



**BULGARIAN ACADEMY OF SCIENCES
NATIONAL INSTITUTE OF GEOPHYSICS, GEODESY AND
GEOGRAPHY**

Department of Geodesy

**БЪЛГАРСКА АКАДЕМИЯ НА НАУКИТЕ
НАЦИОНАЛЕН ИНСТИТУТ ПО ГЕОФИЗИКА,
ГЕОДЕЗИЯ И ГЕОГРАФИЯ**

Департамент Геодезия

**Monitoring on coseismic deformations in the Aegean
Sea region based on SAR data**

Prof. DSc. Eng. Mila Atanasova - Zlatareva

**Проследяване на косеизмични деформации в
района на Егейско море въз основа на данни от РСА**

проф. дн инж. Мила Атанасова - Златарева

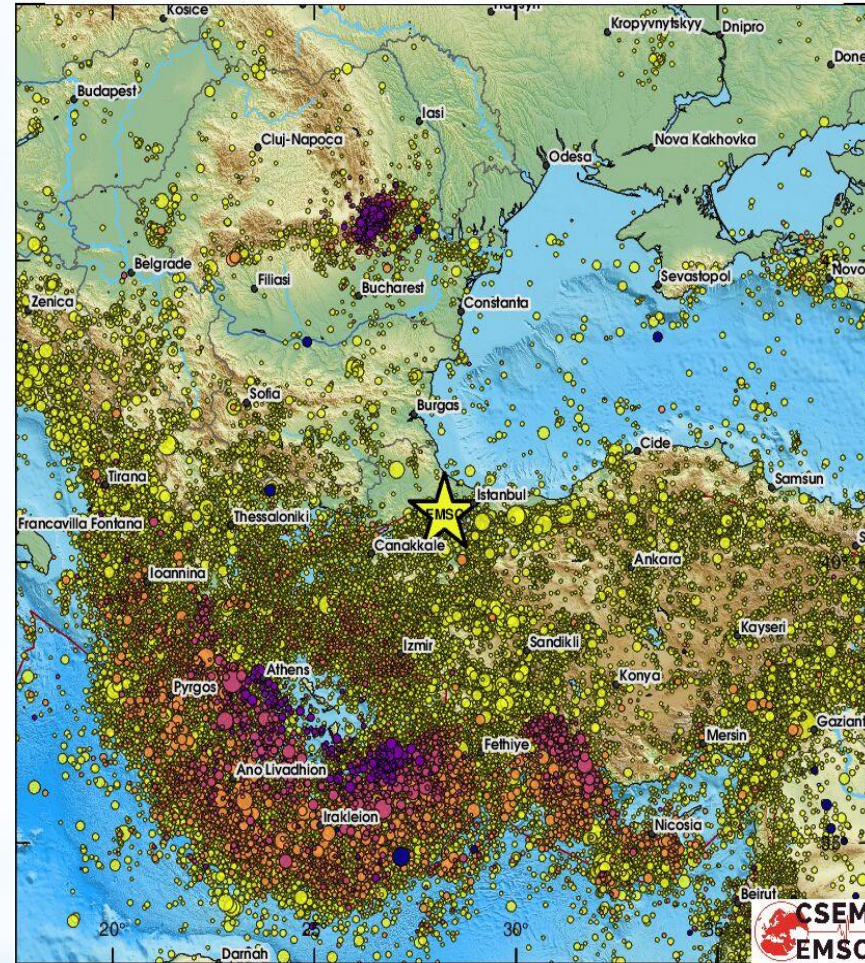
Introduction

- The current study is focused on one of the significant challenges for our society - registration, monitoring and improvement of post-earthquake prevention.
- A contemporary method that has proven its place in this type of research is the Differential Interferometry (DInSAR) method, which uses as output data values for the intensity and phase of the radio signal reflected by natural and anthropogenic objects.
- The Aegean Sea region is one of the most seismically active areas in the Balkans and Europe

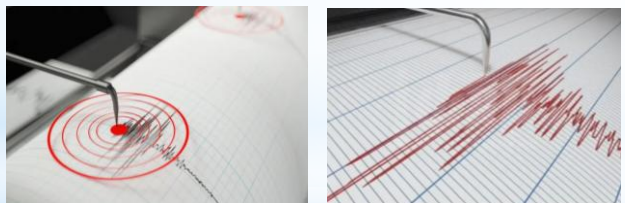
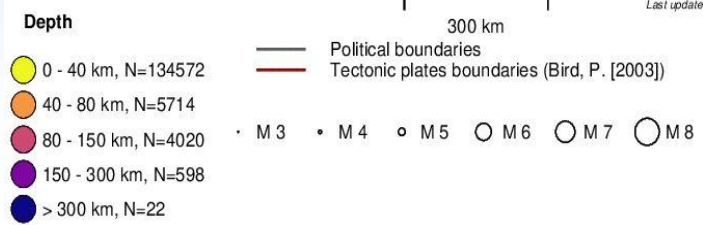
EMSC manual location

M:6.2 2025/04/23 - 09:49:11 UTC
 Lat: 40.83 Lon: 28.23 Depth: 15 km

Background data: ISC + EMSC catalogues from 1960/07/13 - 13:00 to 2025/04/23 - 09:00
 (Total number of events with M>3: 144926)



Last updated: 2025-04-23 at 11:33 UTC



EMSC

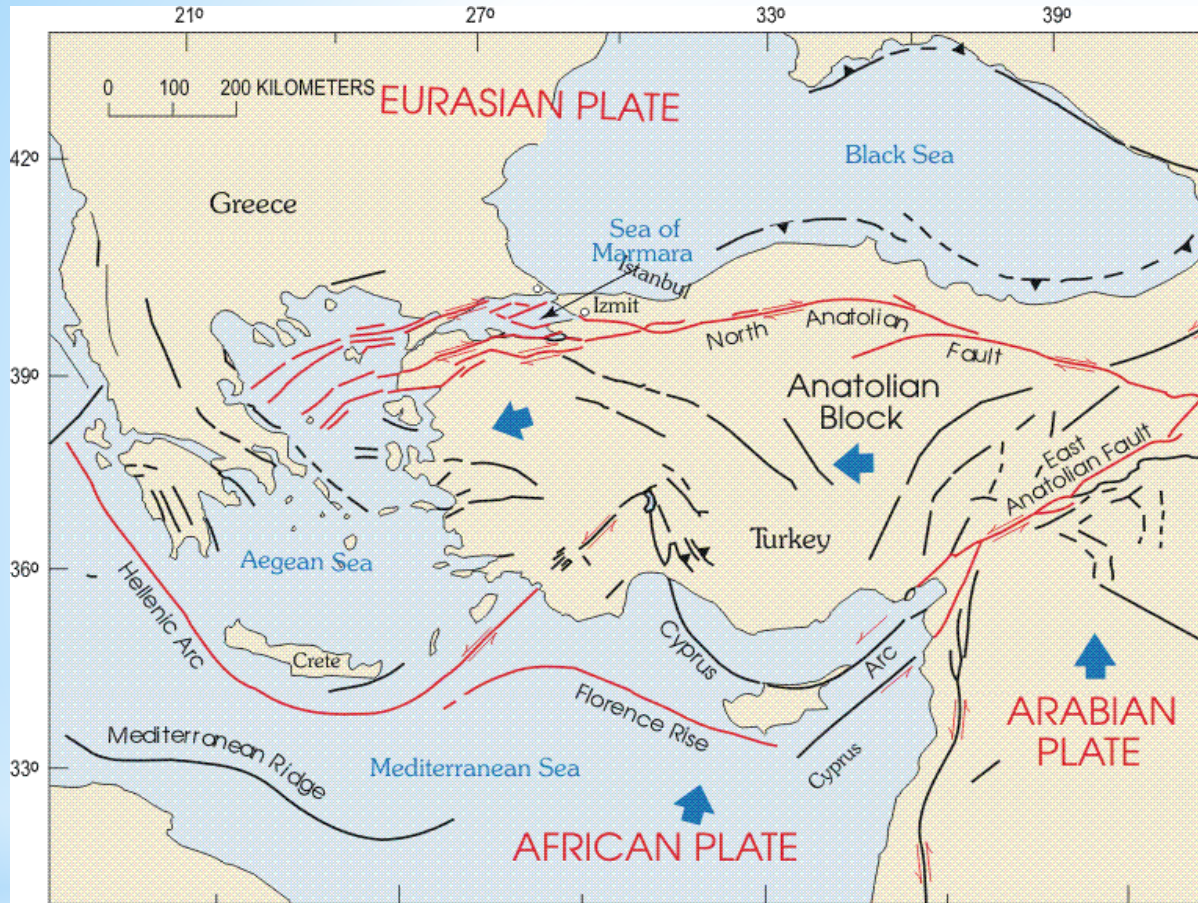
Motivation

The research interest is focused on detecting deformations of the Earth's crust resulting from earthquakes recorded in the Aegean Region. The Aegean Region is a seismically active tectonic zone with high deformation rates due to its location at the convergence area of the African and Eurasian plates, including the Aegean-Anatolian microplate.

The research is related to the work on the project "Study of coseismic deformations of the earth's crust for the territory of the Balkan Peninsula using satellite data" which was launched in December 2023.

The main task of this project is to demonstrate operational readiness for determining the magnitude of deformations of the earth's surface, the size of the affected area and preparation of maps of surface displacements that occurred after a seismic event.

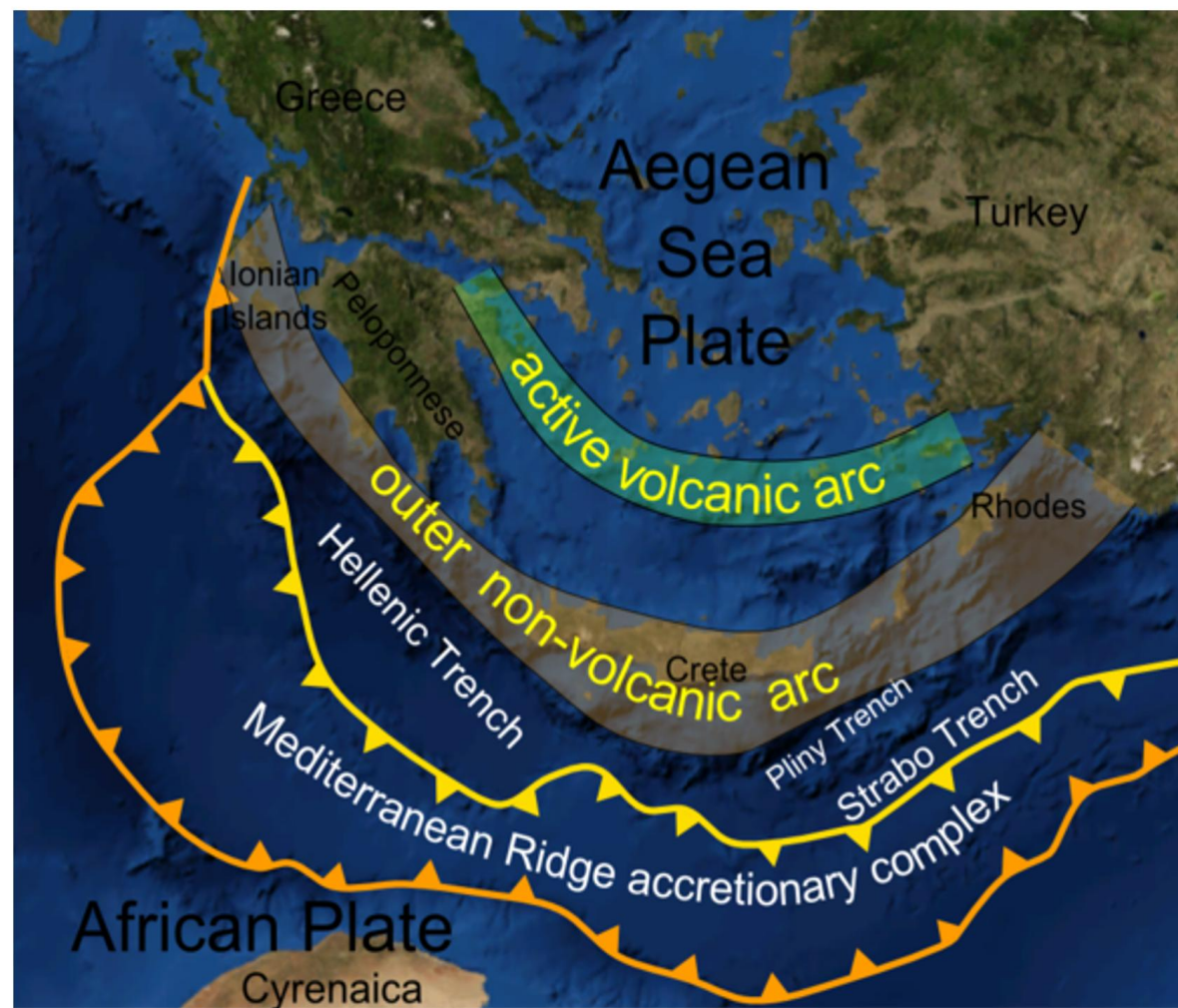
Research object



The westward movement of the Anatolian block results from: differences in rates of motion between the Arabian and African plates; different directions of motion between the Anatolian block and Eurasian plate to the north; subduction of the African plate beneath the Anatolian block at the Hellenic and Florence trenches. The Arabian plate is moving to the north faster than the African plate, both relative to a stable Eurasian plate.

The result is a westward moving wedge incorporating most of Turkey and Greece. Before the crust under the Aegean Sea was described as a part of the Anatolian plate, and the different directions of motion were explained as the plate rotating counterclockwise. New measurements found that motion of the Aegean region differed from the previous model, so the Anatolian and Aegean Sea plate are now considered distinct from each other.

Research object

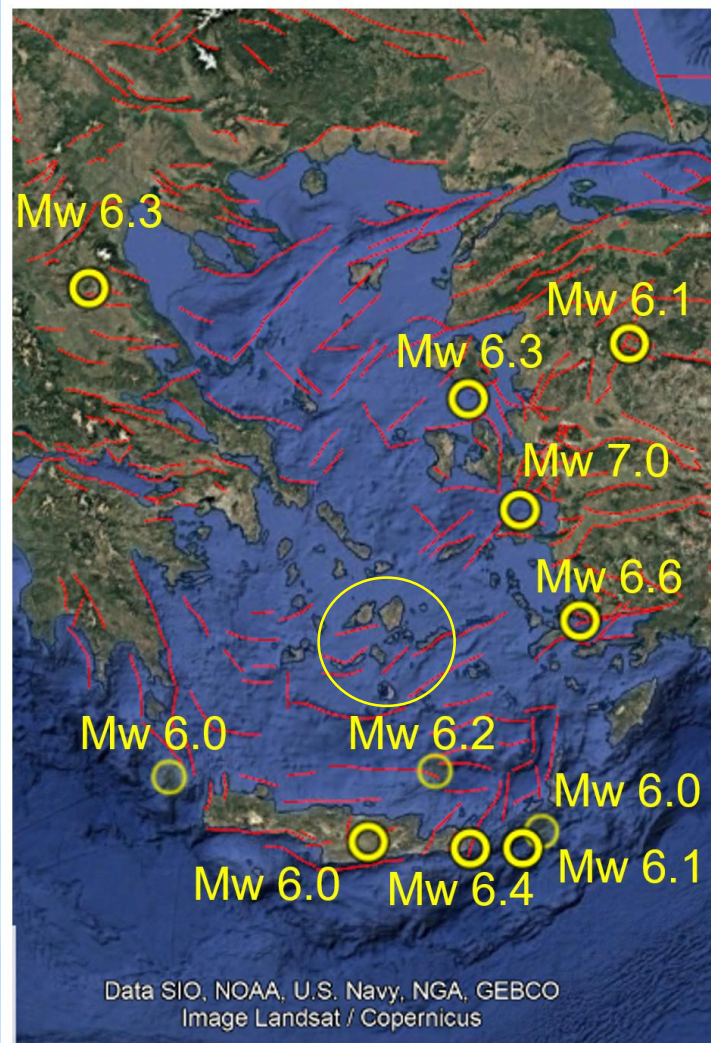


The **Aegean Volcanic Arc** (also known as the Hellenic Arc) is formed by the subduction of the African Plate under the Eurasian Plate, extending from the Isthmus of Corinth on the Greek mainland to the Bodrum Peninsula on the Turkish mainland. The active part of the arc consists of numerous dormant and active volcanoes, some of which are Milos, Santorini, Columbo, Kos, Nisyros, etc. The Santorini-Amorgos Fault Zone, characterized by frequent earthquakes, highlights the tectonic complexity of the Aegean Sea.

Main tectonic and volcanic structures of the Aegean region

https://en.wikipedia.org/wiki/Aegean_Sea_plate

Research object



Map Earthquake Mw>6.0

<https://www.emsc.eu/>

Earthquakes Northeast the Santorini Island in the February 2025 – Cycladi

south

Coseismic displacement after the earthquake of September 27, 2021 on the Crete island, Mw 6.0

west

Coseismic displacement after Larissa of March 3, 2021 Mw 6.3

East

Coseismic displacement after Kos-Bodrum earthquake on July 20 2017, Mw 6.6

Coseismic displacement after Samos-Izmir earthquake from October 30 2020, Mw 7.0

Coseismic displacement after earthquake Balıkesir - Turkeysh on August 10 2025, Mw 6.1

Method and Data



Methods

Coseismic deformations of the Earth's crust occur during a strong seismic event with a magnitude above 5.0 and have manifestations on the Earth's surface at points close to the epicenter of the event.

Coseismic displacements are determined mainly by satellite observation methods that use both GNSS data and InSAR technology - a combination that has been applied very successfully in recent years

Data

The spatial distribution of the earthquakes, the time interval to have occurred after 2015 and the magnitude of the event to be greater than Mw 6.0 are the limitations set in our research activity, since the main method for observing the deformations of the Earth's crust used in this study is the InSAR technology. The data used to achieve the objectives of the study are the SLC products from the Sentinel 1 A and B mission, which are available after 2015.

Method and Data

Scientific research methods

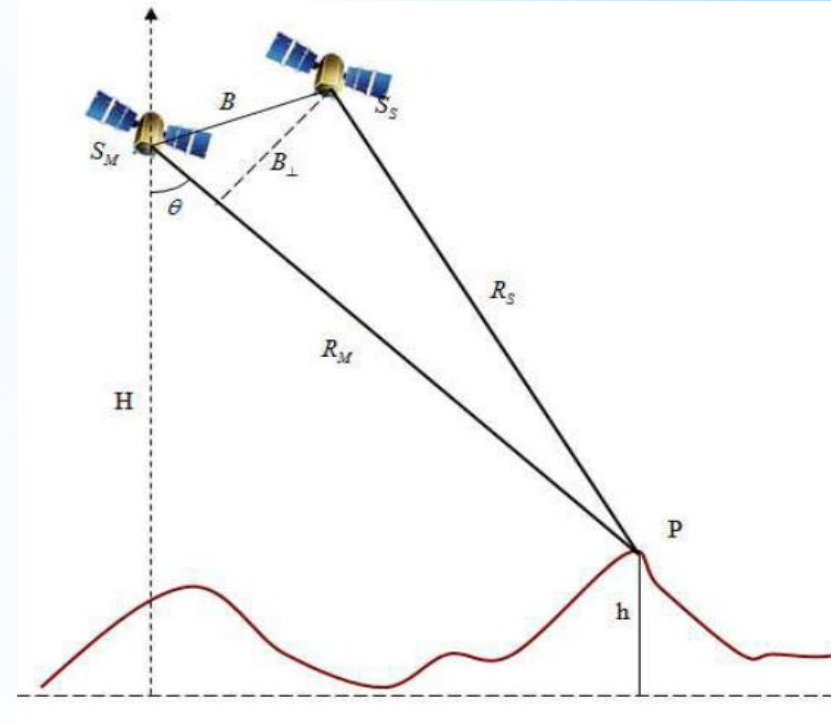
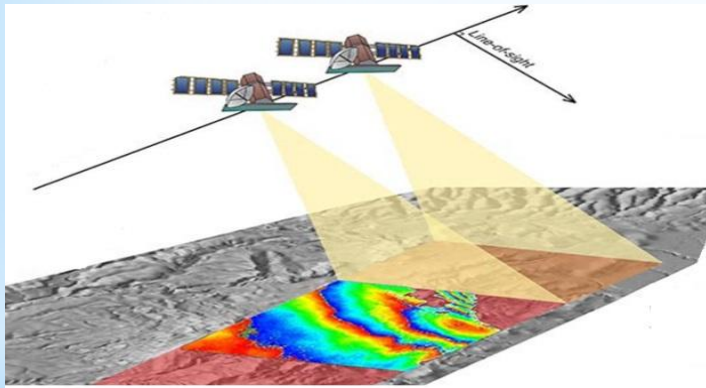
The main research methods used is InSAR method with its further developed methodologies:

- ✓ DinSAR- Differential Interferometric Synthetic Aperture Radar
- ✓ SBAS InSAR- интерферометрия с Small Baseline Subset
- ✓ PS- InSAR- Persistent Scatterer Interferometry
- ✓ MT-InSAR- Multi-temporal Interferometric Synthetic Aperture Radar

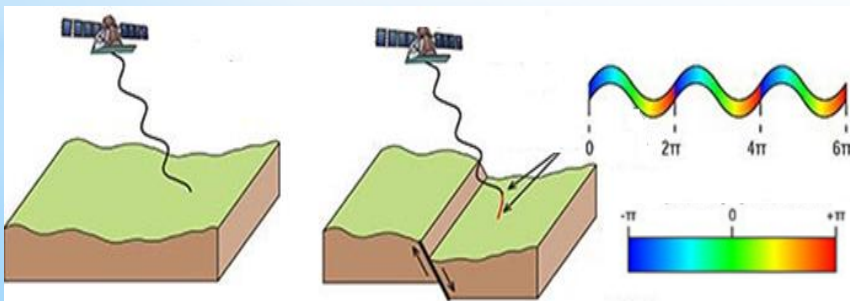
Basic principles of the InSAR method

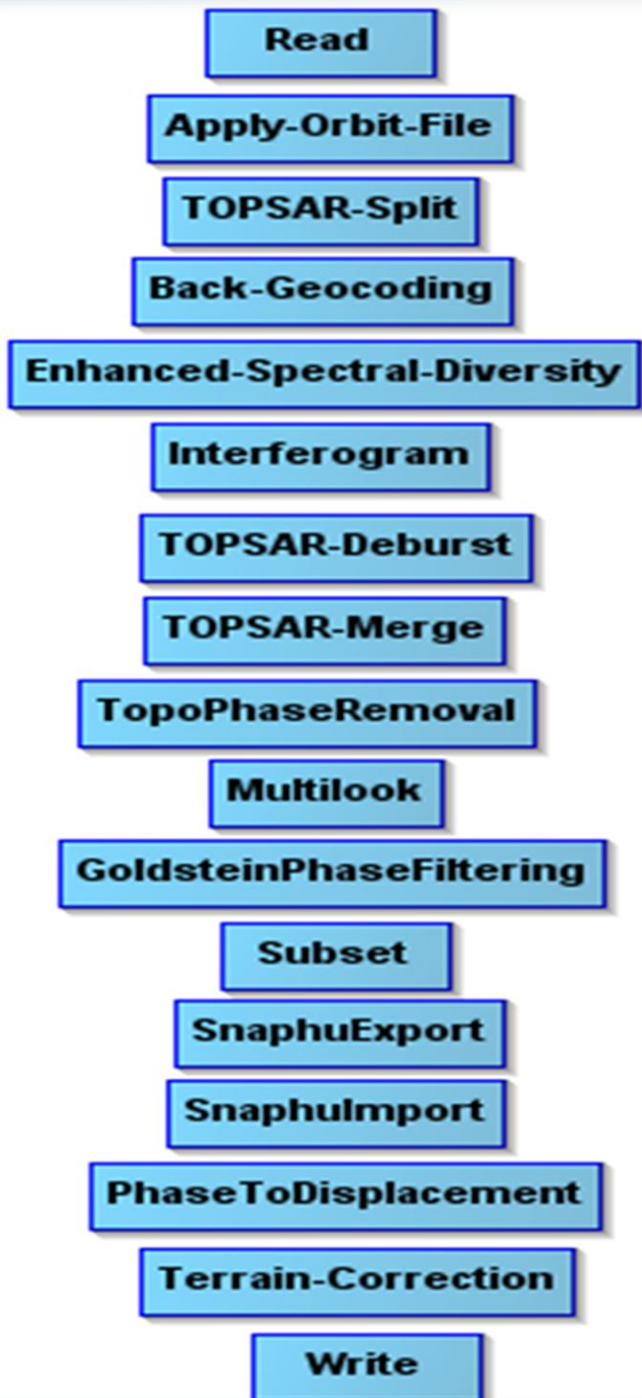
The target (P), located at a height h , is recorded from two radar positions S_M (master) and S_S (slave). The distance between S_M and S_S represents the Interferometric Baseline B and the perpendicular baseline. R_M and R_S are the distances between the sensor position when recording the data and the target.

$$\Phi_{int} = \phi_{elev} + \phi_{disp} + \phi_{atmos} + \phi_{flat} + \phi_{noise}$$



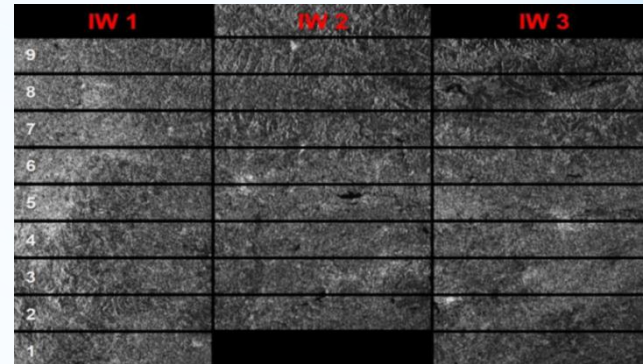
Φ_{int} - the phase of each pixel of the interferogram
 ϕ_{elev} is the topographic phase (DEM);
 ϕ_{disp} - the phase of displacement, along the line of sight (LoS);
 ϕ_{atmos} is the atmospheric phase;
 ϕ_{flat} is the flat earth phase, which is an error caused by the curvature of the reference surface;
 ϕ_{noise} is the phase noise caused by either variability in scattering from the ground surface pixel, thermal noise, or co-registration errors



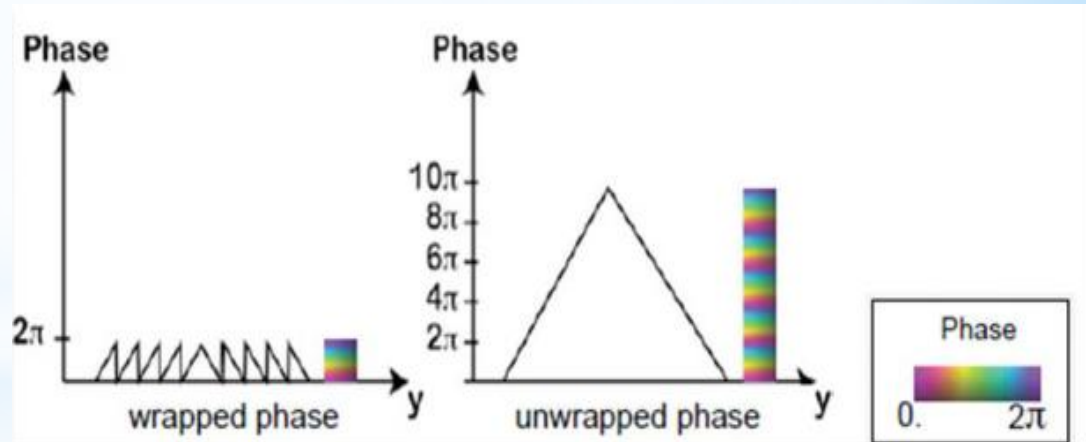


Procedure for processing SLC data by differential interferometric method

- Processing of TOPS DInSAR



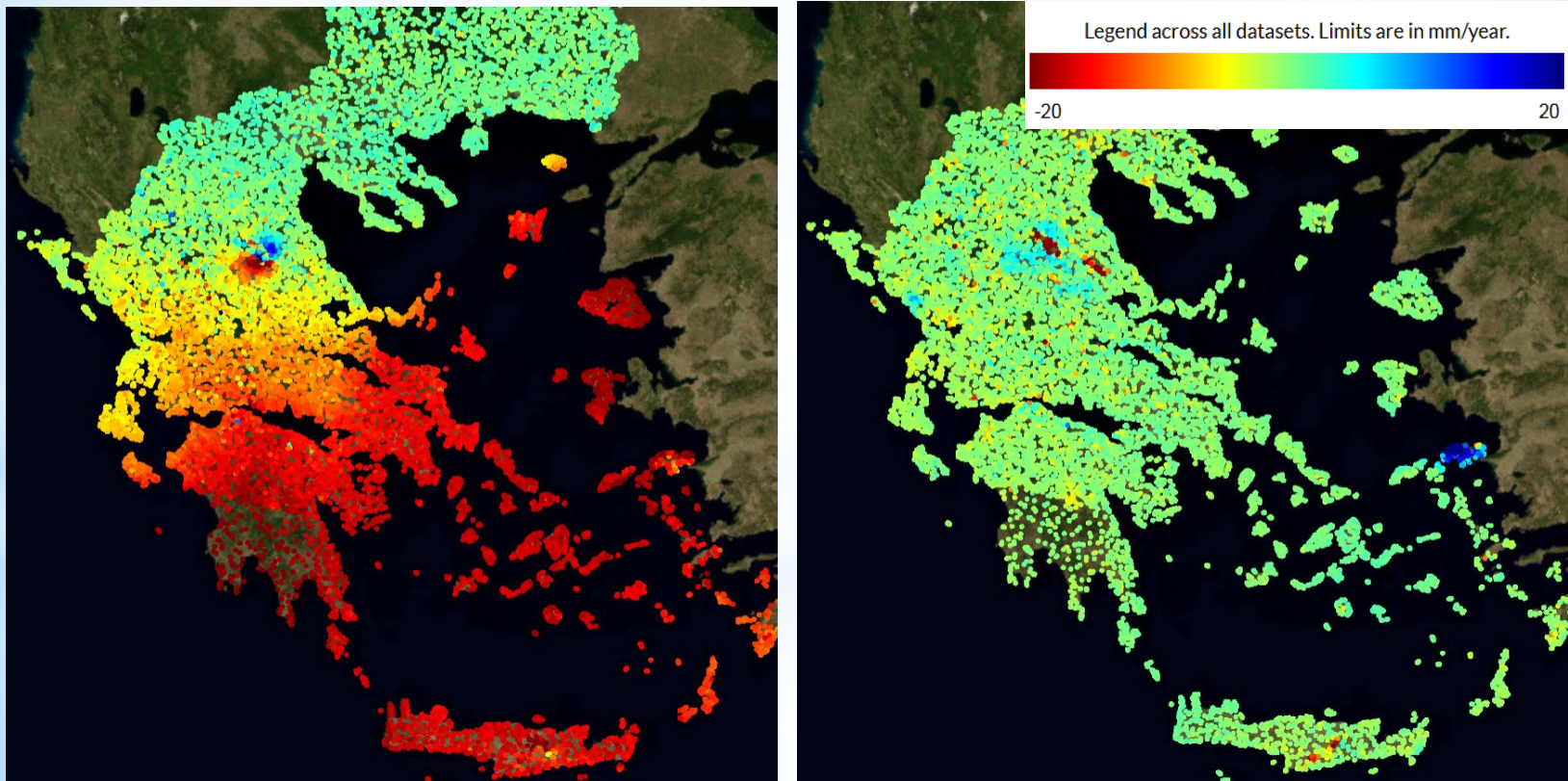
- Visualization of the wrapped and unwrapped phase



- Determining displacements in time series from IFIs

European Ground Motion Service (EGMS)

Multi-Temporal Interferometric Synthetic Aperture Radar (MT-InSAR) technique was applied to monitor land deformation in the period between Jan 01 2019 and Dec 31 2023 with Sentinel-1 data obtained from ESA. The processing was done from EGMS. From the analysis of the results, in the Aegean region is occurring surface movement at a moderate rates in the west in confirmation of the statements about the movement of the Aegean microplate. During the investigations were observed coseismic vertical deformation the separate areas.

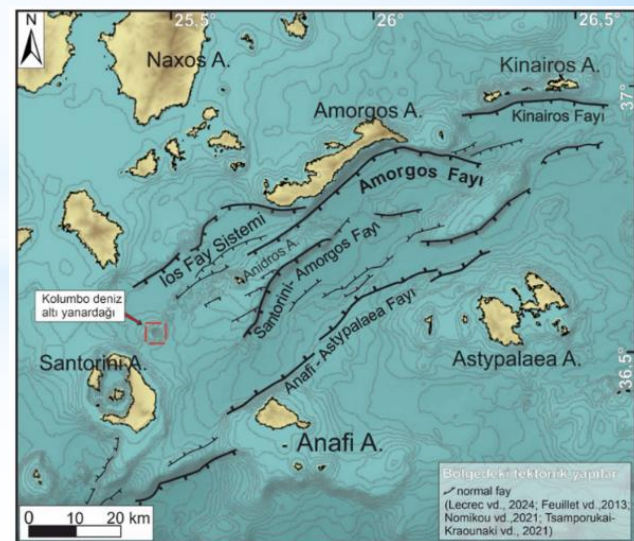
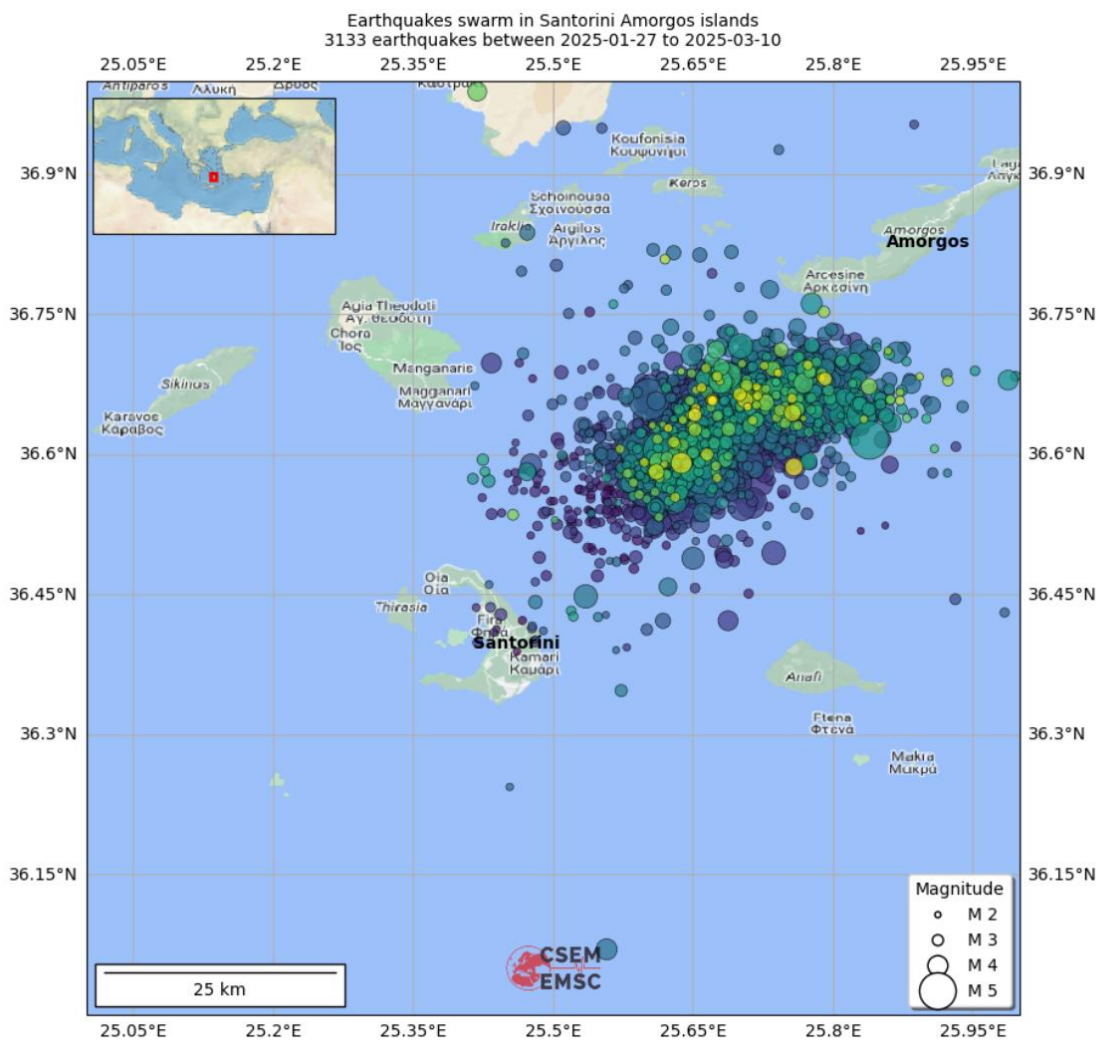


Horizontal (East/West) and Vertical movement from EGMS MT-SAR for period 2019-2023

Earthquakes Northeast the Santorini Island in the February 2025

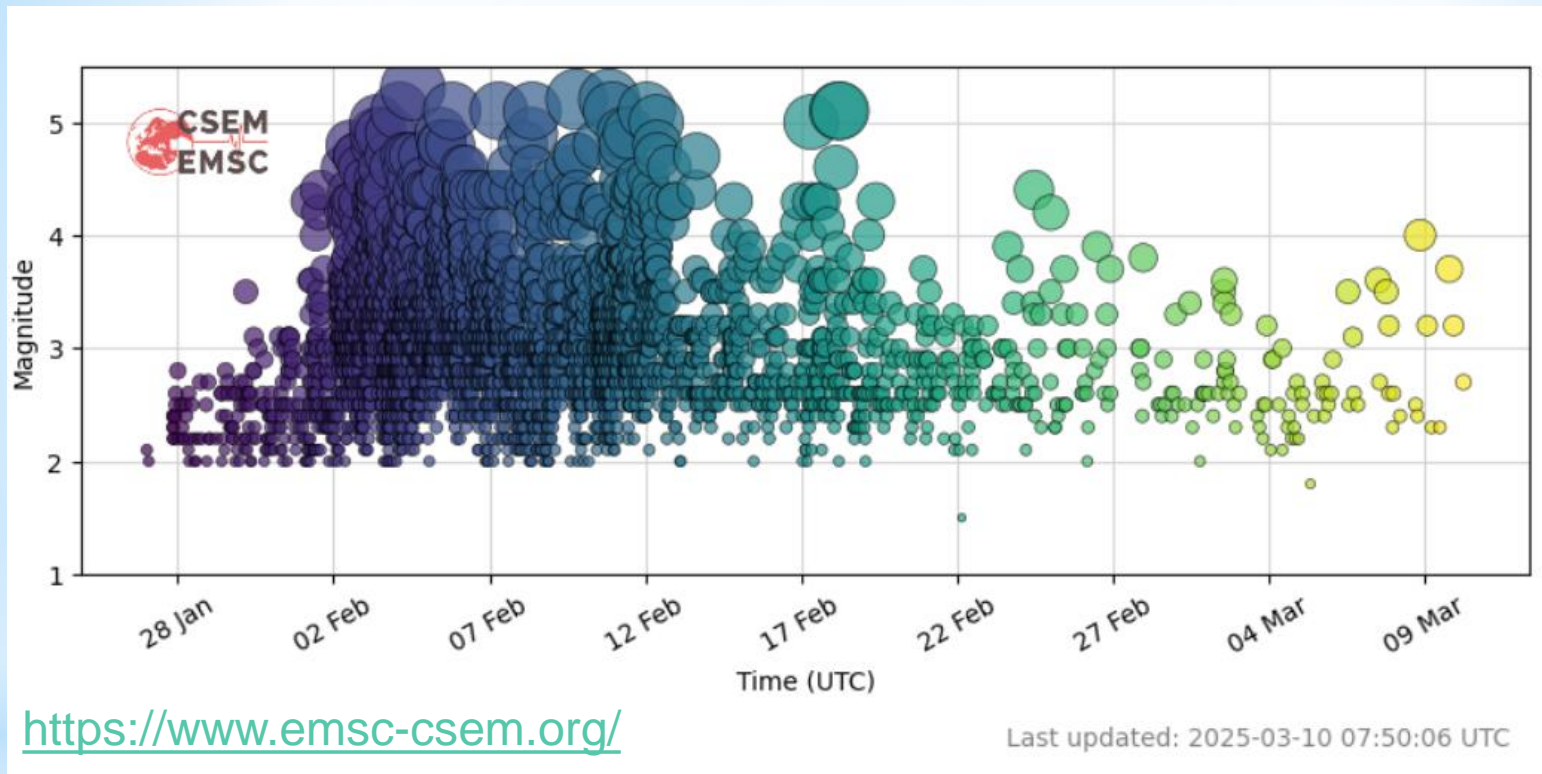
Spatial distribution of seismic activity from European Mediterranean Seismological Centre(EMSC)

A seismic swarm of earthquakes clustered together, most of which have a magnitude of between 3 and 5, has been recorded northeast of the island of Santorini. An important feature of the area where the multiple earthquakes occurred is the tectonic structures in the area and the location of the underwater volcano Columbo.



Earthquakes Northeast the Santorini Island in the February 2025

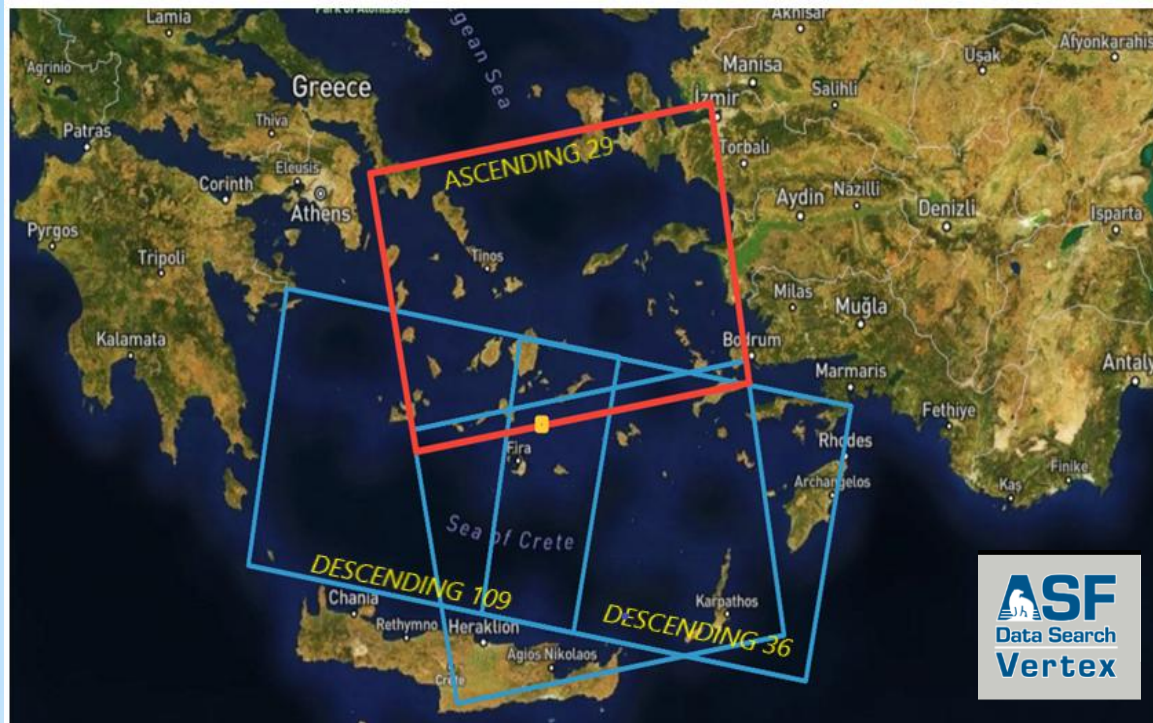
Time distribution of seismic activity from the European Mediterranean Seismological Centre (EMSC)



The size of each point is related to the magnitude of the earthquake.

Coseismic displacement after the earthquakes evented Northeast the Santorini Island in the February 2025 were estimated This ongoing activity, classified as an earthquake swarm, has produced a maximum recorded magnitude of 5.3 Mw, but no on the earth's surface movements recorded

DATA



To record the displacements that occurred in the Cyclades region for the period from **24 January to 7 March 2025**, we processed SAR images from Sentinel-1 TOPS - Terrain Observation with Progressive Scan; We used a total of 12 radar images from two overlapping ascending and descending orbits

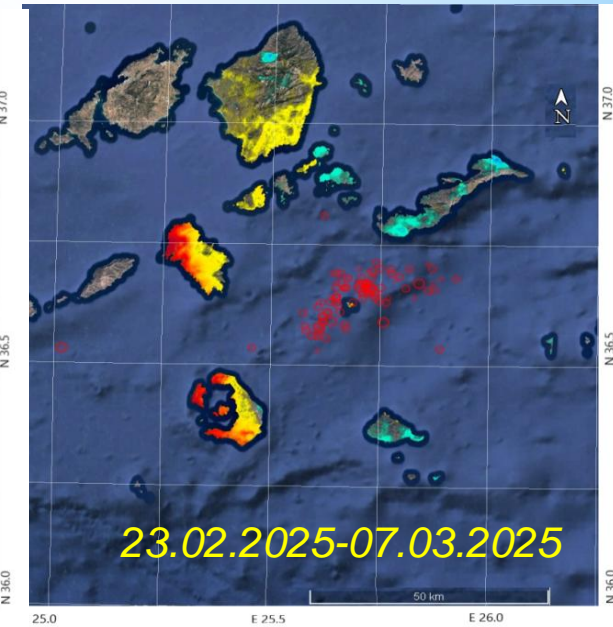
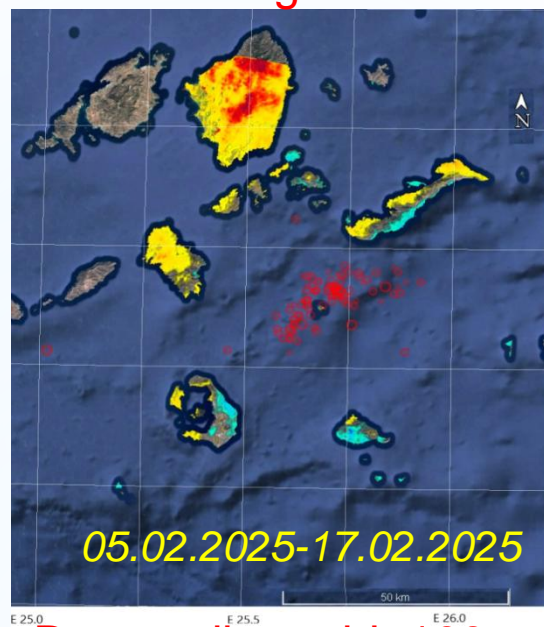
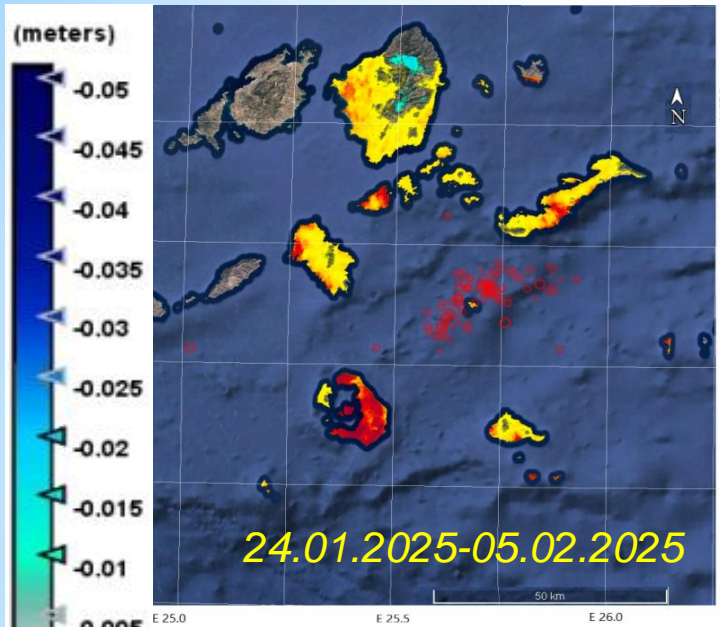
Orbit	Master-Date	Slave Date	Track	Perp Baseline [m]	Wavelength [cm]
Descending	24.01.2025	05.02.2025	109	-1	5.6
	05.02.2025	17.02.2025	109	1	5.6
	17.02.2025	01.03.2025	109	18	5.6
Ascending	30.01.2025	11.02.2025	29	-49	5.6
	11.02.2025	23.02.2025	29	-27	5.6
	23.02.2025	07.03.2025	29	-74	5.6

Displacement by LoS direction;

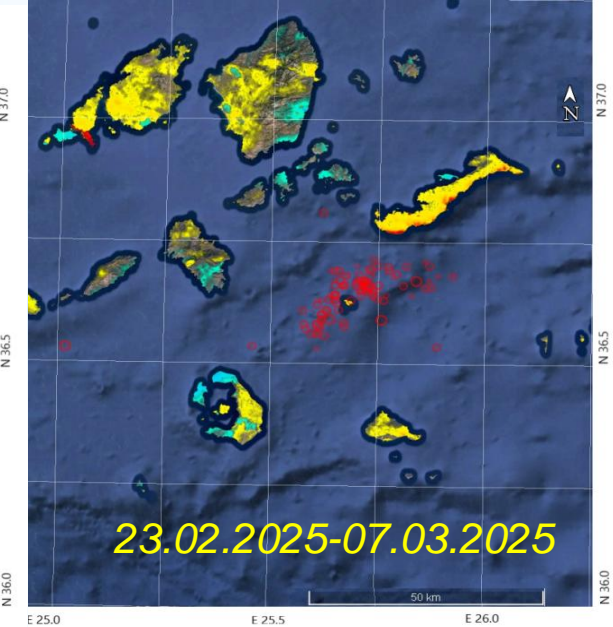
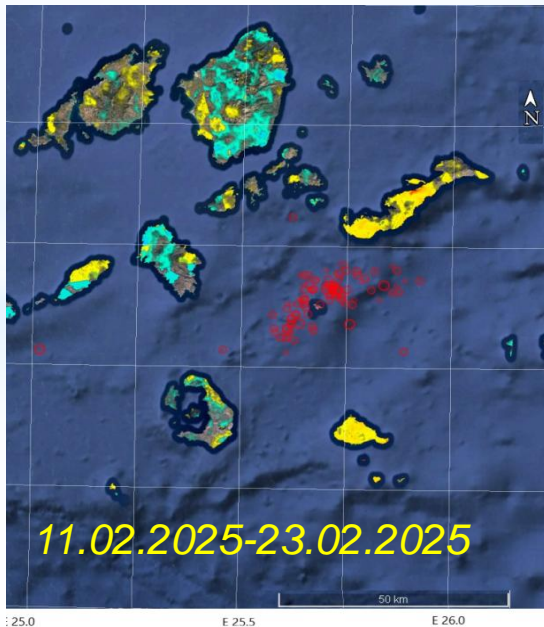
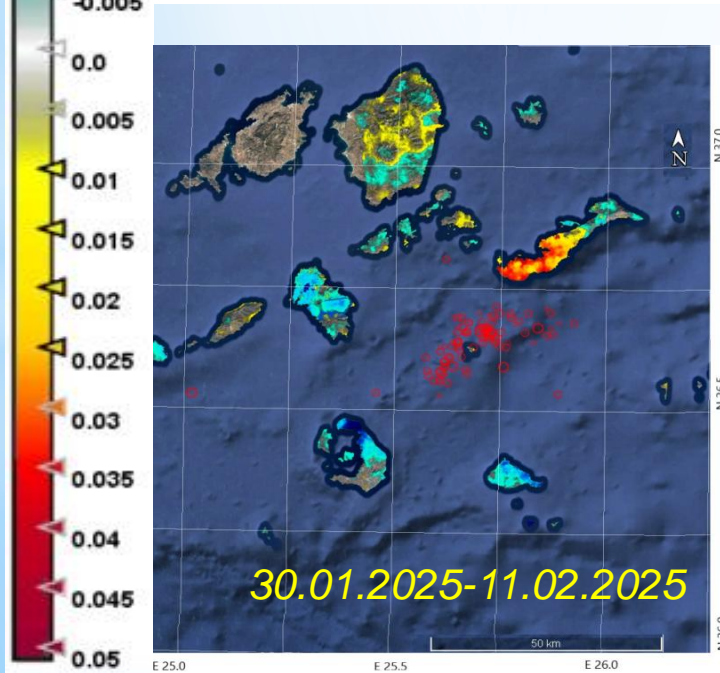
red points EMSC

<https://www.emsc-csem.org/>

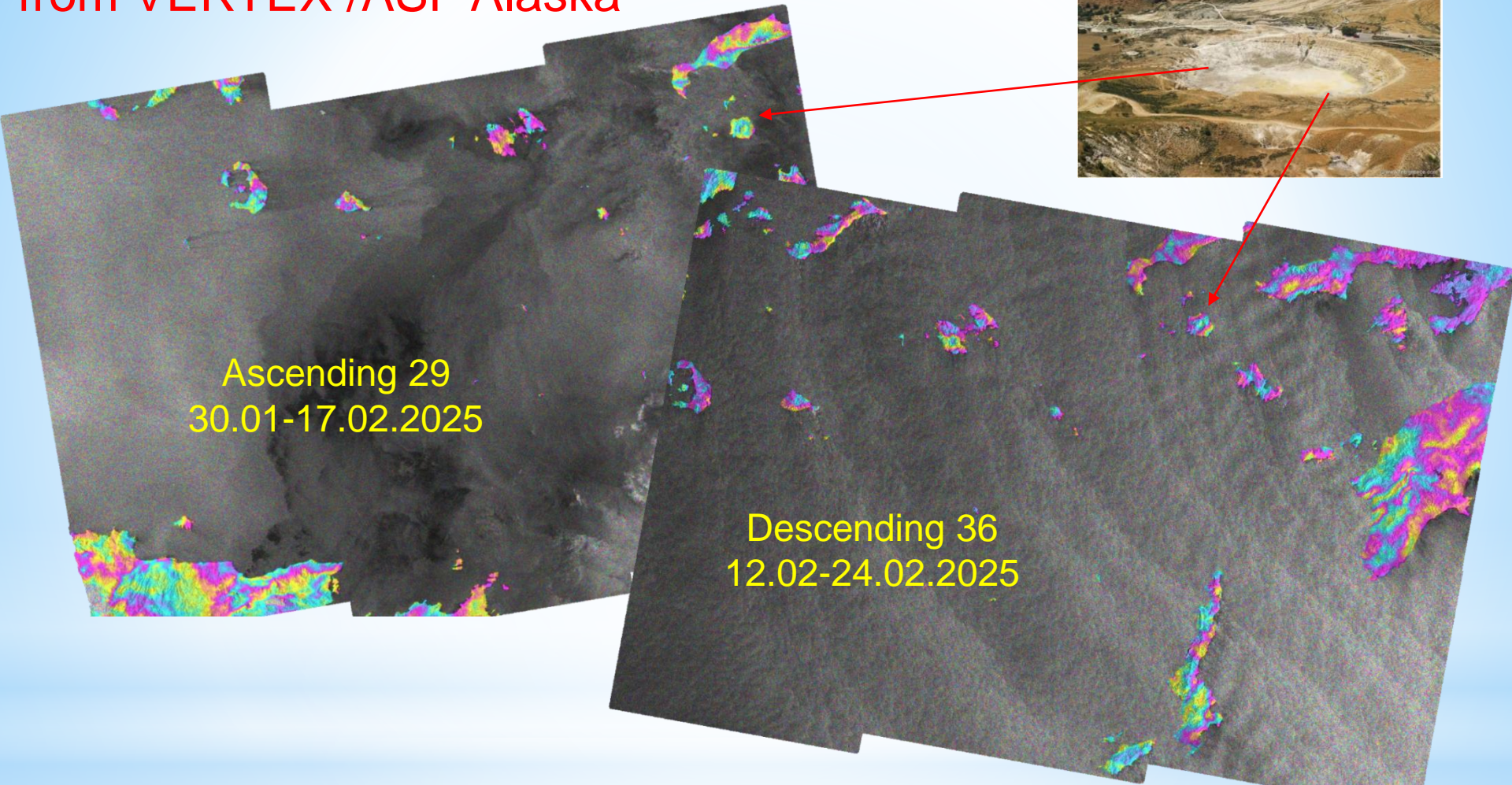
Ascending orbit 29



Descending orbit 109

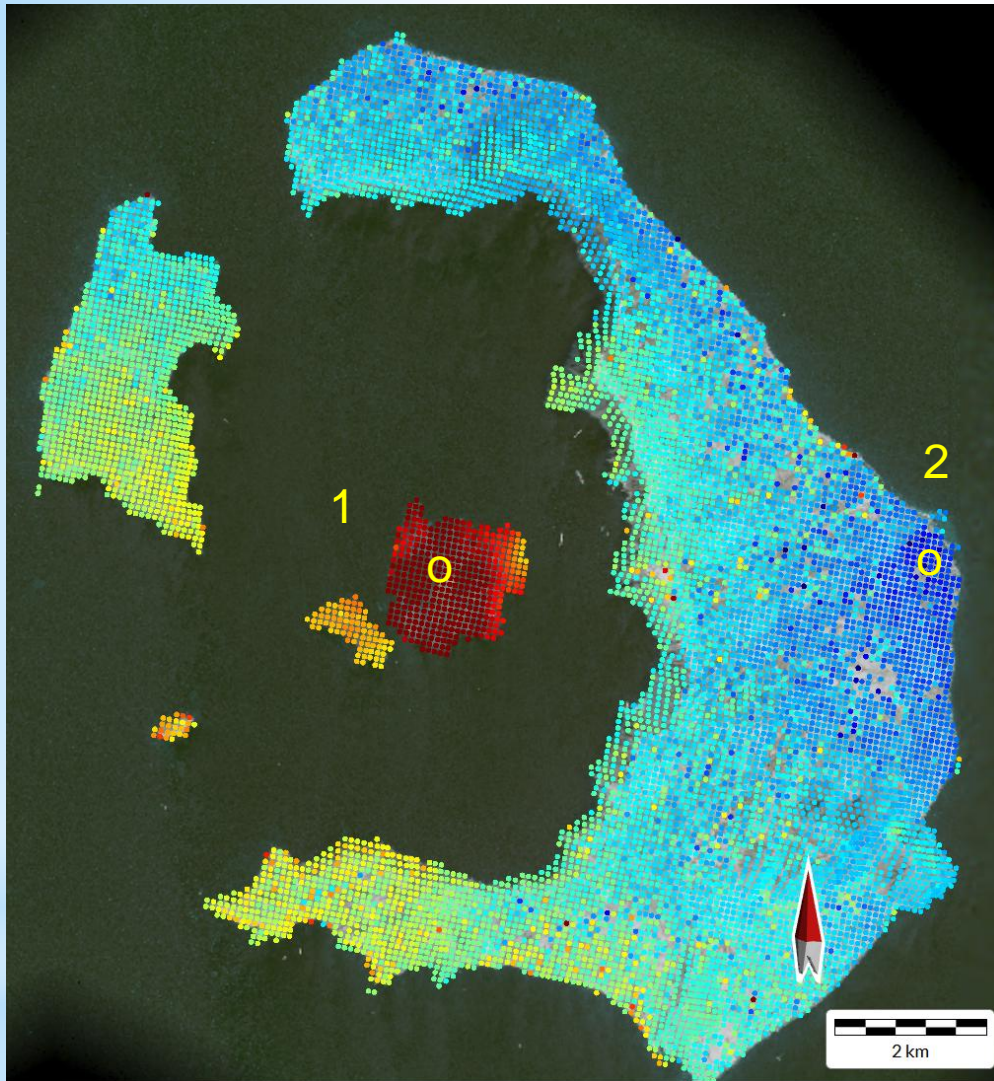


Interferograms freely available from VERTEX /ASF Alaska



Time series of interrrferograms for the Nisyros volcanic area processed using the GAMA software over 12 days from 01Jan 2021 to today (or 6-day) are available on VERTEX /ASF Alaska. The area of the island of Santorini falls within the range of the interferograms provided by ASF, for the same time period for ascending orbit 29 and descending orbit 36. <https://search.asf.alaska.edu/#>

Vertical Component 2019-2023 (vector), from EGMS



Legend across all datasets. Limits are in mm/year.



EGMS provides consistent, regular, standardised, harmonised and reliable information regarding natural and anthropogenic ground motion phenomena over the Copernicus Participating States and across national borders, with millimetre accuracy.

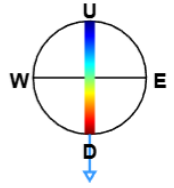
EGMS Ortho: to derive two layers; one of purely vertical displacements (the one described by this metadata), the other of purely east-west displacements. Both layers are resampled to a 100 m grid.

EGMS Ortho is visualized as a vector map of measurement points colour-coded by average velocity (vertical or east-west components). Each point is associated with a time series of displacement, i.e. a plot with values of displacement per acquisition of the satellite.

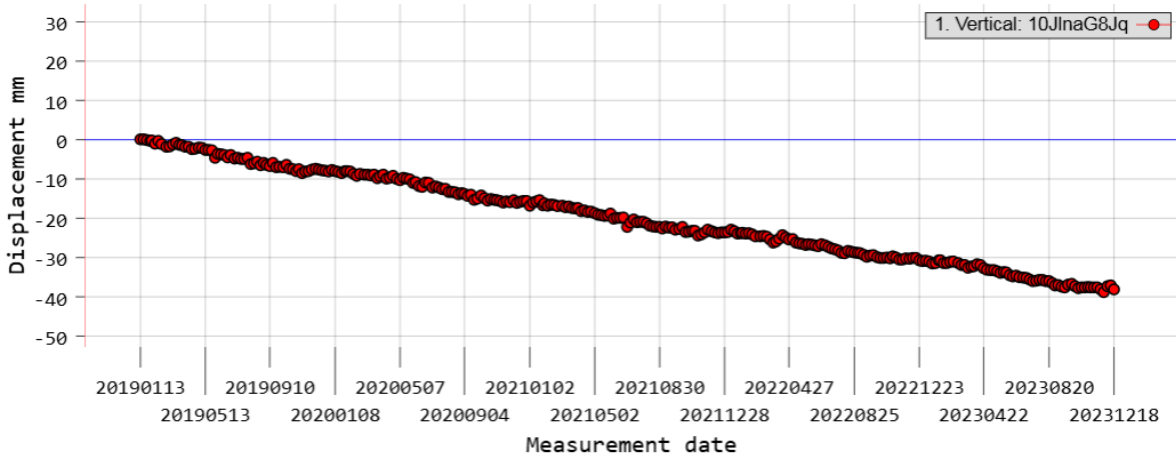
Vertical movement by MT-SAR for period 2019-2023 from EGMS

Dataset: Vertical
Point ID: 10JlnaG8Jq
Position: 1621150.00 N 5703850.00 E 70.50 m
Mean velocity: -7.60 mm/year
RMSE: 0.50 mm

Incidence angle: 0.00°

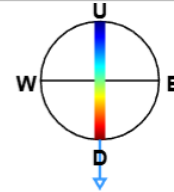


point 1

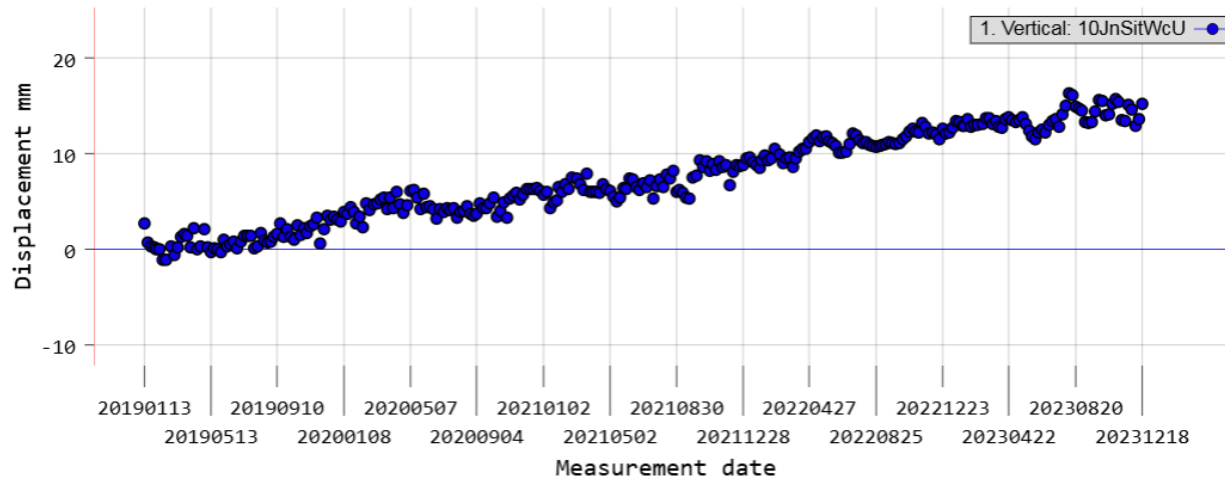


Dataset: Vertical
Point ID: 10JnSitWcU
Position: 1623350.00 N 5711450.00 E 13.80 m
Mean velocity: 3.20 mm/year
RMSE: 0.90 mm

Incidence angle: 0.00°



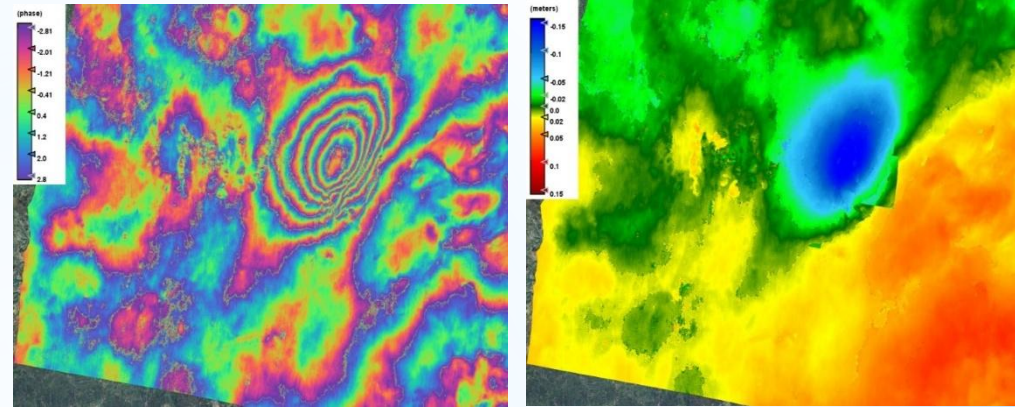
point 2



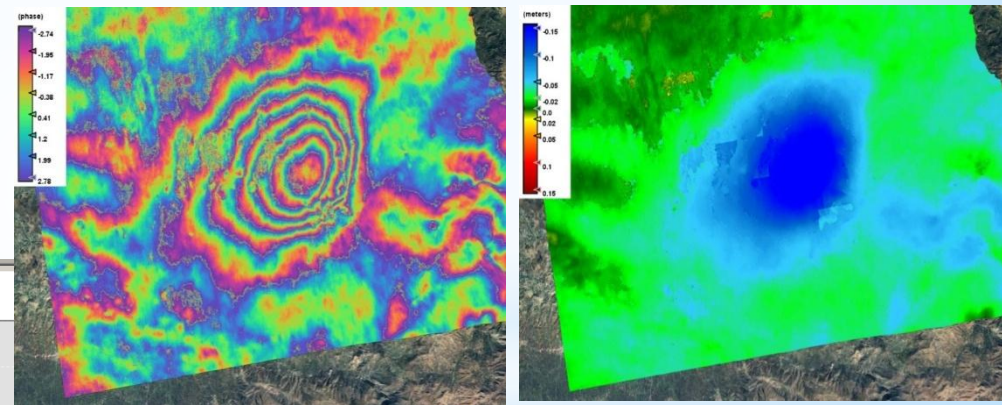
Mapping of the deformations of the earth's crust after the earthquake of September 27, 2021 on the island of Crete



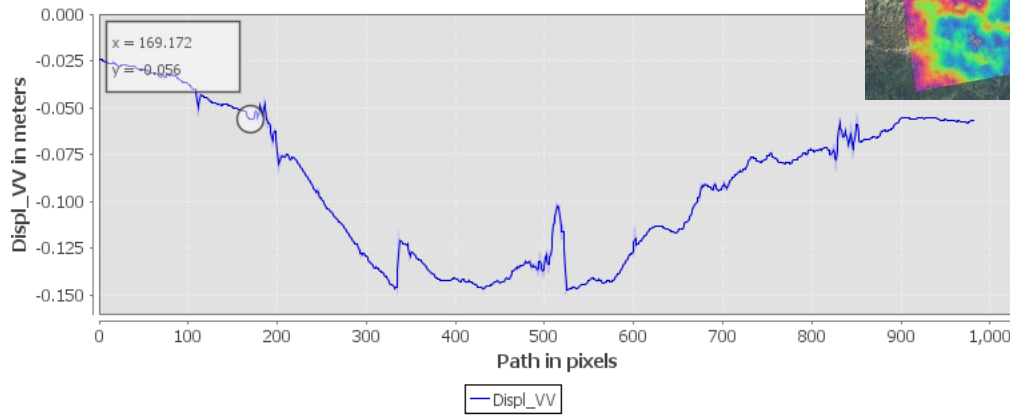
Descending orbits 36 orbit 19 Sep_01 Oct 2021



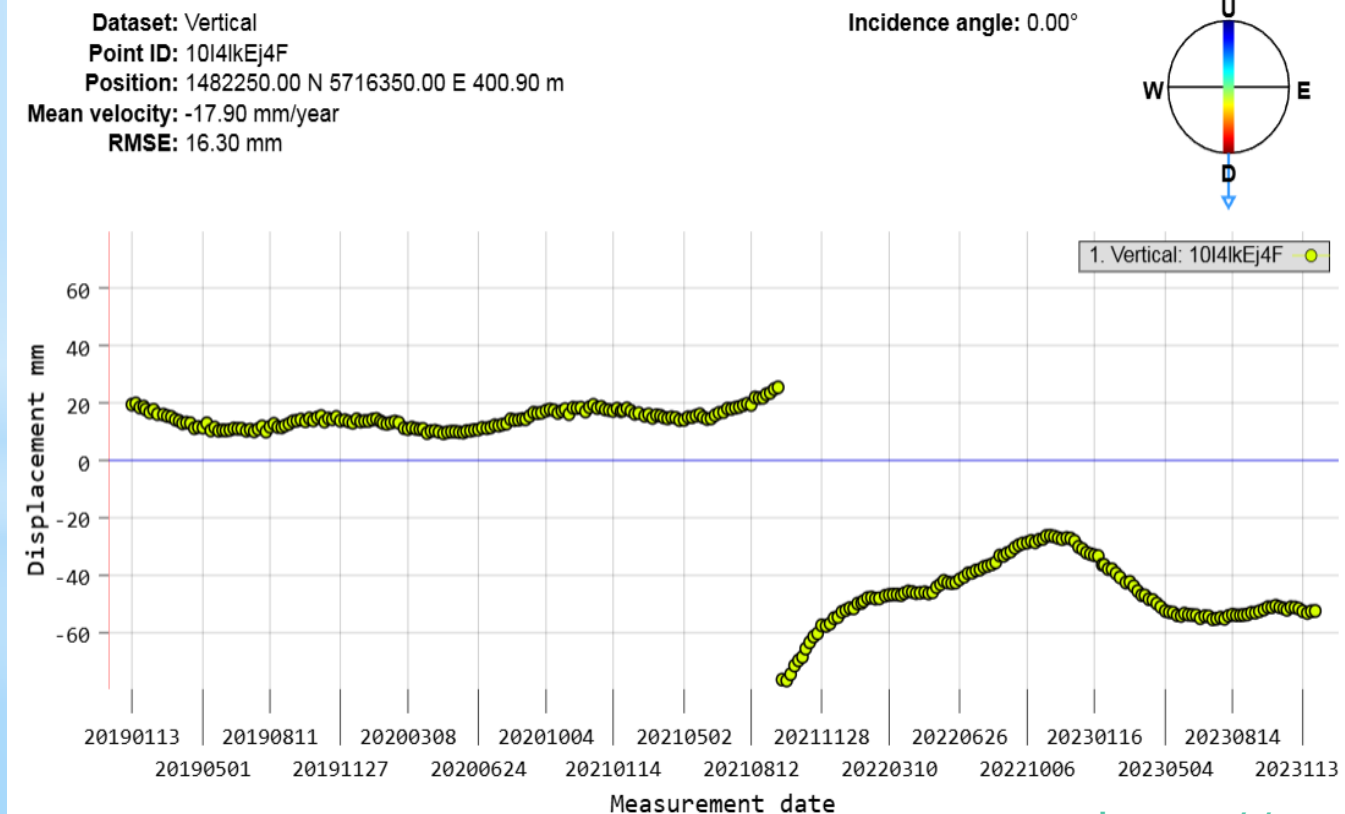
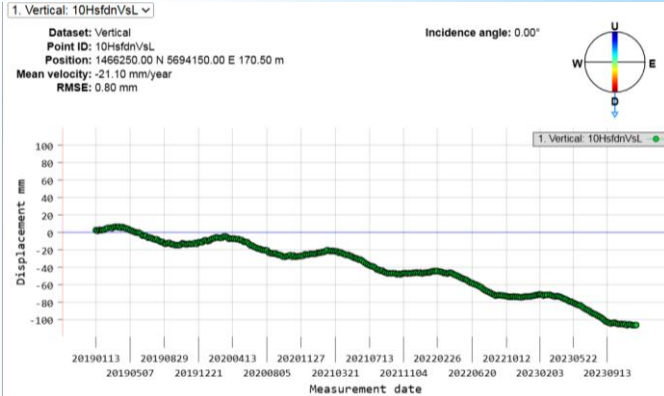
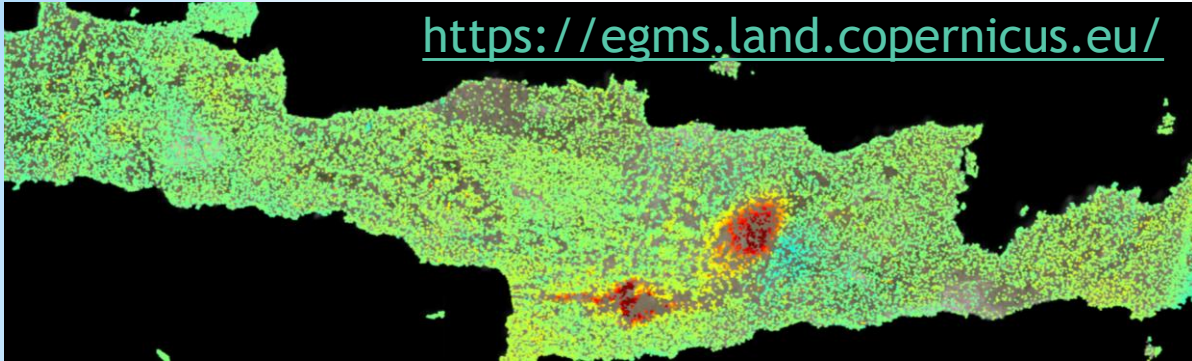
Ascending orbits 102 orbit 23 Sep_05 Oct 2021



Profile Plot for Displ_VV



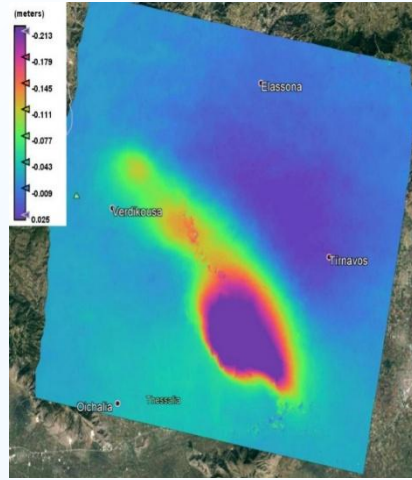
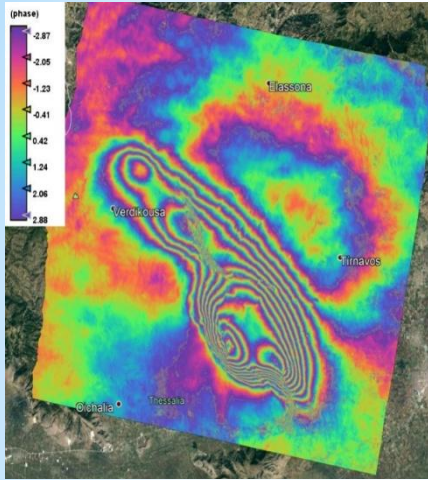
Vertical movement by MT-SAR for period 2019-2023 from EGMS



Determination of coseismic deformations of the earth's crust after the earthquake of March 3, 2021 for the Larissa Mw 6.3

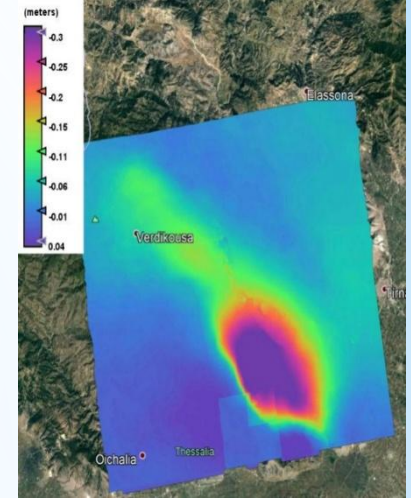
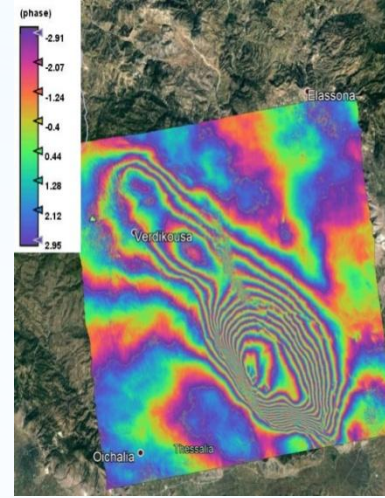
80 orbit

02-14 March

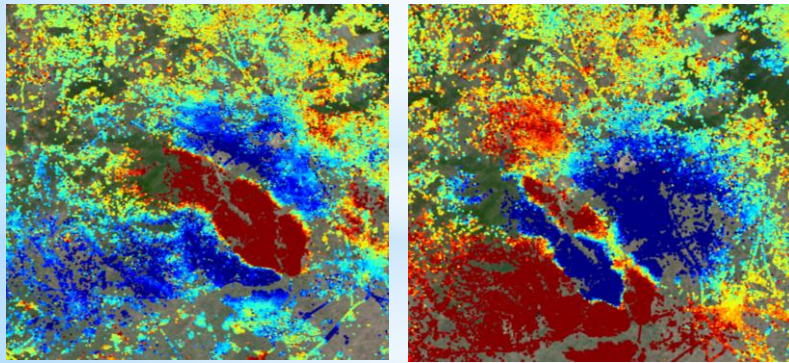


175 orbit

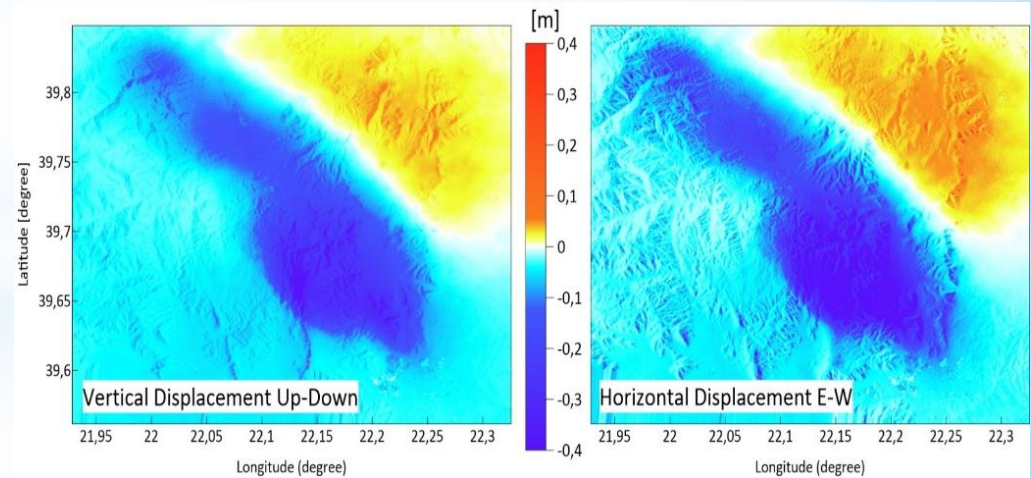
02-14 March



Vertical and East/West movement by EGMS for period 2019-2023



Legend across all datasets. Limits are in mm/year.

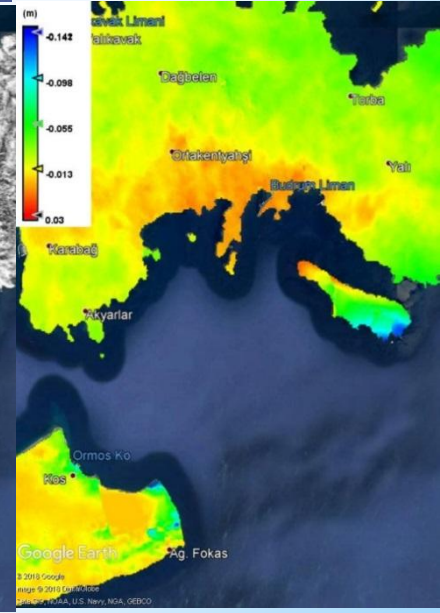
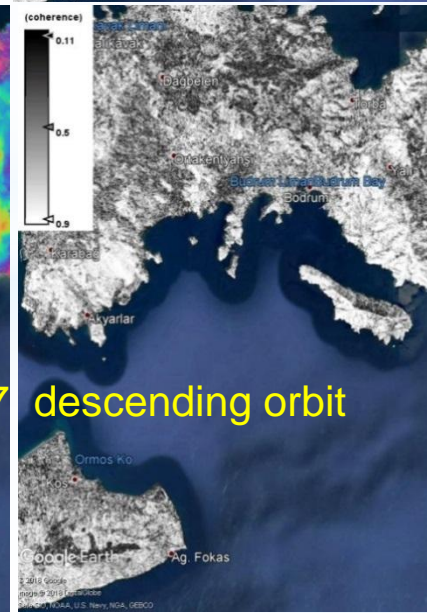
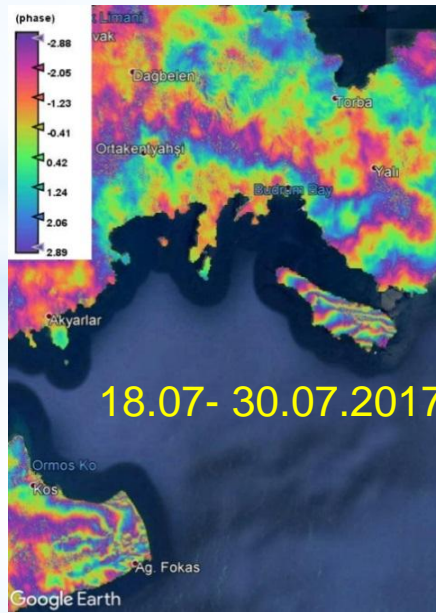
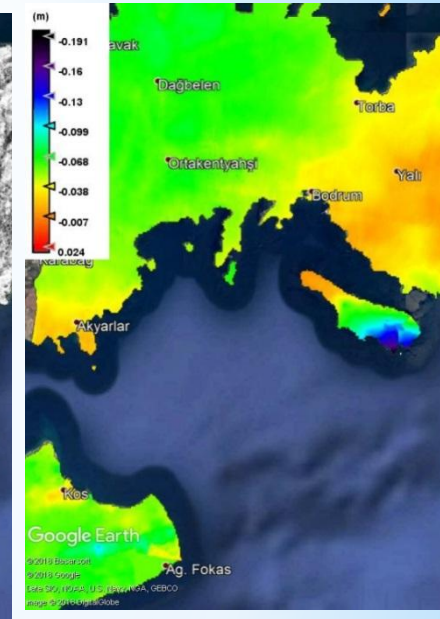
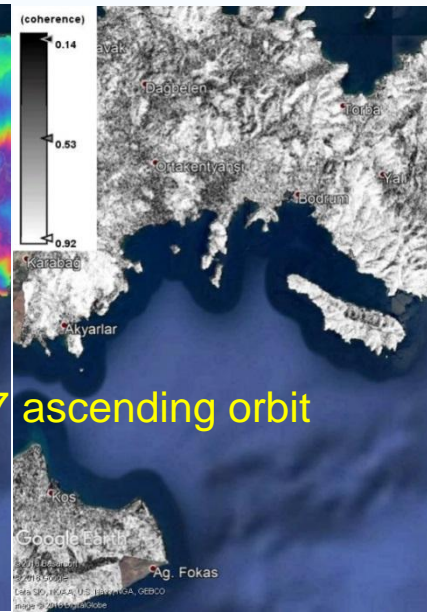
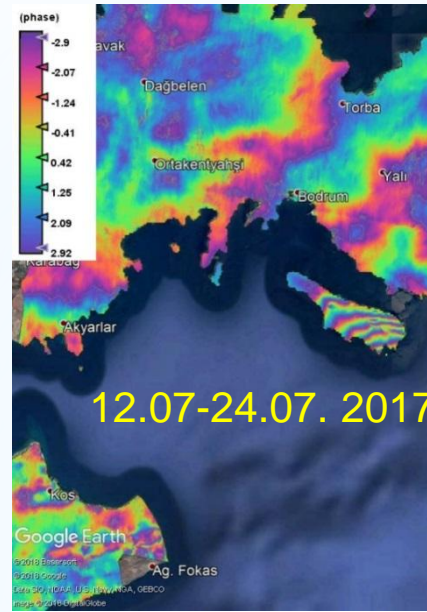


Coseismic displacement after Kos-Bodrum earthquake on July 20 2017, Mw 6.6

A) IF

B) Coherence

C) displacementLOS

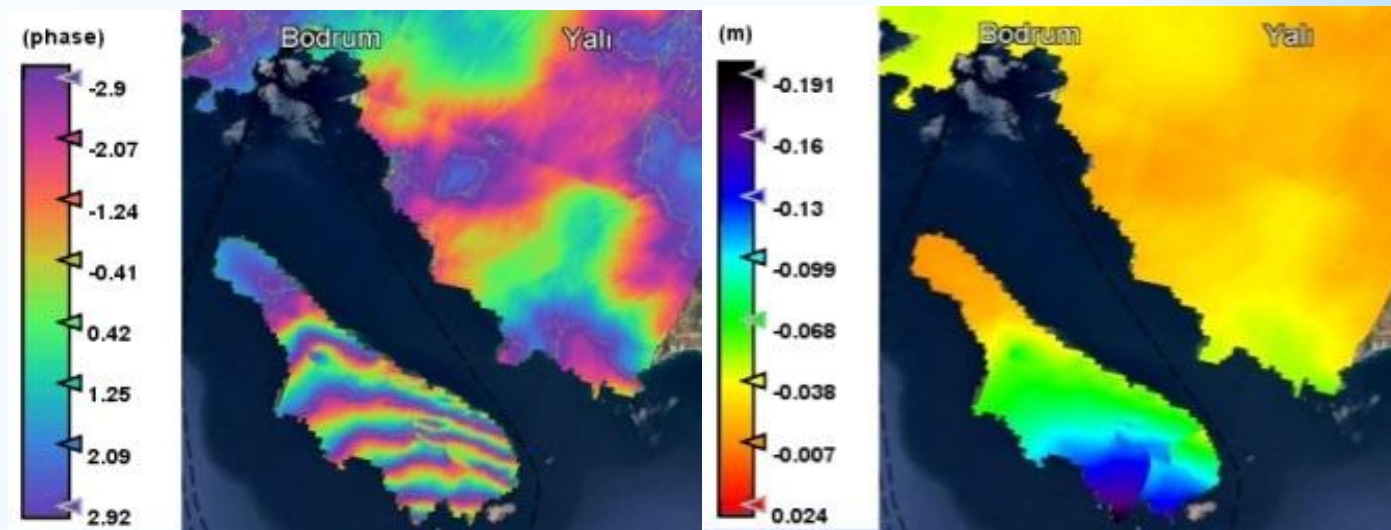


Epicenter and mechanism of the July 20, 2017 earthquake near the Kos island (<https://www.emsc-csem.org>)

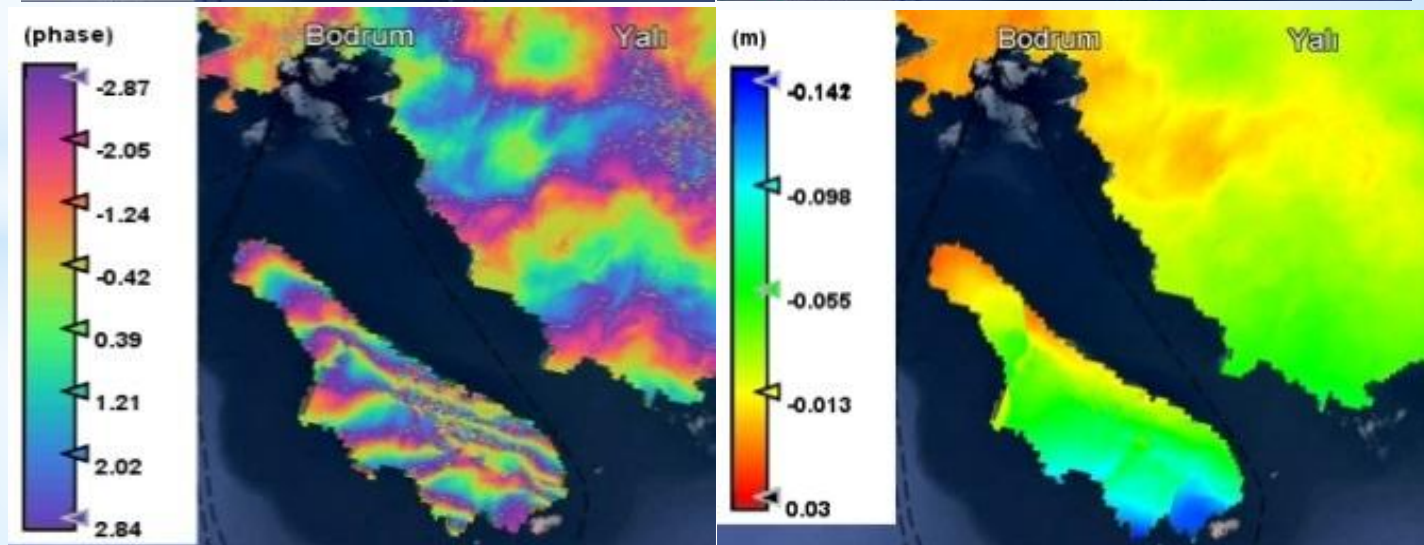
IF D	Orbit type/number	B_{perp} [m]	Modeled coherence
12.07.2017 – 24.07.2017	ascending orbit/ 131	33,24	0,96
18.07.2017 – 30.07.2017	descending orbit/ 36	5,51	0,98



12.07-24.07. 2017
ascending orbit



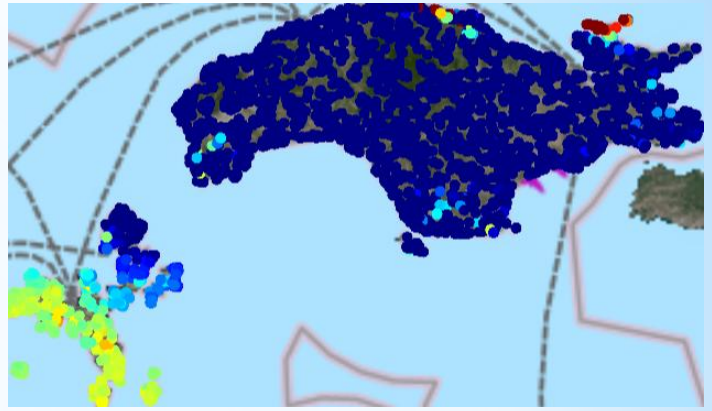
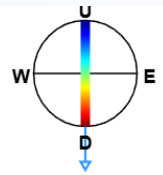
18.07-30.07.2017
descending orbit



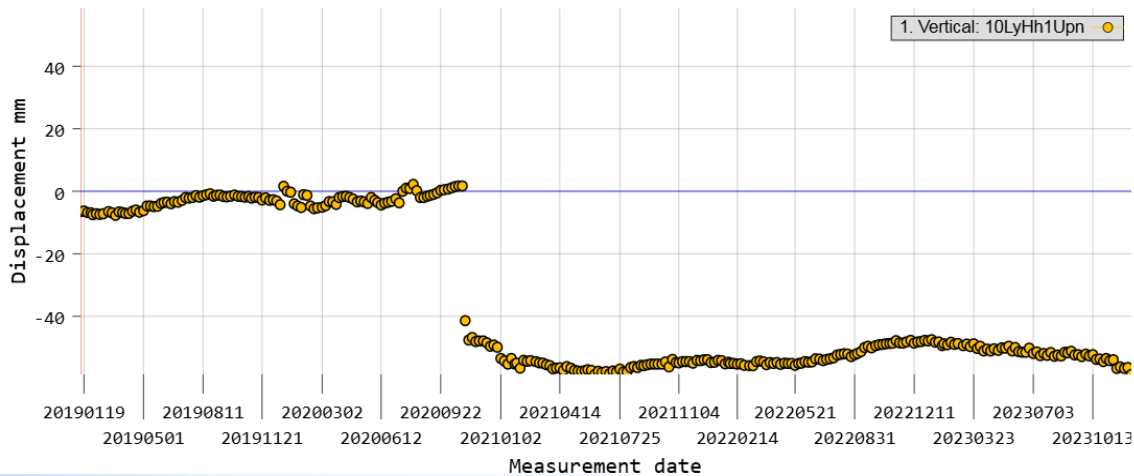
Coseismic displacement after Samos-Izmir Earthquake from 30 October 2020 Mw 7.0

Dataset: Vertical
Point ID: 10LyHh1Upn
Position: 1801650.00 N 5812350.00 E 0.80 m
Mean velocity: -13.90 mm/year
RMSE: 11.30 mm

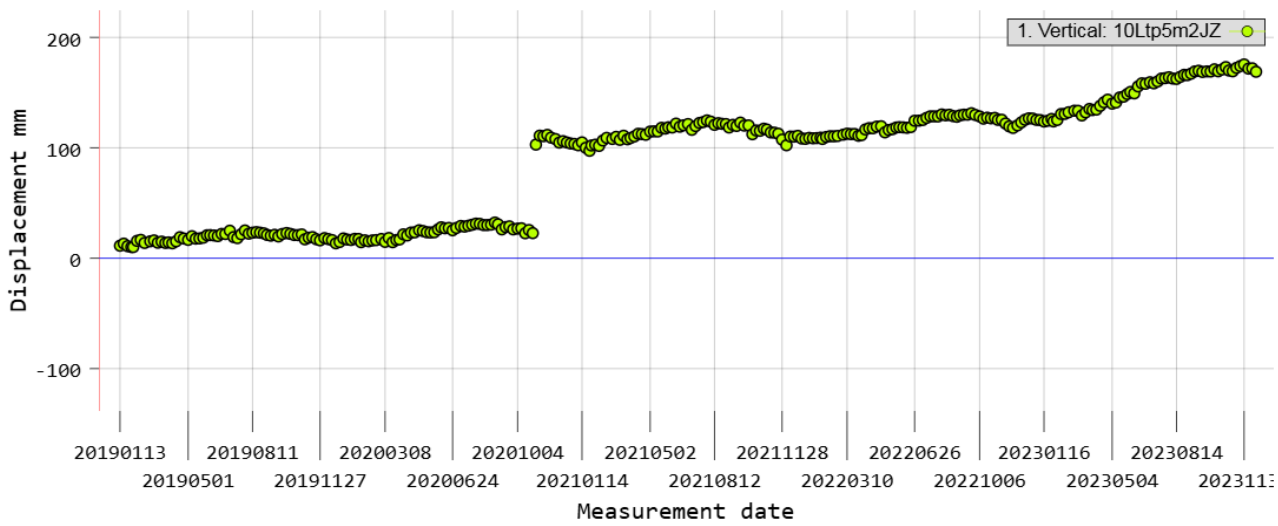
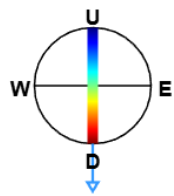
Incidence angle: 0.00°



<https://egms.land.copernicus.eu/>

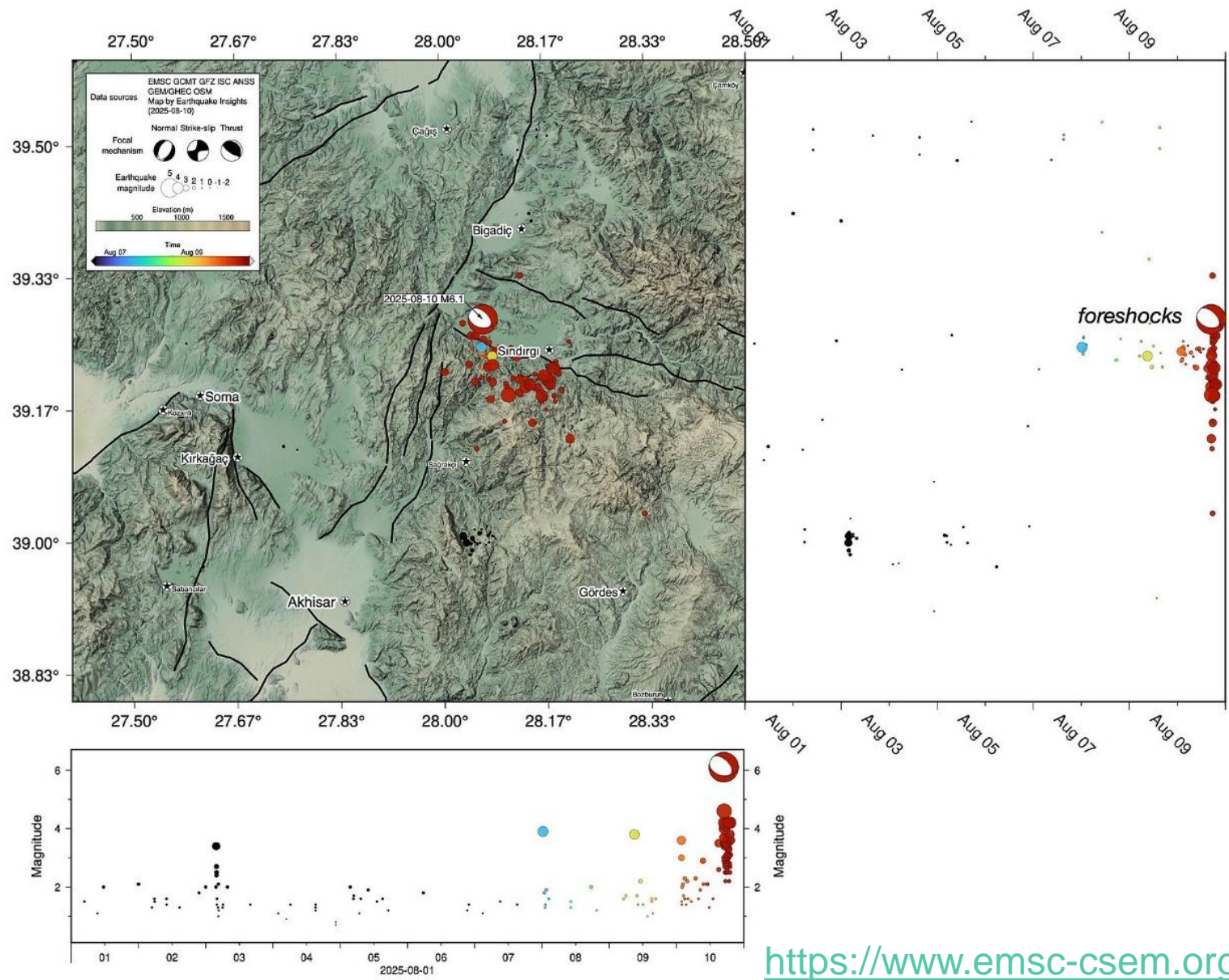


Incidence angle: 0.00°



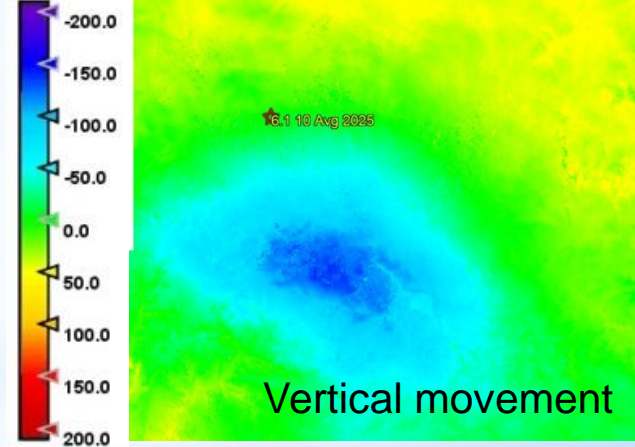
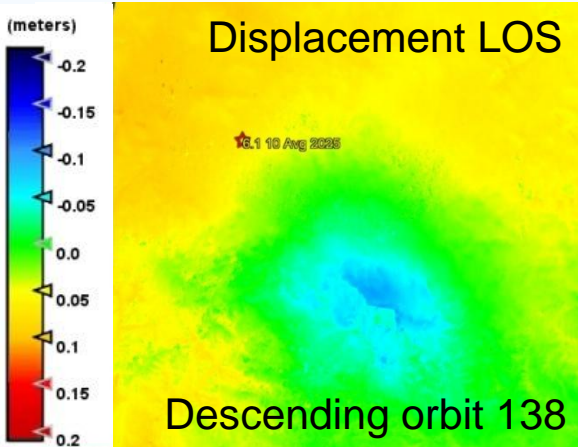
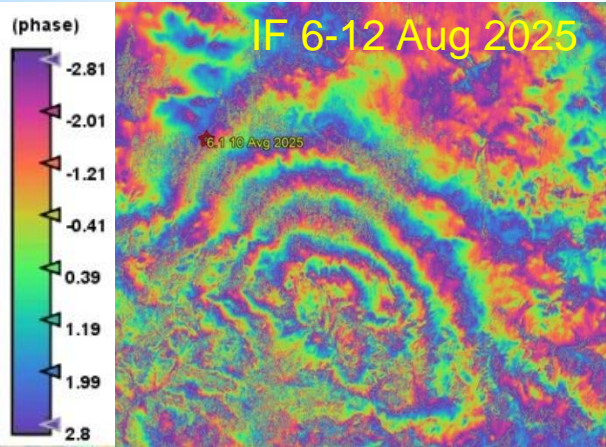
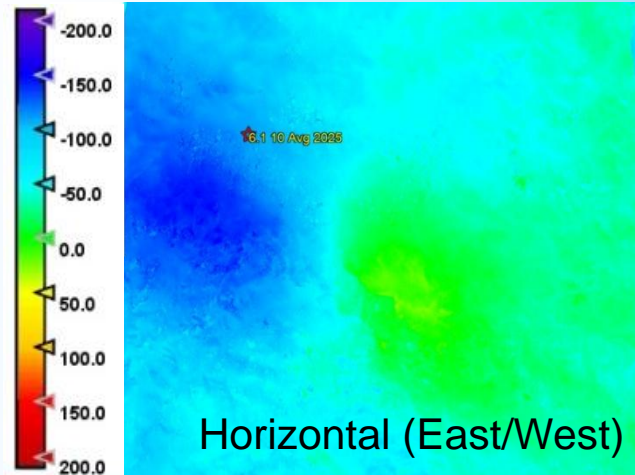
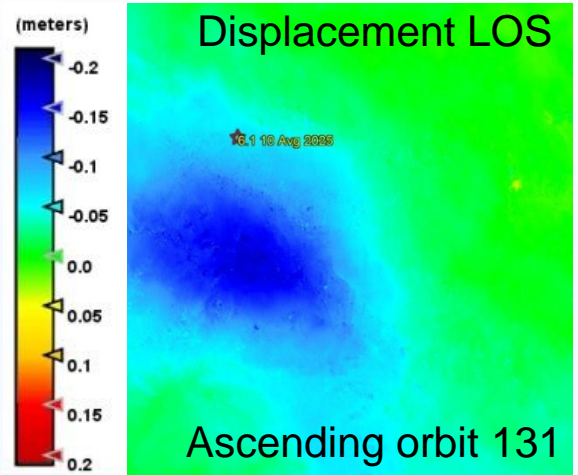
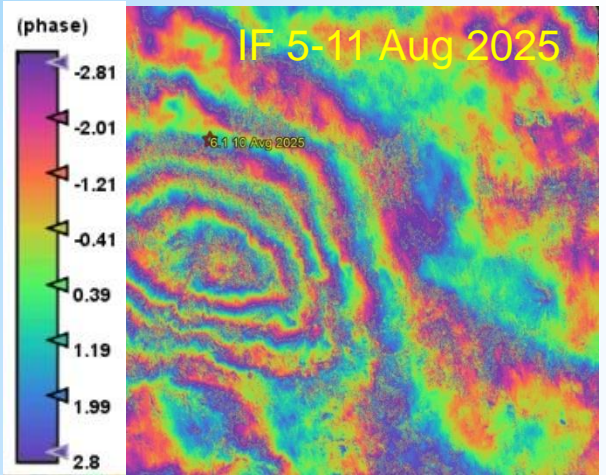
The Samos island is located in the eastern Aegean Sea, a well-known extensional terrain, as it is found on the back-arc area behind the Hellenic subduction.

Earthquake August 10 th 2025, Mw 6.1 Balıkesir



<https://www.emsc-csem.org/>

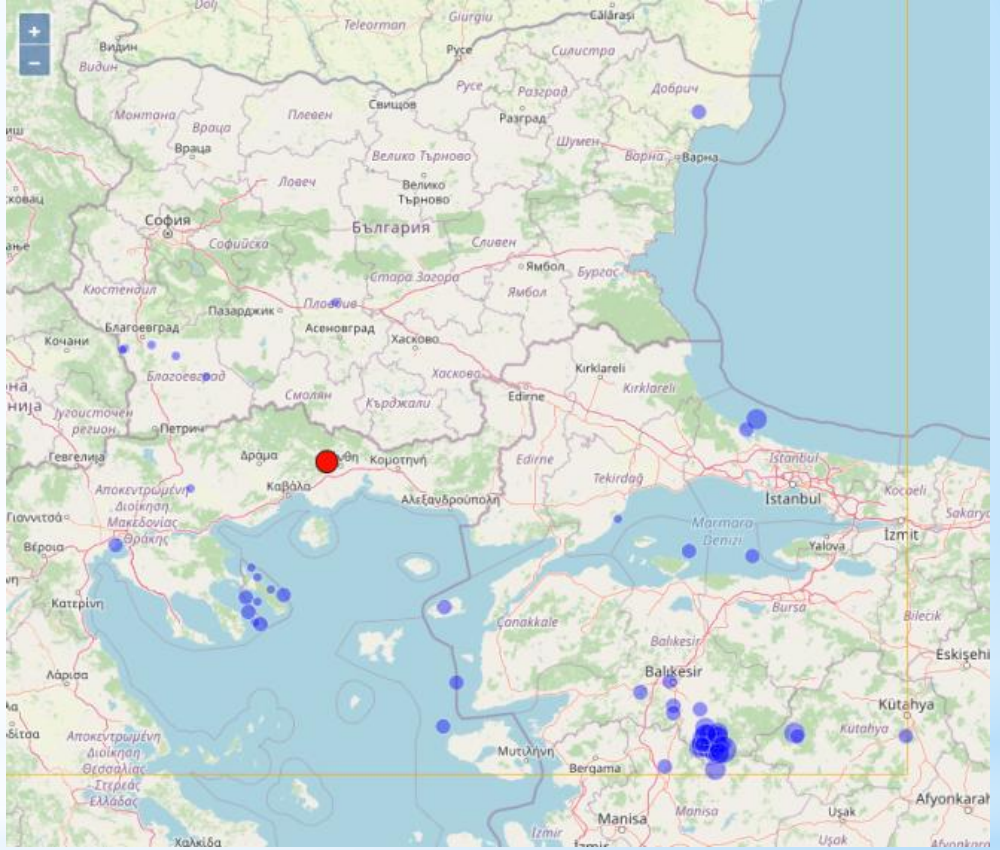
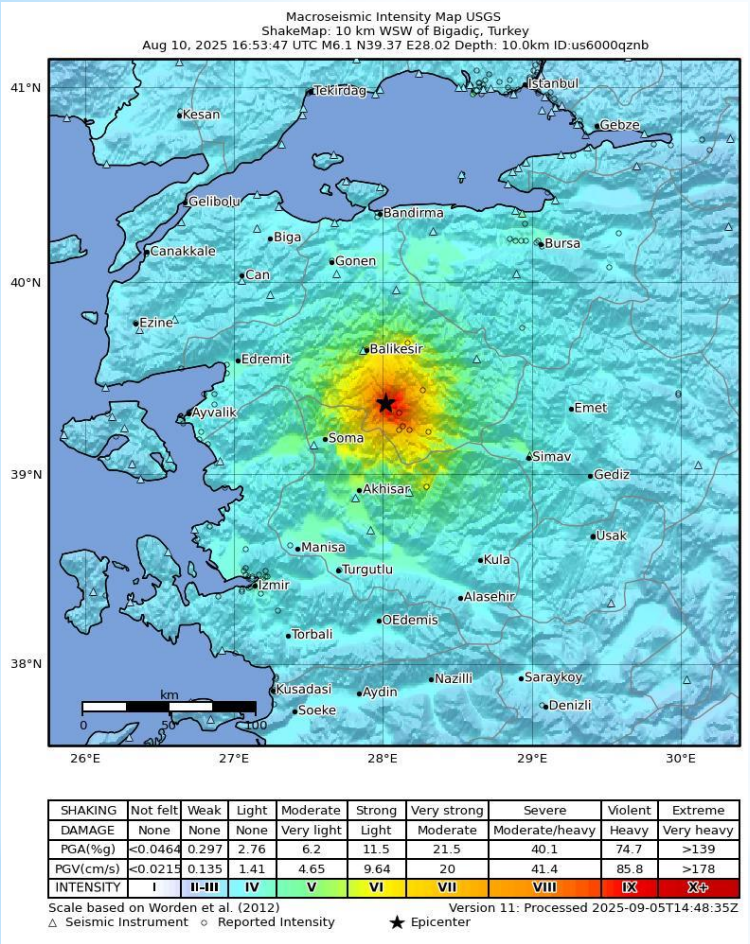
Coseismic displacement after earthquake Balıkesir (10.08.2025)



The latest strong earthquake with magnitude M 6.1, shook the northwestern Turkish province of Balıkesir, causing the collapse of dozens of buildings. We took the opportunity the next day from event to determine the size and extent of the areas affected by coseismic deformations.

Coseismic displacement after Earthquake Balıkesir

October 27 2025, Mw 6.0???



On 27 October, a Mw 6.0 event struck the same area on earthquake August 10 th 2025, Mw 6.1 Balıkesir and injuring 68 people

Conclusions

- The processing methodology applied made it possible to obtain interferograms that visually represent the displacements around the epicenters.
- SAR data were used to obtain information indicating the actual surface displacements.
- The presented examples demonstrate the application of Earth observation satellite technologies, such as InSAR, for the study and monitoring of the seismogenic zones of the Balkan Peninsula and Aegean Sea region, emphasizing their importance and advantages in establishing regularities in the movements in these zones.
- The good correspondence between the InSAR maps and regional tectonics shows that the SAR method is a reliable and very useful source of information. Its advantage is that this information is obtained for large areas and in a relatively short time after the event, which helps in the preparation of maps for overcoming its consequences and updating plans for preparing for future strong events in the same area.
- Приложената методология на обработка позволи получаването на интерферограми, които визуално представят преместванията около епицентровете.
- Данните от SAR бяха използвани за получаване на информация, показваща действителните повърхностни премествания.
- Представените примери демонстрират приложението на технологиите за спътниково наблюдение на Земята, като InSAR, за изучаване и мониторинг на сеизмогенните зони на Балканския полуостров и региона на Егейско море, като се подчертава тяхното значение и предимства при установяване на закономерности в движенията в тези зони.
- Доброто съответствие между InSAR картите и регионалната тектоника показва, че методът SAR е надежден и много полезен източник на информация. Неговото предимство е, че тази информация се получава за големи площи и в относително кратко време след събитието, което помага при изготвянето на карти за преодоляване на неговите последици и актуализиране на плановете за подготовка при бъдещи силни събития в същия район

Благодаря за вниманието !



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