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From Picture to Movie: Twenty Years of Ground Deformation Recording Over Tuscany Region (Italy) With Satellite InSAR

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Synthetic Aperture Radar Interferometry (InSAR) techniques have been long exploited for detecting and mapping slow-moving ground surface displacements due to their millimeter accuracy, non-invasiveness and wide area coverage. A review on different applications of Persistent Scatterers InSAR approaches, proposed and applied over Tuscany region (Italy) across time, is here presented. The study area is characterized by both subsidence of alluvial plains and landslides on hilly and mountainous reliefs. Tuscany has a leading role in Italy in the field of interferometric applications: the first InSAR analyses, which date back to 2003, were performed at local basin scale, by exploiting various PSI-based approaches for risk mapping. The first InSAR applications at regional scale date back to 2009, relying on historical SAR archives of ERS and ENVISAT satellites for updating subsidence and landslide inventory maps at a certain temporal date. Nowadays, the availability of Sentinel-1 SAR data with a regular and systematic 6-days acquisitions plan, allows near-real time monitoring of deformative scenario at regional scale rather than solely mapping of geo-hydrological phenomena. Most recent innovative InSAR applications over Tuscany region scan the territory, exploiting the regular repeat pass of Sentinel-1, and promptly highlight the sites affected by the highest ground movements with high temporal frequency. Such approaches permit us to pass from a static 'picture' of regional slope instability to a weekly updated 'movie' with improved detail, useful for civil protection practices. These last ongoing works significantly enhance the value of multi-temporal InSAR approaches for investigating and managing geo-hazards over the Region.

Keywords: InSAR, Persistent Scatterers Interferometry, Tuscany, ground deformations, monitoring

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INTRODUCTION

Synthetic Aperture Radar Interferometry (InSAR), based on the analysis of the phase difference between multi-temporal SAR images, has demonstrated to be a reliable technique to detect and map slow-moving ground displacements with millimeter precision thanks to their non-invasiveness, high resolution, wide area coverage and cost-efficiency (Massonnet and Feigl, 1998; Rosen et al., 2000).

Until recently, the full-effective exploitation of C-band satellites, such as the ESA (European Space Agency) sensors ERS 1/2 and ENVISAT or the CSA (Canadian Space Agency) RADARSAT-1 and RADARSAT-2 platforms, was limited by the relatively long revisiting time (35 or 24 days) and the quite long latency time for the delivery of the acquired SAR data (Rucci et al., 2012). The second-generation X-band satellite constellations like COSMO-SkyMed, launched by ASI (Italian Space Agency), and TerraSAR-X, developed by DLR (German Aerospace Center), are characterized by higher resolution and a shorter revisiting time, from 4 to 11 days. Nevertheless, their expensive exploitation, spatial coverage and irregular acquisition plans (due to both scientific and military use) greatly constrain their use (Showstack, 2014). The new ESA Sentinel-1 mission ensures the C-band SAR continuity and reduces these limitations by guaranteeing global and costless observations with a revisiting time of 6 days and providing an efficient service reliability with near-real-time delivery for risk management applications.

Tuscany region (Italy) has been long monitored with InSAR data (e.g., Canuti et al., 2005; Lu et al., 2010; Brugioni et al., 2013; Bianchini et al., 2015; Solari et al., 2016; Rosi et al., 2018) and it is nowadays the first Italian region to test a continuous interferometric analysis based on Sentinel-1 PSI (Persistent Scatterers Interferometry) products for monitoring geo-hazards with a 6 days repeatability.

In this mini-review we summarize various past and recent InSAR applications over Tuscany region at both local and regional scale, and we focus attention on the on-going innovative regional monitoring of ground movements in "near real-time" by means of the most recent advancements in multi-temporal interferometric tools (Raspini et al., 2018; **Figure 1**). This most recent approach marks the passage from a static 'picture' of the regional deformation scenario to a weekly updated 'movie' that can be useful for civil protection practices. Research gaps and potential future perspectives for developments in the field are also highlighted.

OUTLINES OF TUSCANY REGION, ITALY

Tuscany region extends up to about 23,000 km^2 in west-central Italy. Tuscany is administratively divided into 10 provinces (namely Firenze, Arezzo, Siena, Grosseto, Pisa, Livorno, Massa-Carrara, Pistoia, Prato, and Lucca), each divided into smaller municipalities.

The territory is composed of different morphologies, mainly characterized by gently rolling hills and flat areas bordered by mountainous ridges. The lowlands of Tuscany are either interior valleys, such as that of the Arno River, or coastal plains along the Tyrrhenian sea (**Figure 1**).

Tuscany is overall characterized by several subsidence areas in its wide alluvial plains and by landslides, mostly occurring on the hilly and mountainous sedimentary, metamorphic or volcanic reliefs (Carmignani et al., 2013). Some references dating to the 1990s stated that about 0.3% of the total regional surface is involved in mass movements for a total area of about 68.72 km^2 (Catenacci, 1992; Bertocci et al., 1995) and the present situation is worsen.

The most comprehensive regional landslide inventory derives from integration of different landslide databases, such as Basin Authorities Inventories, Geological Maps and Municipal Structural Plans, and includes 91,366 phenomena (Rosi et al., 2018). Subsidence phenomena mainly occur on coastal plains (e.g., in Maremma plain in Grosseto province) and in some internal plains due to ground water overexploitation (i.e., Florence-Prato-Pistoia basin and Chiana plain), fine-grained sediment consolidation due to load imposition or geothermal activity (i.e., Larderello in Colline Metallifere area) (Raucoules et al., 2003; Botteghi et al., 2015; Rosi et al., 2016; Solari et al., 2017; Del Soldato et al., 2018).

PAST InSAR RECORDS OVER TUSCANY REGION

Tuscany is one of the first Italian regions monitored with satellite techniques, involving data achieved by space-borne SAR. The first relevant applications dated back to 2000s and were tested at basin scale. In Colombo et al. (2003) the subsidence phenomenon of the Firenze-Prato-Pistoia basin, which is about 400 Km^2, was studied by means of SAR images acquired by ERS-1/2 satellites. These data, spanning a time interval of two years (August 1998–July 2000), were processed through classic Differential InSAR (DInSAR) techniques (Gabriel et al., 1989; Costantini et al., 2000).

Such an approach proved its potential for mapping ground lowering deformation bowls and for analyzing the effects of aquifer overexploitation on the terrain surface, so far not deeply studied through other traditional monitoring techniques. A phase variation of 2π radians on the differential interferogram corresponded to a terrain movement of 28–30 mm measured along the satellite Line Of Sight (LOS). This displacement is assumed as real vertical component of ground motion due to the type of movement (subsidence) and the flat morphology of the basin (Colombo et al., 2003; **Figure 1**).

Atmospheric disturbances and phase decorrelation caused by temporal changes of the terrain properties can affect the quality of the interferograms. The development of robust techniques based on the interferometric analysis of long stacks of SAR images (i.e., multi-interferogram approach), such as the Permanent Scatterers (PS) (Ferretti et al., 2001) or the small baseline (SBAS) (Berardino et al., 2002), allowed the limitations of traditional DInSAR approaches to be overcome. In the following years, Canuti et al. (2005) and Farina et al. (2006) used these advanced multi-interferogram InSAR (A-DInSAR), now generally pointed out as PSI (Persistent Scatterers Interferometry) approaches, for mapping ground deformations at basin scale over the Arno River alluvial plain, within the SLAM project (Service for Landslide Monitoring) funded by ESA (**Figure 1**).

Other applications from A-DInSAR techniques within the Arno River basin exploited the information on mean deformation rates of ERS and ENVISAT PSI data for the detection and mapping of mass movements (i.e., Agili et al., 2004;

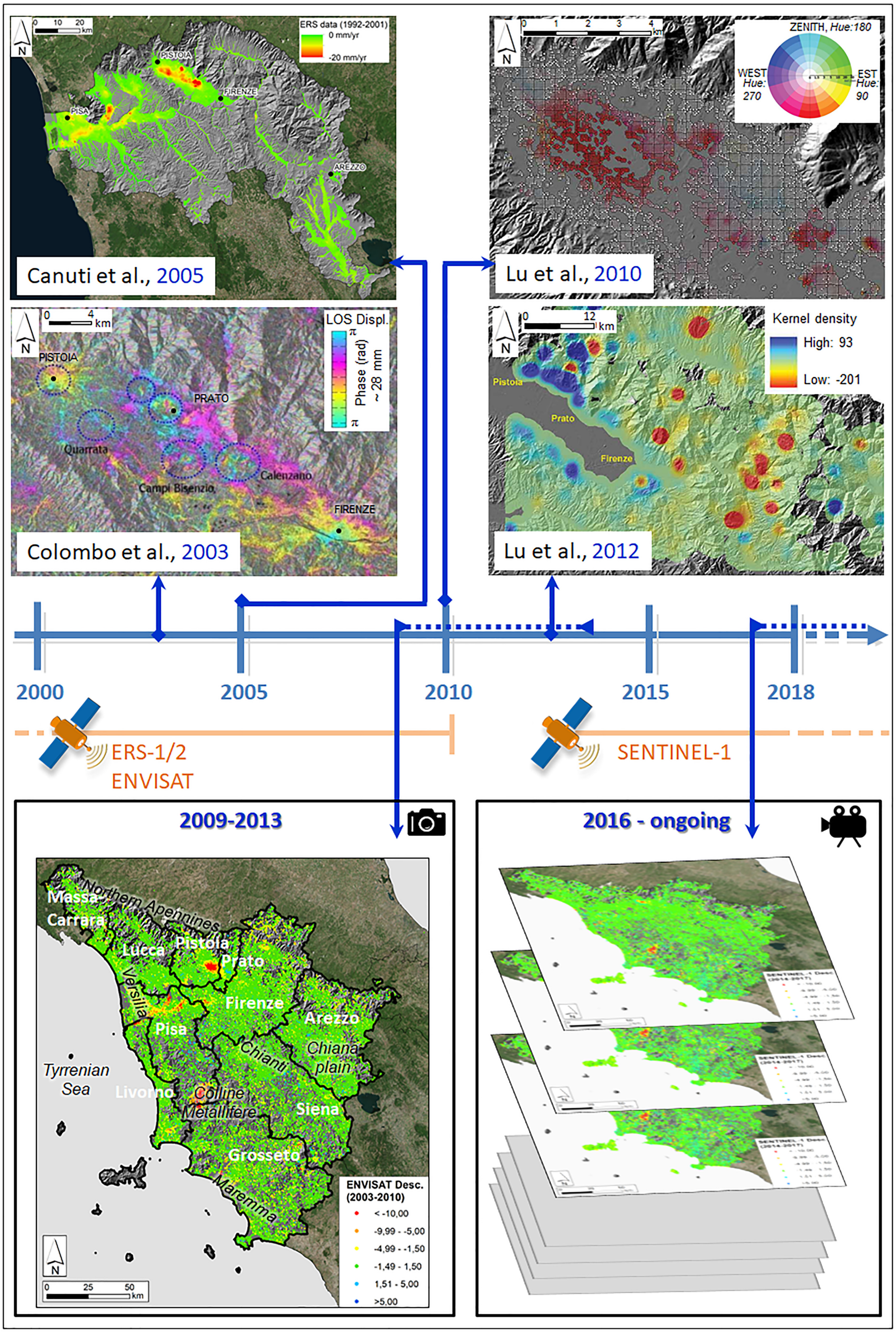

FIGURE 1 | Overview of past and recent InSAR applications in the Tuscany Region, Italy (modified after Colombo et al., 2003; Canuti et al., 2005; Lu et al., 2010, 2012; Rosi et al., 2018. We have obtained the copyright permissions to use already published figures).

Brugioni et al., 2013) and for the assessment of hazard and risk (Lu et al., 2014). In particular, interesting works that include innovative statistical PSI-based elaborations, are found in Lu et al. (2010, 2012), namely the PSI-HSR (PSI - Hue and Saturation Representation) and the PSI-HCA (PSI - Hotspot and Cluster Analysis) (**Figure 1**). The PSI-HSR consists of a new method for synthesizing the displacement vectors from both ascending and descending orbits and representing PSI point targets using the hue–saturation scale. The Pistoia-Prato-Firenze basin, affected by intensive groundwater withdrawal during the last decades and therefore by intense subsidence, was monitored with ERS and RADARSAT PSI data and was displayed by means of a HSR color ramp for an easy interpretation of moving velocities. The subsidence boundary and zonation were clearly mapped, on the basis of a homogeneous transition in the hue–saturation color wheel (in the map from yellow in the west to magenta in the east) and the lowering deformation rates reach up to 30 mm/year during the period 1992–2001 and 40 mm/year during the period 2003–2006 (Lu et al., 2010). The PSI-HCA approach consists of an automatic procedure for rapid detection of slow-moving landslides from PS data by means of a statistic tool (i.e., Getis–Ord Gi* statistics) that highlights spatial clustering of high-velocity PS benchmarks, representative of the possible existence of intensive mass movements (Lu et al., 2012).

At local scale, some works focused on single subsidence phenomena in Tuscany region: Canuti et al. (2006) reported subsidence mapping in the Lucca plain in north-western Tuscany, by comparing groundwater fluctuations with ground displacements recorded by ERS SAR. Rosi and Agostini (2013) presented the ground lowering in the Cornia river basin in South Tuscany through ENVISAT SAR data acquired in 2003–2010 and processed with PSI techniques, showing mean values of about 35 mm/year in the geothermal area of Larderello and 10 mm/year in the Venturina area due to the overexploitation of the aquifer. More recently, Solari et al. (2016, 2017) studied subsidence in the urban area of Pisa on the Arno coastal plain in relation to stratigraphical factors and urbanization: the spatial distribution and temporal evolution of ground displacement rates were quantified by means of different sensors: ERS, ENVISAT, RADARSAT-2, and COSMO-SkyMed images elaborated with the PSInSAR and SBAS algorithms and integrated with stratigraphical and geotechnical information.

Some further PSI-based studies at local level in Tuscany Region deal with the analysis of landslide-affected areas at municipal scale or at the scale of the single phenomenon: some examples are Rosi et al. (2013) who characterized a landslide in Ricasoli Village (Italy) in the Upper Arno river Valley using PS satellite interferometry combined with geotechnical investigations and numerical modeling, and Bianchini et al. (2015, 2017) who investigated the slope instability in Volterra area (Pisa) through InSAR and GIS tools for landslide-induced damages evaluation and risk analysis.

The main work based on A-DInSAR techniques with a regional coverage in Tuscany was carried out in the framework of the DIANA (Dati Interferometrici per l'ANalisi Ambientale – Interferometric data for environmental analysis) project funded by Tuscany Region authority in 2009–2013 (**Figure 1**). DIANA dealt with landslide and subsidence detection and mapping of the whole regional territory by exploiting ERS and ENVISAT PSI data, distributed by the Italian Ministry of the Environment and Protection of Land and Sea, and processed by PSInSAR and PSP-DIFSAR approaches (Costantini et al., 2008). In this project, the mean deformation rates recorded by PSI radar targets were analyzed for the boundary updating of mass movements and for the evaluation of their state of activity and intensity by means of photo- and radar-interpretation procedures (Farina et al., 2008; Cigna et al., 2010; Bianchini et al., 2012; Tofani et al., 2013) supported by ancillary layers (e.g., DTM, topographic and geological maps) and some focused field checks. The existing regional landslide inventory map was updated to 2010 with historical ERS and ENVISAT interferometric data, and results can be found in Rosi et al. (2018). Natural and anthropogenic subsidence in Tuscany region was also studied at regional level: in Rosi et al. (2016) a regional subsidence map was provided by exploiting ENVISAT data ranging in time from 2002 to 2010, following the approach proposed by Rosi et al. (2014). Several subsiding areas were identified and some of them (i.e., Arno Lower plain, Arno Middle plain, and Larderello geothermal district) were analyzed in detail (Rosi et al., 2016).

The overall spatial coverage of the Tuscany region with the ERS satellite dataset is widely incomplete, whereas the ENVISAT dataset covers the entire regional territory. However, these data present a static deformational scenario that is updated to a given date (last available acquisition of ENVISAT satellite in 2010) as a standing "picture" of the regional geological hazard setting.

ON-GOING InSAR MONITORING

The most recent InSAR application in Tuscany region that was set up since 2016 is based on the systematic processing of current SAR Sentinel-1 data through the SqueeSAR algorithm (Ferretti et al., 2011), thus providing a PS continuous streaming for monitoring and mapping of terrain motions (Raspini et al., 2018). This is innovative near-real time monitoring of ground instability at regional scale that scans the territory every 6 days by exploiting PSI Sentinel-1 data that rapidly points out the fastest deformations and most hazardous sites over the whole Tuscany Region.

Firstly, PSI-based ground deformation maps are generated for both ascending and descending geometries to obtain a synoptic and retrospective view of the main areas affected by ground deformation. Secondly, in order to achieve the transition from historical analysis to a near real-time monitoring program based on SAR, once a new Sentinel-1 image dataset is available, then it is automatically downloaded and added to the existing archive: the new data stack is therefore entirely reprocessed to generate new ground deformation maps and updated time series (TS) of displacement. A series of subsequent updates is created every 6 days using Sentinel-1A/B SAR images, providing a weekly updated 'movie' of the regional deformational scenario (**Figure 1**). By following the creation of updated ground deformation maps, TS of each measurement point is systematically and automatically analyzed to identify any change in the deformation pattern within a defined temporal span of the TS (i.e., in the last 150 days). If a velocity-change occurred (TS change), a breaking point is identified and the average deformation rates before and after are re-computed: if their difference $|\Delta V|$ is higher than 10 mm/year, the point is highlighted as an Anomalous Point (AP) (**Figure 2D**).

Due to the intrinsic characteristics of A-DInSAR techniques (e.g., the one-dimensional measure of ground movement along

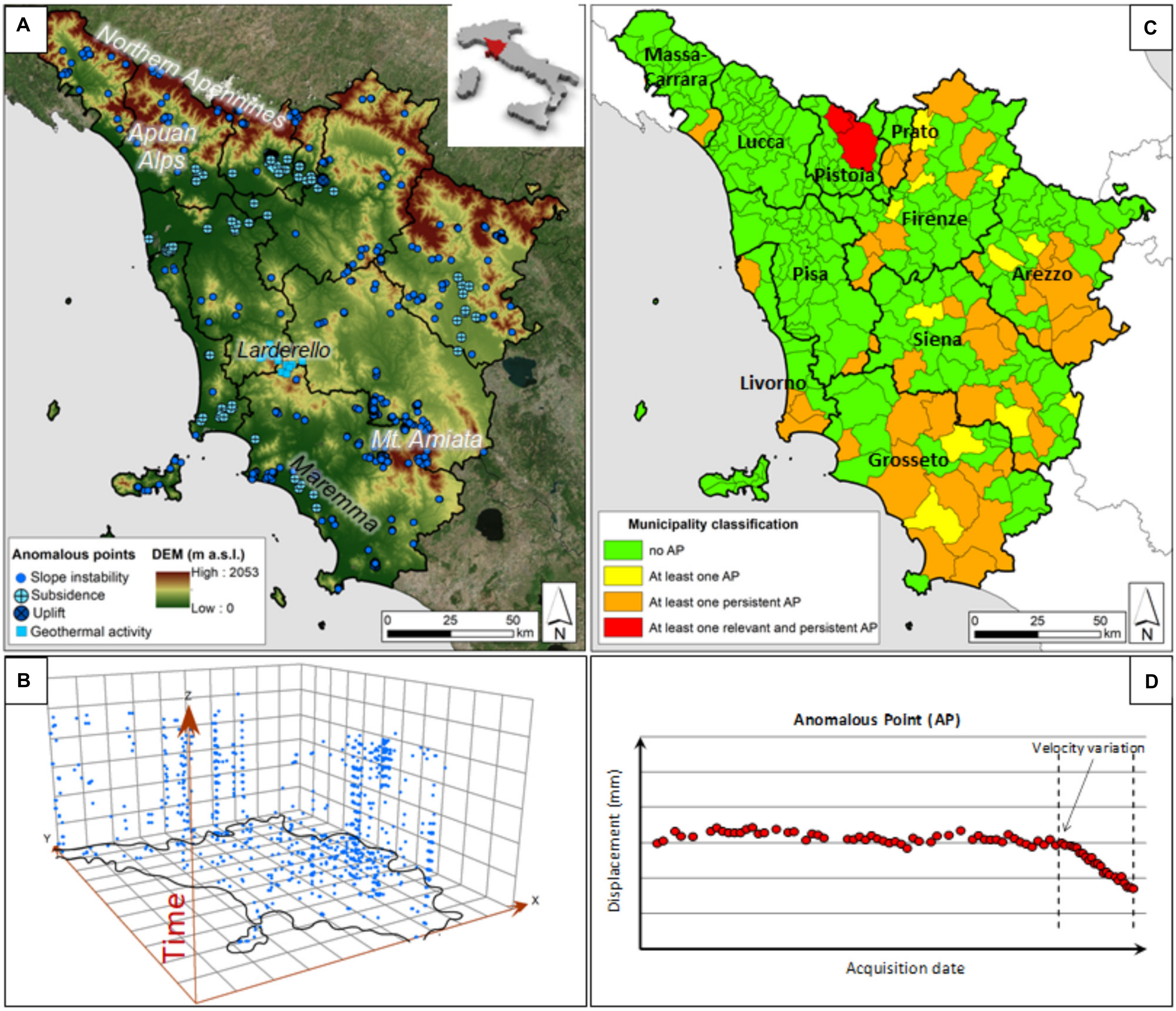

FIGURE 2 | (A) Spatial distribution of the main Anomalous Points (APs) recorded in the Tuscany Region; **(B)** space-time cube graph of Aps; **(C)** weekly bulletin that contains a municipality classification of traffic light like color-codes with respect to the increasing attention level depending on the presence of Aps (modified after Raspini et al., 2018. We have obtained the copyright permissions to reproduce the already published figure); **(D)** persistent scatterers temporal series of an AP.

the LOS and the point-like scattered distribution of radar benchmarks), the radar-interpretation of the TS changes is carried out with the support of auxiliary thematic information (i.e., topographic, geomorphologic, geological, and land use maps, optical aerial and satellite images). The velocity variations in the deformation pattern of APs in each SAR update are radar-interpreted by assigning them a possible triggering factor. Each AP is characterized by two important parameters: the spatial consistency and the temporal persistency. The spatial consistency defines the presence of AP clusters, whereas the temporal persistency refers to the repeated occurrence of the same AP across time in the same area. Considering these two parameters, only APs repeatedly occurring in following updates and forming a cluster is considered representative of a relevant change in the temporal evolution of a geo-hazard. On the contrary, APs that are identified only in one single update or not spatially correlated with other APs are discarded from further interpretation because they likely would be related to local variations, possibly due to phase unwrapping errors or atmospheric artifacts.

In **Figure 2A**, the spatial distribution of the main APs recorded over Tuscany during 1 year of activity of the monitoring system is shown. Most related to slope instability are located on the main mountainous relieves of the region, i.e., on the Apuan Alps and Apennines to the N-NE and on Mt. Amiata flanks to S, in agreement with the regional pattern of the 'sliding index' recently shown in Rosi et al. (2018). Relevant AP clusters are related to subsidence phenomena in the internal and coastal alluvial plains and to local uplifts in Firenze and Grosseto provinces. Another significant group of anomalous points is in Larderello due to geothermal activity.

A space-time cube graph, which is a 3D box consisting of two horizontal dimensions of space (geographic plane) and one vertical dimension of time, is also provided (**Figure 2B**) for depicting the time-slicing across the whole AP datasets. Therefore, this bounding box shows a more detailed 3D view of the temporal occurrence of APs: some anomalous points are transient, whereas others are persistent in temporal duration, e.g., for the APs in the Firenze-Prato-Pistoia plain or in the northern mountainsides of Mt. Amiata.

The remote sensing detection of APs across time is designed to capture any significant changes in the deformation pattern occurring within the territory of the Tuscany Region, such as precursor movements related to major events (i.e., accelerations recorded before landslide failures). This monitoring system leads to the production of a weekly bulletin that contains a municipality level that can be interpreted as a geological alert. The bulletin (**Figure 2C**) represents the regional territory divided into municipalities that are classified according to four classes of traffic light like color-codes with respect to increasing attention level, according to the National Civil Protection guidelines. A red color means the presence of at least one temporally and spatially persistent cluster of APs considered relevant since it involves critical elements at risk in the territory (e.g., urban fabric, roads and others strategic infrastructures). These municipalities require detailed scale investigations to better understand the causes of APs and the effective deformational scenario of the area. As a result, the bulletin can be used as a useful early warning tool for weekly updating of the regional geo-hydrological setting and for focusing detailed field checks.

DISCUSSION AND FUTURE PERSPECTIVES

Advances in InSAR processing algorithms across time have permitted the passage from local and specific studies up to wide-area investigations over whole regional territories. Moreover, recent evolutions in satellite technologies (from first ERS missions up to present Sentinel-1 constellation) have allowed more advances in environmental applications.

The transition from satellite monthly acquisitions, which only permit a static overview at a given date, up to weekly satellite acquisitions, which led to a dynamic continuously updated 'movie' of the geo-hydrological scenario, has enabled possibilities to systematically track the temporal evolution of ground deformations for early warning purposes and civil protection practices.

Tuscany region is affected by a wide range of geo-hazards, such as slow-moving landslides and subsidence. In many cases Tuscan towns and cities date back to the Medieval and Renaissance periods (Bertocci et al., 1995): thus, over the centuries, many urban areas were built directly within landslide bodies or nearby unstable slopes, since gentle morphology is more suitable for urban settlement with respect to mountainous chains, but it can be very prone to soil erosion and surface mass movements.

The Italian Law no. 267/98, which was approved after the disastrous Sarno event in southern Italy that claimed over 150 lives, pointed out such situations and defined territorial management strategies as a first Italian attempt for mapping geo-hydrological risk zonation (Barbieri et al., 2004; Pasuto et al., 2004) to be defined in the so-called Hydrogeological Setting Plans. These inventories would need to be periodically updated and the most critical sites should be regularly monitored.

To this aim, multi-temporal satellite InSAR approach used as a near-real-time monitoring tools can offer a great support for investigating slow-moving geo-hazards at regional scale. It continuously provides updatable terrain measurements especially throughout the detection of "Anomalous Points" (APs) over large areas for focusing further on-site investigations that can be tailored on the requirements of authorities in charge of environmental management, thus reducing costs, time efforts and optimizing field work.

The "near-real time" monitoring with remote sensing approach is a complex task, but nowadays the presented systematic gathering of new SAR data and the continuous research advances can progressively reduce constraints and uncertainties and, as future perspective, an alert system can be set with increased performance and reliability.

AUTHOR CONTRIBUTIONS

SB conceived and wrote the manuscript. FR, LS, MDS, AC, and AR contributed to writing and improving the quality of the paper. NC coordinated the work.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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