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InSAR satellite data - application for seismic sources in the Balkan Peninsula

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Outline

- Introduction

✓InSAR technique applied for recent **M6+ earthquakes** in the region of Southeast Europe including Greece and Turkey.

- Methods and Data

✓ SAR satellite images from Sentinel-1A and 1B
✓ SNAP software package
✓ Differential radar interferometry method (**DInSAR**).

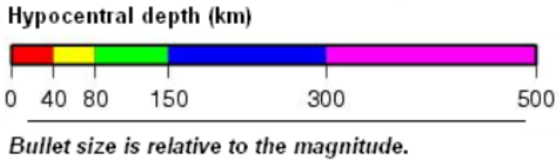
- Results

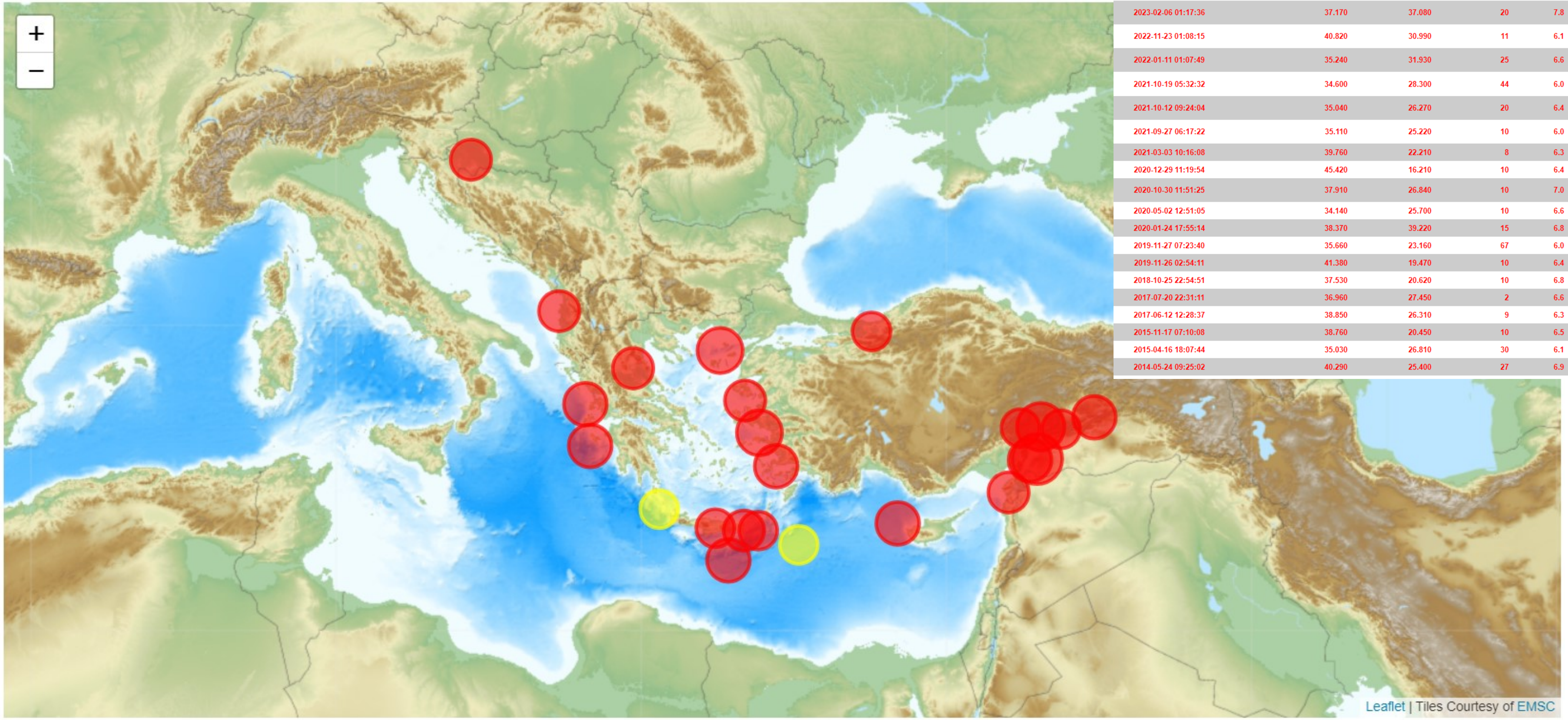
✓ Interferograms and deformation maps are built for several earthquakes in the Balkan Peninsula region:
Croatia 2020, Greece 2021, Türkiye and Syria 2023

- Conclusions

Introduction

M6+ 2014 - 2023





Date & Time UTC	Lat. degrees	Lon. degrees	Depth km	Mag. [+]	Region
2023-02-20 17:04:29	36.160	36.020	10	6.3	TURKEY-SYRIA BORDER REGION
2023-02-06 12:02:11	38.070	36.470	5	6.0	CENTRAL TURKEY
2023-02-06 10:26:48	38.030	37.960	20	6.0	CENTRAL TURKEY
2023-02-06 10:24:49	38.110	37.240	10	7.5	CENTRAL TURKEY
2023-02-06 01:28:17	37.130	36.810	10	6.7	CENTRAL TURKEY
2023-02-06 01:17:36	37.170	37.080	20	7.8	CENTRAL TURKEY
2022-11-23 01:08:15	40.820	30.990	11	6.1	WESTERN TURKEY
2022-01-11 01:07:49	35.240	31.930	25	6.6	CYPRUS REGION
2021-10-19 05:32:32	34.600	28.300	44	6.0	EASTERN MEDITERRANEAN SEA
2021-10-12 09:24:04	35.040	26.270	20	6.4	CRETE, GREECE
2021-09-27 06:17:22	35.110	25.220	10	6.0	CRETE, GREECE
2021-03-03 10:16:08	39.760	22.210	8	6.3	GREECE
2020-12-29 11:19:54	45.420	16.210	10	6.4	CROATIA
2020-10-30 11:51:25	37.910	26.840	10	7.0	DODECANESE ISLANDS, GREECE
2020-05-02 12:51:05	34.140	25.700	10	6.6	CRETE, GREECE
2020-01-24 17:55:14	38.370	39.220	15	6.8	EASTERN TURKEY
2019-11-27 07:23:40	35.660	23.160	67	6.0	CRETE, GREECE
2019-11-26 02:54:11	41.380	19.470	10	6.4	ALBANIA
2018-10-25 22:54:51	37.530	20.620	10	6.8	IONIAN SEA
2017-07-20 22:31:11	36.960	27.450	2	6.6	DODECANESE IS.-TURKEY BORDER REG
2017-06-12 12:28:37	38.850	26.310	9	6.3	NEAR THE COAST OF WESTERN TURKEY
2015-11-17 07:10:08	38.760	20.450	10	6.5	GREECE
2015-04-16 18:07:44	35.030	26.810	30	6.1	CRETE, GREECE
2014-05-24 09:25:02	40.290	25.400	27	6.9	AEGEAN SEA

Introduction

The 2020 Croatia earthquake

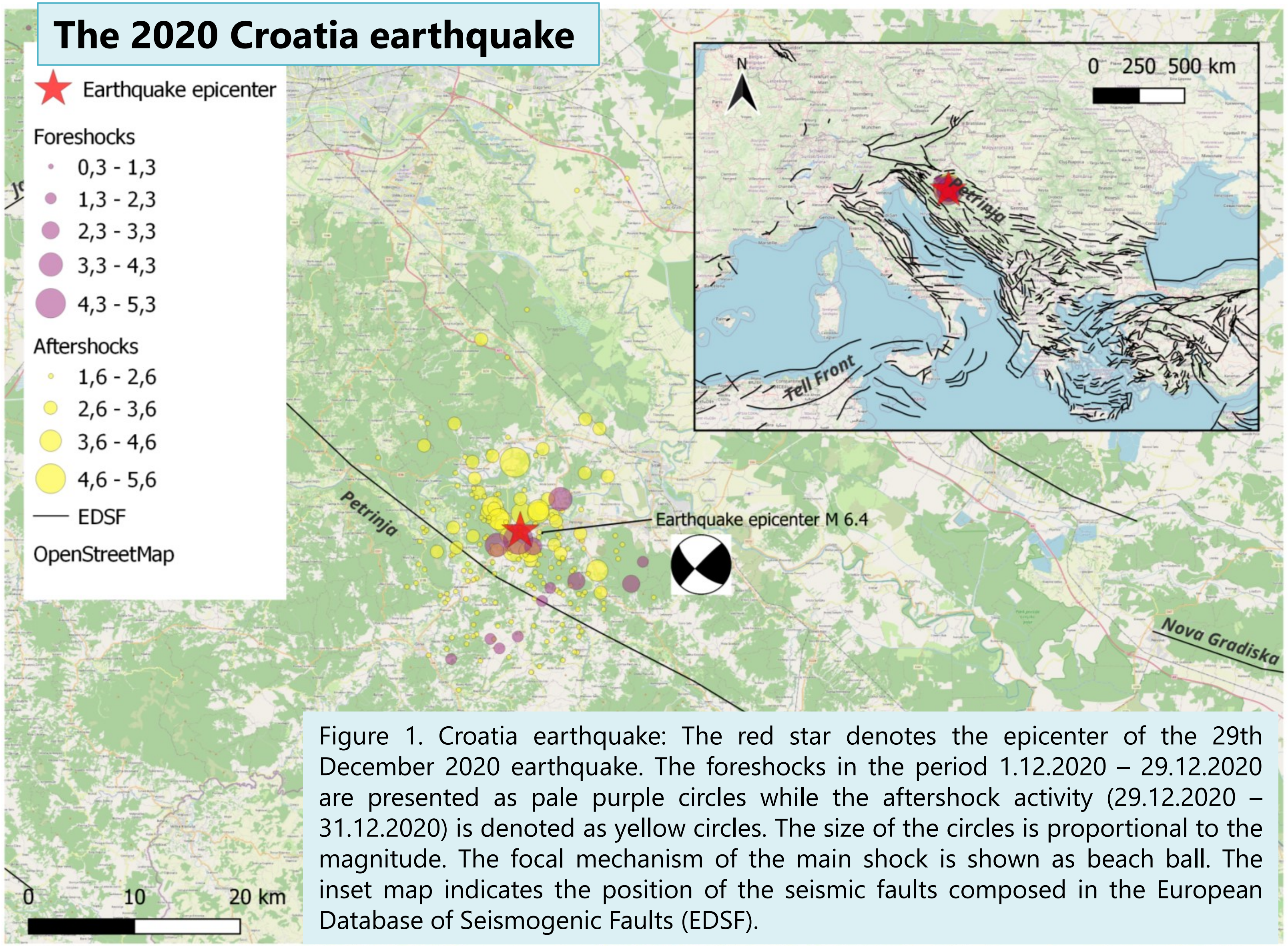


Figure 1. Croatia earthquake: The red star denotes the epicenter of the 29th December 2020 earthquake. The foreshocks in the period 1.12.2020 – 29.12.2020 are presented as pale purple circles while the aftershock activity (29.12.2020 – 31.12.2020) is denoted as yellow circles. The size of the circles is proportional to the magnitude. The focal mechanism of the main shock is shown as beach ball. The inset map indicates the position of the seismic faults composed in the European Database of Seismogenic Faults (EDSF).

The destructive 2020 earthquake in Croatia was an earthquake, measuring **6.4 on the moment magnitude scale**, hit Croatia on 29th December 2020 at 12:19 local time. Its epicenter (45.42 N, 16.12 E) was located near the village of Strašnik, approximately 6 km southwest of Petrinja and 65 km south-southeast of Zagreb with estimated hypocentral depth of 4 km. This is **the largest earthquake in Croatia** since the epoch of the modern seismic instruments. Similar size earthquake occurred in 1880 near Zagreb and three more large earthquakes (M>6) hit the region within a radius of 200 km from the December 2020 earthquake epicenter since 1900. The main shock and most of the aftershock seismicity are located on the **Petrinja composite seismogenic fault** that is well described in the European Database of Seismogenic Faults (EDSF) and denoted as HRCS027. The focal mechanism suggested by MedNet Regional Centroid - Moment Tensors (INGV) is depicted as beach ball and represents almost pure **strike-slip movements** (Figure 1).

Introduction

The 2021 Greece earthquake

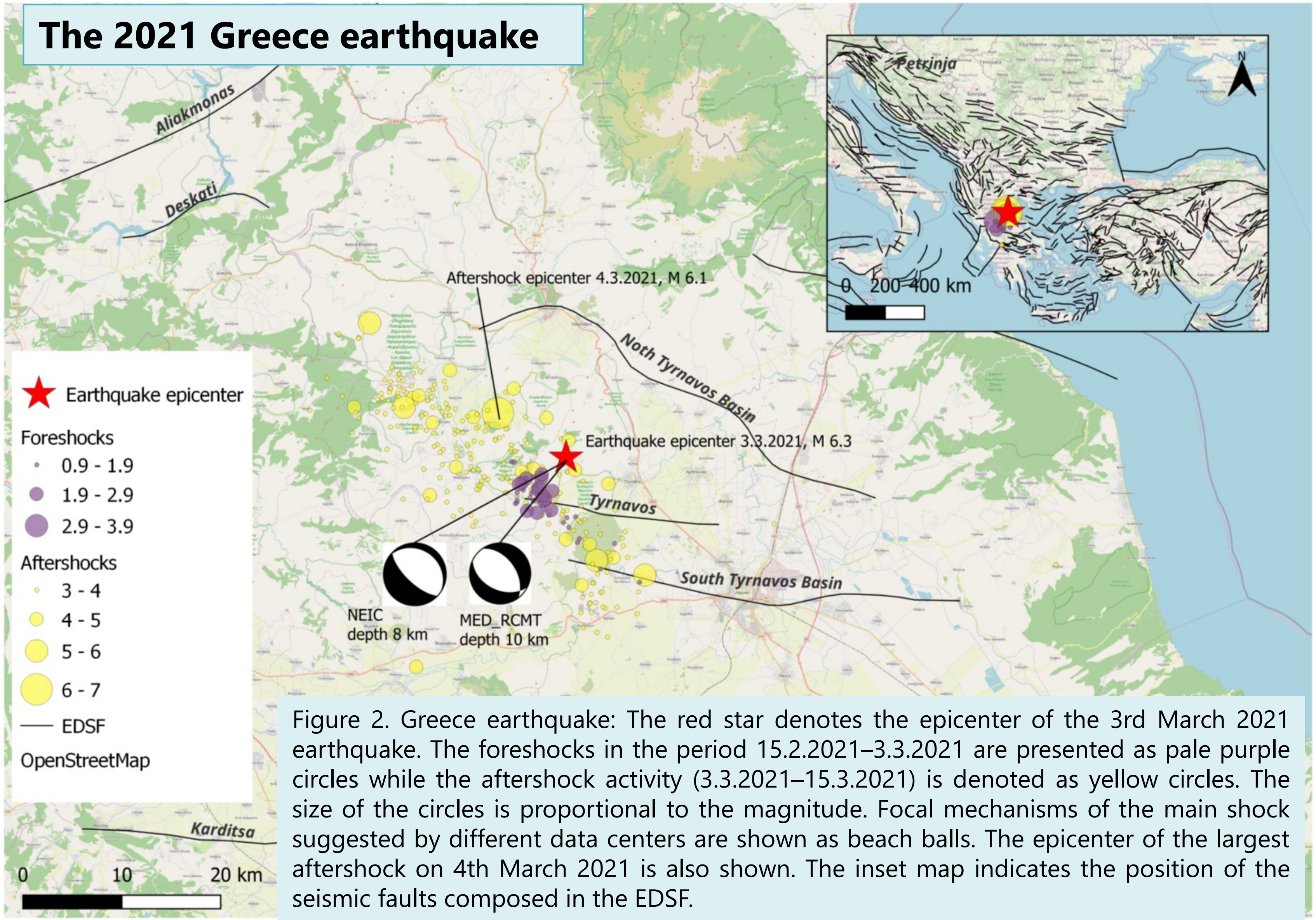


Figure 2. Greece earthquake: The red star denotes the epicenter of the 3rd March 2021 earthquake. The foreshocks in the period 15.2.2021–3.3.2021 are presented as pale purple circles while the aftershock activity (3.3.2021–15.3.2021) is denoted as yellow circles. The size of the circles is proportional to the magnitude. Focal mechanisms of the main shock suggested by different data centers are shown as beach balls. The epicenter of the largest aftershock on 4th March 2021 is also shown. The inset map indicates the position of the seismic faults composed in the EDSF.

The earthquake of March 3, 2021 (**M_w6.3**) in central Greece, also known as **Larissa earthquake** shook the country at 12:16 local time (Fig. 2). The epicenter (39.7884 N, 22.1913 E) is located 22 km west-northwest of Larissa, where the population is approximately 144 000, and 7 km west of Tyrnavos. The hypocenter is situated at a depth of 8 km. On March 4, 2021, at 20:38 local time another similar event with tremor magnitude (M_w6.1) took place approximately 29 km NW of Larissa. Many aftershocks were triggered, including an event of Mw5.6, which occurred on 12th March and initiated further damage to structures. According to the EDSF the main earthquake`s epicenter is situated on the **Tyrnavos fault** with annual slip rate in the range between 0.05 – 0.4 mm/y. Two focal mechanisms of the main shock, suggested by two data centers are visualized in Figure 2 to show the differences in calculating the mechanism of the earthquake generation.

Introduction

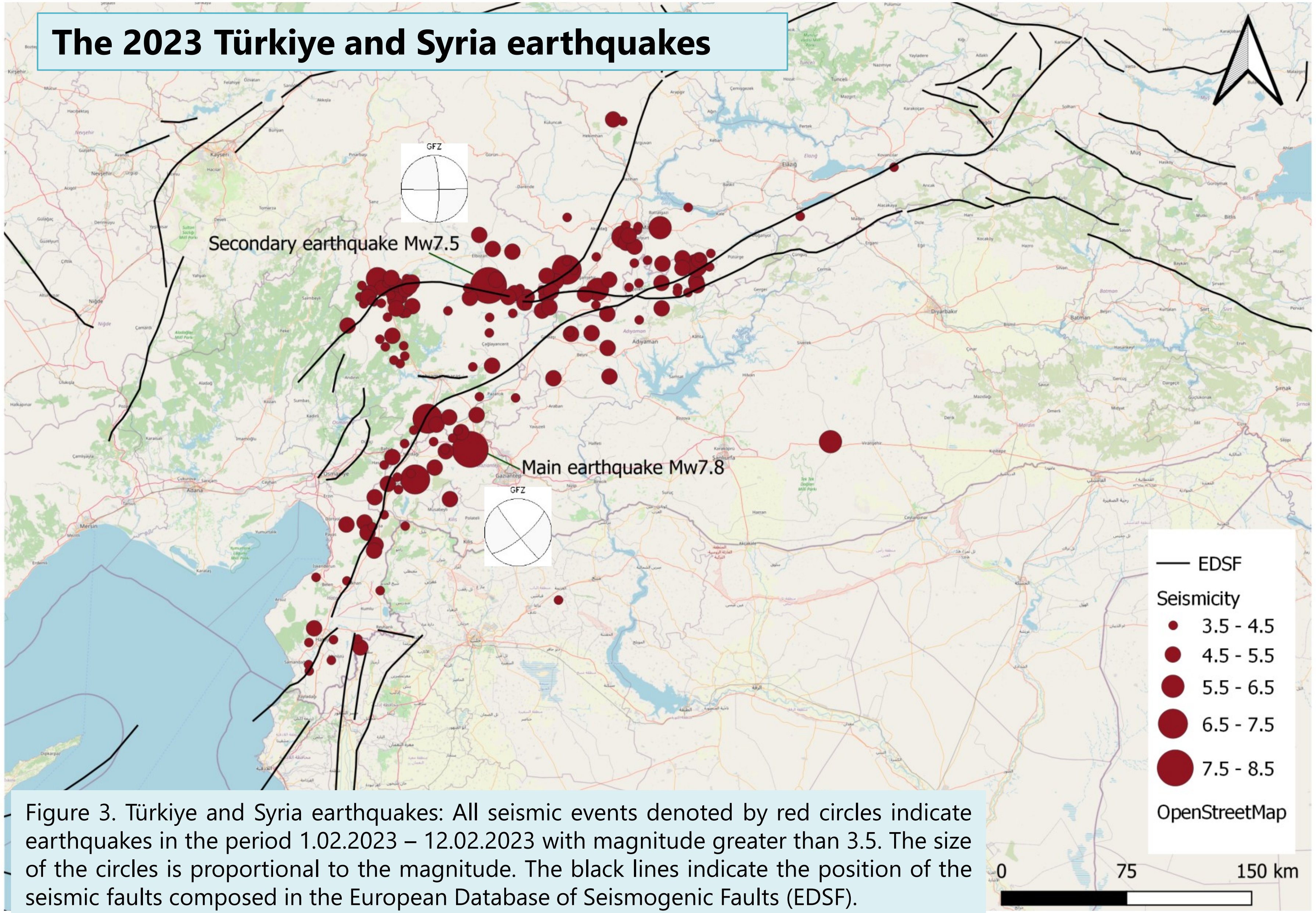


Figure 3. Türkiye and Syria earthquakes: All seismic events denoted by red circles indicate earthquakes in the period 1.02.2023 – 12.02.2023 with magnitude greater than 3.5. The size of the circles is proportional to the magnitude. The black lines indicate the position of the seismic faults composed in the European Database of Seismogenic Faults (EDSF).

Devastating earthquake struck southern and central Türkiye, as well as northern and western Syria on February 6th, 2023 at 01:17 UTC. The estimated moment magnitude is **M_w7.8** and the **maximum Mercalli intensity of XI**, which refers to extreme scale level. The earthquake hypocenter was at a depth of 17.9 km according to USGS and 5 km according to KOERI. The epicenter is located 34 km west of Gaziantep and close to the border with Syria. Another strong earthquake (M_w7.5) occurred nine hours later near the province Kahramanmaraş. According to GEOSCOPE it had a depth of 13 km, according to KOERI of 5 km. Both of the earthquakes epicenters and suggested focal mechanisms from GFZ are shown in Fig. 3. EAF and Dead Sea Transform Fault are crossing near the epicenter of the main shock.

Methods and Data

The **main objective** of this study is to **obtain interferograms** and **deformation maps** for several earthquakes in the region of the Balkan Peninsula including the devastating earthquakes in Türkiye and Syria 2023.

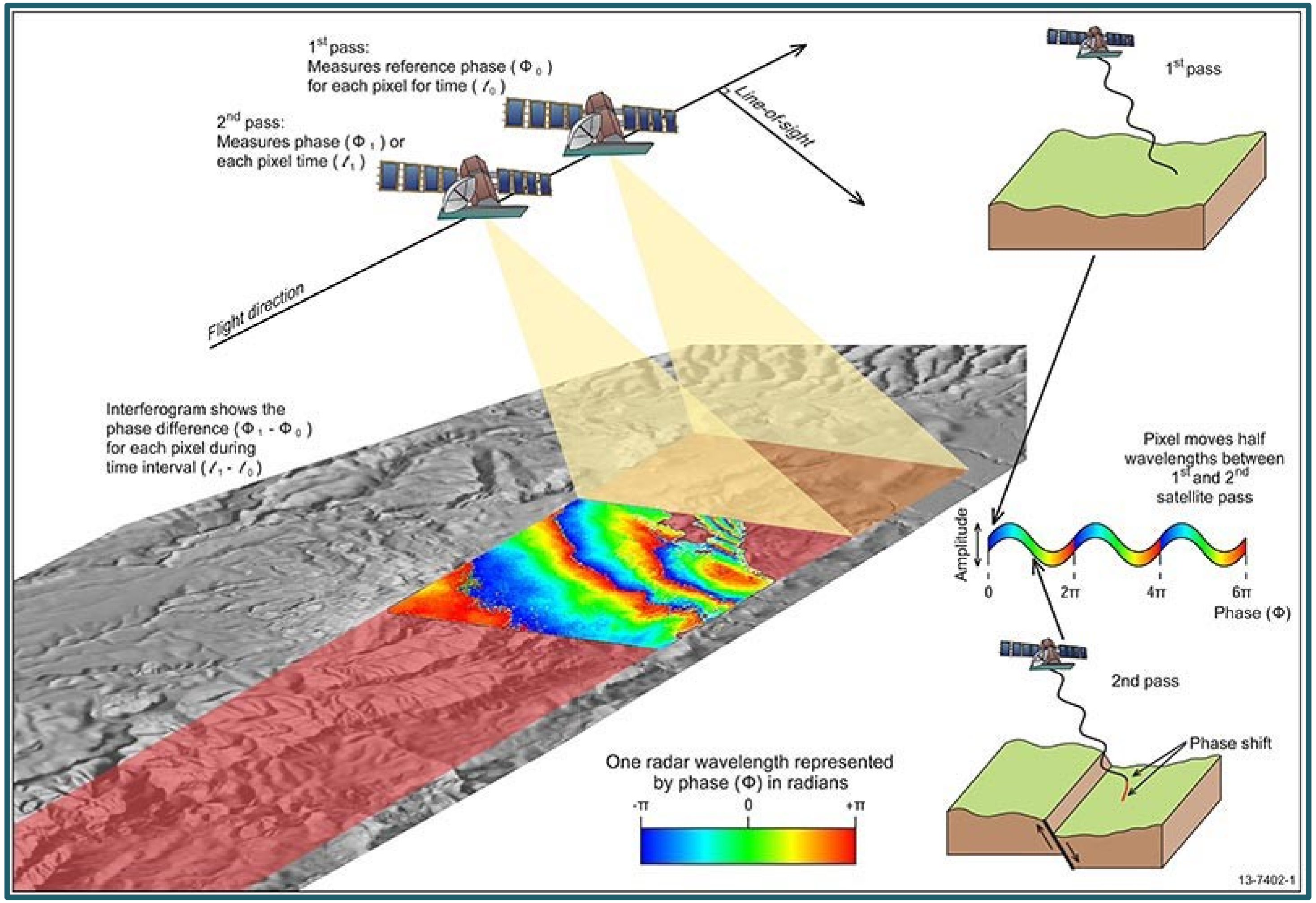


Figure 4. Two SAR images of the same area are acquired at different times. from: (https://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/geodetic-techniques/interferometric-synthetic-aperture-radar)

In order to do that we collected **SAR satellite images** which cover as short period as possible before and after a given earthquake (Figure 4).

The data from Sentinel-1 is available via the open access hub at: https://scihub.copernicus.eu/.

Sentinel-1A was launched on 3 April 2014 and still in orbit, while Sentinel-1B (launched on 25 April 2016) does not provide data due to a power issue since 23 December 2021 and the mission end was announced in August 2022.

The software product for processing the data is SNAP (freely distributed by ESA).

https://eo4society.esa.int/resources/snap/

Methods and Data

In order to create an interferogram a pair of two radar images must be processed. Using the flow chart shown in Figure 5 the process of generation of interferogram and afterwards the displacements in SNAP is divided into 4 steps.

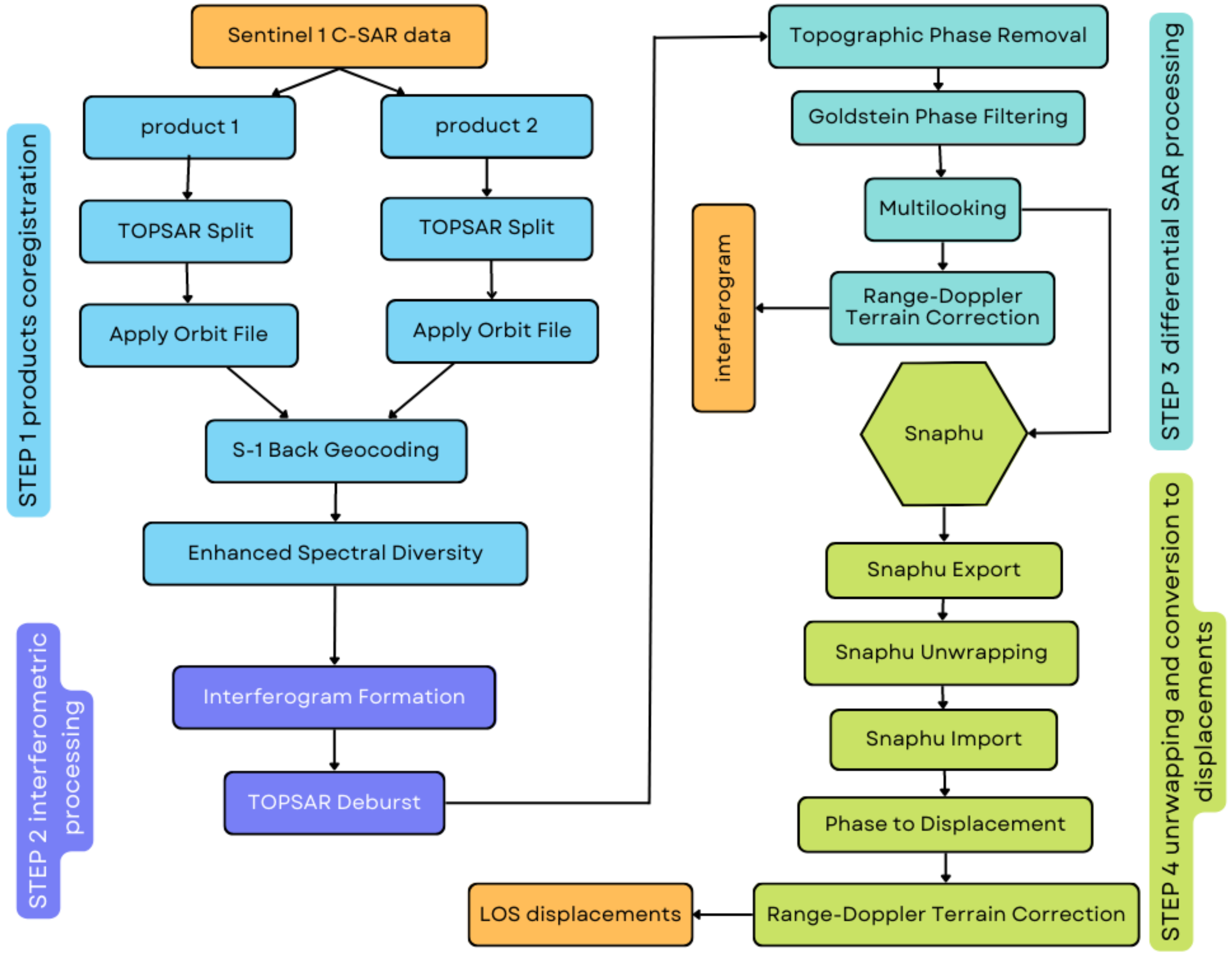


Figure 5. Flow chart of the data processing using SNAP software (Dimova & Raykova, 2023).

The vertical and horizontal displacements are calculated via the formulas below and after combining the computed Line-of-Sight (LoS) displacements from the ascending and descending orbits.

$$Displacement_{up-down} = \frac{Displacement_{LoS}}{\cos \theta_{incident}} \qquad Displacement_{E-W} = \frac{Displacement_{LoS}}{\sin \theta_{incident}}$$

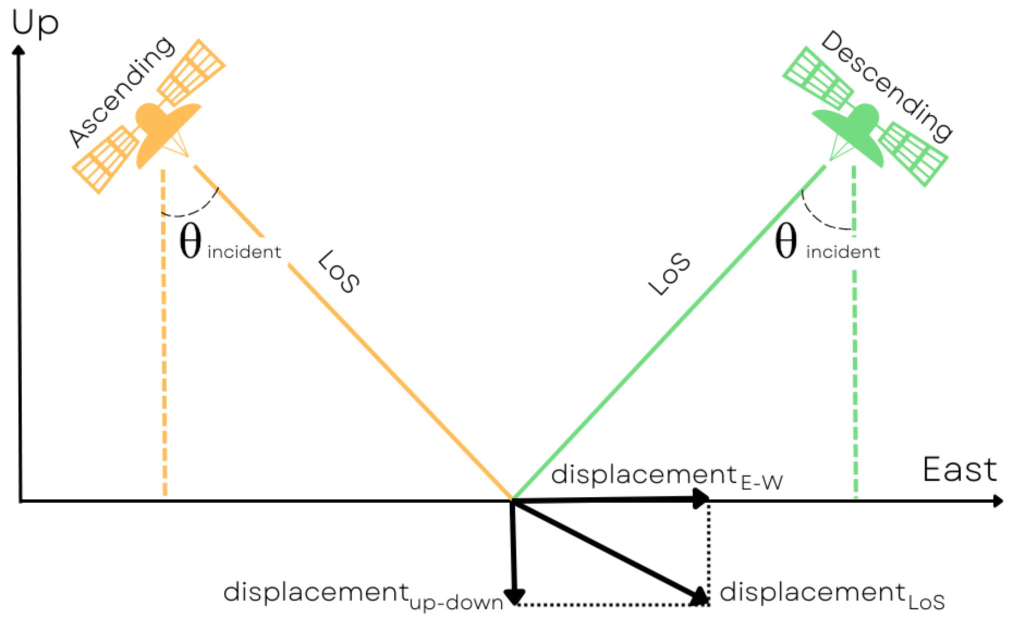
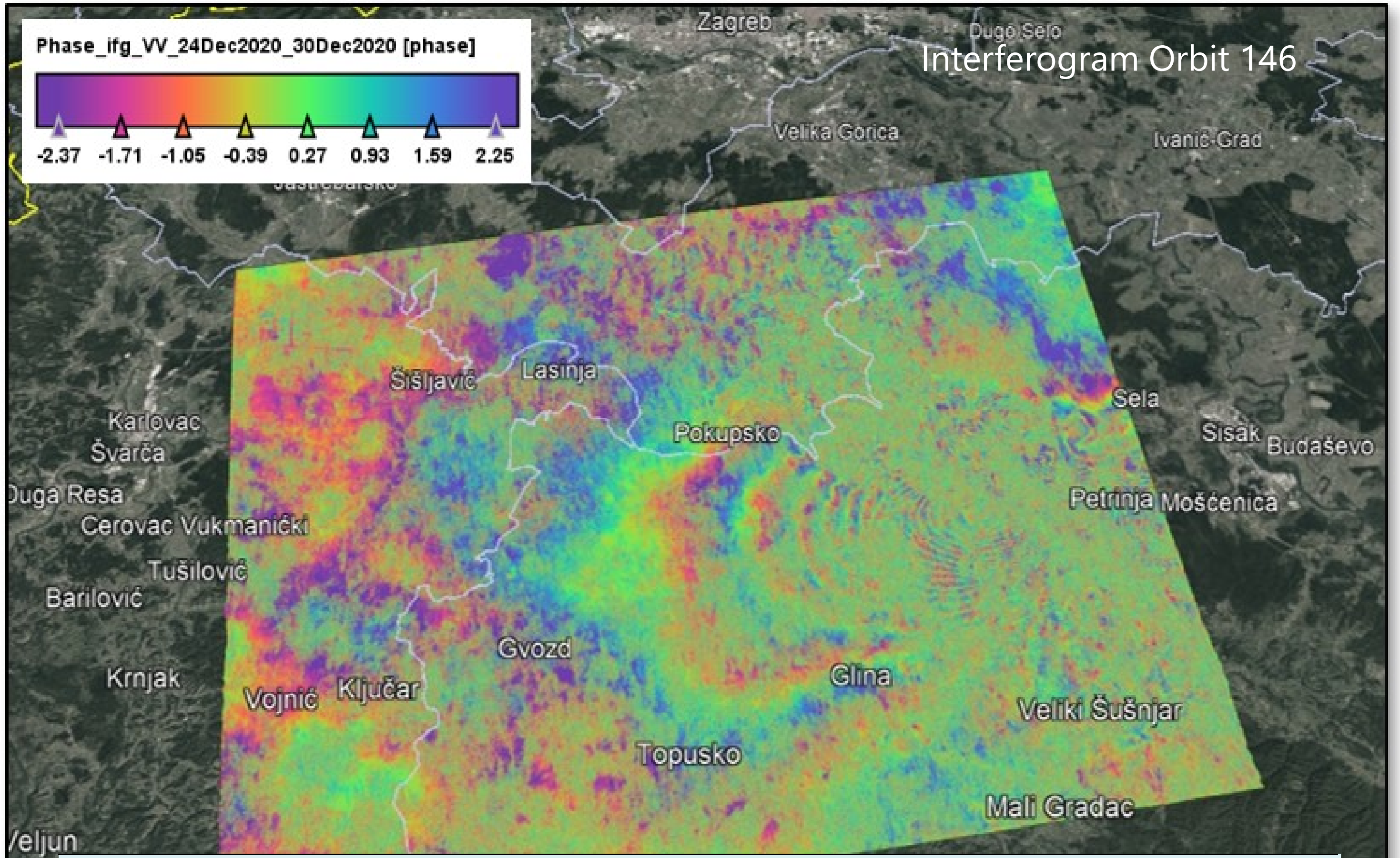
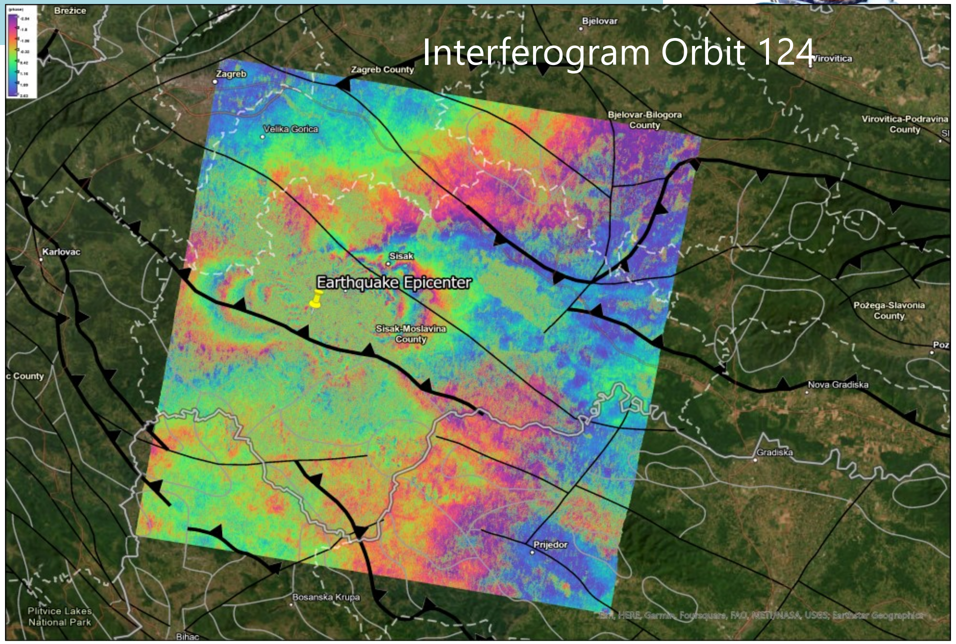


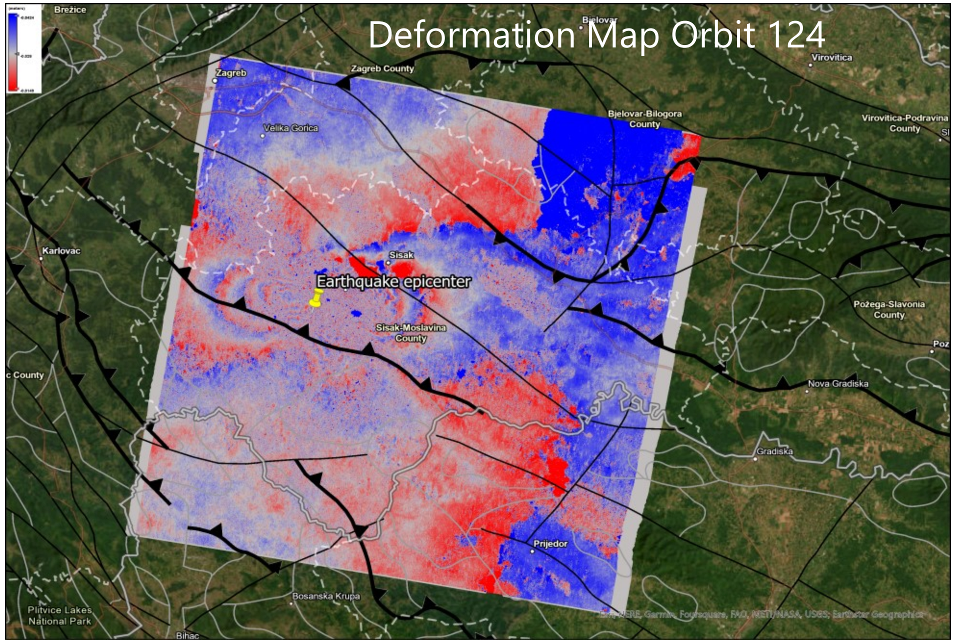
Figure 6. Decomposition of the LoS displacement into vertical (up–down) and horizontal (E–W) components (modified after Tzouvaras et al., 2020).

Results: The 2020 Croatia earthquake



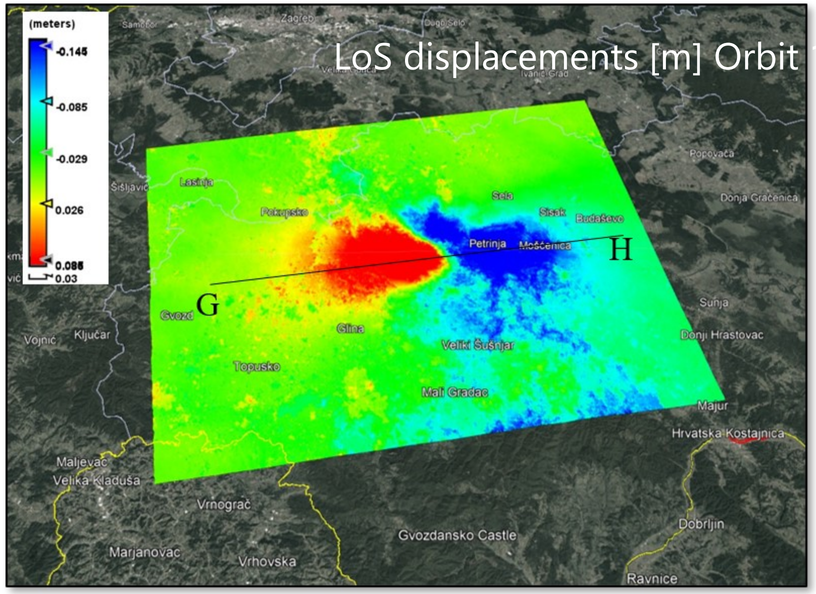
	Mission	Swath	Master	Slave	Orbit	Pass
Croatia earthquake	Sentinel-1B	IW2	23.12.2020	4.01.2021	124	Descending
	Sentinel-1B	IW2	24.12.2020	-	146	Ascending
	Sentinel-1A	IW2	-	30.12.2020	146	Ascending

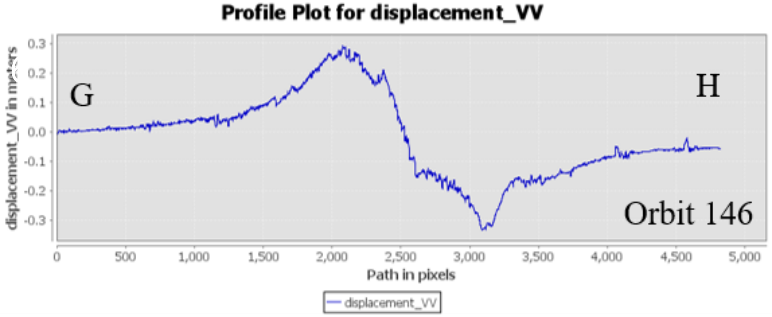




The interferograms for both orbits are quite poor and the fringes are difficult to be distinguished. Most probably this is caused by the highly **vegetated area** which influence the coherence between the two images. The black lines show the main faults in the EDSF.

Results: The 2020 Croatia earthquake

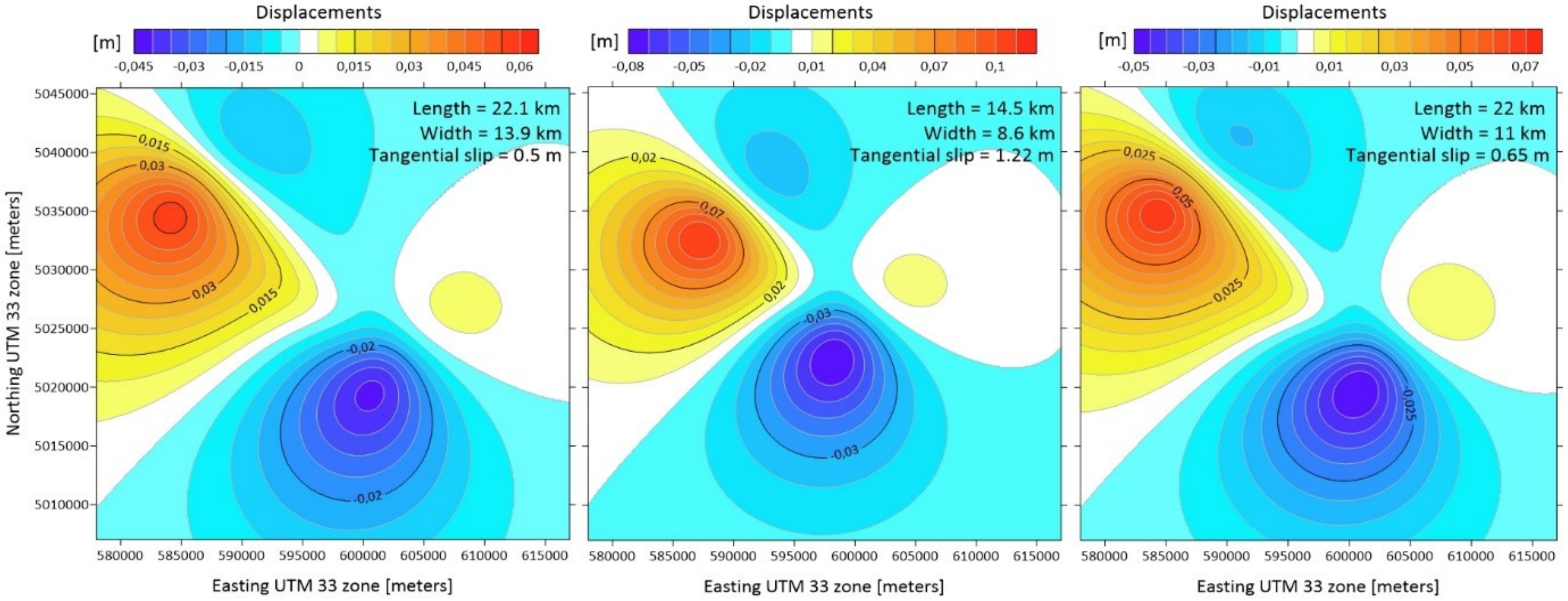




The **profile G–H** for Croatia indicate positive uplift followed by the negative subsidence in the range between **0.3 to -0.32 m.**

The **obtained deformation map** is in good accordance with the seismic faults in the region. Well observed fault zone that extends from **NW to SE** and corresponding to the geological data.

Comparison between the results obtained by DInSAR procedure and the model of Okada.

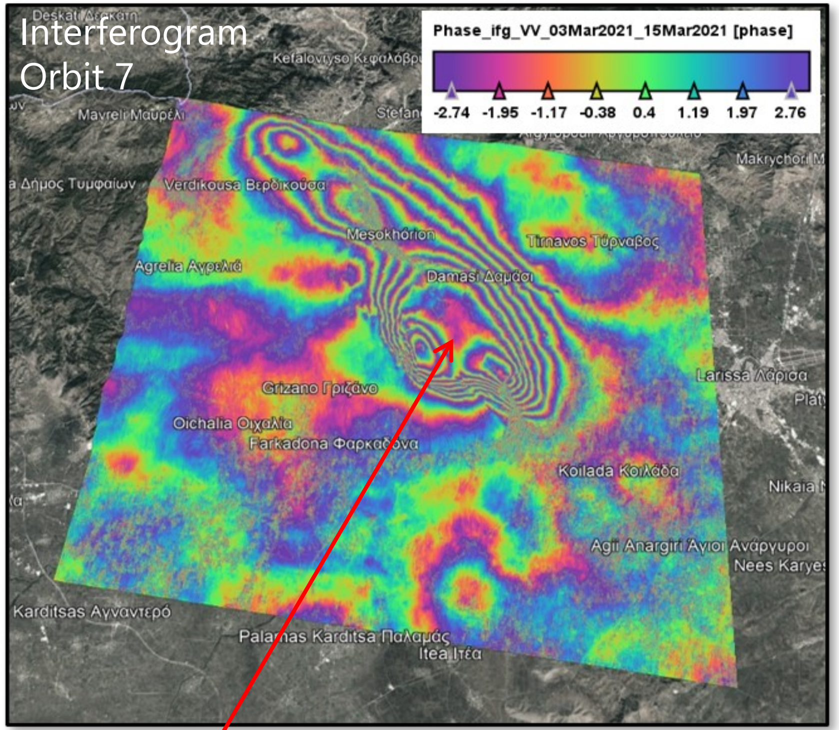


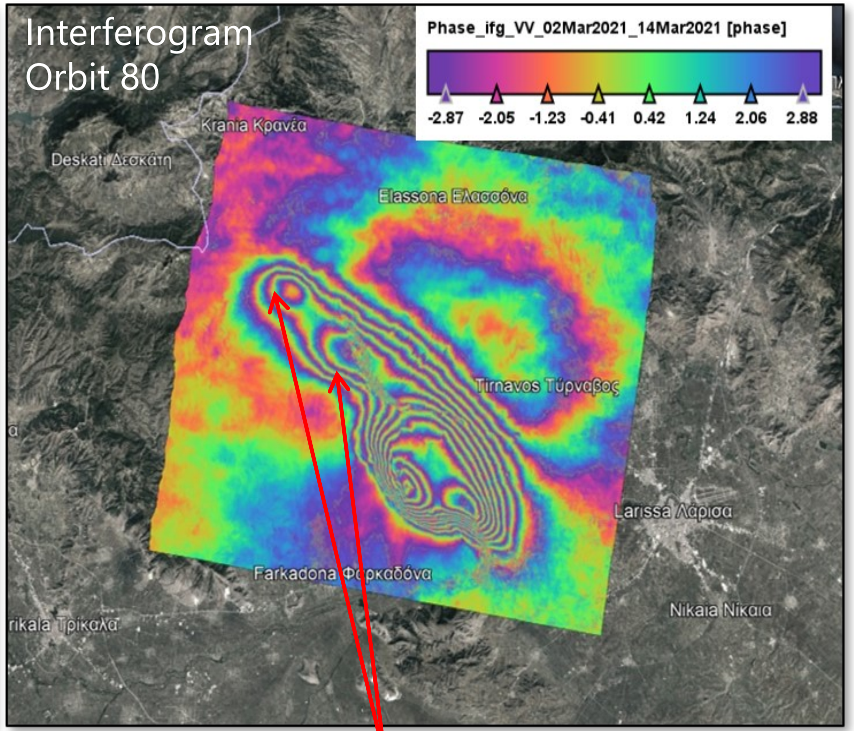
The model proposed by Okada solves analytically equations for both point and finite rectangular sources assuming a homogeneous elastic half-space. For Croatia earthquake we calculated theoretically **surface displacement** according to a specified rectangular dislocation for specific depth and focal mechanism.

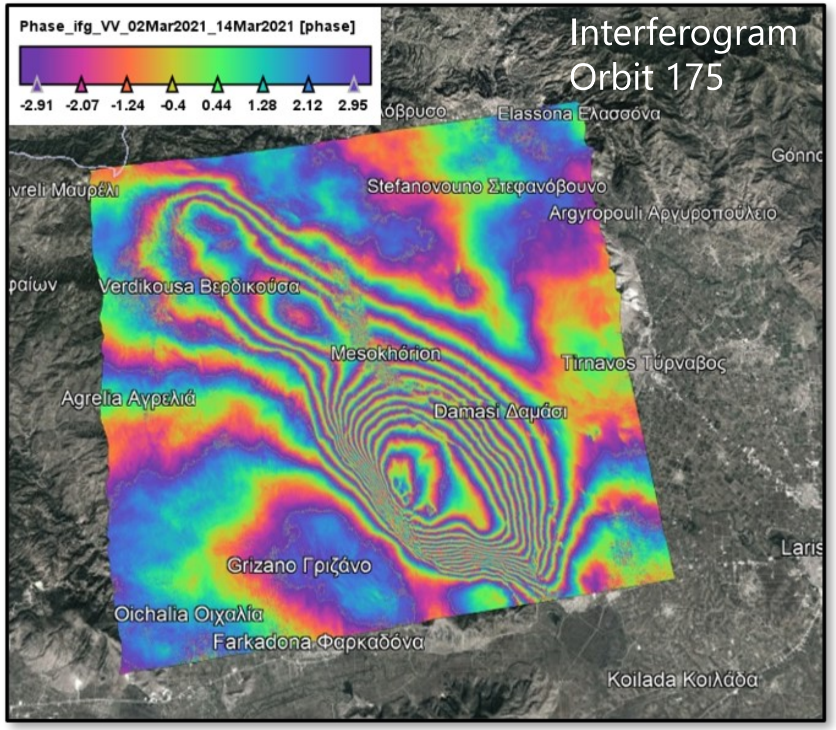
The **three different types of geometries** for Croatia earthquake and their dimensions are shown here. They are calculated taking into account the empirical relationship among the moment magnitude of the studied event, the rupture length, the rupture width and the surface displacement over the fault. Best coincidence with the observed LoS displacements is for the **second geometry** (length = 14.5 km, width = 8.6 km and slip = 1.22 m). The results show **strike-slip fault.**

Results: The 2021 Greece earthquake

	Mission	Swath	Master	Slave	Orbit	Pass
Greece earthquake	Sentinel-1A	IW3	3.03.2021	15.03.2021	7	Descending
	Sentinel-1B	IW1	2.03.2021	14.03.2021	80	Descending
	Sentinel-1A	IW3	2.03.2021	14.03.2021	175	Ascending







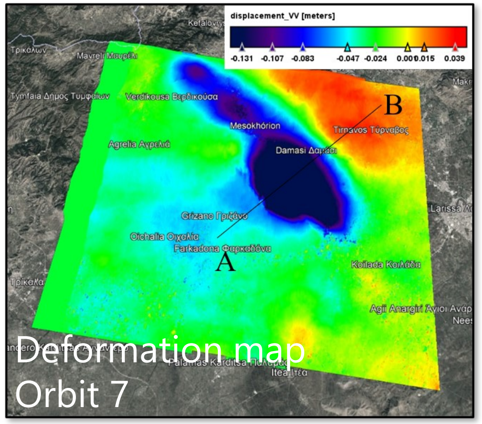
The **main shock** on 3rd March in Greece.

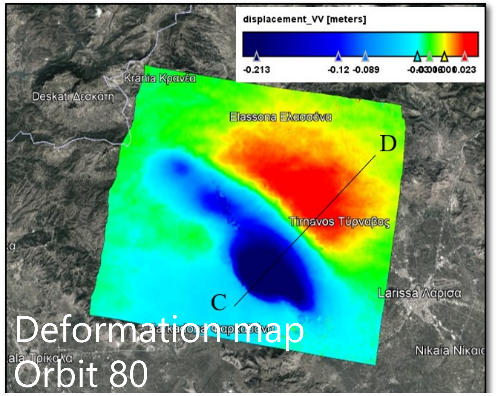
The wrapped phase is represented by colored palette as each fringe is equal to **28 mm**.

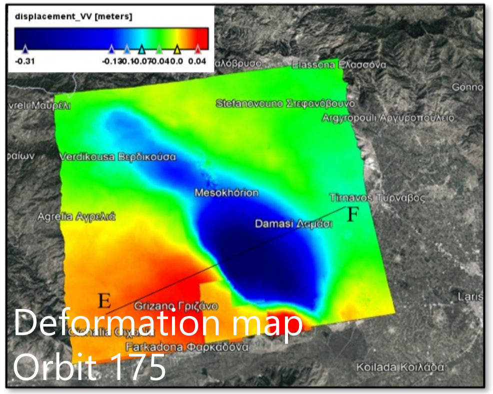
The **subsequent aftershocks** on 4th and 12th March are recognized in the upper left side of the interferogram as smaller circles.

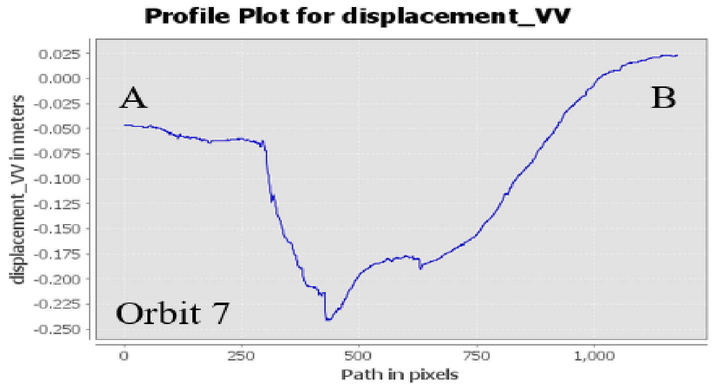
The difference in the incidence angle for each pixel leads to a **difference in the interferograms** for each pair of images.

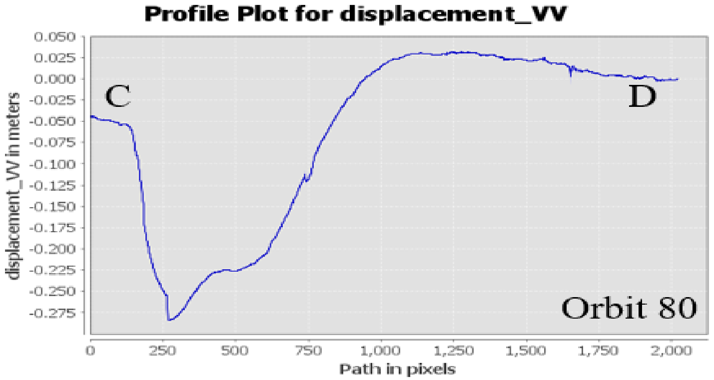
Results: The 2021 Greece earthquake

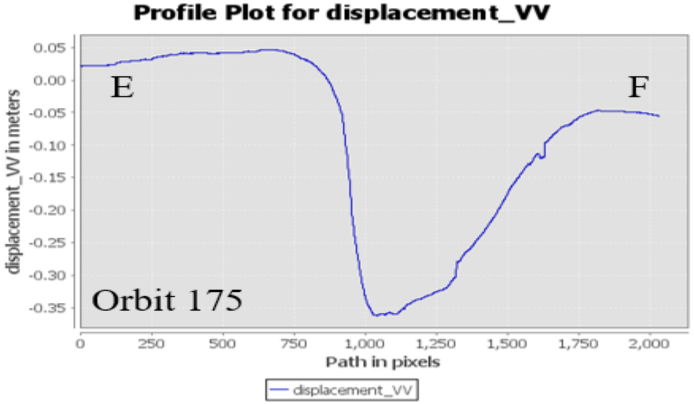








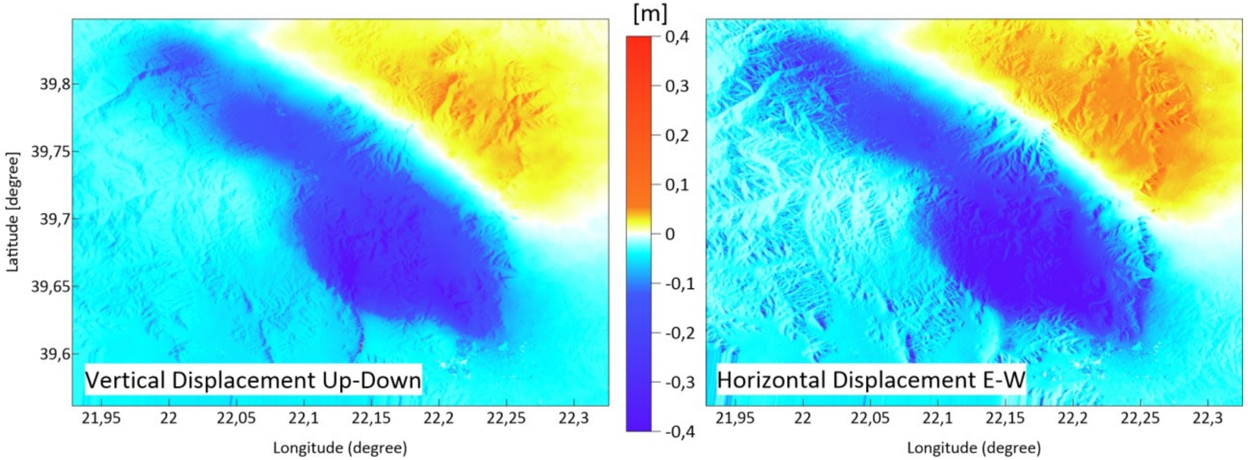




Plot profiles of the LoS displacement for Larissa event (A–B, C–D, E–F).

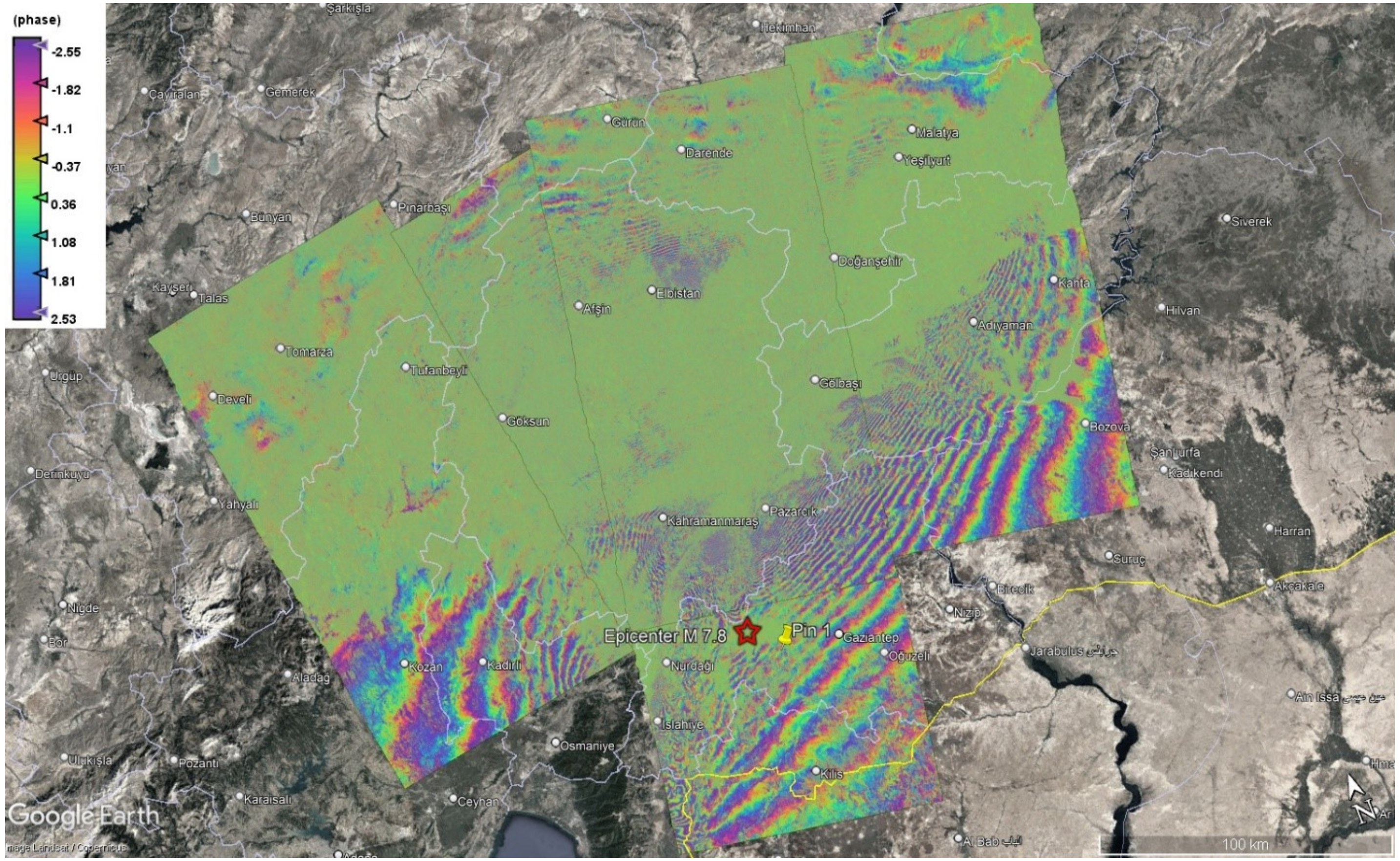
Profiles A–B, C–D and E–F clearly show the vertical subsidence of 0.24 m for Orbit 7, 0.28 m for Orbit 80 and more than 0.35 m for Orbit 175.

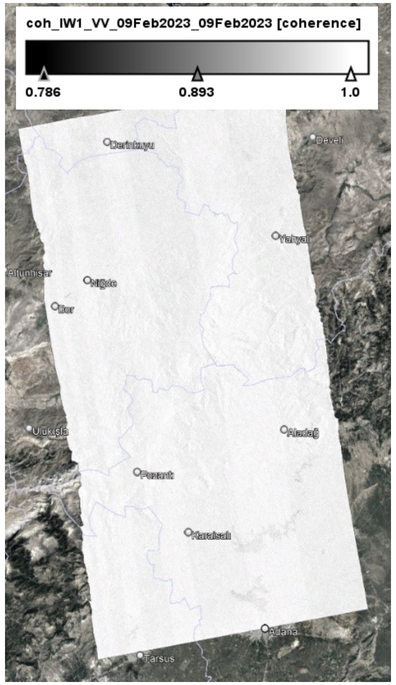
We combined the LoS displacements data from the ascending and the descending orbits. After extracting the displacement value for each pixel and using formulas presented in the methods we plotted the **vertical (up-down)** and **horizontal (E-W) displacements** results via Surfer software.



The vertical (up–down) and horizontal (E–W) displacements using both the ascending 175 orbit and the descending 7 orbit. The uplifting is presented by blue color and the subsidence with red color.

Preliminary Results: The 2023 Türkiye and Syria earthquake

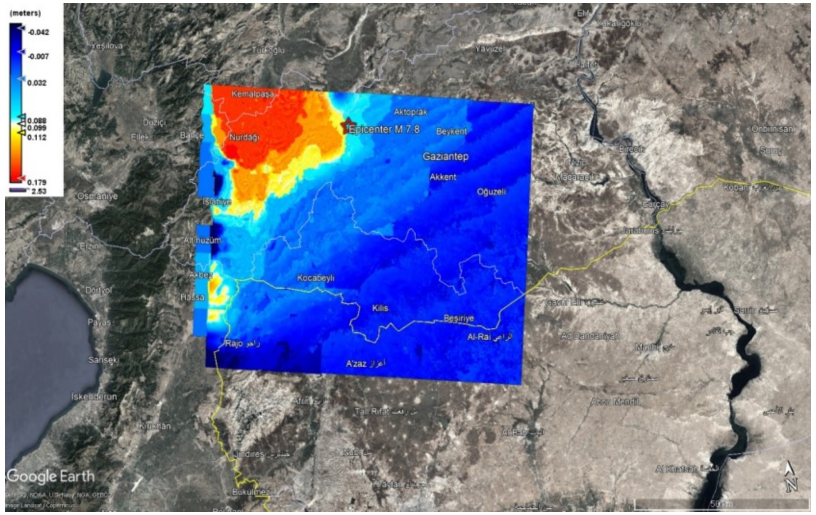




Coherence. Orbit 14: 28.01.2023-9.02.2023. Coherence is used to verify the legitimacy of the derived phase data. Usually, the threshold is 0.3. In the case of this huge earthquake for some of the pairs we get a minimum **coherence of 0.8**.

Preliminary results of deformation map is presented below. We can see that at some areas the **displacements reach values greater than 2.5 m**. The epicenter of the main shock is visualized as red star.

Swath	Slice Number	Master	Slave	Orbit	Pass
IW1, IW2, IW3	8	28.01.2023	9.02.2023	14	Ascending
IW1, IW2	13, 14	29.01.2023	10.02.2023	21	Descending



In total we selected, downloaded and **processed 3 pairs** of available images. The results are exported as *.kml* files and visualized via Google Earth Pro software.

Conclusions

The method applied in this specific study is suitable for **determining the spatial extent of surface deformations** due to natural hazards, like **earthquakes**. The results obtained by the DInSAR procedure complements the geological, geophysical and seismological studies of such events. The **SAR satellite data is very useful and perspective** due the **precise space resolution** and the relatively **short time interval of acquisition** the data after an earthquake.

Using SAR satellite data, we analyzed a series of images and produced **interferograms** and **deformation maps** for **three earthquakes in the Balkan Peninsula** region and in **Türkiye and Syria**. In the presence of vegetation or varied terrain, the proposed method has its disadvantages, like in **the case of Croatia earthquake**, where the interferogram **is not so clear**. The **2021 Greece earthquake** is studied using the proposed orbits, as well as by converting the **LoS displacement** into **vertical** and **horizontal (E-W)** ones. The presented results for 2023 Türkiye and Syria earthquakes are **preliminary**, thus after processing **more images** from different orbits, we will combine all the data and **create more complex image** of the different scenes.

References and Acknowledgements

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Kandilli Observatory KOERI: http://www.koeri.boun.edu.tr/new/en.

SNAP - ESA Sentinel Application Platform v8.0.9, http://step.esa.int/main/toolboxes/snap/

Tzouvaras M., Danezis, C. & Hadjimitsis, D. G. 2020. Differential SAR interferometry using Sentinel-1 imagery-limitations in monitoring fast moving landslides: the case study of Cyprus. *Geosciences*. **10**(6), p. 236. https://doi.org/10.3390/geosciences10060236.

United States Geological Survey (USGS): https://earthquake.usgs.gov/earthquakes/eventpage/us6000jllz/executive.

If you are interested check our poster **Seismic Network of Sofia University: first seismic station by Reneta Raykova and myself**

Thank you for your attention!

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