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Advanced MT-InSAR Landslide Monitoring: Methods and Trends

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Abstract

MT-InSAR (Multi-temporal Interferometric Synthetic Aperture Radar) is a powerful remote sensing technique used to measure earth surface displacements and monitor their trend throughout the years over different times. It employs multiple time series of SAR images and extracts spatial height information over large scales of illuminated areas. It is a proficient technique to acquire all season day and night data with high accuracy and wide spatial coverage. Although conventional InSAR technique have vast successful applications but several limitations like decorrelation of phase, error in phase unwrapping and atmospheric artifacts hinders its use, which, in fact, have resulted in the development of more innovative multi-temporal InSAR (MTInSAR) techniques which has proved an enhancement in accuracy and consistency of extracted deformation time series. This paper provides a review of development of MTInSAR techniques, basic principles behind them, their strengths and limitations and a review of the applications of the advanced algorithms proposed in the literature and deformation measurement trends being followed. The paper accomplishes discussions on the main strengths, limitations, cross-comparison among approaches and the associated research trends.

Keywords: Landslide; Multi-temporal InSAR; SBAS; PSInSAR

Introduction

Interferometric Synthetic Aperture Radar (InSAR) technology is a well consolidated operational tool used worldwide for measuring crustal deformation in order to understand earth dynamics related to volcanic, seismic activities and landslides. A landslide is short lived and suddenly occurring geological hazard in hilly areas which include all downward or sudden movement of surface material like rocks, clays, sand and gravel resulting from natural cause such as earthquakes, heavy rainfall, cloud burst, snow melting, volumetric change in ground moisture content. Many surface deformation measuring techniques have been developed having different accuracy and processing time. Compared to other surveying techniques, a space borne synthetic aperture radar interferometry (InSAR) has proved an effective technique based on microwave pulses emitted by a SAR instrument placed on satellite. It offers a high density of measurement points over the unsafe or unapproachable large areas. Main Features of InSAR includes; microwaves (1 mm to 1 m wavelength, 0.3 to 300 GHz frequency); different wavelengths are used for different purposes (bands: X, C, S, L, P); unique polarization component (helps to distinguish the structure of the earth surface); longer the wavelength, the more radar can penetrate the clouds, rain and even the ground; higher frequencies enhance resolution. Some Limitations of InSAR are; Line of Sight (LOS) ambiguity (indistinctness); decorrelation (Slopes, Vegetation); data is not very cheap and readily available; low sensitivity to horizontal. Differential InSAR approach refers to the process, where a pair of images is used for the interferometric analysis to identify and quantify the surface movement. The word differential implies the subtraction of the topographic phase contribution from the SAR interferogram. Applications of D-InSAR includes; geophysical monitoring of natural hazards, such as landslides, earthquakes, floods and volcanoes; detecting land subsidence due to ground water, oil extraction and mining; detection of displacements in dams, bridges and the buildings of heritage; tracking displacements over time; detecting oil spills from ships and forest fire; vegetation/crop health and reservoir monitoring; snow, forest, urban and wetland area mapping. The past two decades have witnessed how InSAR has become matchless in addressing the needs and answering questions where classical optical remote sensing techniques have been unable or failed to tackle. Many applications of studying and monitoring natural hazards have been accomplished right from volcano [1-3] earthquake [4-6], landslide [7-9], urban ground deformation [2,10,11], bridge deformation [12] and to infrastructure monitoring [13]. However, challenging problems of temporal and spatial decorrelation of radar signals, atmospheric artifacts, long-wavelength aliasing and orbital errors have claimed an improvement over conventional InSAR method. Multi-temporal InSAR (MTI) techniques have become popular and emerged as a tool to measure deformations due to its ability to overcome aforesaid limitations such as temporal, geometric decorrelation and atmospheric in homogeneities.

MTI analysis has assisted earth surface deformation measurements along the sensor target direction i.e., line of sight (LOS) accuracy of centimeter to millimeter level. This article aims at performing a complete review of advanced InSAR techniques that are used for performing a complete analysis of the millimetric deformation of landslide surfaces. The conceptual difference of these techniques resulting in different levels of performances is here for a general review. The remaining paper organization is as follows; MT-Insar Time Series presents various MT-InSAR methods including their strengths, limitations and applications, Surface Deformation Measurement Trends present deformation measurement trends and conclusion follows.

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MT-Insar Time Series

Some of the radar targets exhibit stable back scattering over the decades for years and the phase information extracted from these stable targets may be useful. Usai et al. [14] suggested that useful information can be extracted from pixels that keep high coherence over a long period and enhancement can be attained by combining multi-temporal SAR data taking this inherent information from radar wave returns into account [14]. A Multi-temporal technique in which multiple images of the area under investigation are acquired at different times presents advancement both in terms of landslide deformation detection capabilities and qualitative estimation of deformation. These techniques processes multiple acquisitions taken over times to provide distinctive displacement patterns of surface motion in the year as well as surface uplift or subsidence due to seasonal variations. Over the decade, ample techniques of combined analysis of the SAR image sets have been proposed by various names, for example persistent scatterer interferometry (PSI), PS-InSARTM (refers to the type of identified pixels based primarily on their phase changes with respect to time) [15-18] and referred to the type of pixels identified based on phase correlation in space [19], interferometric point target analysis (IPTA) [20], small baseline subset (SBAS) technique (refers to the method of interferogram generation) [21-26], P-SBAS a parallel algorithmic approach recently developed [27], Stanford method for persistent scatterers (StaMPS) [28], coherent point target (CPT) technique [29,30], spatial-temporal unwrapping network (STUN) algorithm [30], temporarily coherent point InSAR (TCP) InSAR) [31] and SqueeSARTM [32]. These techniques are developed to mitigate some of the conventional InSAR weaknesses. Among these IPTA have maximum number of publications where as PSInSAR and SBAS being most cited techniques [33].

PSInSAR

This approach called Permanent Scatterer technique was established by the SAR group of Politecnico di Milano, in the nineties [34]. In the SAR research groups this technique is referred as PSInSARTM as the trade mark. PSI principle mostly evolves to identify pixels based on their phase variation with respect to time and the pixels that use their phase correlation in space. It involves in simultaneous analysis of interferograms utilizing the pixels with in the resolution cell which exhibit stable amplitude backscattering and coherent phase, in the complete set of interferograms within data stack. Such identified targets with stable behavior are called persistent scatterers. PSs are not affected by the baseline decorrelation. Sometimes a target may have erratic or noncoherent phase with a stable amplitude characteristic and some targets behave as if they are PS but only within a portion of the images within the data stack, such targets are not PS [15,16,19]. PSI is an appropriate method for urban area as PSs are more abundant there. Advantage of this algorithm is that whole of the data acquired can be used to form interferograms without baseline decorrelation and surface motion can be detected precisely up to few millimeters with significant density of measurement points. A master stack of interferograms with baselines greater than the critical baseline can be formed, which may have resulted phase decorrelation in case of distributed scatterers. Residual DEM error can be calculated and PS can be geolocated on google earth. More PSInSAR details and its applications are reported by Werner et al. and Ciampalini et al. [20,35]. Here PS-InSAR technique is applied to extract information related to land deformation. This method was successful in detecting a considerable amount of PS targets. The deformation rate was between -2.4 mm to 1.9 mm per year showing an alternation between uplift and subsidence. The origin of this deformation is suggested to be related to tectonic and climatological origins [36].

Stable Point Network (SPN)

The Stable Point Network (SPN) is developed in order to process large of radar image data stacks to achieve millimetric measurements of ground deformation intended for reducing geometric decorrelation resulted with imperfect selection of PS. SPN requires a minimum number of images to identify the points that are electromagnetically stable during the period of study by selecting PS using three different selection criteria; stability of amplitude, interferometric and spectral coherence. This selection process is a crucial step as the precise measurements of ground deformations will be primarily achieved in these electromagnetically stable points [37]. SPN built on interferometric processor DIAPASON developed by CNES in 1992 has been applied successfully in long wall mining with millimetric precision complementing local and in situ surveying techniques, monitoring ground subsidence in urban environments [38-40]. Its other successful applications in which average subsidence measured with the SPN technique remained close to subsidence measured by topographic leveling of ground deformation phenomena are also reported by Crosetto et al. and Herrera et al. [41-43].

A Persistent Scatterer Pair (PSP)

A Persistent Scatterer Pair (PSP) technique is developed for the identification of PSs in a complete series of SAR images having full-resolution. The PSP method is different from ordinary persistent scatterer interferometry techniques [44-46] and its successive developments as it over powers the problems of atmospheric artifacts, orbital errors and slowly varying disturbances by not relying on filtering process which results in loss of resolution. It depends upon both identification and analysis of PSs in closely spaced pairs of points affected by the same disturbance with in the relative signal. PSs are normally scarce in the image scene, and it is needed to pair points to identify them, which are not only nearest neighbors but relatively close. Huge number of arcs which connect possible PSs is required to test. It is an efficient approach with highly connected graph to pair points whose nodes identify the PSs. The higher connectivity of the graph and large number of arcs guarantee a reliable PS identification and more truthful displacement measurements even when strong scattering structures are not there in the scene (like natural terrains having dense vegetation or smooth surfaces which do not change much with time). PSP technique is inherently robust as it does not require preliminary compensation for atmospheric and spatially correlated artifacts present in the sensed signal. The PSP SAR interferometry has been extensively used and validated not only based on low and high-resolution SAR data acquired by ERS, Envisat, and COSMO-SkyMed, but also amicably used for SAR data from other sensors. Costantini et al. [47] reported the quality characteristics and several application examples of the PSP technique validated based on COSMO-SkyMed data [47].

Small Baseline Subset (SBAS)

The Small Baseline subset method [48-50] is a of multi-temporal InSAR technique for detecting slow moving deformations with millimeter precision using a stack of SAR interferograms. Detailed SBAS algorithmic is provided in Lanari et al. [51]. The SBAS, is a methodology of interferogram formation by generating many small

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spatial and temporal baseline interferometric pairs in order to reduce decorrelation and topographic effects. Atmospheric phase is separated by low-pass filtering in spatial domain and high-pass filtering in temporal domain. Deformation maps in case of ERS/ENVISAT resolution and in Sentinel-1 resolution can be formed. Finally, in the SBAS approach multi-sensor SAR data collected by different radar sensors with the same illumination geometry can be collectively processed to retrieve fully the long term deformation [34]. More details about SBAS and its applications are reported in Lauknes et al. [52]. Gheorghe et al. [53] theoretically compared two algorithms and presented results that show the differences between them. An average velocity of -2 mm to 2 mm per year for PS and-1.6 to 1.6 mm per year for SBAS analysis is perceived and author [53] considers the SBAS as most suitable for a geological study because it maximizes coherence over large areas and has noise mitigation capabilities.

Coherent Pixels Technique (CPT)

Coherent Pixels Technique (CPT) an algorithm of Mora et al. [30] is a PSI technique which permits isolation of complete deformation evolution, the DEM error and the artifacts contributed by atmosphere to from a stack of interferograms. Depending upon the linear or nonlinear deformation extraction, CPT is divided into two steps. First, average deformation velocity and the DEM error is estimated for the retrieval of linear terms by adjusting the model function to interferometric data only over the pixels having stable coherence in the stack of interferograms over the study time. Coherence or amplitude stability criterion is followed for coherent pixels selection. Second approach detects deterministic targets induced by manmade structures by taking advantage of high density of measurement points. The algorithm takes into account the different behavior of spatial and temporal atmospheric artifacts to isolate their respective phase contributions to derive the nonlinear deformation. Multi-looking the interferograms reduces the spatial resolution during coherence estimation. An atmospheric phase screen for each image is extracted by applying a combination of temporal and spatial filters in a sequential way to find nonlinear terms of deformation. A detailed CPT description can be consulted in Blanco-Sanchez et al. and Mallorqui et al. [29,54]. The CPT has been applied to detect and monitor subsidence successfully in Murcia City [55]. The magnitude of measured deformation rate (1.01.2 mm/year) has been proven very similar while processing both for X-band and C-band datasets.

IPTA

IPTA is applied on selected point target that exhibit persistent scattering behavior over a prolonged observation period [20]. Errors resulting from atmospheric artifacts in SAR scenes separated by large baselines are reduced through the use of multiple scenes of the site and higher measurement accuracy can be achieved. Several manmade structures over urban areas, infrastructures or exposed rocks outside the cities showing visible scattering are helpful in achieving estimates of the progressive terrain deformation in millimeters [11].

SqueeSAR

Efficiency of PSI and SBAS techniques is best in urban areas because of the availability of high density objects that produce a strong signal to noise ratio. However, it has been noticed that many other signals hardly distinguishable are present in the background; they do not produce high signal to noise ratio being located in non-urban areas mostly. Land slide site has scarce vegetation that show low coherence values because satellite signals are returned with poor energy over heavily vegetated areas. Such areas which show poor consistent scattering are known as distributed targets and are more efficiently evaluated through SqueeSAR technique is advancement on the PSInSAR algorithm. SqueeSAR is the only algorithm that TRE offers due the its redundancy as it provides a significantly increased ground points coverage over non-urban areas by taking advantage of both point like and spatially distributed scatterers for interferometric processing. Interferometric coherence is also increased based on statistical approaches. LOS velocity map in Figure 1 below shows the results of PS detection in the image data acquired over an Alpine area and confirms the effectiveness of this new approach [32]. Detected scatterers by PSI, SBAS and SqueeSAR techniques in the landslide body reported by Mirzaee et al. [56] are compared in Table 1 in which Ep, Lp and Np refer to earlier part, lateral part and northern edge of the landslide, respectively. An increased density of selected targets and meaningful coherence has resulted in better evaluation of the complex landslide activity [56,57].

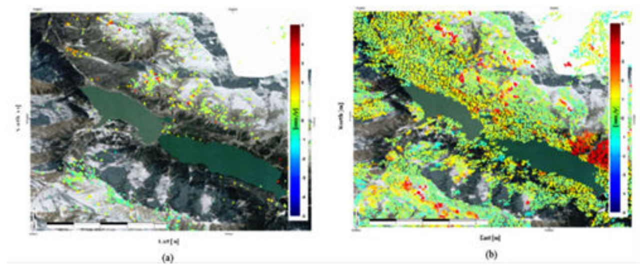

Figure 1: LOS velocity [mm/yr], obtained by (a) PSInSAR and (b) SqueeSAR, for the Cancano lakes region [32].

Techniques	Ep	Lp	Np	Total
PSI	38	27	9	74
SBAS	43	54	24	121
SqueeSAR	71	180	94	345

Table 1: Number of scatterers detected by psi, sbas and squeesar techniques.

Limitations of SqueeSAR include; measurements of displacements, along the LOS direction, are restricted to a fraction of the wavelength. This means that the technique is not suited to movements greater than 300 mm/year, vegetation prevent to radar targets to get identified and consequently hinders the ground deformation detection, the quality and precision of deformation velocity measurements decreases as the distance from the reference point increases, unable to measure deformation in North-South direction since movements are in parallel to the satellite.

Surface Deformation Measurement Trends

InSAR data is being processed by different open source and commercial tools listed below; Open Source Research Packages: ISCE, ROI-PAC, DORIS, GMTSAR, StaMPS and SNAP Commercial Packages: Gamma, GEOMETICA, ENVI SARScape, ERDAS IMAGINE, SARPROZ and DI-APASON. Some of the recent trends being followed using StaMPS, SARPROZ (copyright(c) 2009 Daniele

Perissin) and G-POD services of ESA for land surface deformation monitoring are discussed as under.

Stanfords Method for Persistent Scatterers (StaMPS)

StaMPS a MATLAB based software developed at Stanford University and subsequently upgraded at the University of Iceland, Delft University of Technology and the University of Leeds. The package is equipped with persistent scatterer and small baseline methods and with an option to combine them. It is developed for PSI processing to work well in barren terrain in nonurban areas undergoing nonlinear deformation having no man-made structures. It uses amplitude and phase information of individual pixels to determine the probability of being a permanent scatterer (PS). StaMPS like PSI utilizes amplitude scattering values for initial PS selection, includes SBAS (Small Baseline Subset) method to identify those scatterers that dominates in scattering from the resolution cell and the pixels whose phase decorrelates little for short time periods during filtering called slowly decorrelation filtered phase (SDFP). First PS selection based on amplitude scattering values is carried out and then it is refined in an iterative manner by performing phase analysis in space and time. Utilization of these techniques enables to extract deformation signal with more coverage. Both PS and SDFP selections are combined and deformation is then extracted by phase unwrapping algorithm [58,59].

SARPROZ

SARPROZ (www.sarproz.com), is a MATLAB based GUI designed by Daniele Perissin of Purdue University Netherlands, which is capable of processing different sets of interferograms by different techniques running in the software background. Parameter estimation can be done by PSI algorithm, Capable of estimating APS through different algorithm for graph inversion. Acquired SLC Image data is first converted into a format which SAPROZ recognizes. Then various steps like computation of data statistics, precise orbital application, retrieving weather data from each scene, creating sub set of the area of interest etc. are performed using GUI (Graphical User Interface). SARPROZ automatically downloads the metrological data and precipitation during the acquisition day. Master and Slave Images are extracted from the data set, co-registered and the offset between master and slave images is predicted. Each slave image is aligned to the master image in such a way that each pixel belonging to a portion of the imaged terrain in the slave image is exactly under the corresponding pixel in the master image. Amplitude Stability Index is calculated by generating the co-registered stack, reflectivity map, temporal average of the intensity values of the image datasets etc. [60]. Coarse points are selected and DEM assisted geocoding is performed. Selection of the good tie points depends upon the resolution of the data available. Bright pixels identifiable in reflectivity map are selected manually as Ground control points (GCPs). DEM is then converted to SAR coordinates to support PSI processing. Phase to height and phase to flat constants conversion process is then carried out. Amplitude stability index threshold is applied to create PS candidates to estimate preliminary parameters and Atmospheric Phase Screen (APS). Correlation between DEM and APS is estimated for APS is compensated. After APS removal, height and velocity is computed [12].

Grid Processing on Demand (G-POD)

ESA European Space agency has provided (G-POD) environment with in the research and service support that exploit Earth observation (EO) data in order to provide new EO resources to scientific community. Generic applications can by encapsuled within this environment and high performance computing can be performed on large volumes of archived data sets. The Grid Processing on Demand is a web-based mechanism with user interface for setting up and submitting jobs to G-POD clusters for specific processing (https://gpod.eo.esa.int/). G-POD facilitates access to the ESA high speed computing resources and their EO data archives to provide shared data processing platform to science and industrial community for promoting new earth observation application, their development, operations and validation. The G-POD environment is a complex distributed architecture comprising of logical computing subsystems, web portal, services modules repositories, web data storage and satellite data catalogues [59,61]. A parallel SBAS algorithm (P-SBAS) has been developed [27] within G- POD is an automatic approach which requires SAR data accessed from the ESA archives and setting of few parameters needed for implementation in full the SBAS chain (from SAR raw data focusing upto the displacement time series generation and average deformation velocity maps). G-POD service integrates MTI and DInSAR algorithms developed by CNR-IREA, adapted for parallel processing, including InSAR SBAS, Next InSAR, MERIS MGVI regional etc. [61]. Comparative results of these three trends are shown in Figure 2 below. Over the Sierra Tejeda region very few PS are detected in case of P-SBAS. Deformation patterns derived from StaMPS and SARPROZ are very similar in both the investigation periods (1992-2000 and 2003-2008). Sarproz results thus confirm its StaMPS processing with in SARPROZ and the investigated area has undergone subsidence. Sarproz allows seamless transition between different interferometric approaches like image graph connections, weights on the coherence, different parameters for a priori and a posteriori point selection, including the life time of the targets etc. [62].

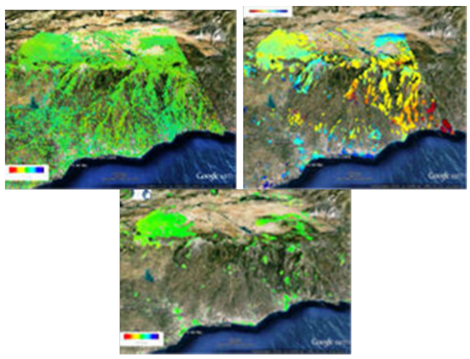

Figure 2: 3D view of the mean LOS velocity maps of ERS-1/2 (1992-2000) from StaMPS (top left), SARPROZ (top right) and P-SBAS (bottom), velocity range is in the interval of -10 to 10 mm/year.

Conclusion

Our review over the efficiency of these MT-InSAR time series PSI, SBAS and SqueeSAR methods showed that in case of landslide studies located in non-urban areas, SqueeSAR is more efficient for landslide deformation studies. The large number of scatterers detected by SqueeSAR showed improvement by 3-4 times as compared to PSI and by about 2 times to SBAS in the landslide regions. SqueeSAR make changes to phase values to improve the coherence over distributed targets. Due to vegetation growth, harvesting, etc. signal becomes untrustworthy in long time observations, such cases can be dealt with methods using shorter temporal difference. The method persistent scatterer pair (PSP) exploits relative properties of adjoining pairs of points only for identification and analysis of PSs, so it is inherently not affected by slowly varying atmospheric artifacts. Among processing trends Grid Processing on Demand (G-POD) is more promising in the cases where specific data handling applications, whole dataset processes and high performance computing is needed in an unsupervised way. G-POD is a flexible, unsupervised, secure, generic and distributed platform for Earth Observation Applications where tasks like data selection, job/process assignment, job monitoring and result publication can be managed easily. For supervised processing of SAR data SARPROZ is more user friendly being a Graphical User Interface (GUI). StaMPS is also being preferred a lot in scientific research as it is an open source software.

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