Risk Analysis in Coastal and Cultural Heritage Areas Using SAR and AI-Based Change Detection Methodologies: The Case Study of Venice Lagoon

Pietro Mastro [(1)*], Antonio Pepe[(1)]

(1) National Research Council of Italy, Institute for Electromagnetic Sensing of the Environment (CNR-IREA), Napoli, Italy,

{e-mail: mastro.p@irea.cnr.it}

Introduction

The detection and monitoring of ground surface changes using multi-temporal, remotely-sensed images represent the most important applications of remote sensing (RS) technologies [1]–[3]. Various applications have extensively used optical RS sensors for change detection (CD). The CD process involves analyzing two or more images captured over the same geographical area at different times to identify significant land cover changes. While optical sensors have been widely used for CD, microwave RS images acquired by synthetic aperture radar (SAR) have been less exploited. However, SAR images in CD are attractive for operational purposes since SAR sensors are active instruments that can operate in any atmospheric and sunlight conditions [4], [5]. Remotely sensed data collected by several constellations of SAR sensors, such as the twin Sentinel-1A/B sensors of the European (EU) Copernicus, enable fast mapping of changes of Earth's surface and allow the time monitoring of areas prone to geohydrological disasters. Coastal flood risk is a global challenge, as about 40 million people living in coastal port cities will likely be subject to one significant coastal flood event per century. SAR remote sensing is a valuable tool for detecting and monitoring flood phenomena and can differentiate between inundated and non-inundated areas [1]–[4]. Flood risk increases due to urban growth, ground subsidence, and climate change. Identifying areas more prone to extreme floods helps optimize urban planners' civil protection actions and evaluate the damage. Recent advances in RS technology have allowed the generation of rapid damage prediction maps and associated models that are helpful in the occurrence of a flood event [3], [5]–[7].

Objective and methodology

In this work, the goal is to analyse the ground deformation (subsidence) occurred in Venice Lagoon in the recent years using the multi-temporal interferometric Small Baseline Subset (SBAS) technique [4], [7] and study the interlinked effects among the background subsidence of the area and the recent extreme flood events that occurred on November 2019. We propose to use a joint multi-pass coherent/incoherent CD strategy that allows analysing a short-term sequence of calibrated SLC images and rapidly computing damaged areas using two different kinds of change detection indices (CDIs). Given a set of three SAR images collected over an investigated area at times t1, t2 (pre-event), and t3 (post-event) (see Figure 1), we can calculate:

1) Mutual differences sigma naught maps between pre Υ_{pre} and Υ_{ev} event acquisitions;
2) The coherence ratio (CR) and the normalized coherence difference ratio (ND) of the pre- and post-coherence event acquisitions.

These indices are then cooperatively used to automatically extract changed areas using a random forest (RF) classifier.

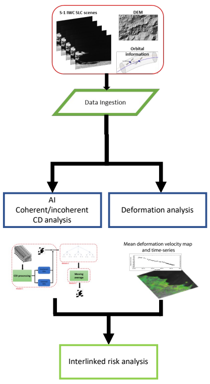

Figure 1. Interlinked risk analysis flowchart.

Experimental results

We conducted a detailed analysis using 180 Sentinel-1 images acquired from January 2017 to December 2021 to investigate ground deformation in the Venice Lagoon. We generated a stack of 1736 short baseline (SB) interferograms and computed the lagoon's time series of deformation and mean deformation velocity map. We also used a series of pre- and post-flood event acquisitions on 12 November 2019 to perform a change detection analysis of Venice using temporal multi-looked sigma nought maps and Coherence Changes Indexes (CCI) from an AI-based methodology. For the change detection analysis, we selected a time series of acquisitions with a temporal baseline of ±6, ±12, ±18 days before (11 November, 5 November and 30 October), during (17 November), and after (23 and 29 November, and 5 December) the flood event. Each SAR image of the time series underwent post-processing using a de-speckling noise filtering algorithm [13] and co-registration using Enhanced Spectral Diversity (ESD) to the 17 November acquisition. We computed sigma nought differences (Δσ_0), and we used triplet of SAR images with temporal baselines of ±6, ±12, ±18, ±30, ±36, and ±42 days with respect to the 12 November pre- and co-disaster InSAR ($ND_{post-pre}, \rho_{post-pre}$) CCI to determine the coherence changes indexes. The results of the interlinked analysis, presented in Figure 1, showed that only a tiny region of the emerged lands in the north and south of the Venice Lagoon is affected by subsidence. Flood events represent a severe threat to the integrity of these areas. The deformation analysis of the city of Venice showed no significant subsidence phenomena (Figure 2). Still, some spot regions over the low-lying lagoon terrains were affected by remarkable signals associated with sea level rise (SLR), which can seriously impact the hydrogeology of the area. More information on the determination of the introduced CDIs can be found in [3]. Figure 3 focuses on Venice City and compares the flooded areas detected by the RF-based proposed method to the one determined by the Copernicus Emergency Management System (EMS). Both maps are coloured red and superimposed on an S1 amplitude map of the city.

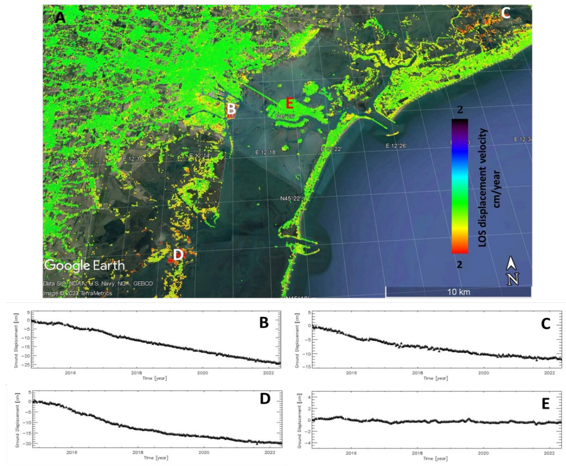

Figure 2. (A) 2014-2022 Mean deformation velocity map of the Venice Lagoon. (B-D) time series of deformation of areas of the north, center and south of Venice lagoon. (E) Time series of deformation of Venice city.

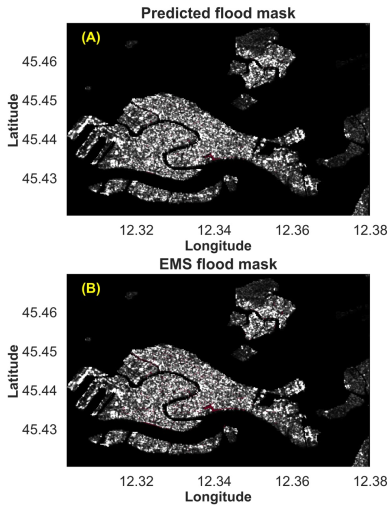

Figure 3. The flood map was determined (A) by the RF-based algorithm and (B) by the EMS. The flood maps are red-coloured and superimposed on an S1 amplitude map of Venice.

Conclusion

The interlinked analysis from the coherent and incoherent change detection methodologies, shows that only little region of the emerged lands in the north and south of the Venice lagoon are afflicted by subsidence phenomenon. In this case, flood events represent a serious threat to the integrity of these areas. Regarding, the city of Venice, the deformation analysis shows no significant subsidence phenomena. However, the incoherent analysis allows us to identify areas of change following the flood event. Areas that certainly need to be monitored to mitigate future risks and preserve the cultural heritage of the area.

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