Impact Assessment of the Catastrophic Earthquakes of February 2023 in Turkey and Syria via the exploitation of satellite datasets

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ABSTRACT

Turkey due to its location within the collision zone between the Eurasian, African and Arabian Plates, is a region prone to earthquakes. The country mostly lies on the Anatolian micro-plate, bounded by two major strike-slip fault zones, i.e., the North and the East Anatolian Fault. On 6 February 2023, the activation of a large segment of the East Anatolian Fault generated two earthquakes of 7.8 and 7.5 magnitude, in southern Turkey. The seismic risk is greater along the plate boundaries, however due to the frequency of earthquake occurrence throughout Turkey, detailed seismic risk maps are crucial and need to be continuously updated towards operational purposes, and as the optimal means towards decision making for disaster risk reduction. Extensive Synthetic Aperture Radar (SAR) satellite image analysis was performed to determine ground displacements caused by the seismic sequence in the wider area around the two epicenters. Pre-seismic line of sight displacements, as well as co-seismic deformation, were estimated, providing critical information about the surface rupture and the overall ground deformation in the affected areas. Earthquakes can induce landslides and other ground displacements causing extensive damage to buildings and infrastructure. Therefore, optical (e.g., Sentinel-2, PlanetScope) and SAR (Sentinel-1) imagery were exploited as a useful tool for assessing the impact of earthquakes on the ground. The monitoring and mapping of these changes, in conjunction with SAR analysis, as well as information on building infrastructure and population density, highlight the overall damage assessment in the region, thus, allowing a better understanding of the impact of earthquakes while providing a more effective response and recovery efforts for decision makers and local authorities towards disaster risk reduction.

Keywords: Disaster Risk Reduction, Earth Observation, ground displacement, Copernicus, Planet, Syria, Turkey

1. INTRODUCTION

On 6 February 2023, two major earthquakes, over magnitude seven (7), and many aftershocks occurred in southeastern Turkey causing significant damages in Turkey and Syria. The sequence of the earthquake affected a densely populated region with few major cities being hit such as Kahramanmaras, Gaziantep, Sanliurfa, Diyarbakir, Adana, Adiyaman, Osmaniye, Hatay, Kilis, Malatya, and Elazig[1] (Figure 1). Unfortunately, the devastating consequences affected people (deaths and injuries), infrastructures/buildings (Figure 2), and Cultural Heritage (CH) landmarks. Specifically, according to a recent death poll, the estimated number of deaths sums up to 50,000 people[2]. Additionally, an estimation of 100,000 injured people[3] and over four million infrastructures/buildings[4] have collapsed during or after the earthquakes. It must be noted that around 2.7 million people remain internally displaced (internal refugees), raising the humanitarian aspect of the earthquake's impact. To date, approximately 2.6 million people live in formal settlements, where there is access to basic

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infrastructure and services, across earthquake-affected areas, while nearly 79,000 are living in container cities. However, across affected areas, nearly 1.96 million people still live in informal sites or next to their damaged houses, in tents or makeshift shelters, with bare minimum living conditions and limited or no access to services[5].

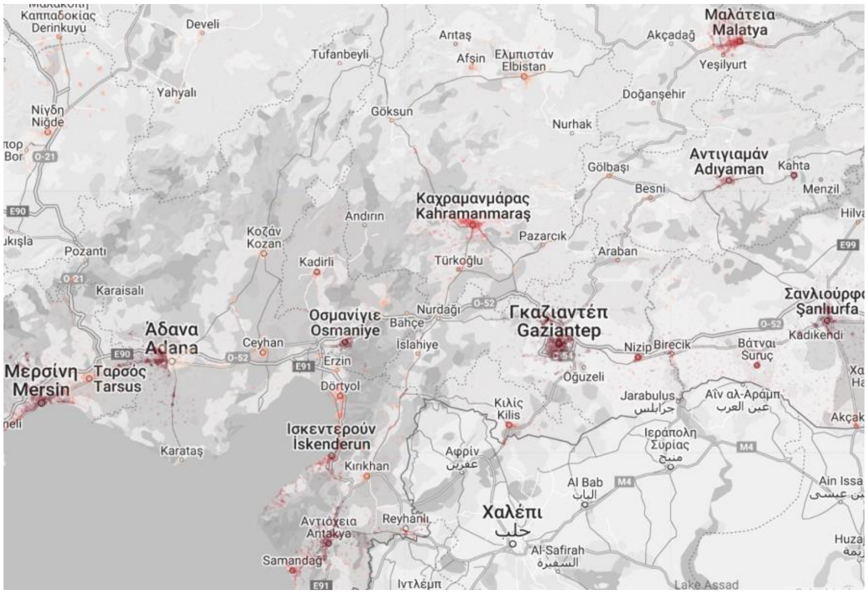


Figure 1: Population Density of Turkey's, affected by the earthquakes, cities before the earthquake events. (Source: USGS website)

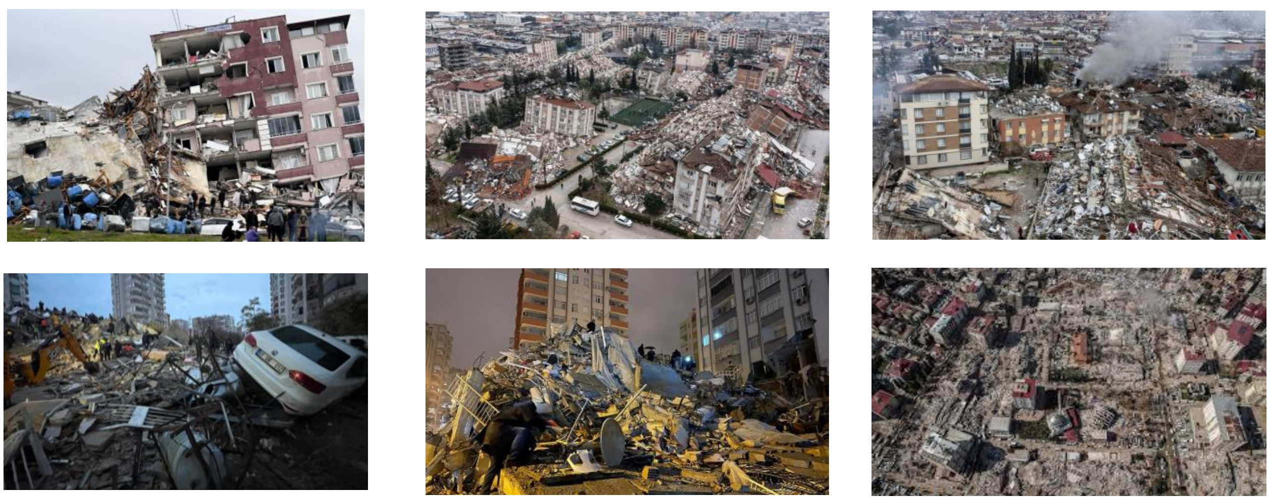


Figure 2: The devastating consequences on buildings/infrastructure after the Turkey's earthquake (Source: BBC News)

A plethora of studies has proved the use of space-based techniques to monitor the impact assessment of earthquake events. The integration of optical and SAR satellite data and image processing techniques is, undoubtedly, among the most effective methods to a holistic approach of assessing an earthquake's impact and its consequences[6]. Since the earthquake of Turkey is quite recent, a few research organizations/institutes in different countries, such as Greece[7,8], Italy[9] and Japan[10–12] have attempted to estimate the displacements after the earthquake using various satellite constellations, such as Sentinel-1, Sentinel-2, ALOS PALSAR etc., and satellite image processing techniques. Optical satellite imageries (e.g., Landsat, Sentinel-2, etc.) have also been effective in damage proxy maps assessment regarding natural and anthropogenic hazards[13,14].

1.1 Tectonic Map and Timeline of the Earthquake

Turkey is a country that is highly susceptible to frequent destructive earthquakes due to its location within the collision zone of the Eurasian, African, and Arabian Plates. The country lies on the Anatolian micro-plate, which is bounded by two major strike-slip fault zones, the North and East Anatolian Faults, as depicted in Figure 3. The seismic events occurring in Turkey are caused by the interplay of four tectonic plates, namely the Arabian, Eurasian, and African plates, as well as the smaller tectonic block known as Anatolian[15]. On 6 February 2023, two earthquakes with magnitudes of 7.8 and 7.5 struck southern Turkey, triggered by the activation of a large segment of the East Anatolian Fault. These earthquakes were the strongest and deadliest to hit the country since 1939[16].

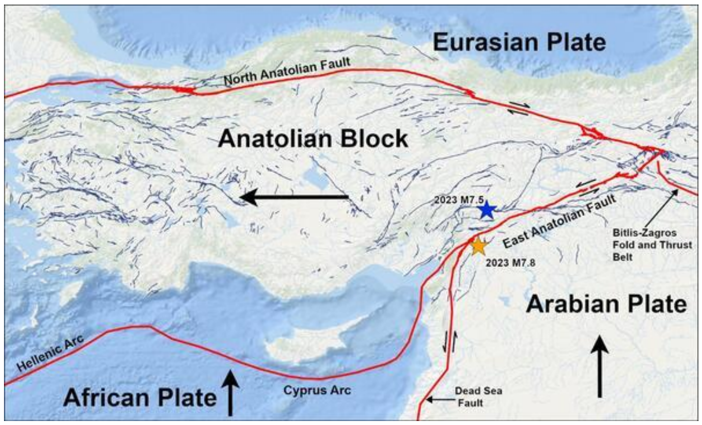


Figure 3: The location of the February 6, 2023, M7.8 (orange star) and M7.5 (blue star) earthquakes. The plate boundaries and active faults in Turkey are shown in red and dark blue respectively. Black arrows show schematically the motions of the African and Arabi

The evolution of the seismic sequence was divided into two main phases (Figure 4). The first phase began on 6 February 2023, at 01:17:36 UTC, with a M7.8 earthquake hitting the province of Gaziantep in Turkey. This mainshock event caused a chain aftershock registering between approximately M2.5 and M5.0 in the area, with approximately one-hundred and sixty (160) events. The duration of the first phase was estimated to be up to nine (9) hours before the second phase occurred. The second phase of the sequence took place 100km north of the first mainshock. The second major earthquake, M7.5, followed by five M5.0+ in the next ninety minutes, again caused a chain of aftershocks with a duration of over twenty-four hours. Overall, this event triggered a sequence numbering about two thousand and eight hundred (2,800) earthquakes above M2.5, that were recorded until 22 February 2023[17].

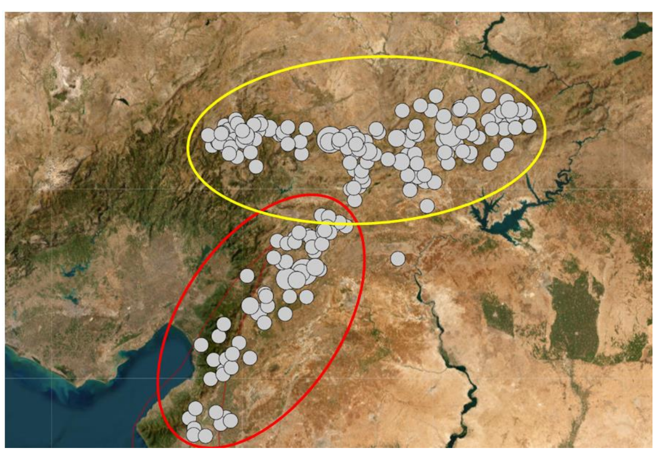


Figure 4: The two phases of Turkey's seismic sequence. The red color indicates the first phase, and the yellow color shows the second phase. Grey circles show the location, and their size the magnitude of every seismic event according to USGS earthquakes' database.

This work presents an initial impact assessment of the catastrophic earthquakes of 6 February 2023 in Turkey and Syria, using extensive Optical and Synthetic Aperture Radar (SAR) satellite image analysis. Optical imagery from Sentinel-2 and

PlanetScope satellites and SAR imagery from Sentinel-1 satellite, were used to assess the impact of the earthquakes on the ground, the infrastructure, humanitarian, and cultural heritage landmarks. The study provides critical information about the overall ground displacements in many of the affected areas, allowing a better understanding of the earthquakes' impact. Moreover, this study provides an overview of next steps recommendations for more effective response and recovery efforts by decision-making and local authorities, towards disaster risk reduction, as well as the implementation of disaster management and mitigation strategies.

2. METHODOLOGY

The rationale of this study is to exploit multiple and different satellite datasets to understand the impact of the earthquakes. Hence, optical and SAR data are used in the overall methodology. The latter includes three (3) different methodologies, leveraging the Sentinel-1, Sentinel-2 and PlanetScope constellations, such as co-seismic change detection analysis, co-seismic horizontal movements estimation, Parallelized Persistent Scatterer Interferometry (P-PSI) and ground subsidence along the faults (using Differential Interferometry-DInSAR), as shown in Figure 5.

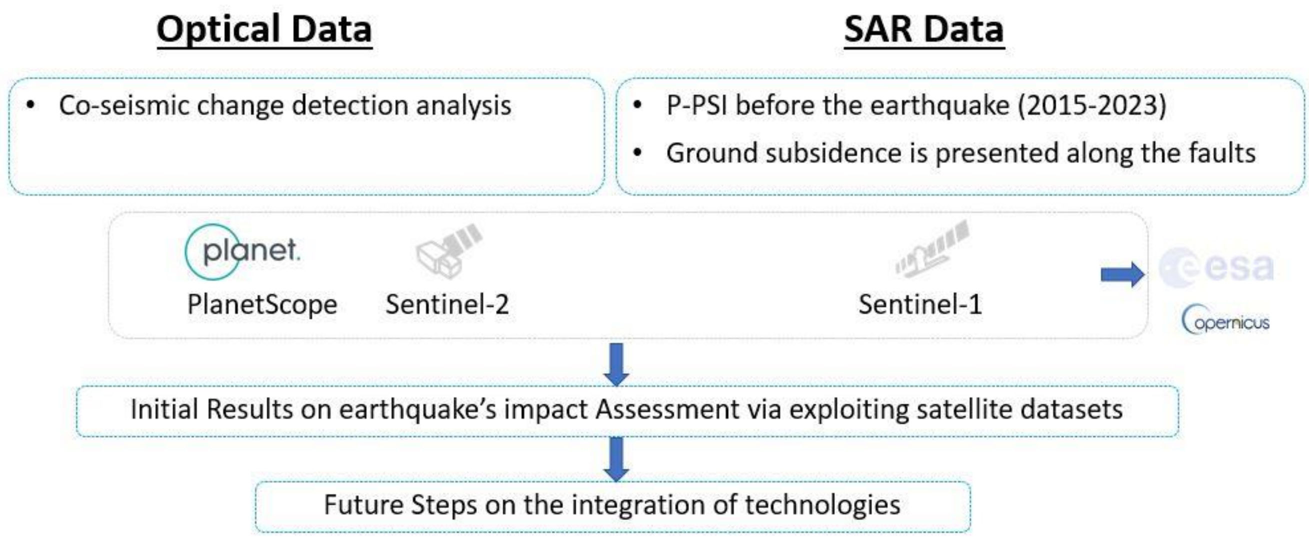


Figure 5: Overall Methodology of the study

2.1 Optical Satellite Dataset and Processing

Co-Seismic Change Detection Analysis: The optical satellite dataset is derived from freely available Sentinel-2 and PlanetScope satellite missions, resulting in a cost-free monitoring analysis (Figure 6). Specifically, as a first step, optical pre-event and post-event images were acquired (Figure 7, Figure 8). Then, the image difference was used to apply a K-Means unsupervised classification (due to the lack of ground truth data to be used as training samples for a supervised one), to detect and discriminate the changed pixels corresponding to collapsed buildings and debris from those corresponding to shadows or other anthropogenic activities, such as agricultural activities, during that time frame.

The building footprints in the affected areas were retrieved via the Global ML building footprints catalog repository, which uses very high spatial resolution images between 2014-2021, semantic segmentation to identify pixels corresponding to buildings using deep neural networks (DNNs), and converts them to polygons[18]. The overlaying of those buildings in the change detection analysis outcome that highlights the areas affected by the earthquakes, determined the number of affected/destroyed buildings within these zones.

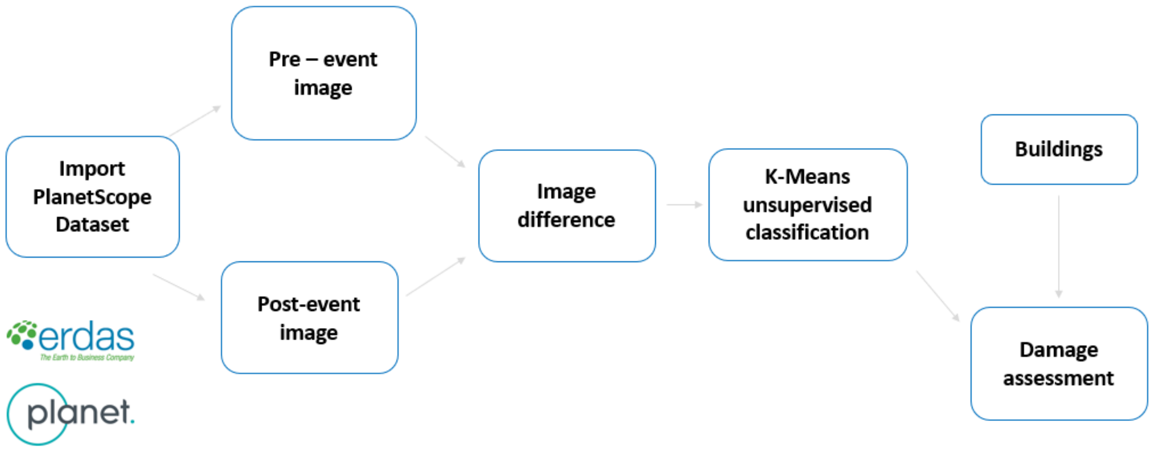


Figure 6: Change Detection Analysis Methodology using PlanetScope Dataset

(a) (b)

Figure 7: (a) Pre-Event and (b) Post-Event PlanetScope Images in Antakya, Turkey

(a) (b)

Figure 8: (a) Pre-Event and (b) Post-Event Sentinel-2 Images in Antakya, Turkey

2.2 SAR Satellite Dataset and Processing

P-PSI Analysis: InSAR time-series analysis techniques are widely used to measure ground motion related to natural or anthropogenic activities, including tectonic activity[19,20], landslides[21], ground subsidence related to groundwater overexploitation[22], rapid urbanization[23], deformation in man-made constructions[24]. To achieve a better overview of the deformation mechanisms in the wider area around the faults associated with the destructive earthquakes in Central Turkey and Turkey - Syria border region a preliminary analysis of surface displacements using multi-temporal InSAR analysis was performed. For the implementation of Persistent Scatterer Interferometry, the P-PSI processing chain[19], developed by the Operational Unit BEYOND Centre for Earth Observation Research and Satellite Remote Sensing of the National Observatory of Athens, was employed. The P-PSI is a fully automated, parallelized implementation of the Stanford method for persistent scatterers (StaMPS)[25]. The main advantage of the P-PSI is the parallelization of the most time-consuming processing steps during the creation of the interferometric stack, with ISCE software[26] and the implementation of the Persistent Scatterers Interferometry technique, with StaMPS software, in big volumes of Sentinel-1 data. Therefore, the P-PSI enables fast processing of big Earth Observation data, for mapping of slow-deforming phenomena. For the pre-seismic time-series analysis, in the broader area near the faults, associated with the February 2023 earthquake sequence in Turkey, 152 Sentinel-1 SLC images of descending satellite pass no.21 from November 19, 2015, to January 29, 2023. The implementation of InSAR time-series analysis revealed deformation insights on more than 2,700,000 permanent scatterers on the ground.

DInSAR Analysis: SAR interferometry is a well-established method for mapping co-seismic surface deformation[27–29]. For the destructive February 2023 Turkey earthquake sequence, a series of co-seismic interferograms were produced, to assess the extent of ground displacement phenomena, associated with the seismic event. Since 2017, a fully automated processing chain, the so-called geObservatory[30], is triggered when a major seismic event occurs worldwide and produces a series of pre-seismic and co-seismic interferograms through SAR interferometry on Sentinel-1 SLC images, using the commercial software ENVI–SARscape. The geObservatory (http://geobservatory.beyond-eocenter.eu/), is an operational service that is developed and operates in the Operational Unit BEYOND Centre for Earth Observation Research and Satellite Remote Sensing of the National Observatory of Athens. Sentinel-1 data, with a good spatial coverage of the affected area, are provided by the Copernicus Data Access Hubs (ESA) and the Hellenic Mirror Site (https://sentinels.space.noa.gr/). Figure 9 provides an overview of the geObservatory's processing chain. As soon as the first earthquake M7.8, on 6 February 2023, 01:17:36 UTC occurred in Central Turkey, the geObservatory was immediately activated and started recording ground deformation, by producing a series of pre- and co-seismic interferograms, associated with the M7.8 as well as all the major seismic events that followed. Table 1 provides information on Sentinel-1 co-seismic image pairs, processed by the geObservatory and employed in the current study.

Table 1: Sentinel-1 co-seismic InSAR calculations for the present study

ID	Seismic events	Primary image	Secondary image	Satellite pass	Perpendicular baselines (m)	Temporal baselines (days)
1	6/02/2023	28/01/2023	09/02/2023	Asc (14) *Frame 114*	176.93	12
2	6/02/2023	28/01/2023	09/02/2023	Asc (14) *Frame 119*	174.67	12
3	6/02/2023	29/01/2023	10/02/2023	Desc (21) *Frame 465*	-105.69	12
4	6/02/2023	29/01/2023	10/02/2023	Desc (21) *Frame 471*	-108.15	12
5	20/02/2023	10/02/2023	22/02/2023	Desc (21)	-65.59	12
6	20/02/2023	09/02/2023	21/02/2023	Asc (14)	-2.03	12

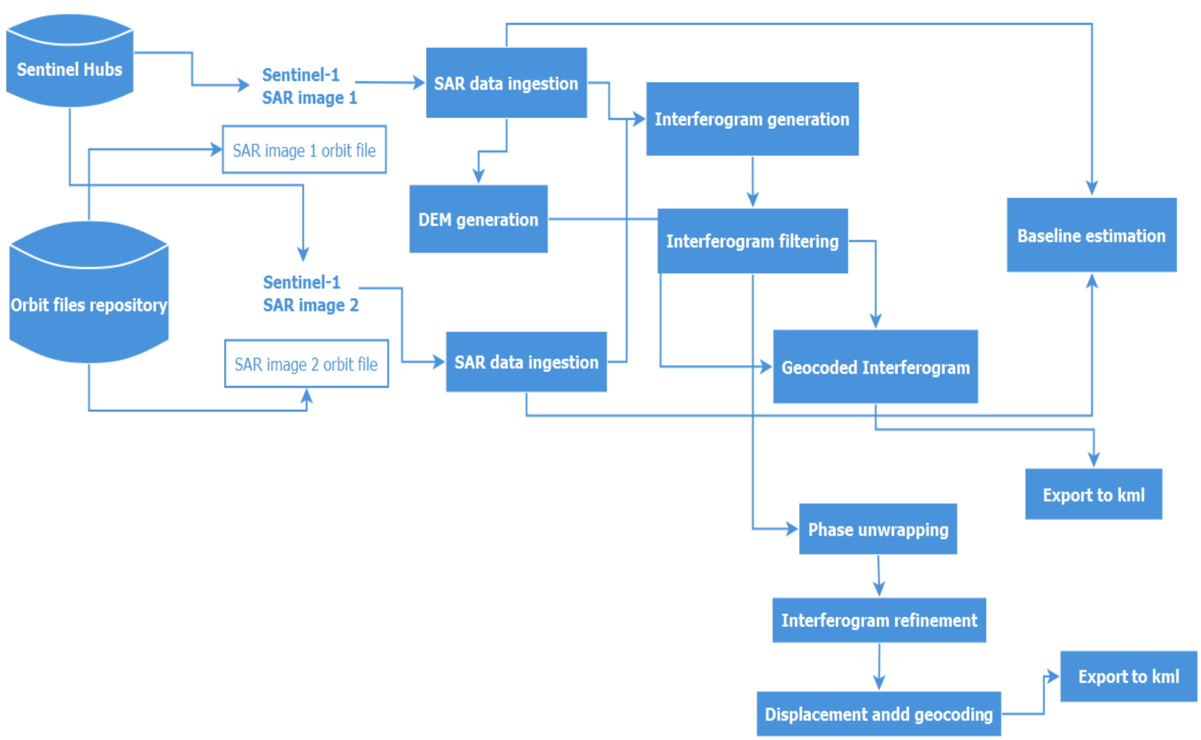


Figure 9: GeObservatory Interferogram processing chain.

3. RESULTS

3.1 Optical

Following the aforementioned methodology, the results from the change detection using optical data are described in this section. Specifically, the change detection analysis in Antakya was carried out using the image difference between February and March 2023 and the Global ML building footprints, as depicted in Figure 10. The area coverage related to the collapsed buildings from the earthquakes and the estimated number of damaged buildings is illustrated in Table 2.

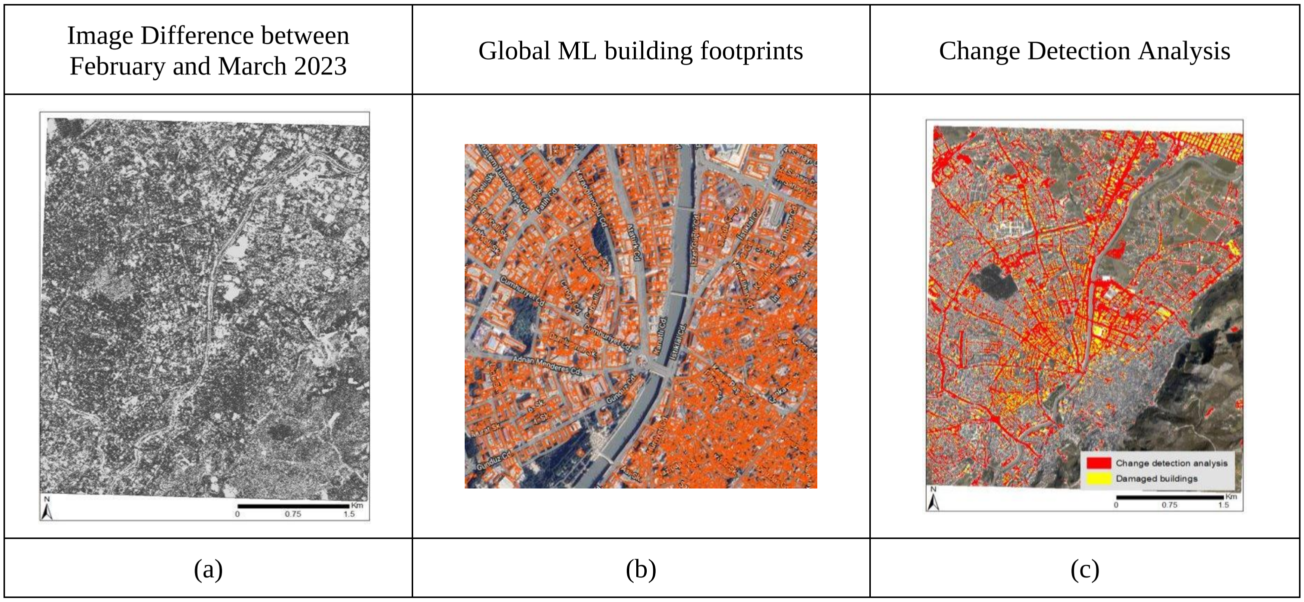


Figure 10: (a) Image difference between the PlanetScope imageries pre- and post- event, (b) building footprints and (c) Kmeans unsupervised classification for determining the affected area and overlaid damaged building footprints.

Table 2: Area coverage related to collapsed buildings from the earthquakes and the number of collapsed buildings based on PlanetScope and Global ML building footprints respectively.

ANTAKYA	**Area Coverage (km^2)**
Change Detection Analysis	6.5 km^2 out of total 20 km^2
Number of damaged buildings	10820

As mentioned before, nearly 2.7 million people remain internally displaced (internal refugees) living in formal settlements with accessibility to basic infrastructure and services (i.e., tents) while the humanitarian aspect becomes greater in Syria where war/politics conflict raises more the humanitarian aspect of the earthquake's impact as unorganized refugee camps have been placed with delay. The earthquake had a devastating impact also in the CH domain where the affected area is rich in CH assets and UNESCO protected monuments. According to the Directorate-General of Antiquities and Museums of Syria reported that the tremor caused minor and moderate injuries to the aforesaid castle. In particular, stones fell from the facades and walls of several buildings, the block of one of the towers on the northern side collapsed. The PlanetScope satellite imageries revealed important spatial information for both aforementioned aspects (Figure **11**).

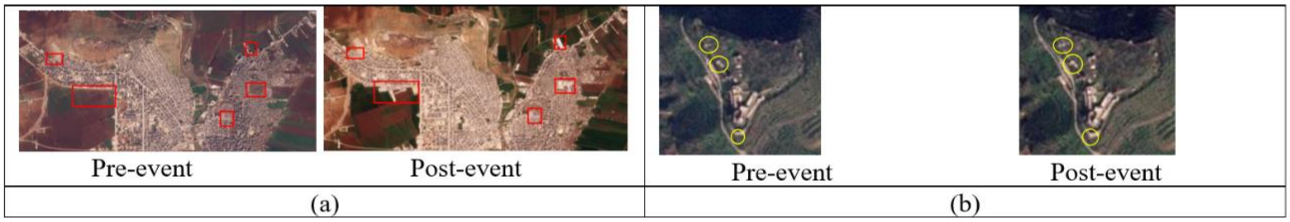
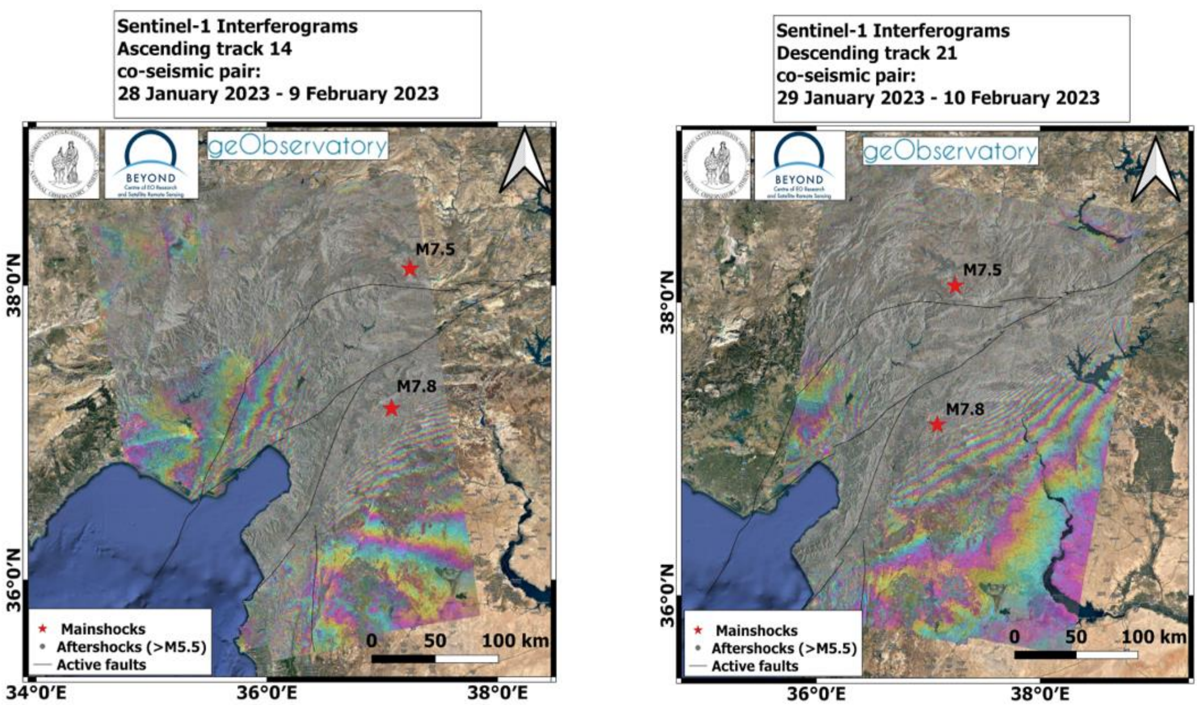


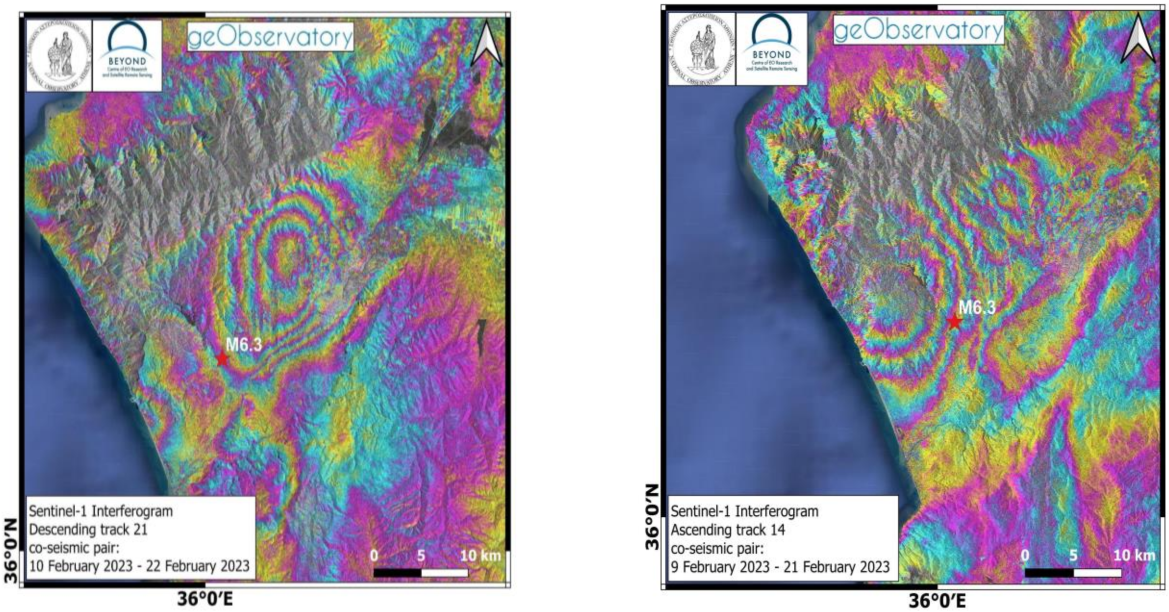
Figure 11: Refugee camps in the Syrian city of Afrin and (b) Marqab Castle in Syria with reported damages from Antiquities and Museums of Syria being detected by PlanetScope.

3.2 InSAR deformation field

Both ascending and descending satellite passes were employed to map ground deformation induced by the earthquakes in Central Turkey and in the Turkey-Syria border region. All co-seismic interferograms produced automatically by the geObservatory service are illustrated in Figure **12**. The M7.8 and M7.5 earthquakes were covered by two Sentinel-1 frames. Each fringe illustrated in the produced interferograms, corresponds to a ground deformation equal to 2.8 cm. DInSAR products provide clear insights about the extent of the affected areas, by these major earthquakes and the spatial distribution of the surface deformation. On the other hand, the implementation of the P-PSI processing on Sentinel-1 SLC images before the seismic events in Turkey, revealed ground subsidence phenomena in the broader region around Iskenderun city, with a maximum rate of -20mm/y. Figure 13 presents preliminary results on pre-seismic Line of Sight (LOS) ground displacement phenomena in a part of the area affected by the earthquake in Turkey. Further, analysis on more Sentinel-1 frames, with a better spatial coverage of the areas near the associated with the earthquake's faults and the epicenters of the earthquakes, will be included in future work. An extended pre-seismic analysis will add extra knowledge on the deformation regime of the broader area around the earthquakes in Turkey and a possible connection of pre-existing ground displacements phenomena with the major seismic events that occurred.



(a) (b)



(c) (d)

Figure 12: Co-seismic interferograms produced by the geObservatory, for February 6, 2023, in (a) and (b) Turkey region (M7.8 and M7.5), and (c), (d) the M6.3 Turkey-Syria border region on February 20, 2023.

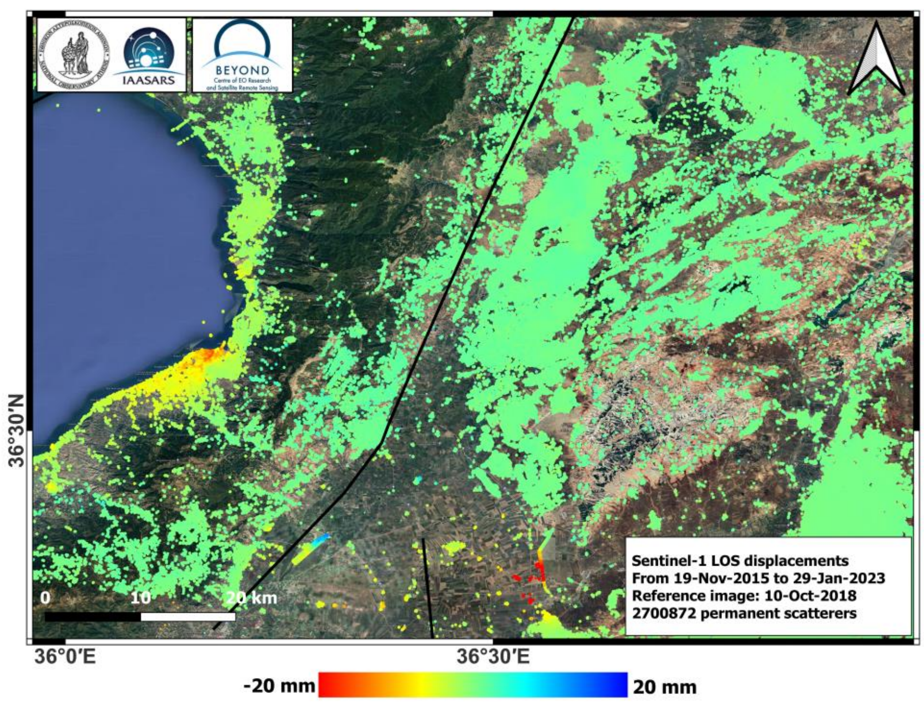


Figure 13: Pre-seismic Line of Sight displacements near the Surgu fault segment in Turkey, estimated with the P-PSI processing chain, by NOA.

4. CONCLUSION AND FUTURE STEPS

The main purpose of the current study is to exploit different satellite-based techniques to an initial impact assessment of Turkey's and Syria's earthquake sequence that commenced on 6 February 2023. Two major catastrophic earthquakes in Southern Turkey and many aftershocks caused extensive losses in lives, injuries and significant damages to buildings and infrastructures. As it is widely accepted, satellite-based data can provide extremely useful information for monitoring the post-effect of an earthquake, on a large scale, with no cost. The exploitation of satellite data, including optical and SAR imagery, provides critical information on ground displacements and overall impact of the earthquakes and their consequences. Hence, the continued monitoring and analysis of the seismic activity in Turkey can be defined as critical for improving disaster preparedness and reducing the risk of future catastrophic events.

The future steps of this study include an extensive analysis of the current results since they are in the initial stage. As a first step, the integration and comparison of the optical and SAR results will be carried out, enabling them to be presented in a common frame (e.g., heatmaps). Additionally, the decomposition of LoS displacements utilizing the ascending and descending tracks can be executed in order to estimate the vertical (up-down) and horizontal (east-west) components of the displacements. Finally, after implementing this holistic approach on the current results, a disaster management recovery and mitigation strategy can be performed and contribute to earthquakes' impact assessment, worldwide.

Acknowledgments

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Sentinel-1 data were provided by the Hellenic Mirror Site and the Sentinel Greek Copernicus Data Hubs (https://sentinels.space.noa.gr/). The BEYOND geObservatory (http://geobservatory.beyond-eocenter.eu/) processing chain was used for the generation of the coseismic interferograms.

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