SAR AND INSAR PROCESSING FOR EARTHQUAKE EFFECTS: A SHORT REVIEW ON BACKGROUND AND NEW POTENTIALS

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Abstract: *Recently, Synthetic Aperture Radar (SAR) and SAR Interferometry (InSAR) have been extensively used for several earthquake engineering applications. This paper, for the first time, offers a short comprehensive review on the use of SAR and InSAR processing for earthquake engineering applications. The most common SAR and InSAR processing techniques, and applications for faulting mechanism modelling and damage detection have been carefully reviewed through literature. Several technical aspects and challenges of SAR and InSAR products are assessed, and possible solutions, potentials, and current/future perspectives of SAR and InSAR for earthquake applications are discussed in detail. The paper significantly contributes to the intuitive recognition of the key role of SAR images for earthquake engineering applications; not only for co-event and post-earthquake evaluations but also for discovering the precursors.*

1. Introduction

Satellite-borne Synthetic Aperture Radar (SAR) is an active remote sensing technology, which sends microwave signals toward the land surface from space and listens to the backscattered echoes. As an all-day all-weather technology (Ebel et al., 2021), SAR is considered to be a promising tool for acquiring useful information on the land surface and objects on the ground. Starting from 1990 with European Space Agency (ESA) ERS1 and 2 satellites acquiring medium resolution SAR images, the era of primary application of SAR for measuring ground deformation through SAR Interferometry (InSAR) hast been started. This successful mission is followed by several other satellite missions, from medium resolution C-band Envisat to high and very high-resolution X-band Cosmo-SkyMed by Italian Space Agency (ASI).

Characterized by a complex nature, i.e., composed of amplitude and phase components, allows different applications for detection and monitoring of the changes and deformations on the ground (such as landslides (Solari et al., 2020), subsidence (Raspini et al., 2022), etc.) imposed by several natural and anthropogenic factors. Tectonic movements and ground deformations due to earthquakes have been commonly detected by Two-pass Differential InSAR through which two SAR images (before and after) are used to form Interferogram to reveal the imposed displacement fields and to reveal the source parameters and mechanisms. Availability of SAR images also has brought new potentials through multi-temporal InSAR (such as Persistent Scatterer (PS) (Ferretti et al., 2000) and Distributed Scatterer (DS) through Small Baseline approaches (Berardino et al., 2007)) processing bringing deformation time histories of land surface and urban areas. With respect to the conventional geodetic approaches, the technology is characterized by several advantages, such as global spatial coverage, high revisit frequency and availability of sensor targets (event in rural areas). Not only a technology for geodetic measurements, SAR images can be effectively utilized for change detection purposes (Fu-Long et al., 2011), which in the case of earthquake effects, it can be translated to the earthquake-induced damage detection. The damaged imposed to structure and infrastructure can change the backscattering process of SAR signals with respect to pre-event condition, which can be detected and measured through several algorithms for change detection.

Considering these unique abilities and potentials of this modern technology, in this paper, a comprehensive review on SAR and InSAR processing applications for detection and modelling of sources of seismic events and detection of earthquake-induced damages is provided. Section 2 presents the common SAR and InSAR processing techniques for measuring the ground deformations due to seismic activities and change detection purposes. In Section 3, some technical aspects of SAR and InSAR products are offered, including extraction of 3D displacement field from InSAR measurements, SAR limitations and introducing freely accessible products. In Section 4, the use of SAR and InSAR for earthquake applications is discussed in detail. Section 5 presents the conclusion of this work presenting the current flow and future perspectives of the technology for earthquake engineering.

2. SAR and InSAR Technical Background

The product of SAR imagery is a complex image, composed of two components: Amplitude and Phase. Considering a single SAR image, these components may not be sufficiently informative to be considered meaningful data. Rather, when another SAR image from the same scene is acquired (at a different time and slightly different view angle), the pair of images (hereafter entitled as Two-Pass (TP)) has the potential to represent useful information. Depending on the application, several SAR images from the same scene (hereafter called as Multi-Temporal (MT)) can be used to derive even more informative data.

The amplitude component is used for several applications, such as amplitude-based (incoherent) change detection (Mastro et al., 2022) (in either TP or MT sense), selection of sensor-friendly targets for further processing steps (within an MT approach (Eskandari and Scaioni, 2023a)), and similar pixel selection purposes (Even, 2021). Any change in the geometrical features, dielectric properties, roughness of the sensor target, and inevitable presence of different noises, can change the amplitude from one acquisition to another. The phase component, which can also be used for change detection purposes in a coherent approach (Martin et al., 2018; Wang et al., 2022a), is the main component for retrieving the ground deformation that occurred within a certain period. The following, the main SAR and InSAR processing and post-processing techniques used for EQ assessment purposes are discussed in detail.

2.1. Two-Pass DInSAR

Using Two SAR images acquired from the same orbit track of a mission, it is possible to perform Differential Interferometric SAR (DInSAR) processing through following steps (so-called processing chain), to derive displacements:

- Pre-processing: this step involves some operations, such as orbit data allocation and co-registration of SAR images.

- Interferogram Generation and Coherence Estimation: In order to generate an interferogram, the complex value of each pixel is cross-multiplied by the complex value of the corresponding pixel in another image. By considering the interferogram as a temporal differential phase image (since both images are spatially consistent, but taken at different times), and choosing two arbitrary locations within the interferogram and take the difference of the interferometric phases between these two points, this double-differential (temporally and spatially) phase $\Delta\varphi_{int}$ can be expressed with several contributors:

$$\Delta\varphi_{int} = \Delta\varphi_{Flat} + \Delta\varphi_{Topo} + \Delta\varphi_{TopoResid} + \Delta\varphi_{Atmos} + \Delta\varphi_{Disp} + \Delta\varphi_{Thermal} + \Delta\varphi_{Noise} \quad (1)$$

  All of the Differential Interferometric SAR (DInSAR) techniques deal with the accurate extraction of useful component of Equation 1 (and estimation and removal of other parts). Usually, the complex correlation coefficient (so-called coherence or spatial coherence) is produced in this step, which is a very informative outcome of InSAR processing (will be discussed in the following sections).

- Flat and Topographic correction: as shown in Equation 1, two first components are Flat (corresponds to the reference surface curvature) and Topographic phase (related to the topographic variations on the earth surface). These components can be simply removed using precise orbit data and Digital Elevation Models (DEM), respectively.

- Phase Enhancement: Interferometric phase is subjected to corruption due to several sources of decorrelation (such as temporal, geometrical, etc.) and errors (Pepe and Calò, 2017). To tackle this issue, phase denoising techniques, such as multi-looking (spatial averaging by the cost of losing spatial resolution) and phase filtering (Xu et al., 2020), can be performed as effective operations to improve the quality of the interferometric phase.

- Atmospheric correction: the tropospheric artifacts influencing the SAR acquisitions have a great contribution in differential measurements (Equation 1), playing as an obstacle for truthful estimation of deformations and corrupts the displacement patterns. The challenge is more manageable as the MT-DInSAR is concerned (Kirui et al., 2021). However, these atmospheric delays may be estimated and pulled out from the TP interferograms through two types of techniques: Empirical (taking advantage of the non-deforming areas in the interferogram (Doin et al., 2009)) and auxiliary (using the independent atmospheric models (Jolivet et al., 2011)).
- Unwrapping: interferometric phase obtained through previous steps are wrapped within 2π. Unwrapping methods create a smooth field of phase differences (unwrapped interferogram) varying $[-\pi, +\pi]$ all over the interferogram by considering a reference portion, which is one of the most critical and complicated steps in interferometric processing. Then, they resolve the altitude ambiguity to transfer the obtained relative complex phase differences into the actual altitude changes (Wegmüller et al., 2002) (an example of co-seismic interferogram and displacement map October 2016 Norcia Earthquake is provided in Figure 1). The quality and stability of interfering signals, identified by means of coherence, plays a crucial role in this step.

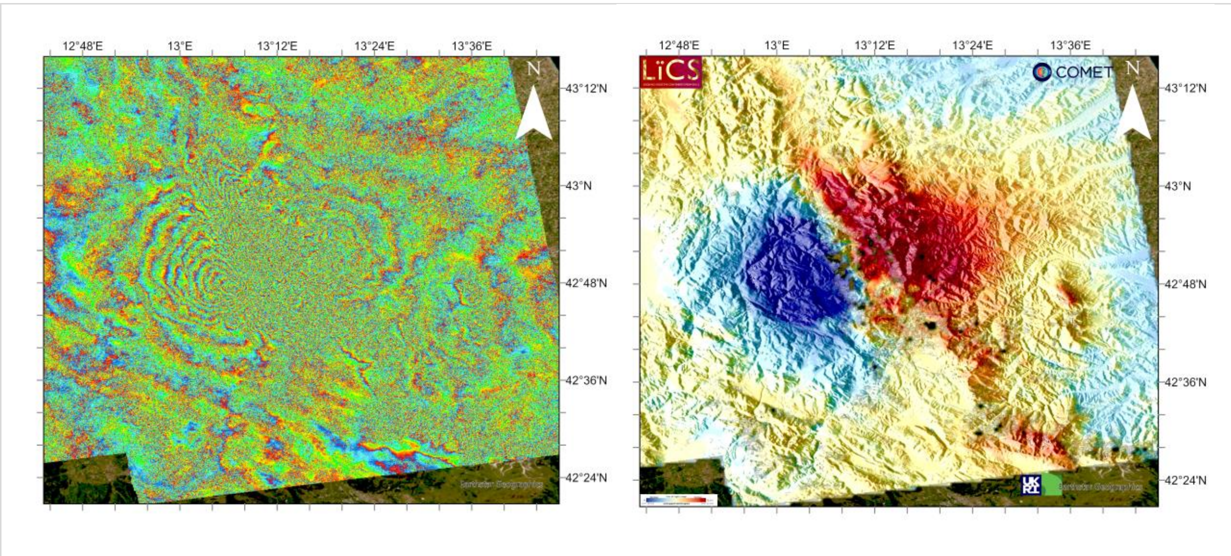

Figure 1. Two-Pass (a) wrapped interferogram and (b) unwrapped interferogram (displacement map) (source: COMIT-LiCS, Event October 2016 Norcia, Italy)

2.2. Multi-Temporal DInSAR and Time-series:

As discussed earlier, the availability of SAR images made it possible to retrieve valuable information on a set of reliable sensor targets (so-called PS and DS) on the ground in a multi-temporal approach by stacking a series of SAR images acquired at different time with a slightly different view angle from the same scene. Through this MT approach, except the first two components in Equation 1, the others can be estimated as valuable information (such as temporal and thermal displacements) or can be estimated and removed from the measurements (such as atmospheric artifacts) in a reliable and accurate manner. One of the most advantages of MT-DInSAR is retrieval of deformation time series for the set of persistent scatters in the scene, as an interesting and valuable information for different applications, revealing the co-seismic displacements and suitable for displacement modelling.

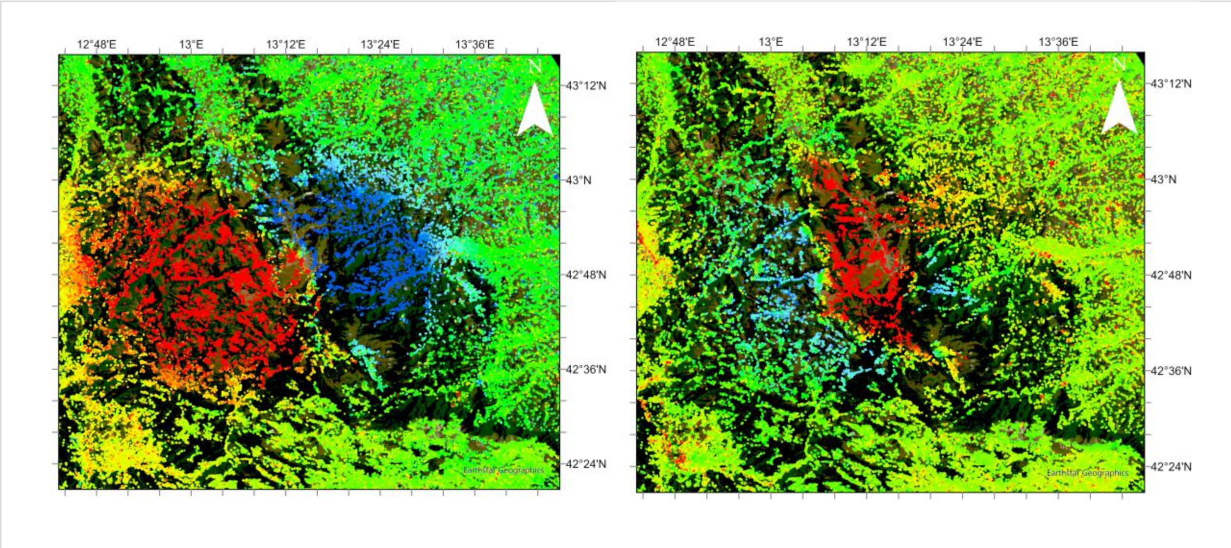

Figure 2. Deformation Velocity Maps (EGMS datapoints derived from multi-temporal InSAR analysis of Sentinel-1 images): (a) East-West and (b) Up-Down (representing the Event October 2016 Norcia, Italy)

2.3. Change Detection Approaches

The use of SAR images for change detection can be categorized into different classes. One of the classifications is related to "supervised" and "unsupervised" methods depending on the presence of ground-truth data as the reference for the algorithms (Saha et al., 2019). Another classification is "incoherent" and "coherent" which concerns the use of the SAR image components (amplitude and phase), with different sensitivities to different levels of changes.

In incoherent methods (also known as intensity correlation techniques), the amplitude of SAR backscattered echoes is used to detect the changes between different data collections by SAR sensor. Figure 3 illustrates the relative magnitude of amplitude backscattered to the sensor from an object and the surrounding area on the ground in urban area. Due to the acquisition geometry of the SAR imagery, it is characterized by several features, including distortions (such as layover and shadow) and backscattering processes (such as surface and double-bounce) (Amjadipour et al., 2022). These features may be affected (or modified) by changes in the geometry and/or surfaces of the sensor targets. Incoherent approaches focus on detection of these types of feature changes, by appropriate pre-processing of the pre- and post-event SAR images (such as speckle filtering (Lee et al., 1994)), quantifying the detected changes, and then, setting the threshold for distinguishing change/unchanged areas (Mastro et al., 2022).

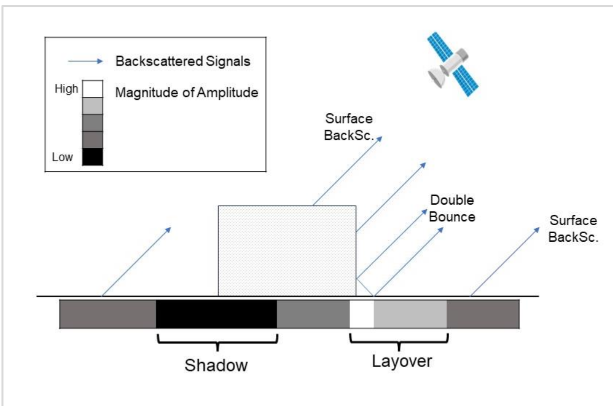

Figure 3. Schematic representation of backscattered echoes: showing different distortions and backscattering processes, and the relative magnitude of amplitude

As far as the coherent approaches are concerned, the phase component of SAR images is the key player for detection of changes through determination of coherence. There are several coherence estimators proposed in literature: from classical window-based approaches utilizing the complex value of the SAR pixel and the neighbouring pixels, to window-independent wavelet transforming approaches (López Martinez, 2003) which take into account only the phase component. (Hammer et al., 2021). The measure, which varies between 0 and 1, is used to evaluate the quality and stability of interferometric phase and renders the similarity of the target (at two acquisitions) in terms of radar reflection. Therefore, even small changes modifying the reflection properties may affect the stability of interferometric phase, leading to lower coherence values.

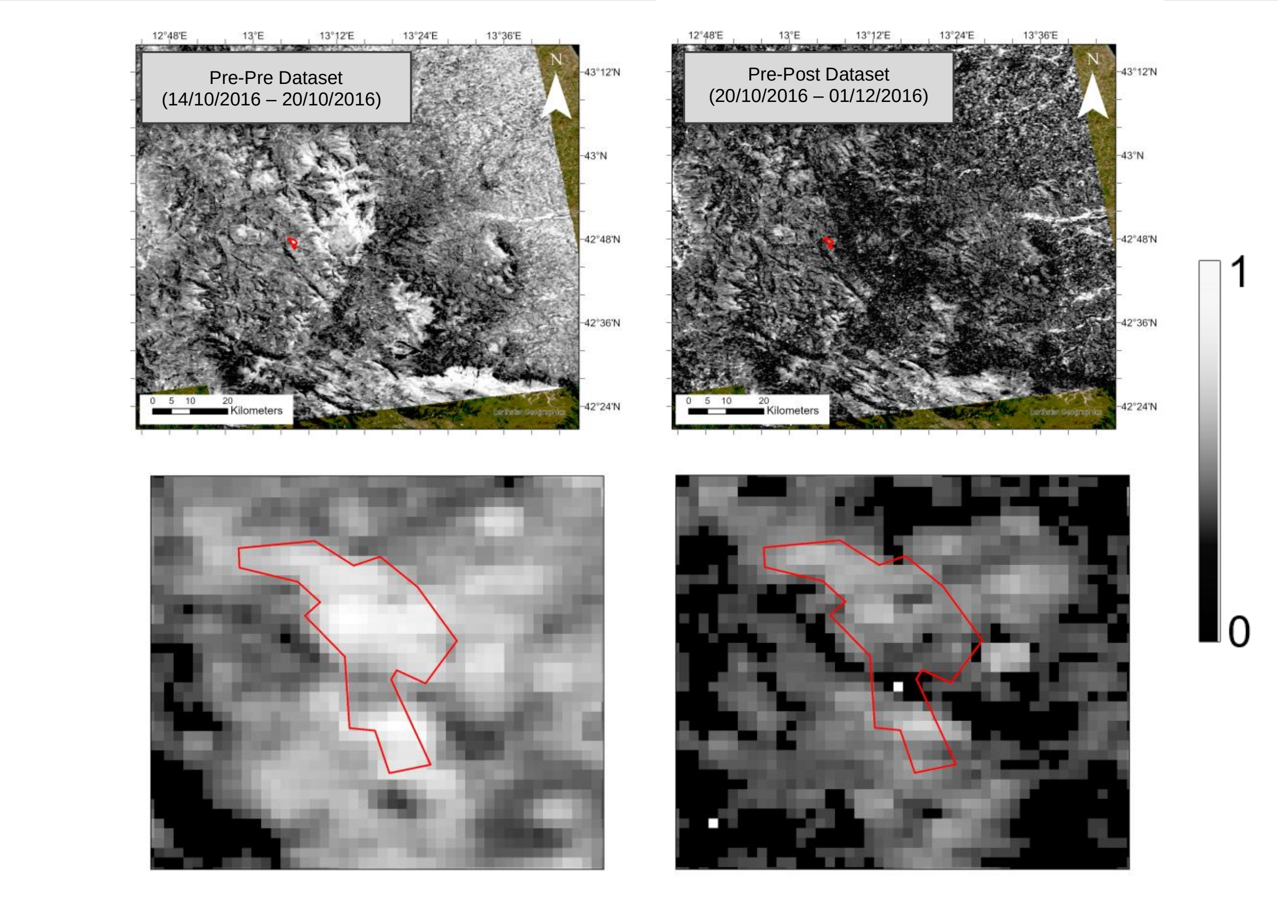

Figure 4. Coherence maps derived from pre and co-event datasets (Event October 2016 Norcia, Italy)

3. Technical Aspects

3.1. Cartesian Displacement Field Extraction

According to the SAR acquisition geometry, all the measurements by SAR sensors are along the Line of Sight (LOS), as depicted in Figure 5. On the other hand, due to the complexity of fault movements and the accompanied ground deformations, it is crucial to extract the deformation components in the cartesian coordinate system (i.e., along Vertical direction: Up-Down (V_V), and along Horizontal directions: East-West (V_{EW}) and North-South (V_{NS})). It efficiently allows for addressing the ambiguity present in the fault plane and focal mechanisms (Pezzo et al., 2014), and for accurate definition of the displacement field caused by seismic events.

One of the ways for this LOS decomposition into the cartesian directions is to benefit from the linear dependency of cartesian deformations to LOS deformations through trigonometric functions of acquisition and orbital angles (i.e., incident (look) angle and azimuth (heading) angle, respectively, indicated in Figure 5) (Dai et al., 2015). For example, considering the LOS displacement velocity (obtained through MT InSAR analysis) representing the deformation of a sensor target, and using a combination of multi-sensor (also known as multi-platform) and multi-track approaches, a linear system can be formed, which is composed of: *i)* three unknowns (3 deformation velocities along cartesian directions); and *ii)* three equations (trigonometric relations between 3 unknowns and 3 LOS deformation velocities obtained from, for instance, ascending and descending of a single platform and ascending or descending of another platform).

It should be mentioned that almost all of the satellite-borne SAR sensors are near-polar orbiting satellites, which makes the technology insensitive (or with low sensitivity) to the North-South direction of land surface deformations (Wright et al., 2004), while with the highest sensitivity to the settlements along the vertical direction. This causes an ill-conditioned linear system (described above) for the inversion to achieve deformations along cartesian directions. It has been shown that utilizing appropriate regularization methods (Mehrabi et al., 2019) and applying the weights to the InSAR LOS measurements (Eskandari and Scaioni, 2023b) can significantly stabilize the inverse problem and enhance the accuracy of the decomposed parameters.

Therefore, it can be seen that the high sensitivity of InSAR measurements to up-down and east-west directions is utilized through DInSAR processing (TP or MT); however, for obtaining north-south direction of deformations (more precisely, along-track deformations), two general classic approaches are mostly considered: *i*) phase-based methods, such as Spectral Diversity method ((Scheiber and Moreira, 2000)), azimuth split-bandwidth interferometry (Bamler and Eineder, 2005), and split-beam Multi Aperture Interferometry (MAI) (Bechor and Zebker, 2006); and *ii*) amplitude correlation-based methods, such as sub-pixel offset tracking (Singleton et al., 2014) and speckle offset tracking (Choe et al., 2021). In general, for revealing the 3D co-seismic displacement field, a joint use of DInSAR and along-track extraction approaches is widely seen through literature (e.g., (Yan et al., 2013; Pezzo et al., 2014; Xu et al., 2021)).

It should be noted that the above-mentioned along-track extraction approaches may fail in detection of small magnitude displacements, and some other approaches, such as Dislocation Model-based methods (Hu et al., 2022) have been proposed to tackle this problem. It has been shown that integration of InSAR measurements with other source of information, such as GNSS (Xu et al., 2022), GPS (Xiong et al., 2022) and strain models (Liu et al., 2018; Hua et al., 2023), is significantly capable of reducing the errors and the uncertainties seen in the extracted displacement fields. Another opportunity for extraction of 3D displacement field is provided by new SAR satellite constellations, such as Capella Space (Castelletti et al., 2021) with multiple orbital planes (comprising also non-polar) which significantly decrease the low sensitivity of SAR measurements to a certain direction of deformations.

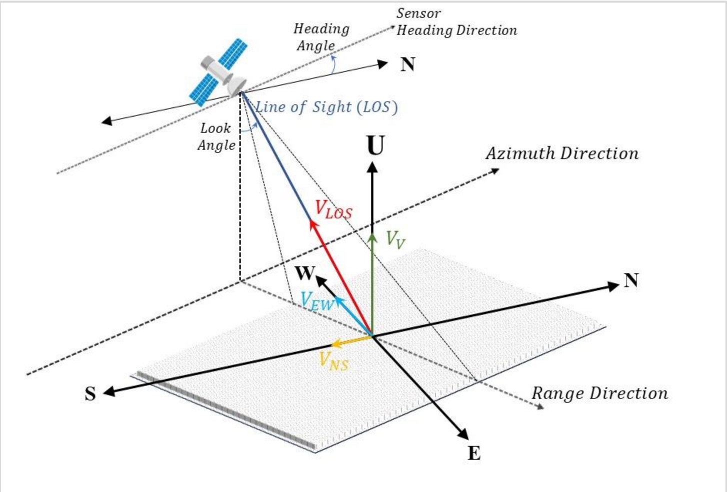

Figure 5. SAR Acquisition Geometry

3.2. Free SAR and InSAR Products

Regardless of the unique potentials of SAR and InSAR for several applications, the technology is characterized by inevitable limitations such as high computational costs and high level of requirements for data management, as well as the need for the experts in the field. However, thanks to the fundings from different institutions and organizations, different types of processed InSAR data are freely available, tackling with the above-mentioned major limitations.

Adopting the state-of-the-art technologies within Looking inside the Continents from Space (LiCS) project, the Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET) has developed a fully automated Seintinel-1 InSAR processing system, so-called LiCSAR (Lazecký et al., 2020; Morishita et al., 2020), covering almost all around the world. Several products (such as wrapped and unwrapped interferograms with different pairs of SAR images, deformation time series, coherence maps, etc) are freely accessible through COMET-LiCS Sentinel-1 InSAR online portal. A special focus is dedicated to unwrapped interferograms containing co-seismic deformations by the purpose of comprehending the spatial and temporal distribution of seismic activities over the world. Another interesting InSAR products are provided by Copernicus Land Monitoring Service (CLMS) through European Ground Motion Service (EGMS). The system, which takes advantage of Sentinel-1 InSAR, offers reliable deformation time series and velocities almost all over Europe with a temporal coverage of 2016-2021 (first release) and 2018-2022 (second update) (Crosetto et al., 2020; Ferretti et al., 2021; Costantini et al., 2022) with nominal temporal resolution of 6 days and different spatial resolutions. Advanced Rapid Imaging and Analysis (ARIA) project, carried out by NASA Jet Propulsion Laboratory (JPL), is another service delivering displacement products using Senitnel-1 InSAR. An interesting branch of products, so-called Urgent Response products, include Flood Proxy Maps (FPM) and Damage Proxy Maps (DPM) targeting significant events (such as earthquakes, hurricanes, floods, volcanic eruptions, etc) all over the world (Bekaert et al., 2019; Bekaert et al., 2023).

4. Application

4.1. Earthquake Precursors

One of the applications of InSAR measurements is to extract earthquake-predictive features from the spatial and temporal pattern of the deformations due to tectonic and fault movements before EQ occurrence. In fact, deformation time-series are of interest for such analyses. Establishing the cause-effect relation in an earthquake forecasting sense is based on the detection of the abnormal behaviour of land surface displacement in a certain time before the earthquake to be considered as the precursor signal.

It has been shown that deformation time-series alone are enough to detect these unusual behaviour through machine learning and/or statistical analysis (Shi and Pan, 2023). On the other hand, in some cases, the geological characteristics and environmental factors are anchored to the analysis to better introduce the earthquake precursor according to ground deformation untypicalities. Regarding for L'Aquila 2009 earthquake, (Nardò et al., 2020) and (Mazzoli et al., 2021) targeted the spatiotemporal pattern of vertical and east-west long-term MT-InSAR-derived deformations over hanging wall (settled on a Quaternary sediments) of the fault system present at the area. It is found that the sudden change in the pattern (from uplift to subsidence, started some months before the EQ occurrence) can be marked as precursor signal. The claim relies on the fact that this change is independent of hydrological factors, and this temporal switch of deformation behaviour is spatially taken place where the co-seismic deformation was cantered. While (Moro et al., 2017) have also included the hydrogeological setting of the area and underground fluid migration processes to extract precursor signals from MT-InSAR-derived land surface acceleration.

4.2. Source Modelling:

Considering the importance of retrieving the earthquake source parameters and slip distribution, this task is commonly carried out by taking these main steps: *i*) determination of orientation and plane of sources (faults) and occurred focal mechanisms, *ii*) modelling InSAR-derived displacement fields, *iii*) tuning the initial values of source parameters and fault geometry, and *iv*) identification of slip distribution. The first step starts by assuming several scenarios with simple rectangular plane (Okada, 1985) for a uniform slip, and by initial evaluation of InSAR displacement fields and the seismological solutions (such as global Centroid-Moment-Tensor (CMT)), the best scenarios matching the observations can be selected. Considering the outcomes of step (i), the InSAR displacement fields are inverted in step (ii) to be modelled through minimizing the modelled-actual residuals. Through step (iii), the initial assumptions for source parameters, including fault geometry and position (such as length, depth, dip, and strike) and slip parameters (such as magnitude and angle), can be tunned and re-fined through several approaches, such as non-linear inversion (Tarantola and Valette, 1982). In Step (iv), the assumed fault planes are meshed into a uniform grid of patches, and the corresponding slip distribution can be obtained through inversion approaches such as linear least square methods (JóNsson et al., 2002). Such methodology is adopted in several research works found in literature, utilizing InSAR displacements achieved through single two-pass DInSAR (e.g., (Pinel-Puysségur et al., 2014; Pezzo et al., 2014)), multiple two-pass DInSAR (e.g., (Yan et al., 2013)), and deformation time-series through MT-DInSAR (e.g., (Liu et al., 2021)).

4.3. Damage Detection:

Damage imposed to structures and infrastructures can be detected through change detection techniques exploiting SAR images acquired before and after extreme events, such as damages due to flood (Tay et al., 2020) and EQ (Wang et al., 2023). As discussed in Section 2.3, the change in the physical characteristics of the sensor targets due to the damage appears in amplitude and/or phase measurements between two acquisitions. For both incoherent and coherent approaches, several algorithms have been developed.

Regarding the amplitude-based damage detection, some approaches benefit from the double-bounce effect (present before the damage, and vanished after the damage to the collapse of bouncing object or accumulation of debris) (Guida et al., 2010), accompanied by enhancement of the method through ridge detection towards automation of the algorithm (Brett and Guida, 2013). Some other methods rely on the difference between the correlation coefficients corresponding to before and after the event (Liu and Yamazaki, 2015), while texture analysis is another branch to detect damages imposed to built environment (Macchiarulo et al., 2023). It has been shown that integrating the optical remote sensing data with SAR amplitude can improve the accuracy of the damage detection and reduces the risk of false alarms due to the possible mismatching and inconsistency arise by co-registration operations (Brunner et al., 2010).

Coherence damage detection is usually carried out by estimation of coherence using a co-seismic pair of SAR images, then, masking out the areas with low coherence by techniques such as threshold-segmentation (Wang et al., 2022b), Maximum Likelihood change estimator (Wahl et al., 2016). In order to avoid false alarms in change detection, especially automated operations, some coherence estimators are introduced to provide a more detectable damaged-undamaged contrast (Wang et al., 2022a). Different versions of coherence damage detection techniques have been developed that exploit time-series of pre-event coherence images (each generated by interfering two pre-event SAR images) to obtain the spatial distribution of non-damaged coherence over the area and produced damage map by cross-evaluation of the co-event coherence image (Jung and Yun, 2019; Hasanlou et al., 2021; Stephenson et al., 2022).

Each approach is sensitive to different types and levels of damages, with different requirements for accurate detection of damages. As depicted in Figure 3, widespread changes are required to change the backscattering processes and magnitude of backscattered echoes (incoherent approach), while small changes can have big influences on the fidelity and uniformity of interfering phases captured before and after the earthquake (Plank, 2014). This offers the sense that the coherent approaches are less responsive to damage detection, however, it is possible to catch small damages which are not easily detected by other remote sensing techniques. Besides, the decorrelations, inevitably introduced due to the difference in time and position of the satellite sensing the same area, result in low coherence values; therefore, the temporal and perpendicular baselines should be limited for application of coherent methods, while the SAR intensity correlation techniques (incoherent methods) are independent from this parameters (Jung and Yun, 2019). Therefore, combined incoherent-coherent approach for damage detection can bring a robust and reliable solution for detection of wide range of damages cause by earthquakes with different severities (Elgharbawi and Zarzoura, 2021; Wang et al., 2023).

Since different SAR satellite missions provide different spatial and temporal resolutions, a careful choice of damage detection techniques should be taken into account. It has been shown that Spotlight mode of Cosmo-SkyMed (1m resolution, however, rarely found for pre-event situation) is greatly effective for single building damage assessment, while Sentinel-1 images are able to provide an estimation on larger scales of assessment. Also, due to the geometric distortions, the joint use of ascending and descending SAR images are important (and sometimes necessary) to have a more comprehensive understanding on the damages imposed to the built environment (Balz and Liao, 2010; Karimzadeh and Matsuoka, 2018; Mazzanti et al., 2022). Beside the key role of damage detection in EQ disaster management and assessment, this valuable information can be used, in an integrated manner, with other types of InSAR-derived findings to correlate the level of damages imposed to the built environment with some parameters, such as displacement field and EQ model parameters (Wang et al., 2023).

5. Conclusion

In this paper, a comprehensive review of the key role of SAR and InSAR processing for earthquake engineering is presented. The most common processing techniques, applications, and technical aspects and challenges of InSAR products have been carefully investigated through literature. The final key points, regarding the potentials and current/future perspectives of SAR and InSAR for earthquake applications are as follows:

- Although earthquake forecasting and precursors detection using satellite InSAR measurements can be a revolutionary step, the subfield is discovered to be obscure and unclear, due to a very small number of works found in literature.
- InSAR measurements have been found, for decades, to be able to reveal the accurate and reliable earthquake source parameters and slip distributions. Linear and Non-linear inversion of InSAR-derived displacement fields is the main Eerth Observation (EO) data source used for these purposes.
- Regarding damage detection methods, it was seen that most of the recent research works are using coherent approaches (or joint use of incoherent-coherent). Application and development of machine/deep learning techniques, and also, integrated and multi-disciplinary approaches are of great interest towards the future course of this subfield (Khelifi and Mignotte, 2020; Joshi et al., 2021; Hasanlou et al., 2021; Karimzadeh et al., 2022).
- Regarding the importance of retrieval of co-event 3D displacement field, the research works are toward the integration of different source of information and development of advanced independent models to tackle the limitations and shortcomings of classical SAR-dependent approaches.

6. Acknowledgement

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