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MONITORING AND INVERSION OF THREE CO-SEISMIC EVENTS ON THE BALKAN PENINSULA

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The Balkan Peninsula is a tectonically active area due to the collision, compression, and rotation of the Adria microplate in the northwest and rotation of the Anatolian plate in the southeast. The geographic region that comprises the Balkans is located in a very complex geological setting where many tectonic plates meet and hundreds of faults exist. These processes generate frequent, though usually small, earthquakes, but occasionally earthquakes with magnitudes above 6.0 occur. In this study, **SAR data from Sentinel-1A** were utilized to analyze the deformation of co-seismic events. The Okada elastic dislocation model was employed to invert the geometric parameters of the fault and the distribution co-seismic slip. The data were selected to primarily reflect the co-seismic effects of the main event, excluding the contribution of foreshocks and aftershocks as much as possible. To enhance the quality of the results, SAR data from both ascending and descending orbits of the satellite were processed using the freely provided software by ESA specifically developed for SAR data analysis. Further processing of the line-of-sight (LoS) results was conducted to decompose them into real movements in vertical (up-down) and horizontal (E-W) components.

Modeling of the events ware carried out using the **Okada method** with different geometries. The results are supplemented with information on well-known faults in the region. Monitoring and inversion of the co-seismic events help further understand the geometry and properties on Earth`s crust movement and tectonic in the region. The results indicate that the maximum uplift and maximum subsidence deformations from these two methods are comparable. Central to Okada's equations are several parameters, each playing a crucial role in determining the characteristics of surface deformation. The focal mechanism of the earthquake, including parameters such as the strike, dip, and rake of the fault, significantly influences the distribution and magnitude of surface displacements. These parameters govern the orientation and slip direction of the fault, directly impacting the resulting deformation pattern. Additionally, the location (e.g., latitude, longitude and depth) and geometry (length and width for rectangular source) of the seismic source, significantly influence the surface deformation. Okada's model allows for precise characterization of the source geometry, enabling researchers to accurately model a wide range of seismic events and fault configurations.

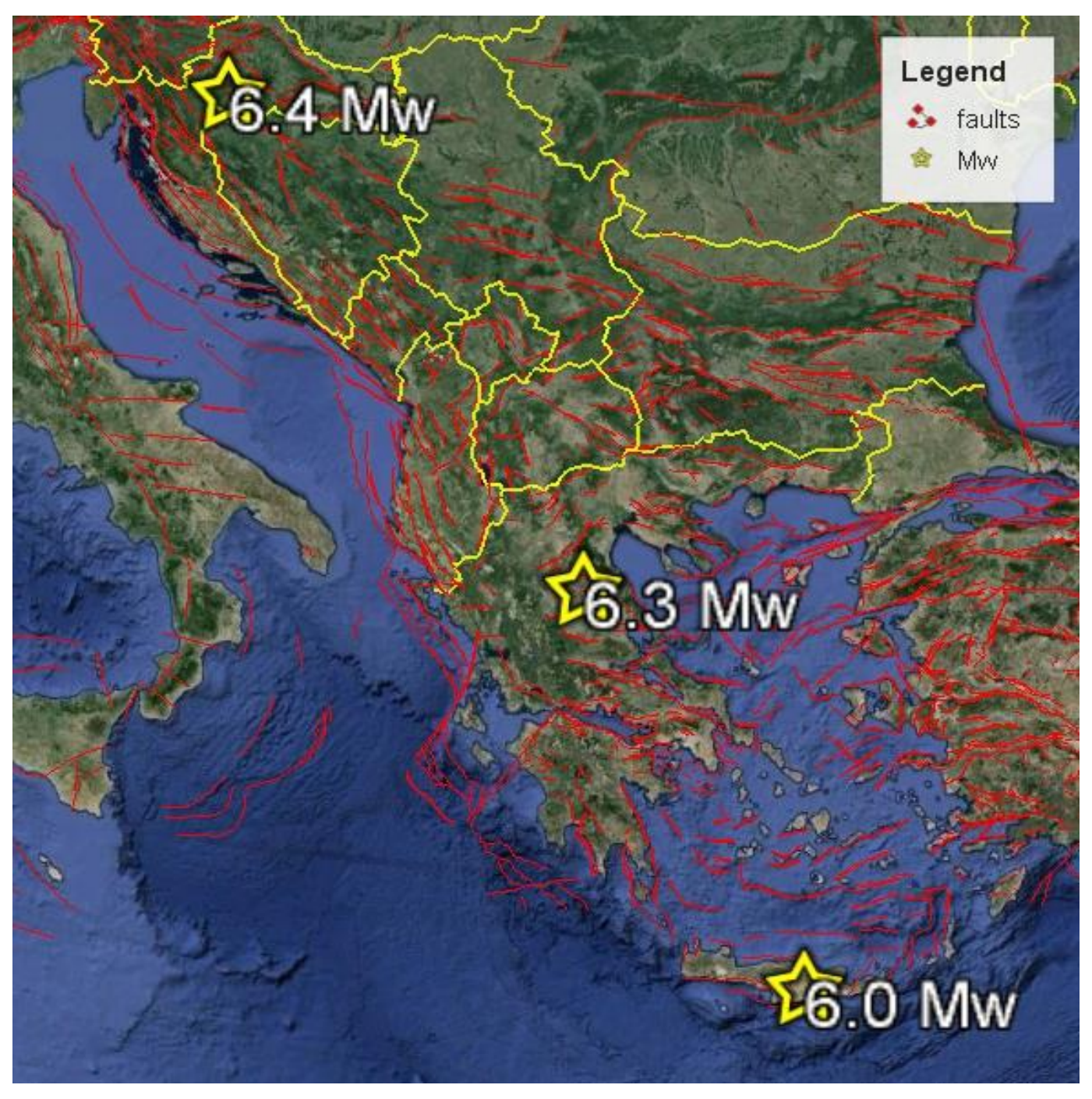


Fig. 1. Locations of the epicenters of the studied earthquakes, their magnitudes and the main faults.

The primary focus of the present study is to create a robust model of the surface displacements that occurred after three earthquakes: the Petrinja earthquake in Croatia on December 29 2020, the Larissa earthquake on March 3 2021, and the earthquake on Crete on September 27 2021. The interpretation of space distribution and co-seismic deformation of major earthquakes in the study area may provide insights into the geodynamic and tectonic processes

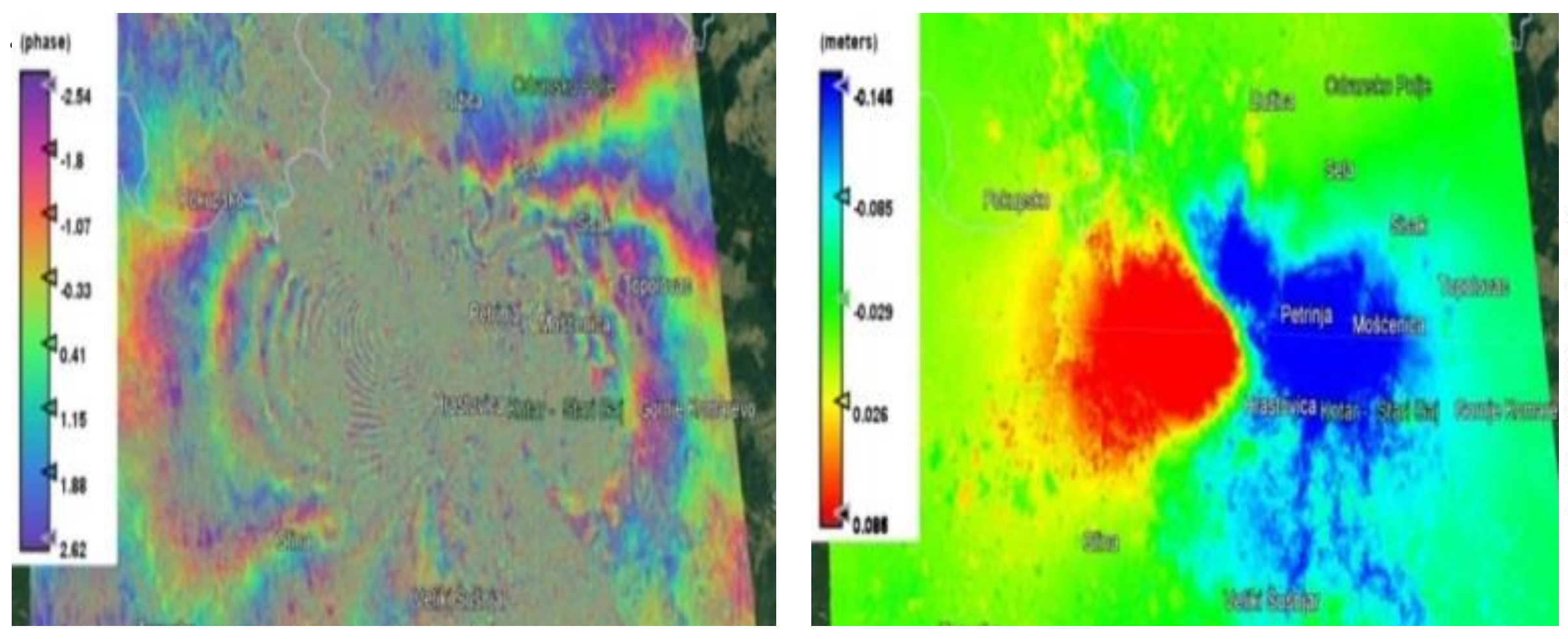
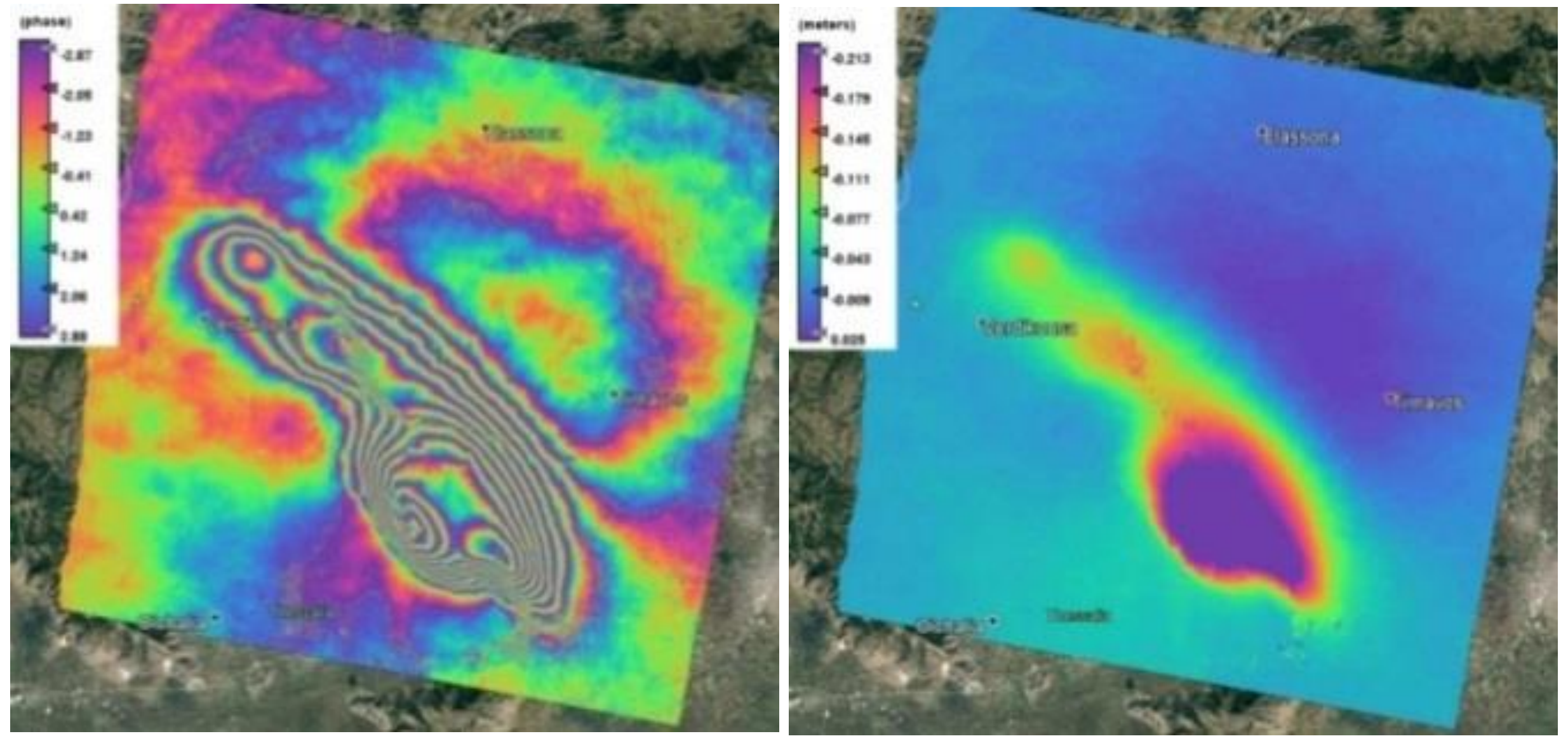


Fig.2. Interferometric image of the Petrinja - Croatia earthquake area on 29 Dec., 2020 ascend. orbit and deformation map along the LOS direction

Descending orbits 80 orbit 02-14 March 2021



Ascending orbits 175 orbit 02-14 March 2021

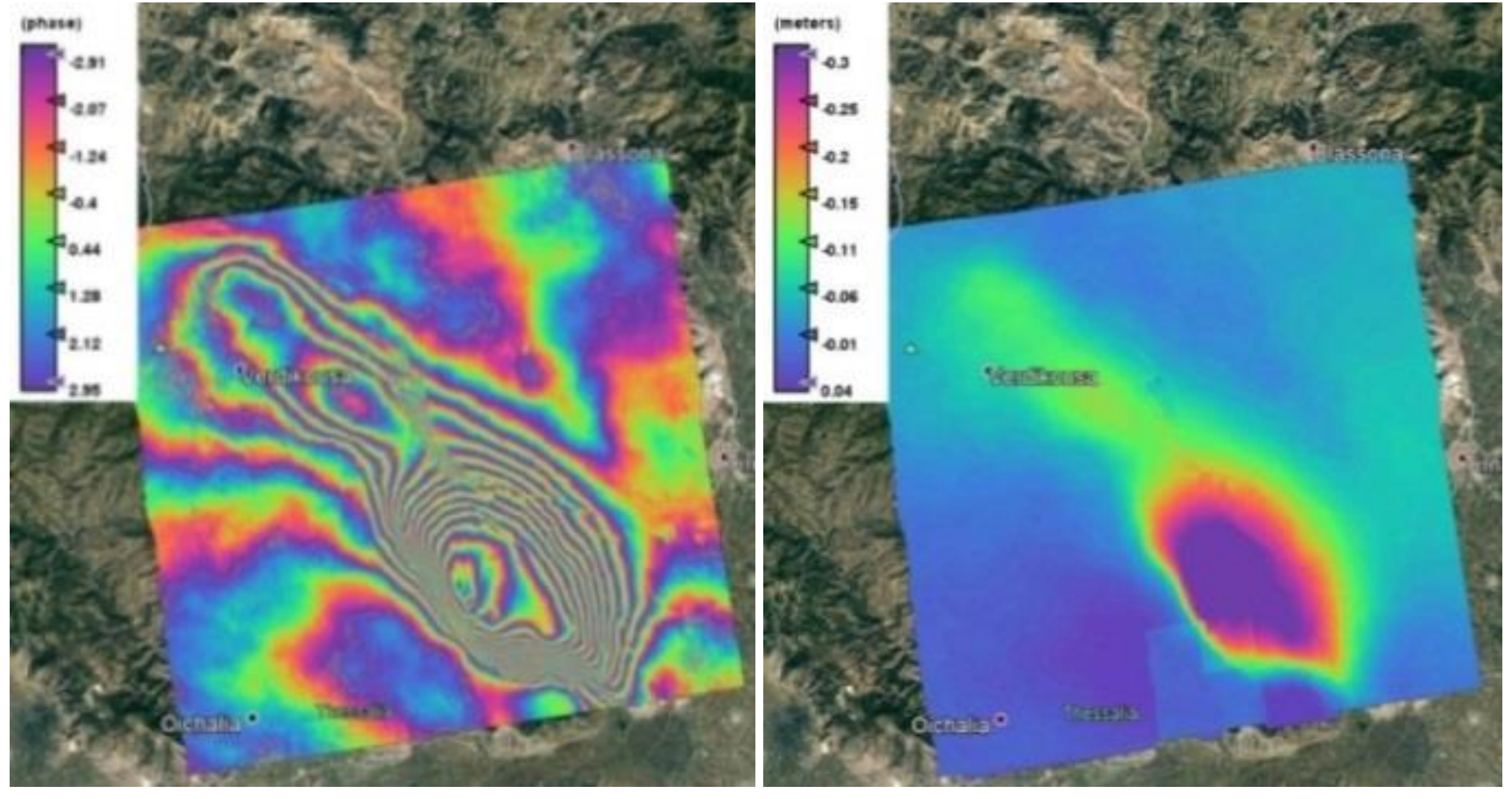
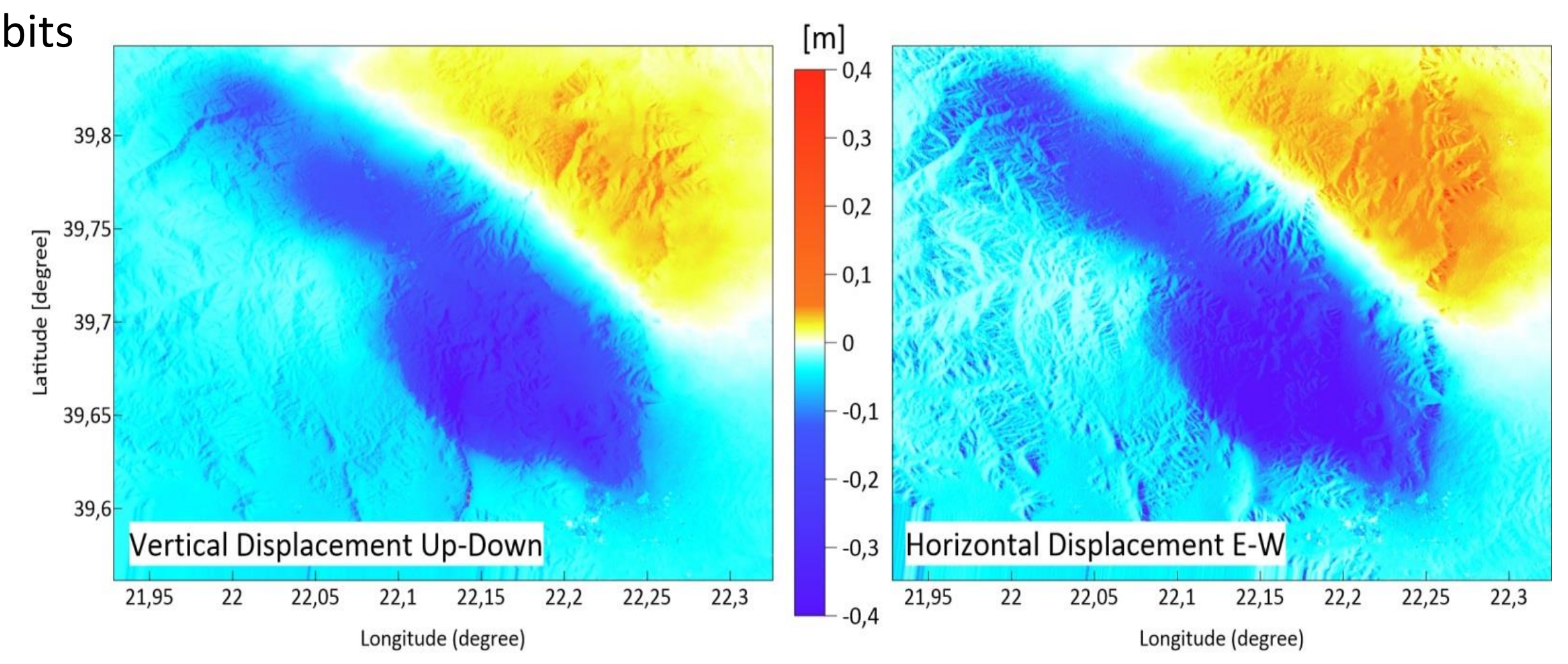
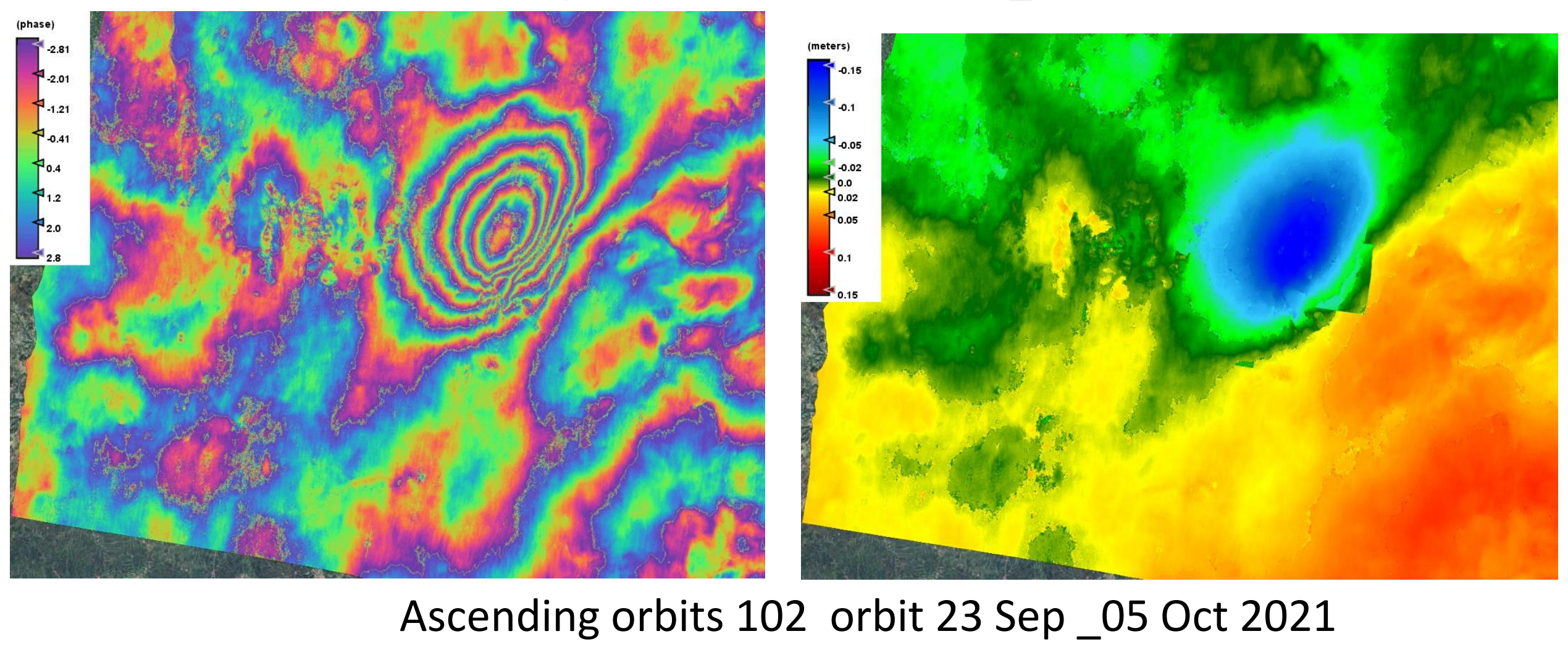


Fig. 4. Interferometric images of the area of the Larissa earthquake and maps of the deformations along the LOS direction determined by the two types of orbits



Descending orbits 36 orbit 19 Sep_01 Oct 2021



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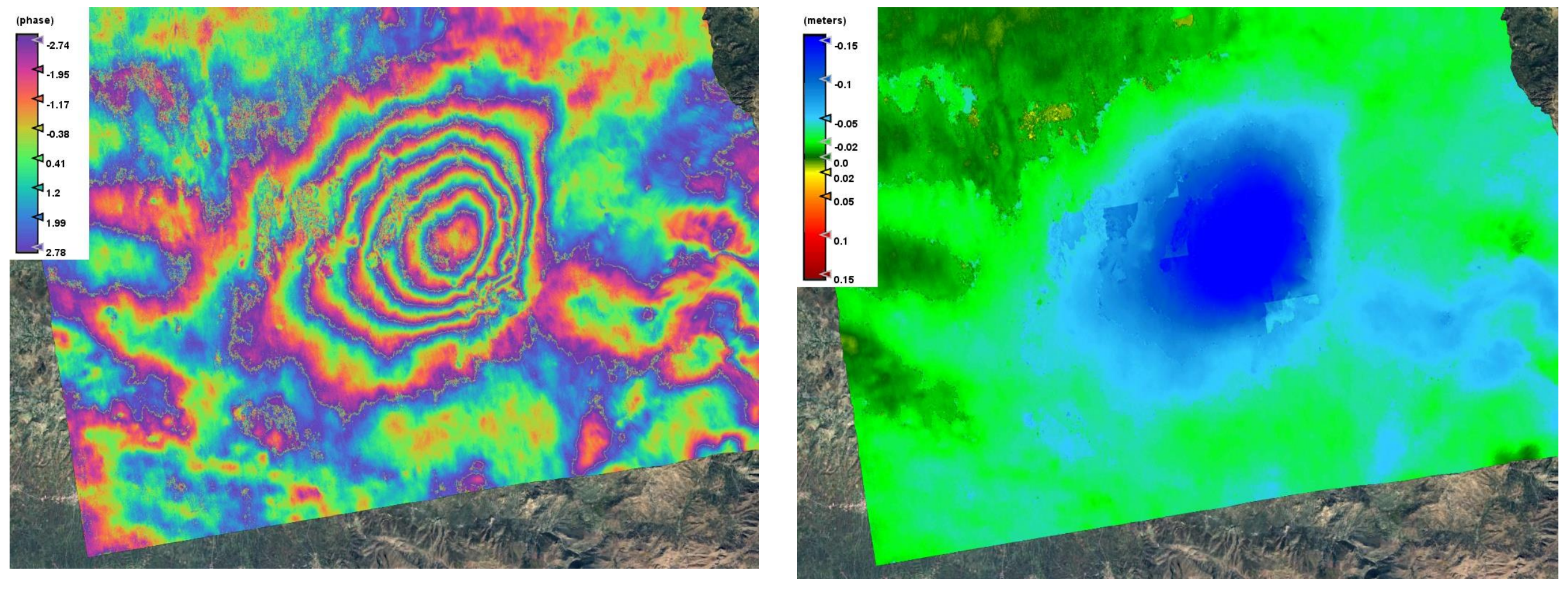


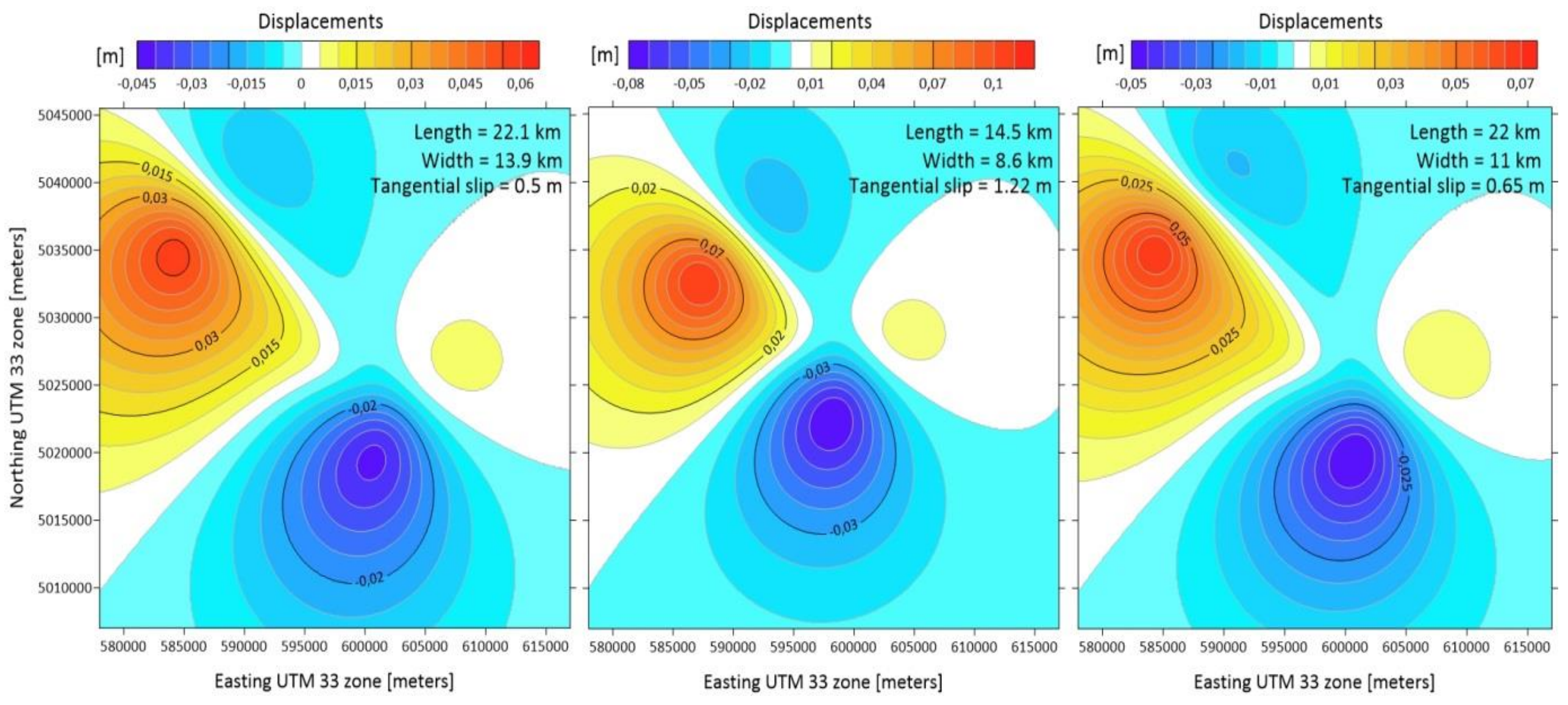


Fig.3. Co-seismic displacements calculated by means of Okada model according three types of geometry for Croatia earthquake.

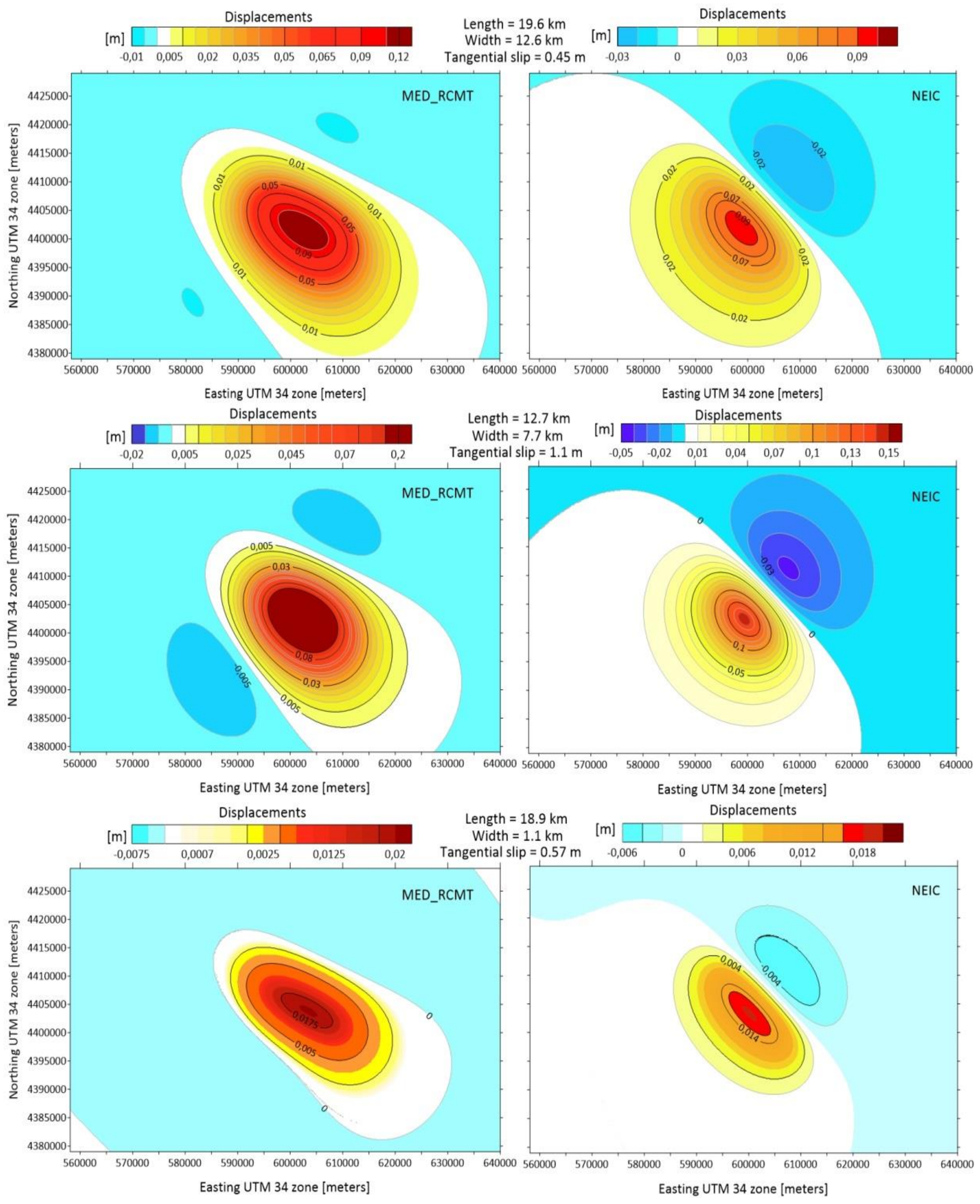


Fig.5. Co-seismic displacements calculated by means of Okada model according three types of geometry and two types of focal mechanisms for Larissa earthquake Greece.

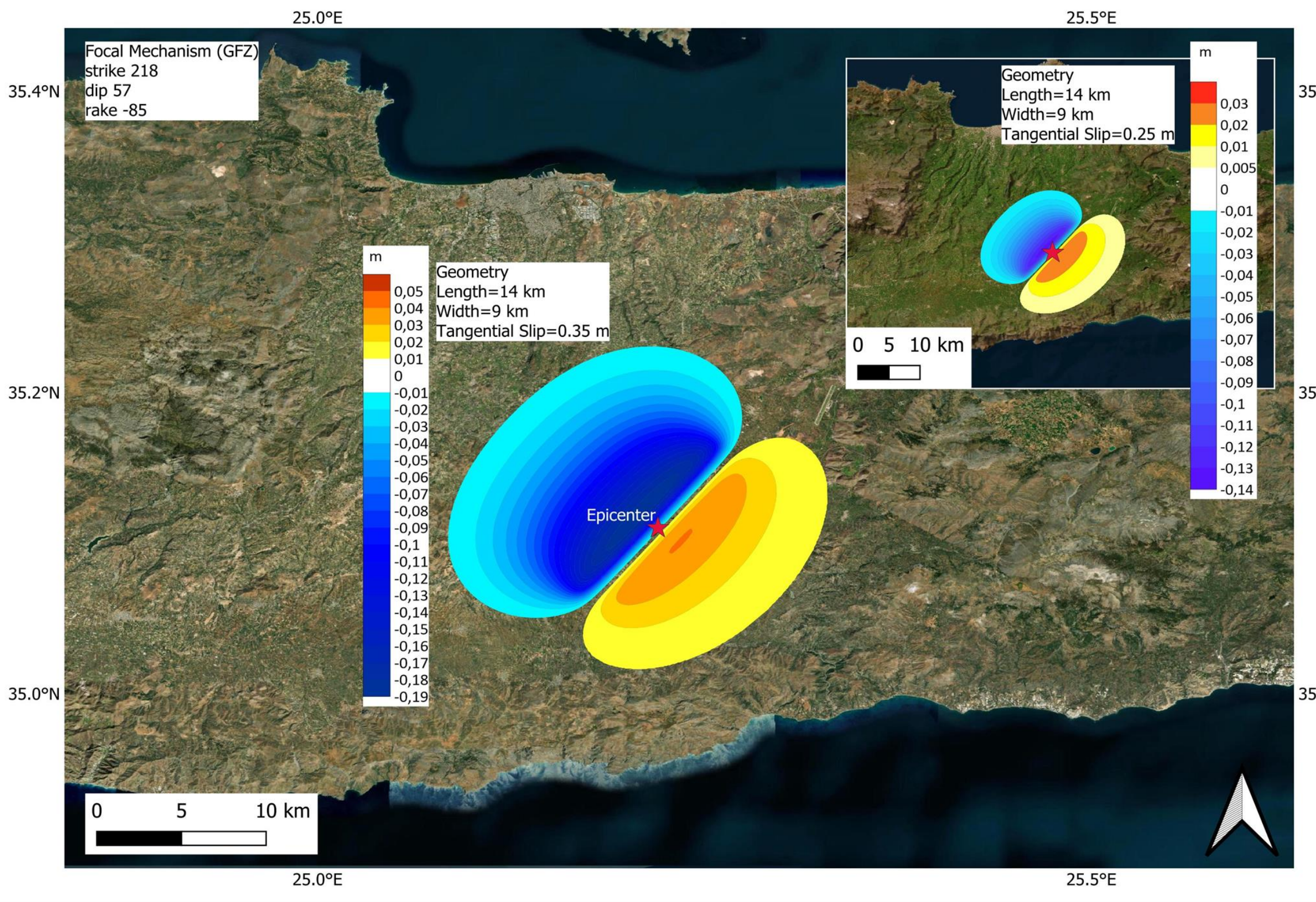


Fig.7 Co-seismic displacements calculated by means of Okada model Crete earthquake September 27, 2021

Fig. 6. Interferometric images of the Crete earthquake and deformation maps along the LoS direction determined by the two types of orbits.

Table 1. Three seismic events with a magnitude greater than 6.0 studied in this research for the region of the Mediterranean Seismic Zone

N	Name	Latitude Longitude	Mw	Dates, time/UTC
1	Petrinya -Croatia	45.42 N 16.12 E	6,4	December 29, 2020
2	Larissa - Greece	39.76 N 22.21 E	6.3	March 03, 2021
3	Arkalochori - Crete	35.11 N 25.20 E	6.0	September 27 2021

In this study, we explore the scientific utility of ground motion observations and the benefits of using GNSS as a source of these measurements, along with discussing the current role of **GNSS in seismic monitoring**. A large earthquake releases sufficient energy to permanently deform the Earth`s crust and cause vibrations, affecting GNSS reference antennas. Permanent GNSS stations located in the study areas are utilized to Identify seismic events in GNSS time series. Jumps in the horizontal and vertical components of the station's position are recorded and used to accurately verify the ground displacements at that point.

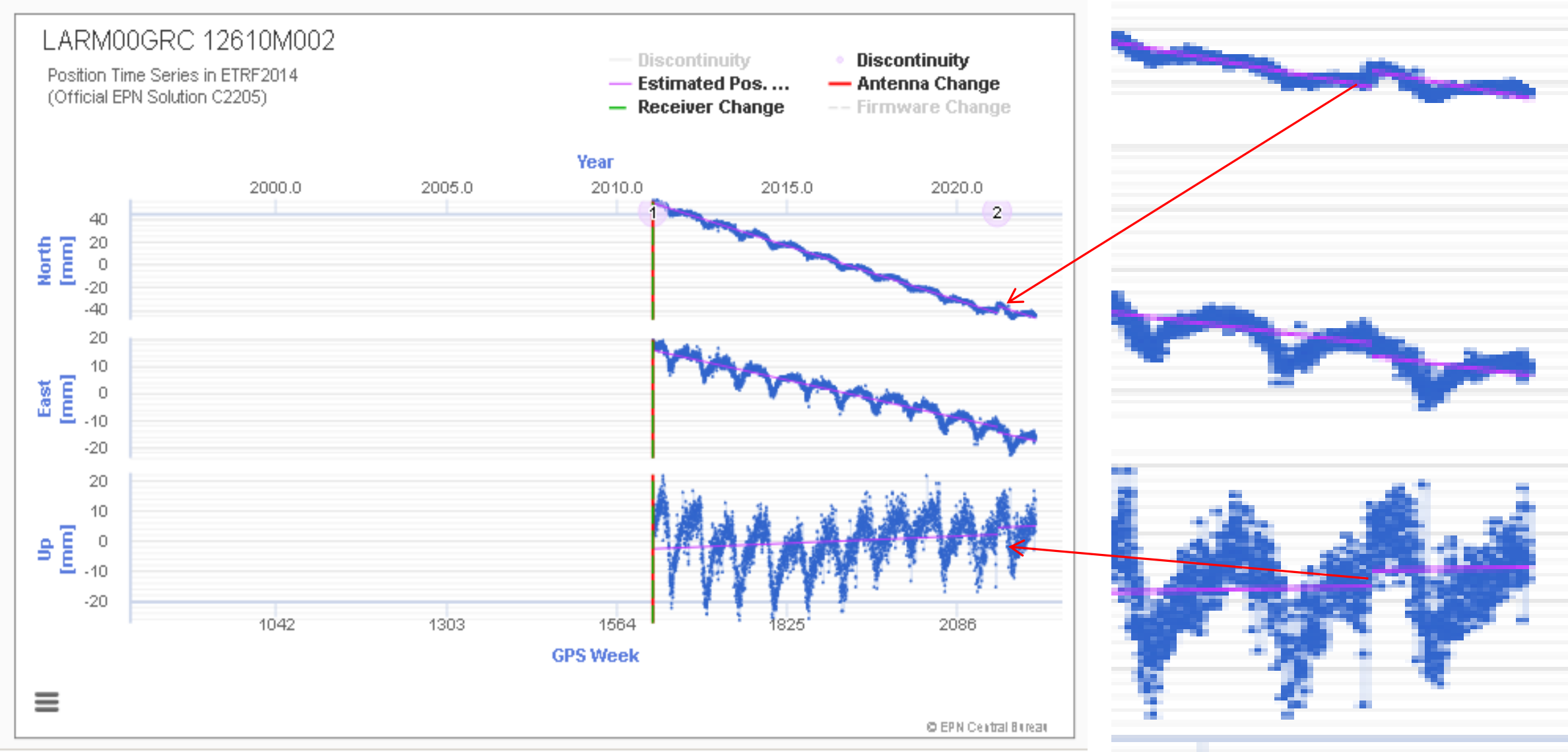
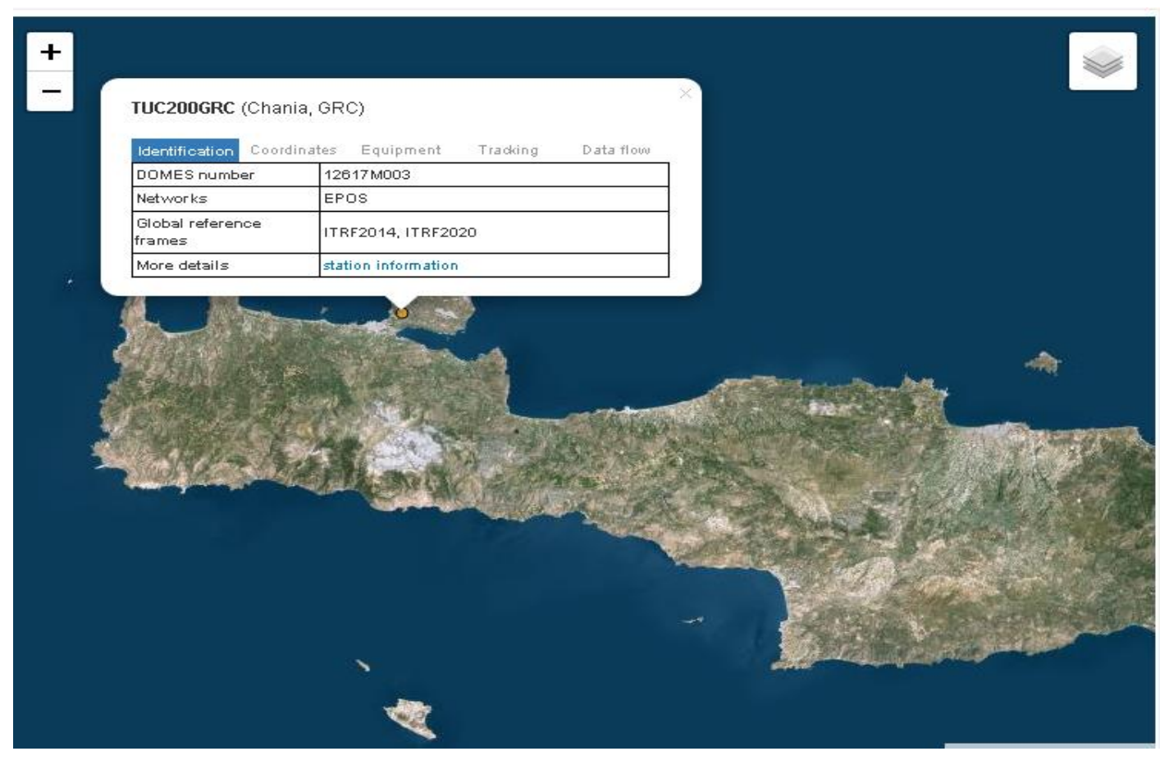


Fig.8. Time series of LARM GNSS station coordinates from the European Permanent EUREF

From EUREF network, GNSS data are used for Julian day 062 of 2021, which coincides with March 03, and analyzed time series of the coordinates of the GNSS station LARM. The LARM point is located southeast of the epicenter of the event. In fig. 8 shows the recorded displacement occurring in the northern and vertical components.



TUC200GRC (Chania, GRC)

DOMES number	12617M003
Networks	EPOS
Global reference frames	ITRF2014, ITRF2020
More details	station information

In the time series GNSS station Chania (Fig.8), no jumps and disturbances were found in the horizontal components and up, with caused by the September 27 earthquake

Fig.8. GNSS station from the EUREF - Chania

CONCLUSIONS

In this study, we focused our research on determining the surface deformations after several earthquakes of magnitude greater than 6.0 in the last 4 years along the Hellenic Arc. The presented results from SAR data processing reveal the co-seismic deformations in the region, which are compared and well agreed with GNSS data from other studies and modelling. The main task is to demonstrate operational readiness to determine the degree of deformation of the Earth's surface, and to prepare displacement maps that could be used by large number of experts. The applied processing methodology, employed by the authors, has successfully generated Interferometric Images that visually depict the displacements around the epicenters. The presented examples demonstrate the application of space technologies such as GNSS and InSAR for researching and monitoring seismogenic zones, highlighting their importance and advantages in establishing patterns in the movements within these zones.

Acknowledgments:

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