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ADATools: a set of tools for the analysis of terrain movement maps obtained with SAR Interferometry

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ABSTRACT

The SAR Interferometry techniques, Persistent Scatterer Interferometry (PSI) among them, are nowadays known as important tools for monitoring Earth surface movements. Several regional and national Ground Motion Services based on PSI already exist. Moreover, since 2022 the European Ground Motion Service will be operational and will annually provide an updated displacement map over the whole Europe. This will suppose a big amount of ground displacement measurements along the European territory. For each measurement EGMS will provide the annual velocity and the time series of deformation covering the period 2014 to one year prior to each delivery. In this context, it will be more and more necessary having tools to ease the management, analysis, and interpretation, of those wide areas and huge amount of data. We present here a first step in this direction: the ADATools are a set of tools to automatically have secondary, and more operational, products derived from a PSI map. Starting from a fast extraction of the most significant Active Deformation Areas (ADA), with the ADAFinder tool, then we can have a preliminary classification of the most probable phenomena (landslides, subsidence, settlements, or sinkholes) that is behind the detected movement, with the ADAClassifier tool. Moreover, LOS2hv tool allows to derive the horizontal (east-west) and vertical components of the movement in case we have maps of ascending and descending geometries. Finally, it is presented a product that analyzes the local displacement gradients to generate potential damage maps in urban areas. The tools will be presented thorough some results obtained on an area of the Granada County with the use of Sentinel-1 data. All the results have been achieved within the framework of the Riskcoast Project (financed by the Interreg Sudoe Program through the European Regional Development Fund, ERDF).

I. INTRODUCTION

Satellite SAR interferometry (InSAR) is nowadays a consolidated technique for ground movement detection and monitoring. InSAR based techniques allow processing areas from regional/national scale up to local scale such as single buildings, providing a high density of displacement measurements at low cost (Carlà *et al.*, 2019; Galve *et al.*, 2017; Crosetto *et al.*, 2016). However, the outputs provided by such techniques are usually not easy to manage, difficult to understand, and demand the need of an expert to interpret those results. This might turn out to be a time-consuming task for users who are not familiar with radar data (Barra *et al.*, 2017).

Since 2014, Sentinel-1 satellites are acquiring data worldwide with a revisit time of 6-12 day. The data have been made available to everyone at no cost. This has prompted the tendency of increasingly using this technique for operational tasks related to monitor ground displacements like for example risk management activities, urban planning or geohazards monitoring. Such tendency is even more consolidated thanks to the regional, national, and European programs to investigate and improve the processing performances and broaden the operational use and application of the InSAR results to monitor ground displacements (Crosetto *et al.*, 2020).

In this context, the development of methodologies and tools to automatize the retrieval of information and to ease the interpretation of the results is a need to improve its operational use. In this work a set of tools, developed in the framework of the projects MOMIT, SAFETY, U-Geohaz and RiskCoast, is presented and an example of use in the framework of the project RiskCoast is shown. The RISKCOAST project focuses its work on the development of tools, methodologies and innovative solutions focused on the prevention and management of geological risks on the coast in a more effective way.

The presented work is as an example of multi scale application of InSAR for geohazard applications. It exploits the Active Deformation Areas tools (Barra *et al*., 2017) developed with the aim of facilitating the management, use and interpretation of InSAR-based results. The test site is the Coast of Granada County. The displacement velocity and the displacement time series have been estimated over the area by processing Sentinel-1 (A and B) SAR images. From these initial InSAR outputs the most significant Active Displacement Areas (ADAs) are semi-automatically extracted using the ADAFinder tool (Barra *et al*., 2017 and Navarro *et al*., 2019). Then we show the subsequent application of ADA classifier and potential damage map generation on different ADAs located in the test area. All the used tools go in the same direction of the European Ground Motion Service (EU-GMS) project, which will provide consistent, regular, and reliable information regarding natural and anthropogenic ground motion phenomena all over Europe (Crosetto *et al*., 2020).

II. METHODOLOGY

A. *Dataset*

A stack of 230 co-registered SAR Sentinel-1 Wide Swath Single Look Complex (SLC) images acquired in Ascending geometry during the period November 2015 to May 2020 has been processed at full resolution. The resolution of Sentinel-1 data is approximately 4×14 m^2. Specifically, one burst has been processed to cover the area of interest. Images from Sentinel-1A and Sentinel1-B satellites have been exploited with a minimum temporal sampling of 6 days. The SRTM Digital Elevation Model provided by NASA was used to process the interferometric products.

B. *Data processing*

This section summarizes the methodology applied in this test site to generate the different products. The methodology applied is based in a multi-step processing procedure which includes four main stages: InSAR processing, ADAs extraction, ADAs classification and Potential Damage maps generation.

The goal of the InSAR processing stage of the procedure is to derive the deformation information of the area of interest from SAR data. The approach is independent of the used PS/SBAS method. In this work, the Persistent Scatterer Interferometry chain of the Geomatics (PSIG) Division of the CTTC described in Devanthery *et al*. (2014) has been used. The main steps of PSIG are: (1) interferogram generation; (2) interferogram network selection taking into account the temporal behavior of the coherence. Such analysis allows to locate and remove those interferograms characterized by low coherence (*e.g*., snow periods in mountain areas); (3) selection of points based on the dispersion of amplitude; (4) estimation of the residual topographic error and subsequent removal from original single-look interferograms; (5) 2+1D phase unwrapping of the redundant interferograms which generates a set of N unwrapped phase images, which are temporally ordered in correspondence with the dates of the SAR images processed, hereafter referred as time series of deformation (TSD); (6) atmospheric phase screening estimation using spatio-temporal filters and removal from the TSDs generated in the previous step; (7) estimation of the velocity of deformation from the TSDs and; (8) geocoding of the results.

The main outputs of the InSAR processing stage is a deformation map composed of a set of selected points, called Persistent Scatterers (PSs), with information on the estimated Line of Sight (LOS) velocity of deformation and the accumulated deformation at each Sentinel-1 image acquisition time, *i.e*. TSDs.

The second step is the ADAs extraction. The main goal is the identification and mapping of those areas where deformation has been measured by the PSIG processing. To this aim we have used the ADAfinder tool (Barra *et al*., 2017; Navarro *et al*., 2019). The input of this stage is the PS cloud of the area of interest generated in the previous step. ADAfinder allows to filter the input potential outlier PSs and ease the detection of ADAs. The ADAfinder employs the information contained in the PS cloud to define each ADA on the basis of their location and density of PSs. It requires some thresholds as the minimum number of PSs making an ADA or the area of influence of each PS need to be defined. In this study the minimum number of PS is set to 5 and the area of influence of each PS was set to 26 m. Each ADA is associated with a quality index which describes the noise level and the consistency of the displacement TSDs among the PSs forming each ADA. The QI ranges from Class 1, which represents the ADA characterized by very high quality TSDs to Class 4. The areas with Class 4 have been neglected in the next steps of this study. For detailed information regarding the procedure to identify the ADAs and assess their quality please refer to Barra *et al*. (2017) and Navarro *et al*. (2019). The outputs of the ADAs extraction stage are two shapefiles containing the filtered deformation map and the ADA map.

The third step is to apply the ADA classifier. The tool provides a preliminary assessment on the nature of the detected ADA. It semi-automatically categorizes each ADA into potential deformational processes using the information provided by ADA finder, PS clouds and ancillary external information. The output of ADAclassifier is an extended version of the ADA shapefile. It adds extra fields to the attributes of the ADAs providing information about the certainty to belong to each one of the four considered processes: Landslides, sinkholes, subsidence's and settlements. A more in-depth description of the ADA classifier tool cand be found at Tomas *et al*. (2018).

Finally, in the last step, the gradients of the displacement of each ADA are used to detect those buildings which are strongly affected by the measured displacements and thus which can be potentially damaged in the future. It works ADA wise. The output of this step is, for each ADA, a 5-class map describing the potential level of damage of the building within the ADA. It is worth noting that it only considers the intensity of the gradient of displacement to anticipate which areas would require a more in detail analysis.

III. RESULTS

The results of the application of the proposed methodology are described in this section. Specifically, we are going to focus on different moving areas located along the coast of Granada. Figure 1 shows the obtained displacement velocity map and the subsequently derived ADA maps.

A. *Displacement maps and ADAs identification*

Figure 1 shows the deformation velocity map generated with the PSIG processing in a test site of the project, approximately 40 x 15 km^2 between Nerja and Castell de Ferro (both located in Granada County, Spain). The green points indicate stability, the red colors indicate movements away from the satellite and the blue colors movements towards the satellite. A total of 215000 PSs were measured in that area. The estimated precision is 1.5 mm/yr. Several sectors affected by deformation phenomena can be easily identified.

The ADAfinder tool extracted 148 ADAs with QI higher than 4. Figure 1 bottom shows its distribution along the area of study. It can be clearly observed that some of them are located along the coastal line.

Figure 2 shows an example of the area framed by the red square in the Figure 1. The figure shows two different examples of identified ADAs along the Highway A7. One with QI=1 and one with QI=4. The figure shows the ADA polygons together with the displacement velocity maps and some displacement time series.

In this case, the TSDs (Figure 2a) show a low level of noise and display a consistent deformation behavior with movements away from the satellite of up to -60 mm (QI=1). On the contrary, ADA (b), with a QI=4, represents the lowest quality of ADA that can be extracted. The TSDs of three of the PSs (Figure 2b) that make that ADA show a higher level of noise and different behavior. In this case, TSD3 exhibits a near linear movement away from the satellite that seems to stabilize at the end of the observation period with a maximum displacement of up to -70 mm, TSD4 displays stability at the beginning of the observation period followed by a small window of time where there is movement away from the satellite and then stability with a maximum displacement of -40 mm, and finally TSD5 showing a smaller movement away from the satellite at the beginning of the observation period and the remains more or less stable compared with the other two TSDs.

B. *ADA classifier*

Figure 3 shows the ADA Classifier main output. It shows the obtained classification for three different processes. Given a process, the ADA classifier assign to each ADA a level of certainty to belong or not to this type of process. Figure 3 shows the level of certainty of the detected ADAs to belong to landslides, subsidence's or settlements class. The level of certainty is 4-class parameters: red means that the ADA is explained by the tested process, yellow is that the ADA is potentially explained by the tested process, green it is not the tested process and grey mean that there is not enough information to classify the ADA.

The results show some potential landslide. Some of them are already known slope instabilities affecting the coast of Granada. Among them can be find the urbanizations of Los Almendros and Alfamar which will be discussed later in this document.

5 areas have been classified as settlements. Some of them lay on the recently built A-7 railway and one on a building close to the port of Motril; both structures were built between 2014 and 2015.

It may be observed that it can be that an ADA can be classified as two or more phenomena. This can happen for different reasons like insufficient ancillary data or simply that the ADA fulfills the different requirements to lay in one or another phenomenon. However, a multiple classification of the same ADA lets the final user know that the detected movement is a complex case.

C. *Potential damage maps*

The last step of the procedure is to perform an analysis of the displacement's gradients at the ADA level. The aim of this analysis is to assess the potential damage to be suffered by a building or infrastructure along time. Such analysis is performed considering only the intensity of the differential displacements affecting each structure.

Figure 4 shows the examples of the obtained potential damage maps in two different areas: Monte de Los Almendros (a) and Alfa Mar (c).

The methodology is still under development. Here we show the preliminary results. The Figure 4a shows the potential damage map obtained over the Urbanization Monte de Los Almendros. The color assigned to each building represent the different level of potential damages considering the intensity of the differential displacements affecting the building. Red color represents the highest level of probability to be damaged along time while green means very low probability. Figure 4c shows the same result but for the Alfa Mar urbanization. The right column of Figure 4 shows the damage inventories obtained from a field work during the year 2019. At a first glance one may see that there is a disagreement between the maps obtained with the proposed methodology and the infield observations. This point is developed in the discussion section.

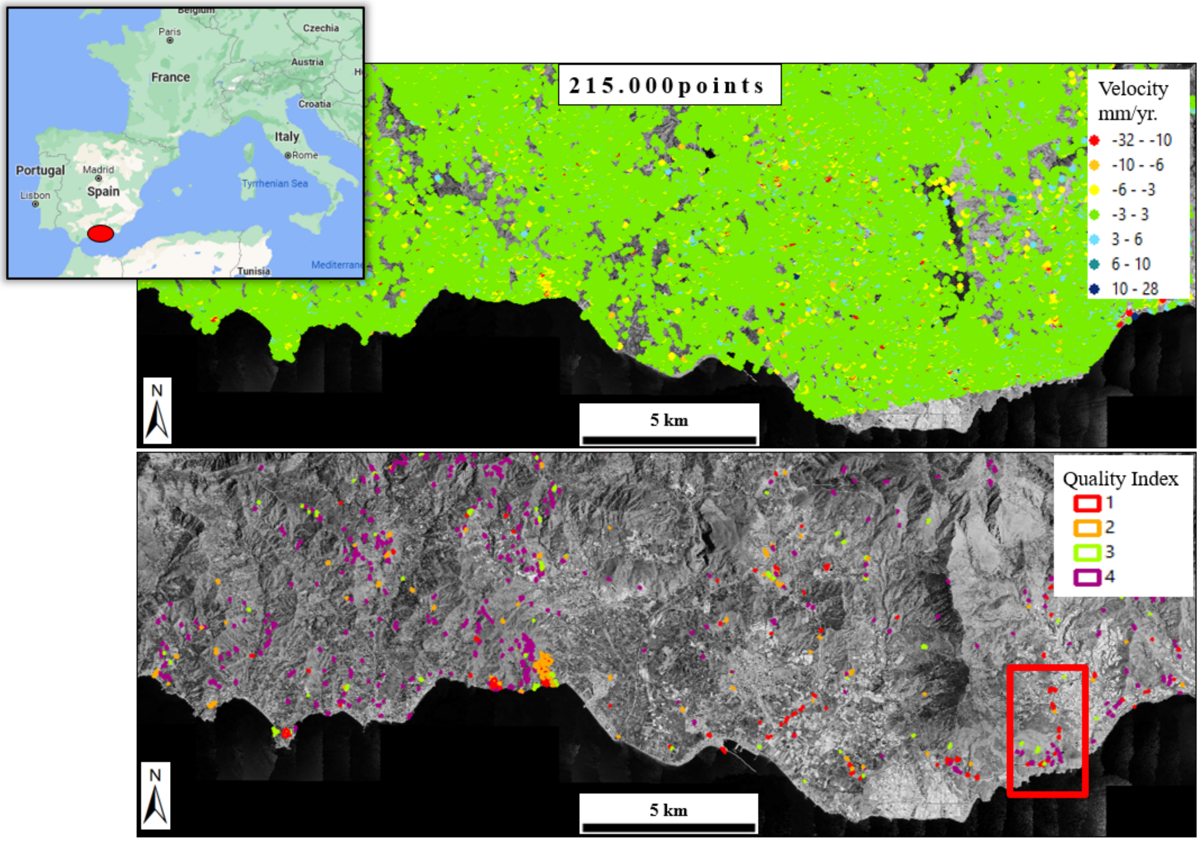

Figure 1. Global view of the results over the area of study. Deformation velocity map (up) and detected ADAs (bottom).

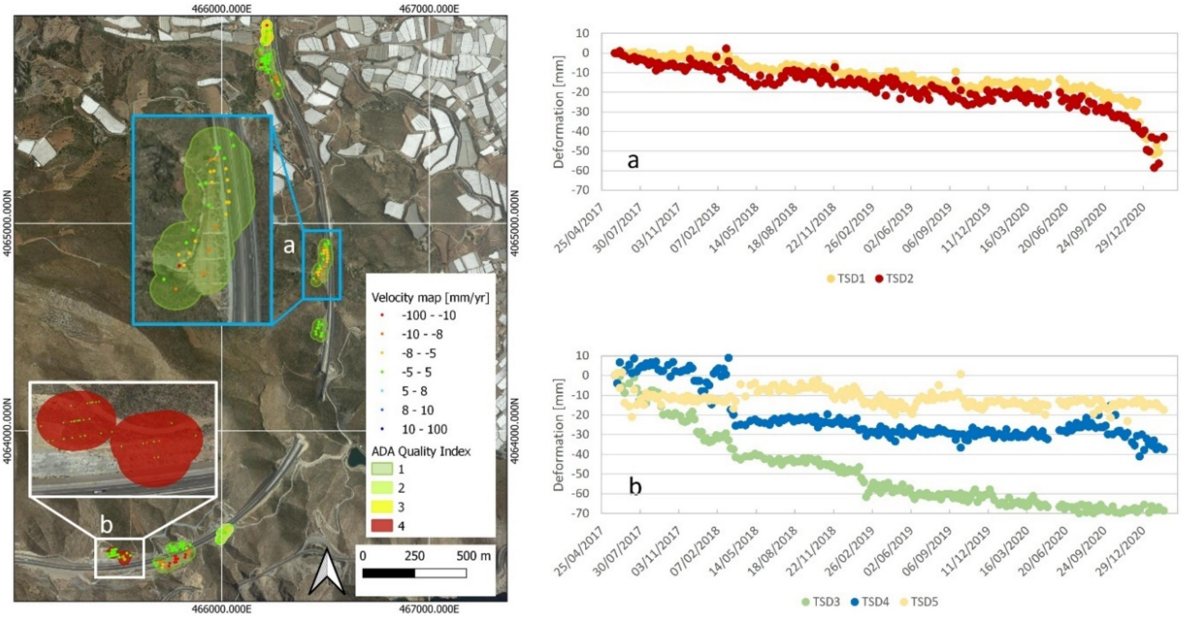

Figure 2. ADA map of the area highlighted by the red frame in Fig. 1, with two amplified ADAs (a and b) affecting two sectors of the A-7 highway. The velocity of deformation of the active PSs showing instability are displayed in this map. Stable PSs have been filtered out by the ADAfinder tool. Two time series of deformation (TSD) are displayed for each sector as example.

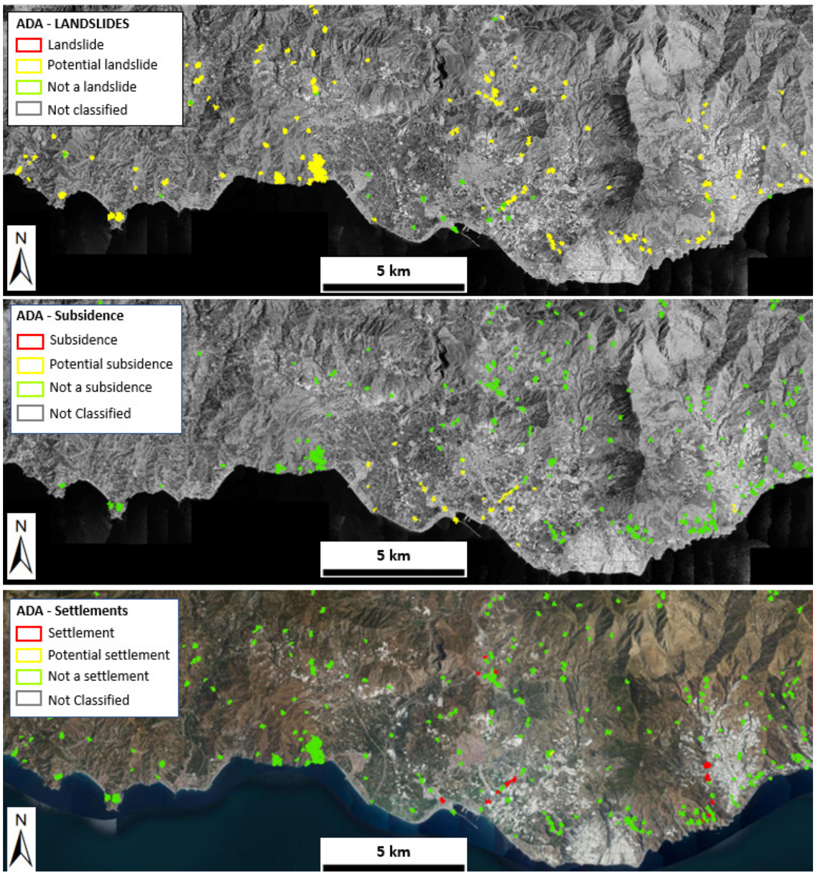

Figure 3. Results of the ADA classifier for three types of processes: (up) Landslide classified phenomena; (centre) Subsidence classified phenomena; and (bottom) settlements classified phenomena.

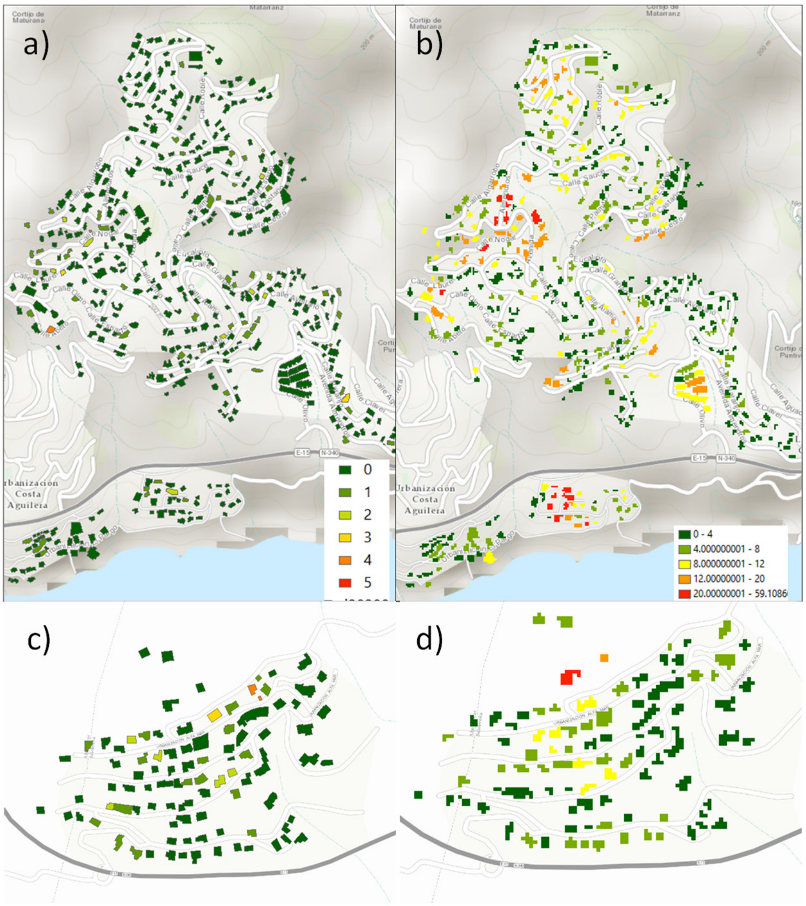

Figure 4. On the left part, the potential damage maps of Monte de Los Almendros (a) and Alfa mar (c). On the right part, the damage inventories obtained from a field work during the year 2019 in Monte de Los Almendros (b) and Alfa Mar (d).

IV. DISCUSSION

The work presented in this article represents an integration of the PSIG processing chain and the ADAtools developed at the Geomatics Division of the CTTC. The main goals are two: (i) to simply and ease the interpretation of the velocity map and TSDs resulting from Advanced DinSAR processing methods, and (ii) to provide more advanced products to support prevention against geohazards and urban-planning activities.

The first aspect to be underlined is that ADA detection does not overcome the intrinsic limitations of the InSAR techniques, *i.e*. the absence of ADAs does not necessarily imply stability since it could also mean non-detectable movement due to unfavorable geometry (Ferretti *et al*., 2007) or lack of information due to low coherence.

The approach has been tested in the Coast of Granada (Spain). Several displacement phenomena have been detected. 148 Active Deformation Areas have been detected. Among them, 5 have been classified unambiguously as settlements and corresponds to recently constructed areas. Some other areas have been classified as potential landslides. The field work and the existing literatures have confirmed that most of them area actually active landslides. The results illustrate very well the high potential of the ADA finder and Classifier. The first one only depends on the DInSAR based results and thus its quality is strongly linked to them. However, the reliability of the ADA classifier relies on the available ancillary data. This can be a strong constrain at different places of the world.

Regarding the Potential Damage maps, we have shown the preliminary results obtained in two active areas: Monte de Los Almendros y Alfa Mar. The results show that there is a noticeable disagreement between the field survey and the maps obtained from DInSAR. However, this disagreement can be explained by different aspects:

- The satellite-based results only take into account the detected local differential displacements. Nor the structural characteristics of the building its foundations. This can strongly condition its vulnerability.
- The disagreement can be also explained because the in-situ damage maps are based on the visual inspection of the visible part of the buildings. Thus, it can happen that the damages are simply invisible.
- Finally, a third reason of disagreement could be explained by the time of inspection. We are looking to a long process on time. This means that the movement has still not damaged the building or that the damages have been repaired. We refer here to those points where damages have been observed in the field but not in our approach.

The results obtained prove that the method applied in this work might prove useful for a fast and semi-automatic detection of geohazards and assessment of its potential effects. The ADAfinder and Classifier tools provide an approach to rapidly assess the InSAR products to detect critical unstable areas that can be easily used by Civil Protections and Geological Surveys. Moreover, the potential damage maps together with the European Ground Motion Service can be a powerful tool for urban planning.

V. CONCLUSIONS

The implemented methodology detects and analyzes ground displacements based on satellite InSAR techniques and the ADAtools. A description and analysis of the results obtained for an area located in Granada County (Spain) have been presented in this paper. The complementarity of the PSIG InSAR technique and the ADA tools have been demonstrated. On one hand, InSAR techniques are able to provide displacement measurements over large areas at low cost, but the difficulty to interpret those results by non-expert users hamper their use by decisions makers. On the other hand, the ADA tools allows a semi-automatic identification of critical areas affected by instability, *i.e*. the ADAs, and provides a preliminary assessment on the nature of the moving process. The ADA tool might be exploited to obtain a fast selection of deformation areas. However, an advanced analysis and interpretation is possible with the combination of all outputs as presented in this work. An integrated analysis of the velocity of deformation map, the TSDs and the ADA map might prove very useful to interpret the geological and geotechnical processes affecting wide areas and to assess the potential effects on buildings and infrastructures. Furthermore, this set of techniques will support the exploitation of the European Ground Motion Service (EU-GMS), which will provide consistent, regular and reliable information on natural and anthropogenic ground motion phenomena all over Europe.

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