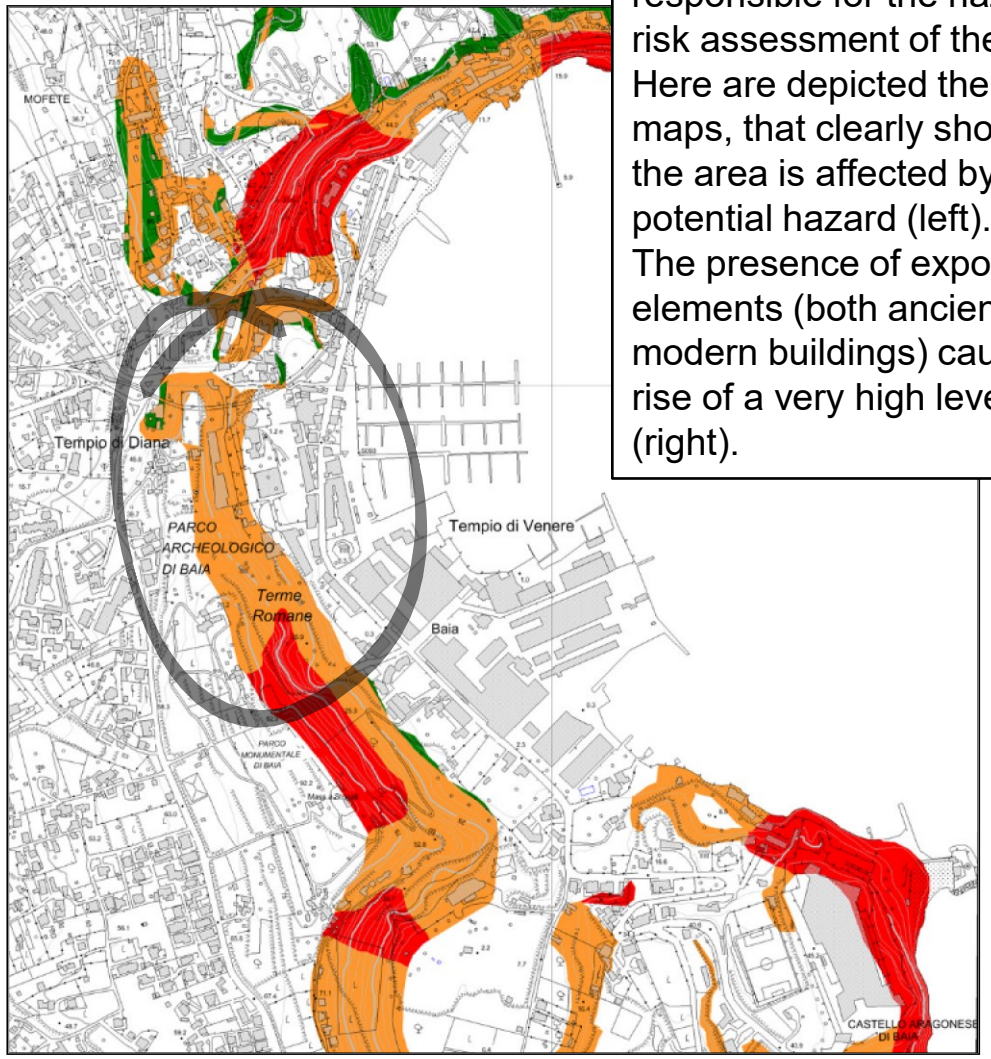
Landslide risk assessment of the Baia area

Landslide susceptibility



Very high
High
Medium
Low

Landslide risk



The local planning authority is responsible for the hazard and risk assessment of the territory. Here are depicted the relative maps, that clearly show that the area is affected by high potential hazard (left).
The presence of exposed elements (both ancient and modern buildings) causes the rise of a very high level of risk (right).

Landslide hazard in the site area

Location of landslides in the area of Roman Thermae of Baia (**A**).

Typical phenomena are rock fall along the steep slopes of the volcano flank (**B**).

Fall can involve not only soft rocks (volcanic tuffs), but also block of masonry, from ancient abandoned buildings (**C**).

OUTLINE

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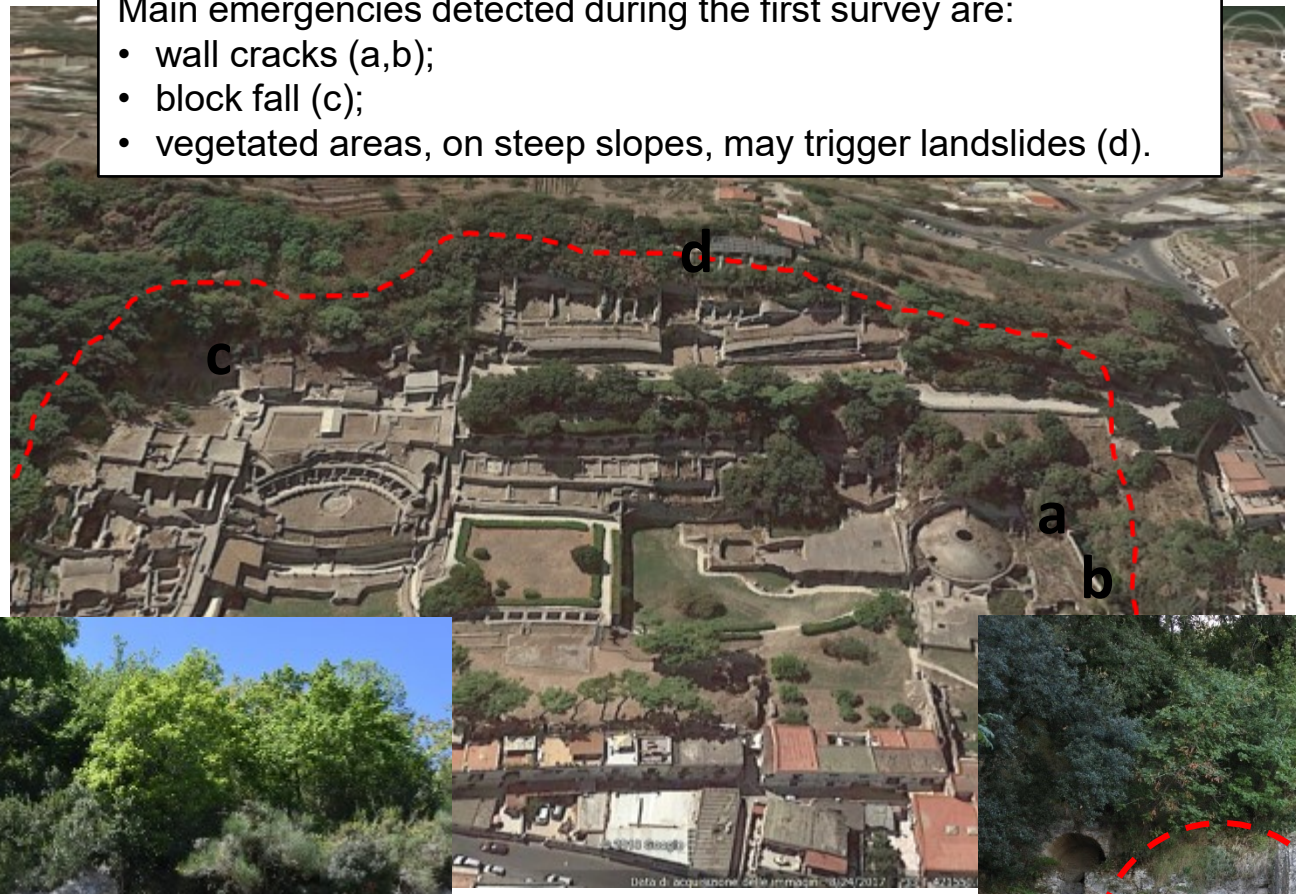
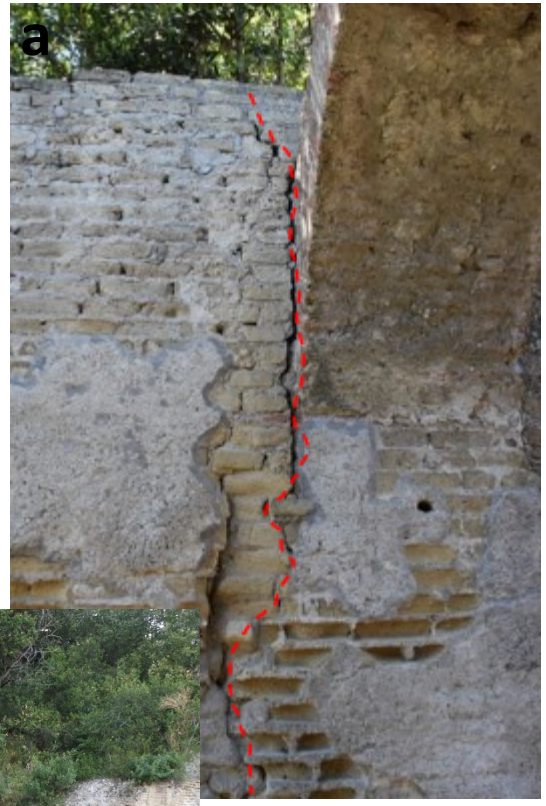
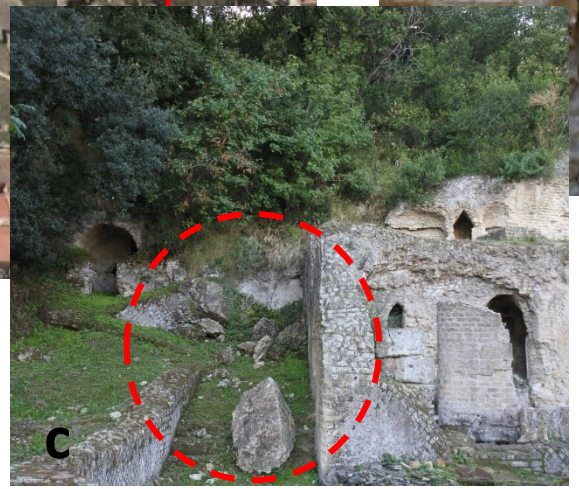
DAMAGE INVENTORY – first assessment

Main emergencies detected during the first survey are:

- wall cracks (a,b);
- block fall (c);
- vegetated areas, on steep slopes, may trigger landslides (d).







Integrated survey

By a UAV survey, a 3D model and an orthophoto were obtained.
This model helps to analyze the area as a whole and to understand the relationships among the different complexes of the settlement.

DAMAGE INVENTORY – detail survey

The analysis of the area and of the type of buildings helps in classifying main ruptures:

- cover detachment (1);
- wall cracks (2, 4);
- block fall (3);
- leaning walls, that need shoring (5).

OUTLINE

- Methodology
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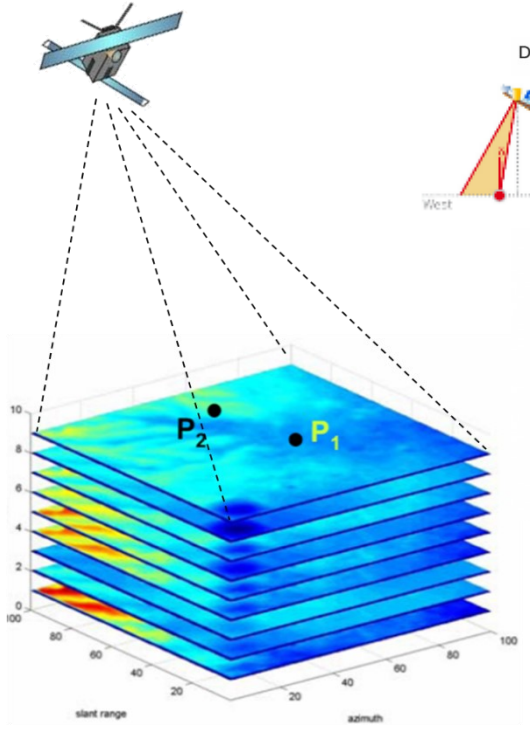
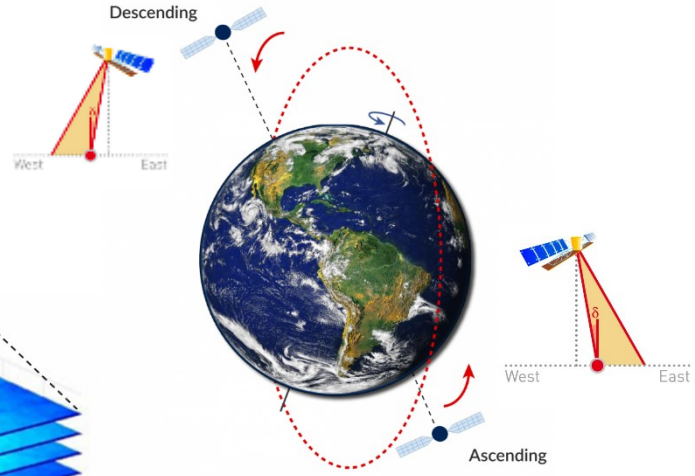
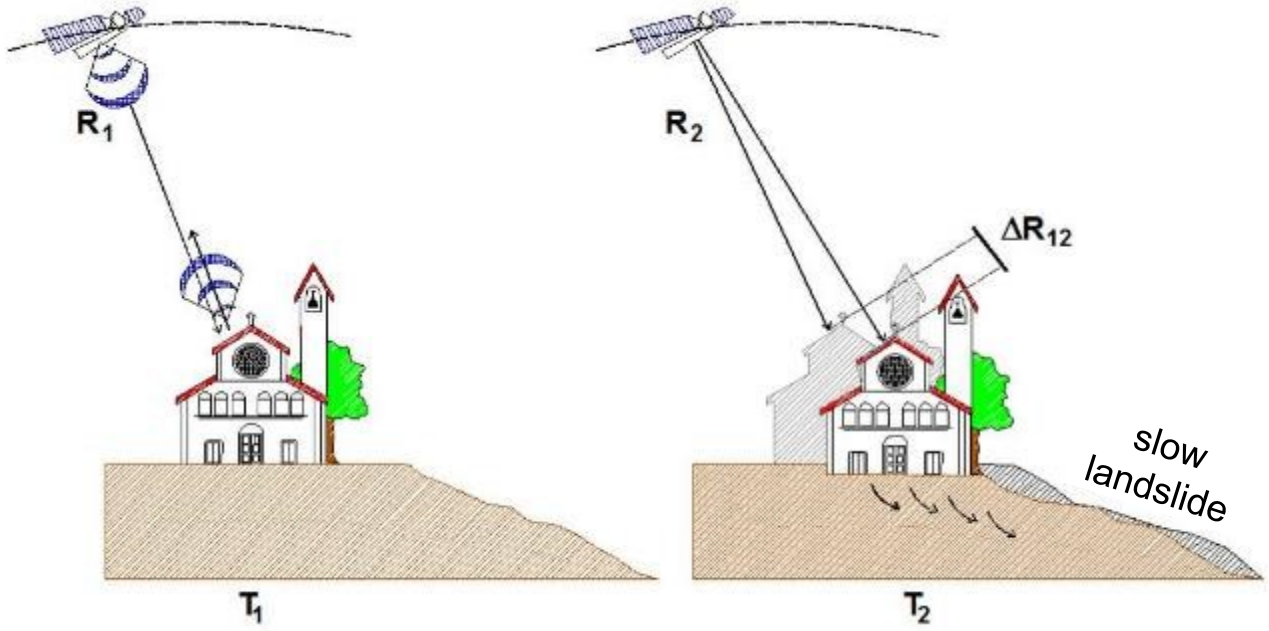
- PSI data interpretation

InSAR for CH monitoring







Through many radar images acquisition and processing it is possible to obtain:

- time series displacement (millimetres precision),

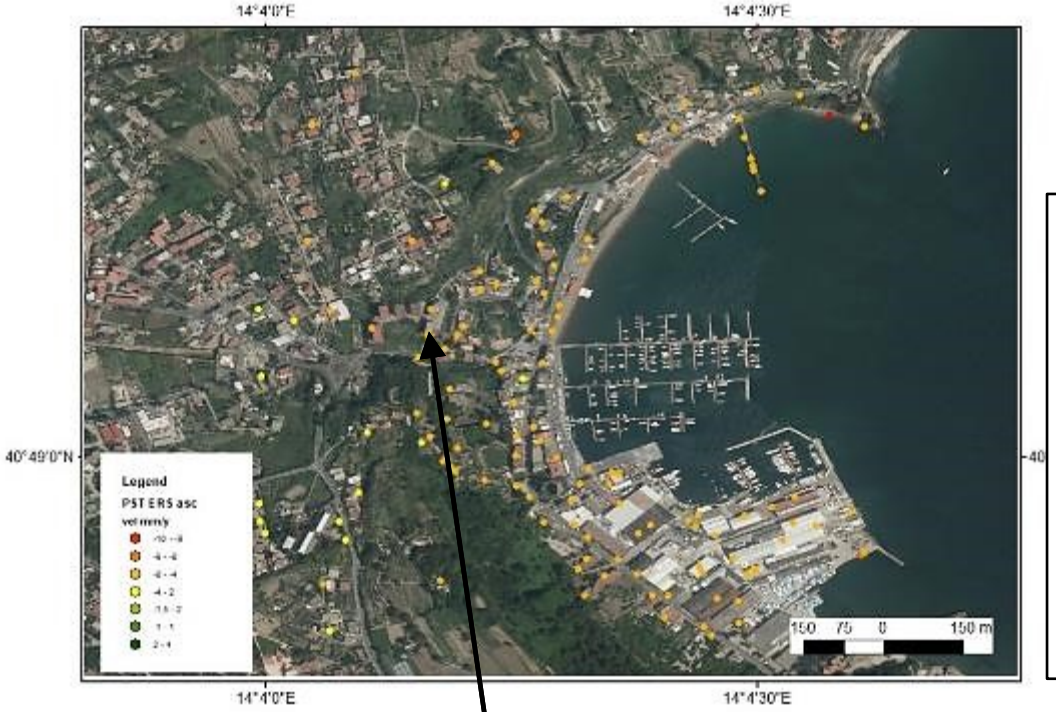
  &

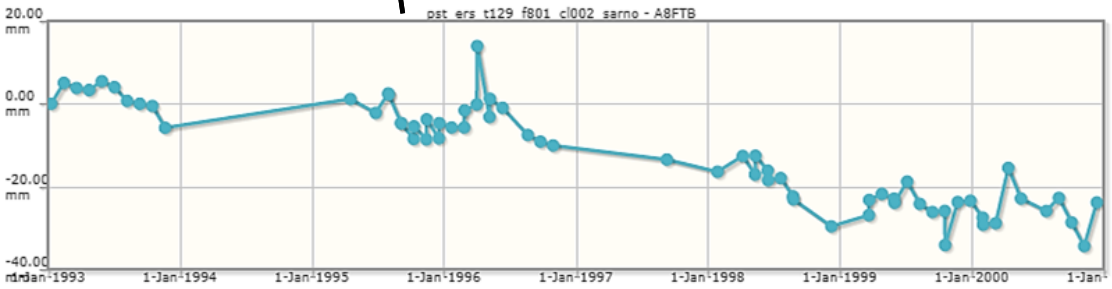
- average year velocity along the LOS (millimetres precision),

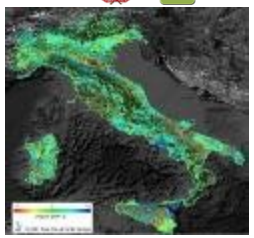
in order to detect ground deformation (e.g. slow landslide, subsidence).

Previous InSAR analysis

PSTA – ERS ASC data (1993-2001)

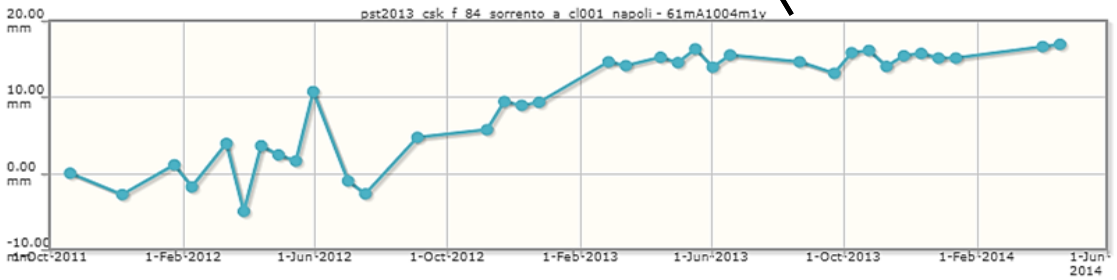






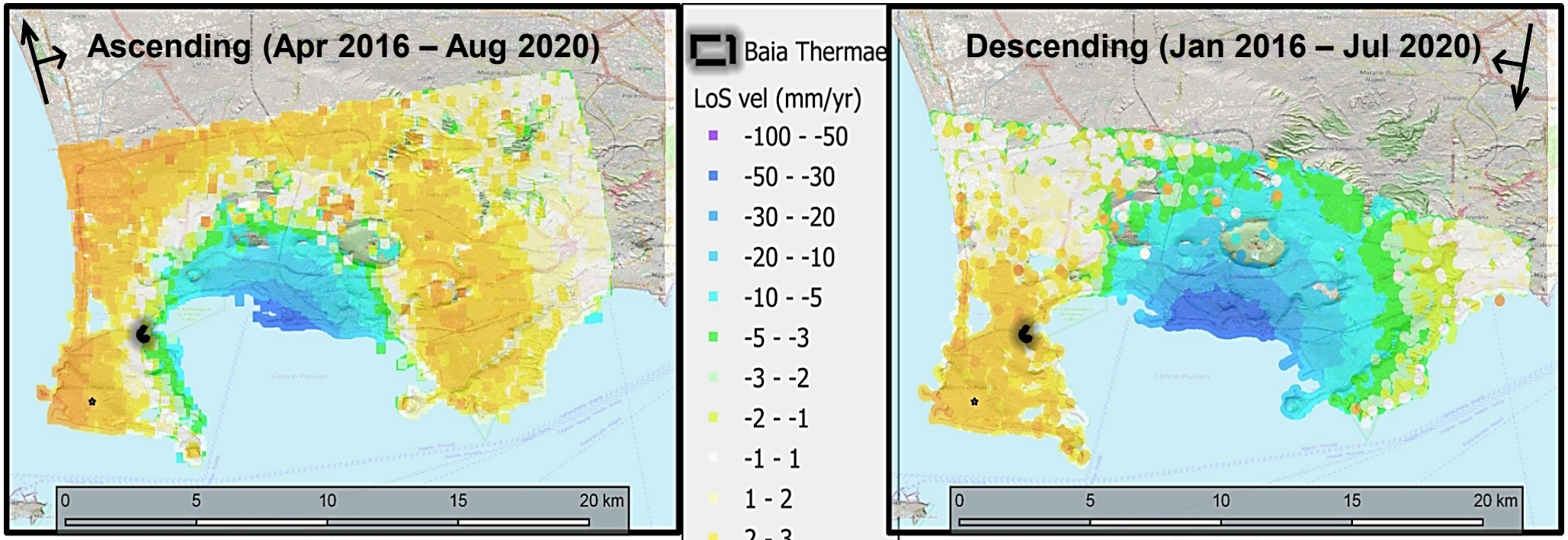
Past InSAR data analysis (from PSTA Italian project) highlights the recent displacement history of the site. Phlegrean Fields are affected by bradyseism, that caused subsidence during '90s (with a fall of up to 2 cm) followed by a 1 cm rise during the period 2011-2013.

PSTA – CSK ASC data (2011-2014)



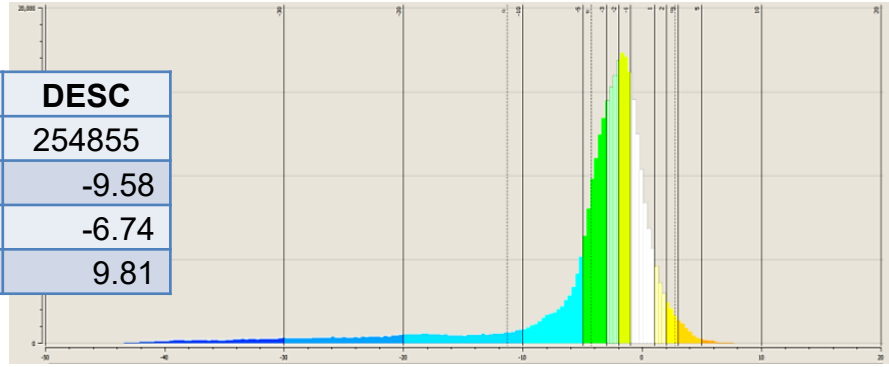
Sentinel-1 PS: first analysis

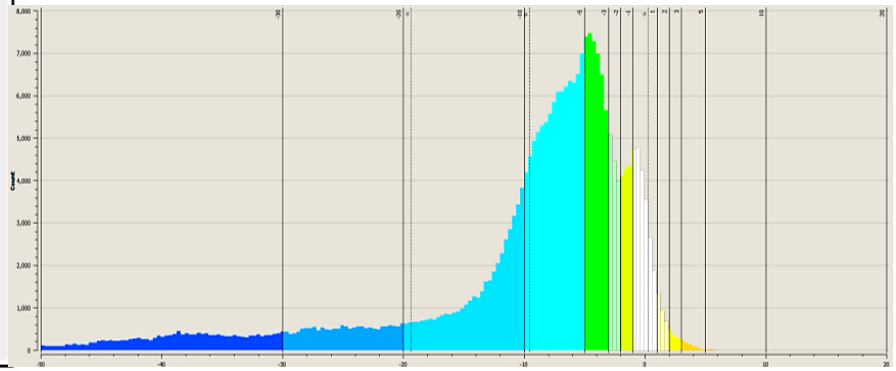
The first processing of Sentinel-1 SAR dataset makes use of a standard approach: for the Reference point the choice has been driven by geological setting (an area external to the main ground motion) and by tool settings (a cluster of PSs with “null” displacement). These conditions led to select as Reference point an area at the foothill of Monte di Procida, on the western side of the caldera.



ASCending

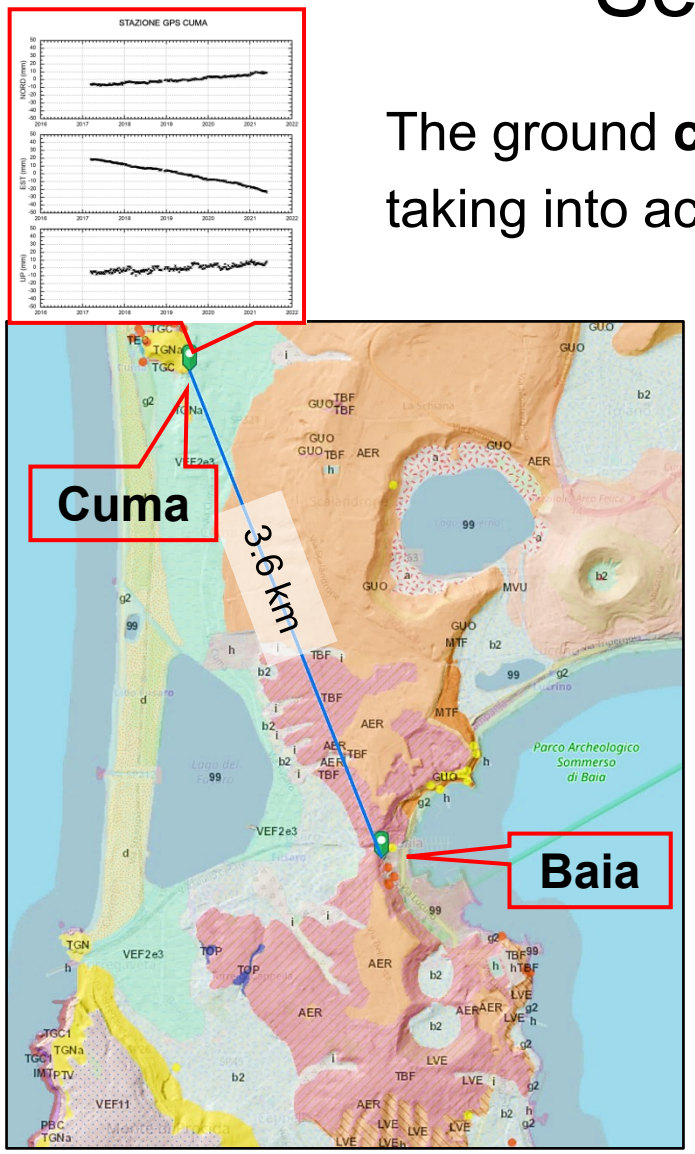
DESCending





ASC		DESC
323968	# PS	254855
-4.28	mean	-9.58
-2.38	median	-6.74
7.04	STD	9.81

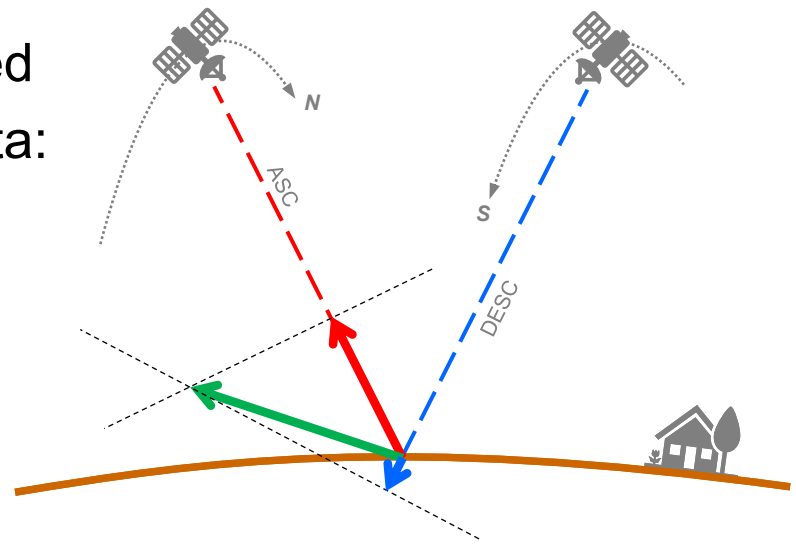
Sentinel-1 PS: GNSS calibration



The ground **calibration** of PSI data has been obtained taking into account these characteristics of GNSS data:

- **proximity** to the site (3.6 km),
- geological **stability** of the station (*outside the caldera*),
- **consistency** of the displacement recorded during the time interval under investigation (upper left box).

The best conditions in the area are represented by the **Cuma** station of the INGV-OV monitoring network.



ASCending LOS
DESCending LOS
GNSS East+Up displacement
GNSS along ASC LOS component
GNSS along DESC LOS component

GNSS calibration values:

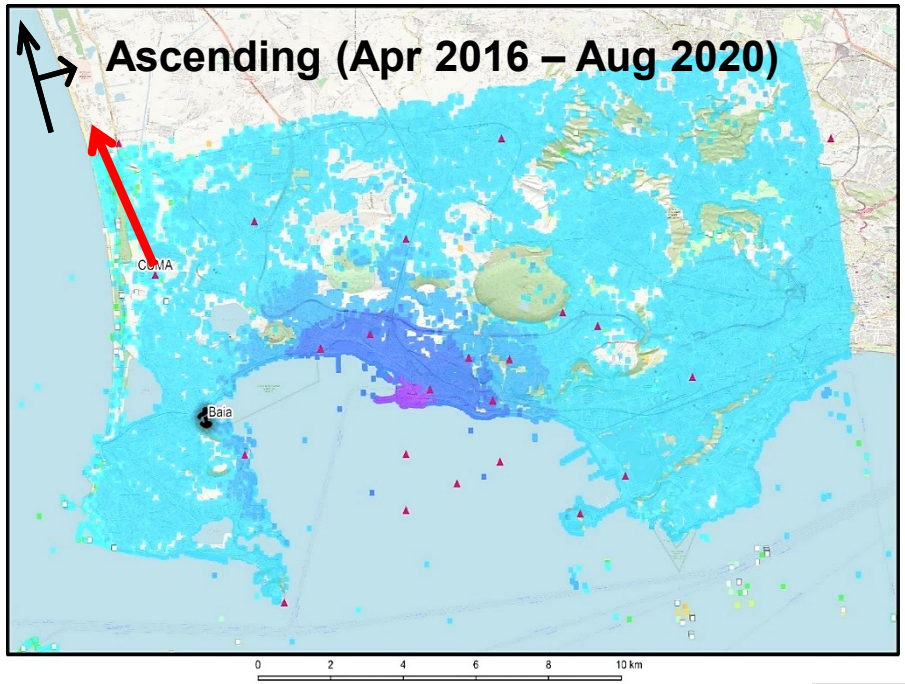
ASC $V_{GPS} = V - 8.07$

DESC $V_{GPS} = V + 3.38$

(displacement rates as: mm/yr)

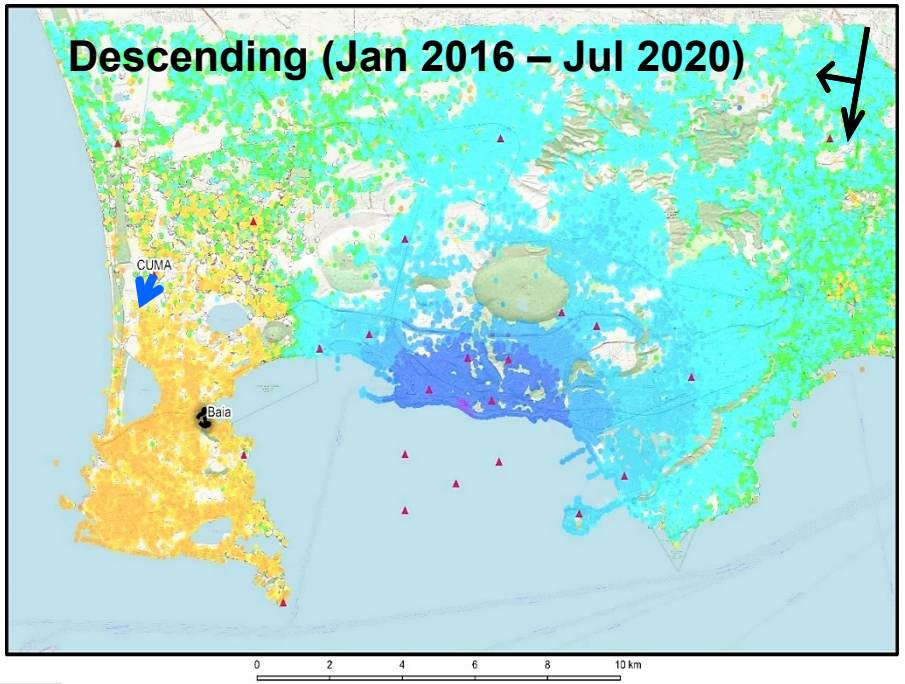
Sentinel-1 PS: calibrated analysis of PS data

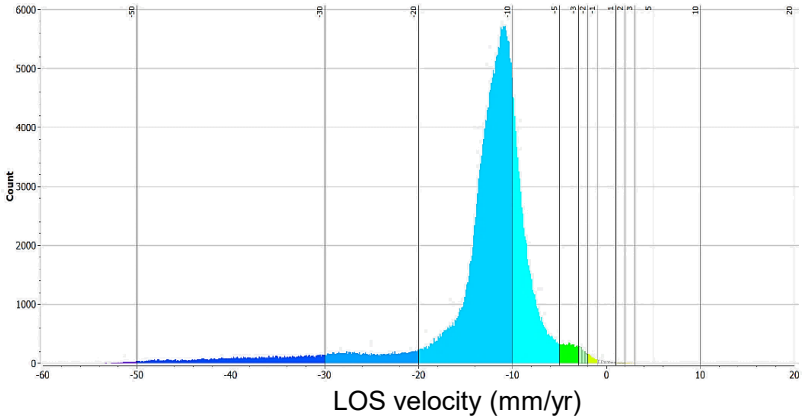
After the calibration of Sentinel1 SAR dataset with GNSS, appears a clear difference between ascending and descending geometries.
The north-west displacement of the Cuma GNSS station overcome in the ASC dataset, that better reflects the ground motion toward the east-looking satellite. On the contrary, in the Baia area, the DESC dataset shows a slight subsidence, because of the prevailing component moving away from west-looking satellite.



LoS vel (mm/yr)

- -100 - -50
- -50 - -30
- -30 - -20
- -20 - -10
- -10 - -5
- -5 - -3
- -3 - -2
- -2 - -1
- -1 - 1
- 1 - 2
- 2 - 3
- 3 - 5
- 5 - 10
- 10 - 20
- 20 - 30
- 30 - 50
- 50 - 100

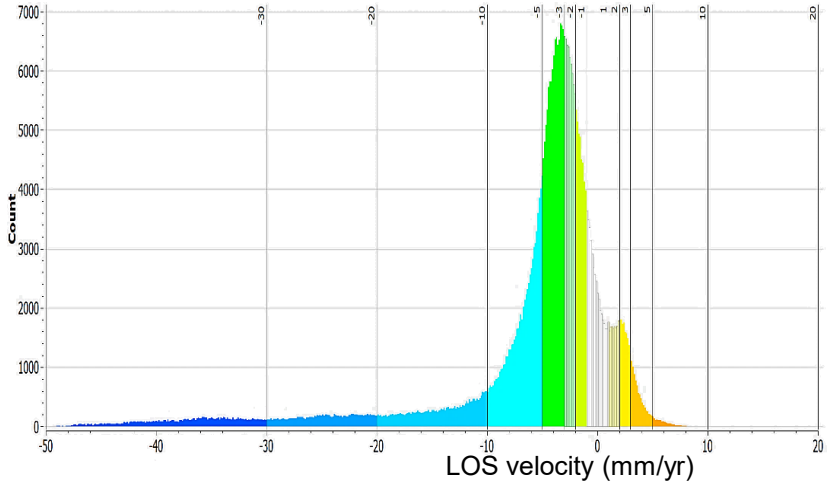




GNSS along LOS component at CUMA

ASC	-8.07
DESC	+3.38

334059	# PS	395016
-13.3	mean	-5.6
-11.6	median	-3.5
7.1	STD	20.1



Sentinel-1 PS: Roman Thermae of Baia area (calibrated)

Ascending (Apr 2016 – Aug 2020)

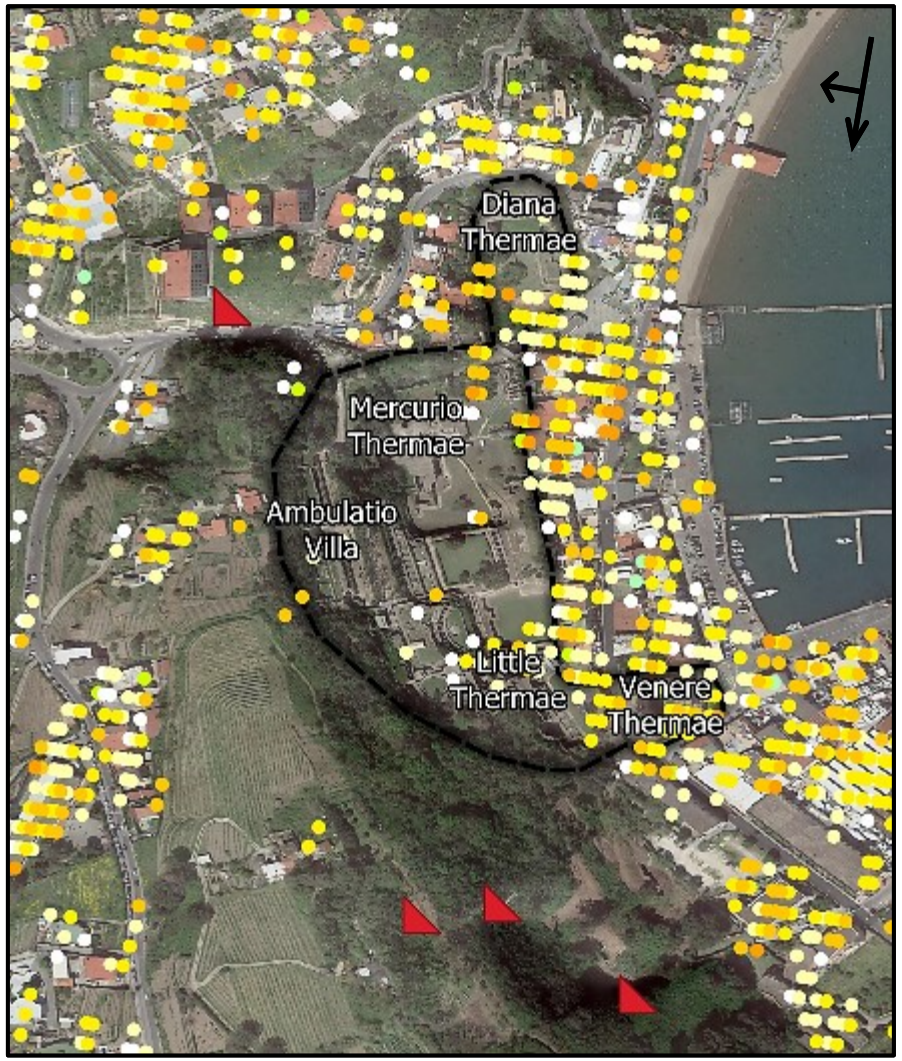
LoS vel
(mm/yr)

- -100 - -50
- -50 - -30
- -30 - -20
- -20 - -10
- -10 - -5
- -5 - -3
- -3 - -2
- -2 - -1
- -1 - 1
- 1 - 2
- 2 - 3
- 3 - 5
- 5 - 10
- 10 - 20
- 20 - 30
- 30 - 50
- 50 - 100

landslide

906	# PS	698
-14.6	mean	2.2
1.5	STD	1.4

Descending (Jan 2016 – Jul 2020)



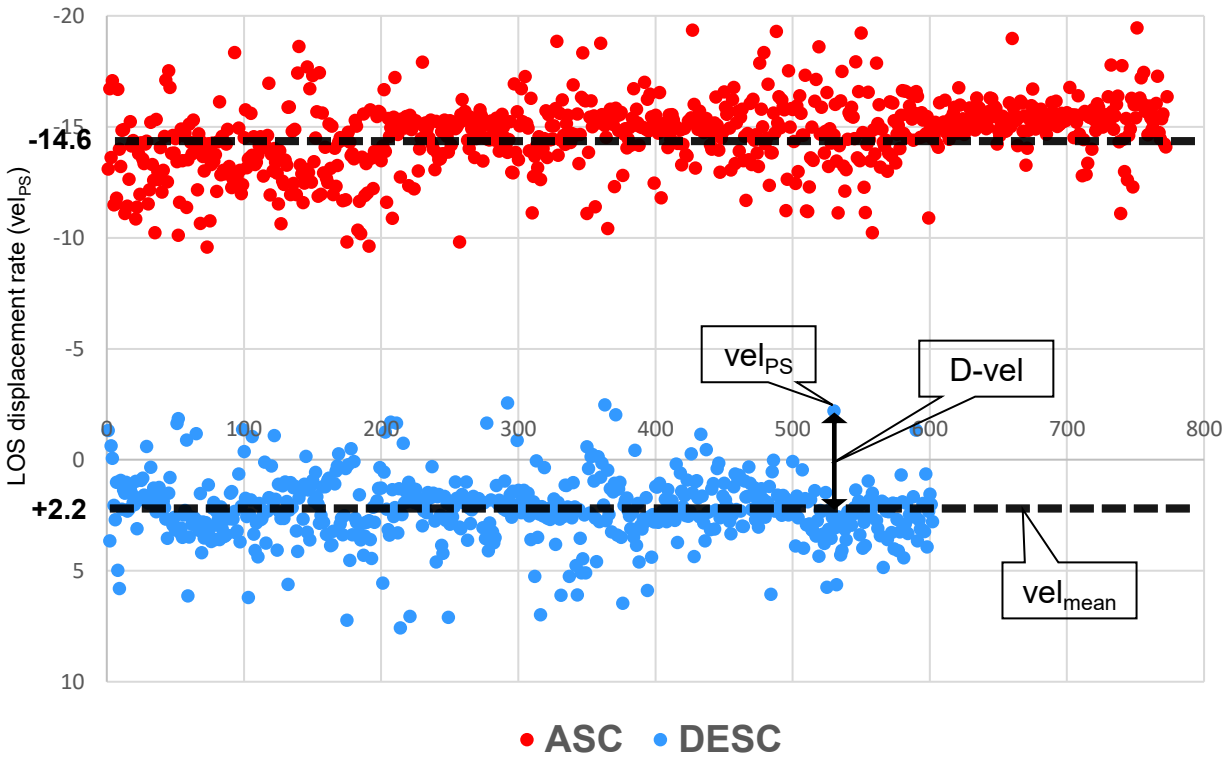
Sentinel-1 PS: differential analysis (D-vel)

The area is affected by high displacement rate, especially for the component along the Ascending LOS.

Thus, in order to highlight **differential ground displacements** at large scale, it is necessary to calculate the difference of displacement rate (**D-vel**) between each measurement point (PS) and the mean value of the whole area.

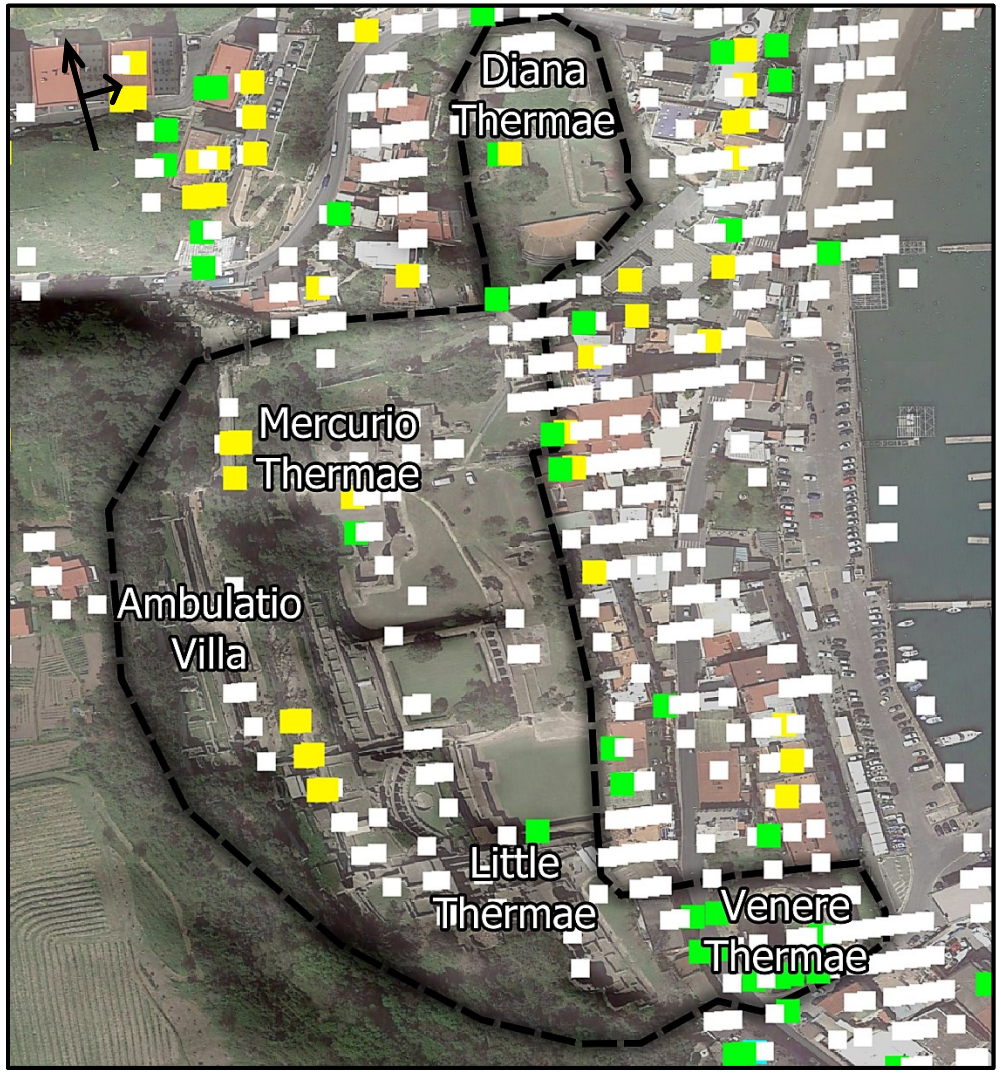
$$\text{D-vel} = vel_{PS} - vel_{mean}$$

ASC	mean D-vel	DESC
-14.6	mm/yr	2.2



Sentinel-1 PS: differential displacement velocity (D-vel)

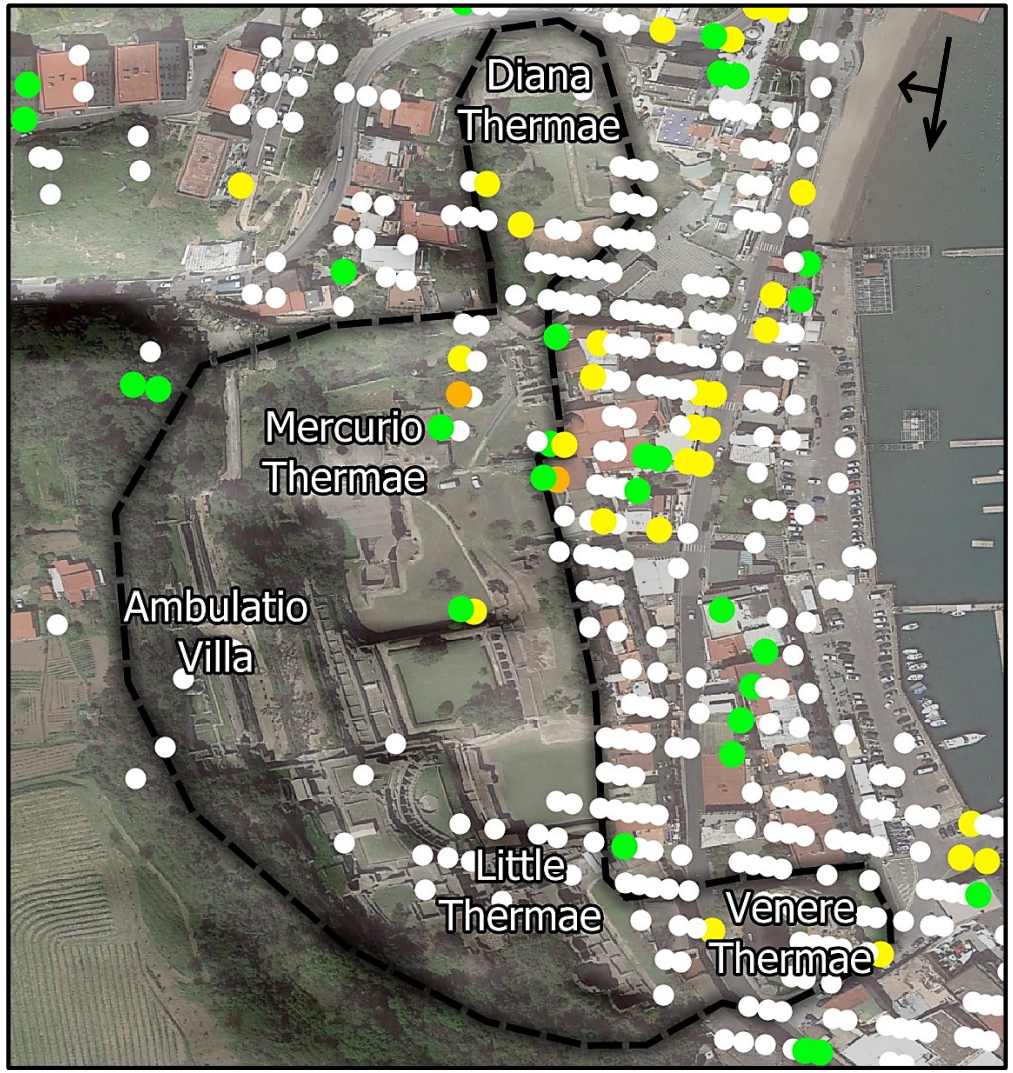
Ascending (Apr 2016 – Aug 2020)



LoS differential displacement velocity, D-vel (mm/yr)

ASC		DESC
	< -10	
	-10 – -5	
	-5 – -2	
	-2 – 2	
	2 – 5	
	5 – 10	
	> 10	

Descending (Jan 2016 – Jul 2020)



OUTLINE

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Sentinel-1 PS: differential displacement velocity

This synoptic view

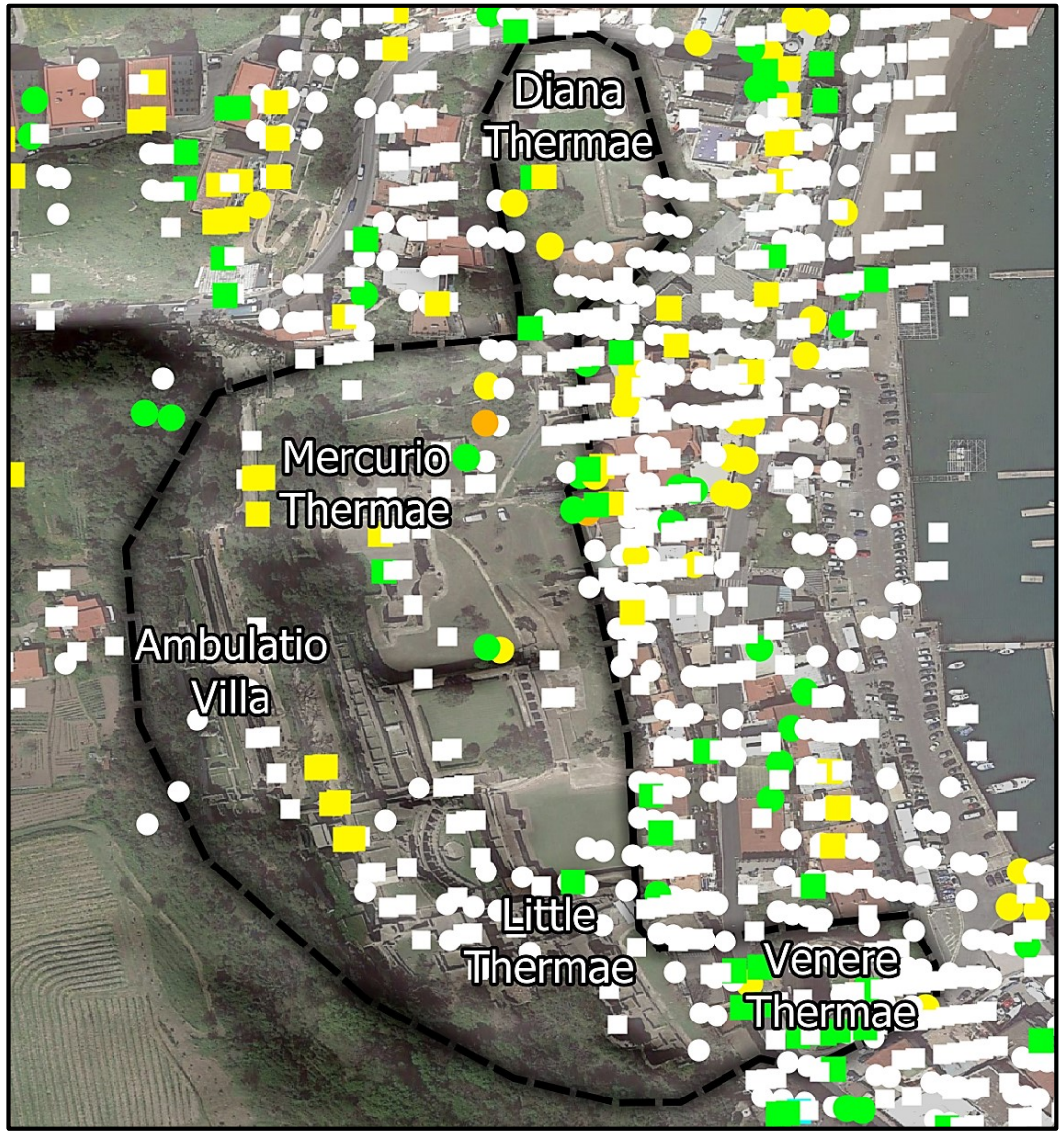
ASC + DESC

better highlight effective distribution of ground motion at a large scale.

Next: some examples of PSI data interpretation from closer point of view.

LoS differential displacement velocity, D-vel (mm/yr)

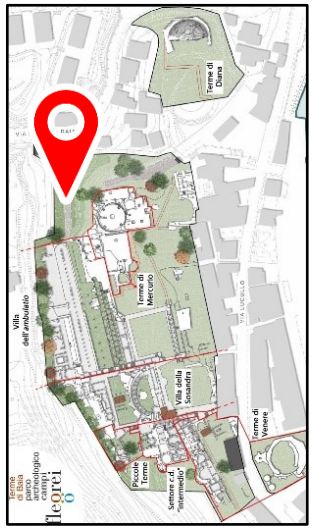
ASC		DESC
	< -10	
	-10 – -5	
	-5 – -2	
	-2 – 2	
	2 – 5	
	5 – 10	
	> 10	

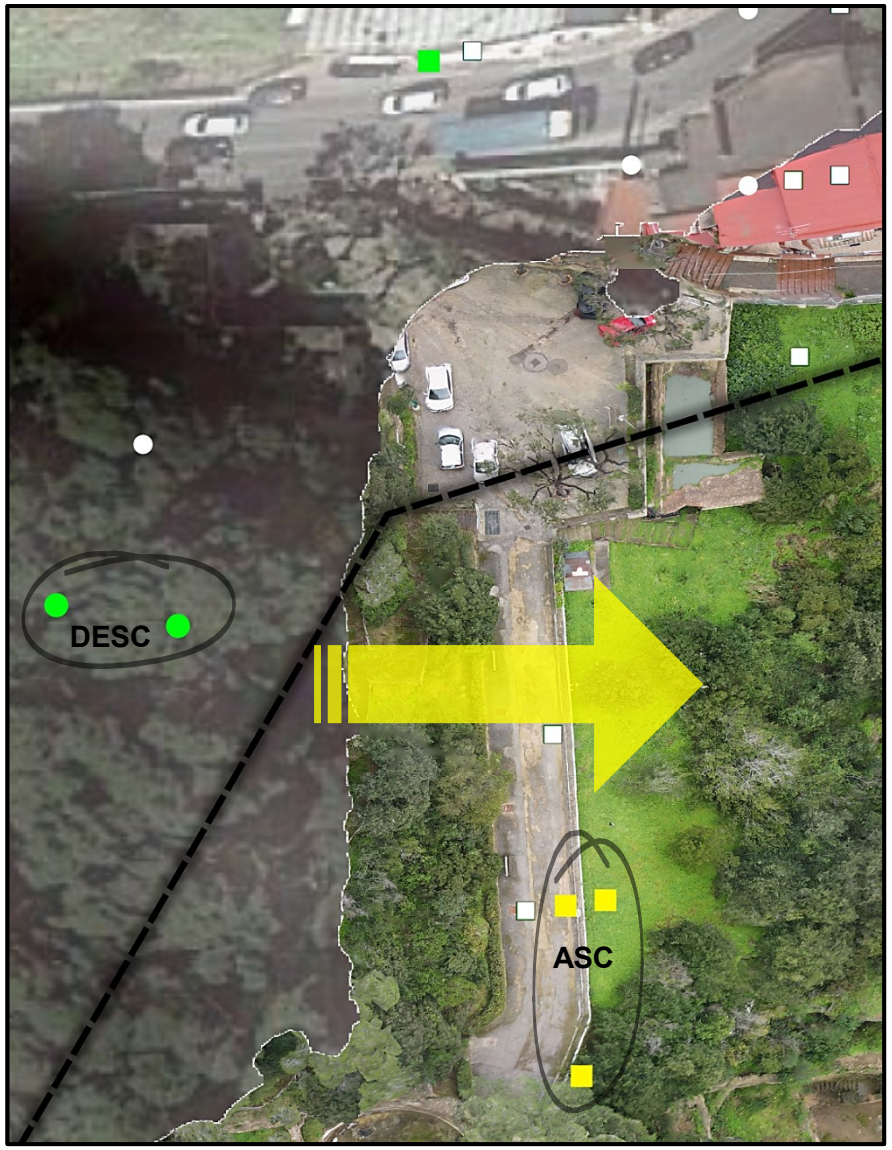


PSI data interpretation: archaeological area entry path

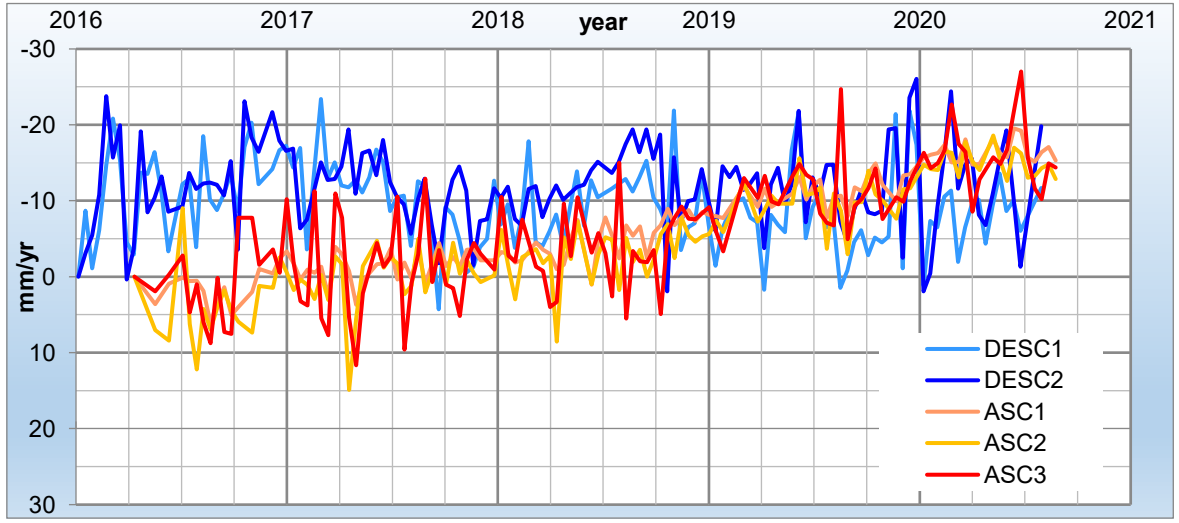
LoS differential displacement velocity, D-vel (mm/yr)

ASC		DESC
	< -10	
	-10 – -5	
	-5 – -2	
	-2 – 2	
	2 – 5	
	5 – 10	
	> 10	





Relative displacement of both datasets, ASC & DESC, of the entry path to the archaeological site, highlights an overall, even if slight, movement towards East, that is downslope (yellow arrow). Relative motion toward satellite for Descending geometry and away from satellite for the Ascending one, means that the horizontal (eastward) component of the displacement prevails over the vertical component.

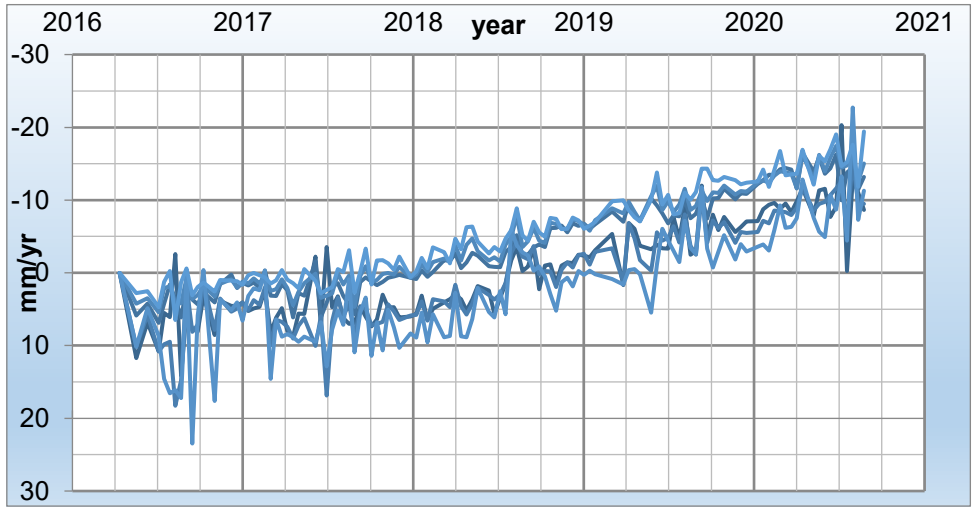


PSI data interpretation: upper terrace

LoS differential displacement velocity, D-vel (mm/yr)

ASC		DESC
	< -10	
	-10 – -5	
	-5 – -2	
	-2 – 2	
	2 – 5	
	5 – 10	
	> 10	

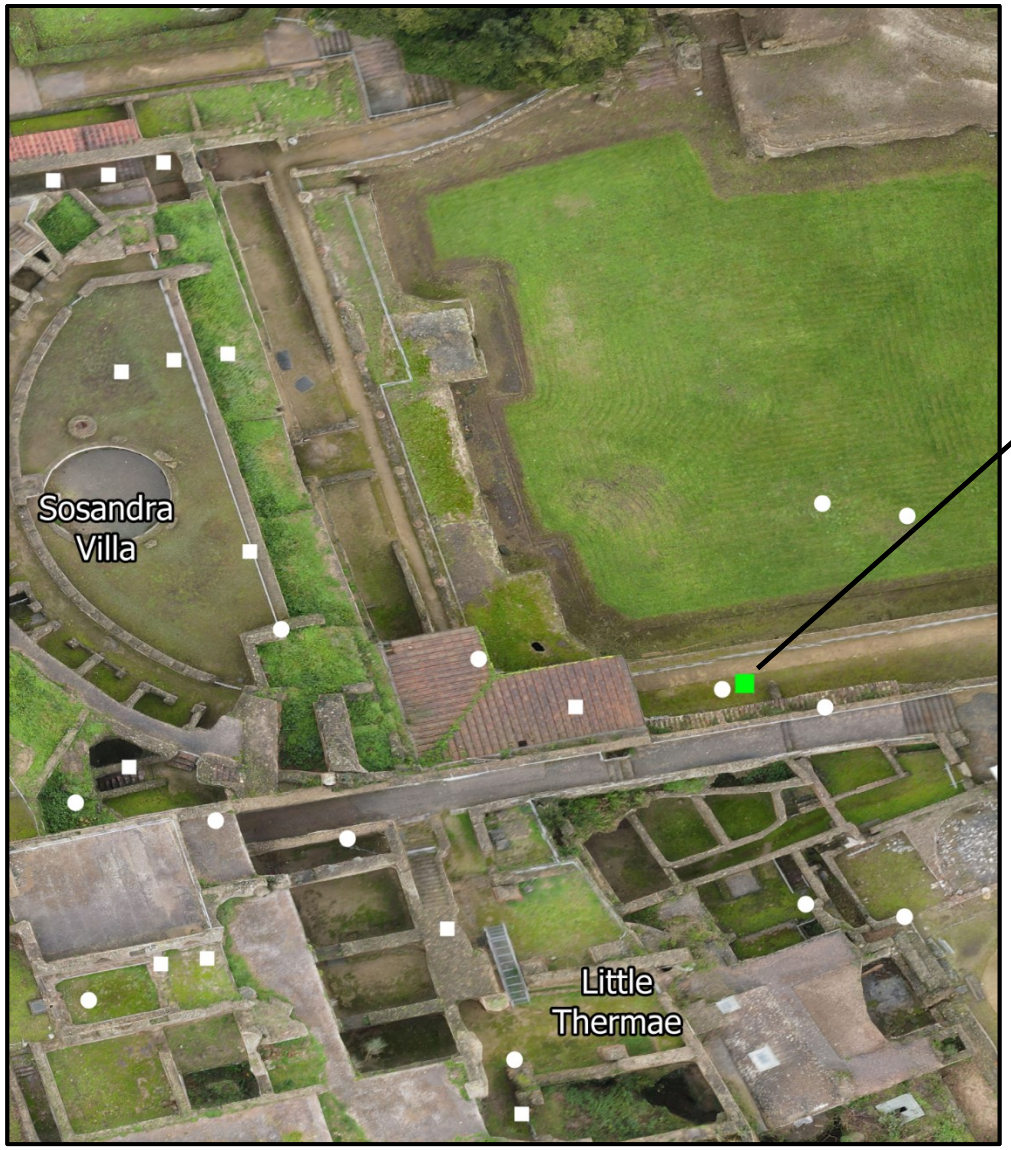
Ascending geometry seems to be more sensitive to radar targets in the site area; this is due mainly to "noise effect“, then to East facing geometry of the slope too. At the edge between *Ambulatio* and *Sosandra* villas a cluster of 6 PSs indicates, consistently, a relatively subsiding area. The crack along the sidewall may indicate this masonry weakness, thus needs to be properly monitored.

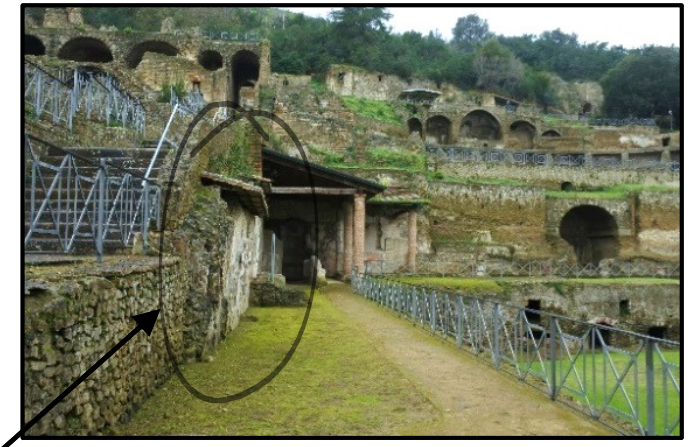


PSI data interpretation: Villa Sosandra

LoS differential displacement velocity, D-vel (mm/yr)

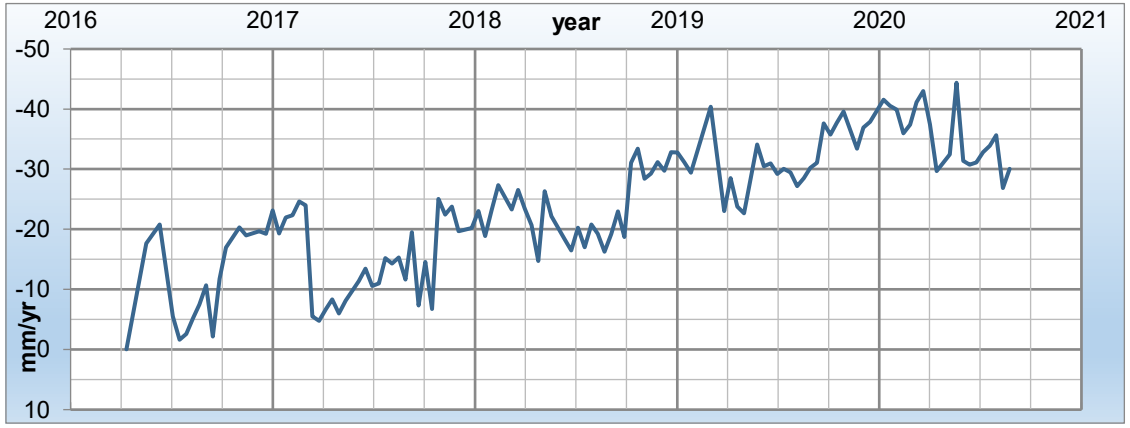
ASC		DESC
	< -10	
	-10 – -5	
	-5 – -2	
	-2 – 2	
	2 – 5	
	5 – 10	
	> 10	





The sidewall between *Sosandra Villa* and *Little Thermae* lost verticality. This is reflected by a relative uplift of one Ascendig PS. In this case the actual outward wall inclination is seen, from the Ascending geometry, as a movement toward the satellite, i.e. a negative displacement along the LOS.

The time history of the PS, in addition to the overall uplift, clearly shows a variable trend. This reflects some common secondary oscillations with a clear seasonal period: an outward push by the earth on the retaining wall, during the rainy period (fall), followed by an opposite trend during the water discharge in late spring.

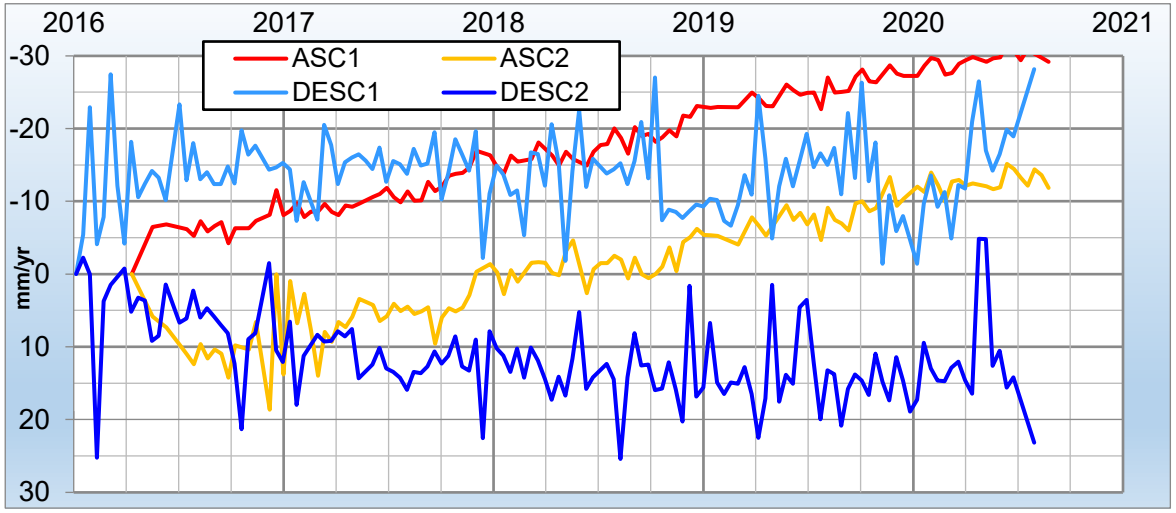


PSI data interpretation: East border

LoS differential displacement velocity, D-vel (mm/yr)

ASC		DESC
	< -10	
	-10 – -5	
	-5 – -2	
	-2 – 2	
	2 – 5	
	5 – 10	
	> 10	

Some modern houses and a church, with the foundation on the buried roman remains, occupy the East border of the archaeological site. In this area the composition of some PSs, from both Ascending and Descending geometry, clearly indicates the occurrence of a differential displacement between the buildings and roman wall remains: subsidence for the first (east side) and uplift for the latter (west side). In this point, on February 26th 2021, a wall portion fell down, without a clear trigger.
But the weakness of the wall seems to have started a few years ago (see below the time history).



SUMMARY

The proposed methodology drives the analysis through an integrated assessment of different elements that contribute to define the exposure level of Cultural Heritage sites to actual local natural hazard.

- The first step is the understanding and correct framing of actual **natural hazard** conditions.
- The second step is the real knowledge of the site, to be acquired by **field survey** and **EO monitoring**, involving experts, managers and stakeholders too.
- Then, **the InSAR dataset is analyzed** and eventually corrected, to highlight the site-scale pattern of ground motion.
- Last comes the **PSI data interpretation** of local events pointed out by previous steps, in order to understand the interaction between structure damage and ground motion. The actual relation reveals if and how building's damages are caused by structural weakness or by ground motion.

The final goal is to set up a proper mitigation and conservation plan and to implement an integrated monitoring system.