Remote sensing techniques for archaeology. A state of art analysis of SAR methods for land movement

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ABSTRACT

The RESEARCH project (Remote Sensing techniques for Archaeology; H2020-MSCA-RISE, 2018-2022, grant agreement: 823987) addresses the design and development of a multi-task platform, combining advanced remote sensing technologies with Geographical Information System (GIS) application for mapping and long-term monitoring of Archaeological Heritage (AH) at risk, to identify changes due to climate change and anthropic pressures. The Earth Observation (EO) processing chain will address significant risks affecting AH including soil erosion, land movement and land-use change. The paper describes one of the main goals of RESEARCH project. It refers to a state of the art analysis of Synthetic Aperture Radar (SAR) methods applied to the land movement detection such as landslide and subsidence. Satellite SAR is a rapidly evolving remote sensing technology that offers a high potential for detecting, documenting and monitoring heritage targets. Satellite SAR interferometry (InSAR), Differential Interferometry (DinSAR) and Persistent Scatterer Interferometry (PSI) are different techniques that, depending on the available data and the required accuracy, can be used for deformation monitoring of AH.

Keywords: archaeological heritage, land movement, Synthetic Aperture Radar (SAR), interferometry

1. INTRODUCTION

Cultural heritage is an irreversible wealth of human civilization and is critical to our understanding of human evolution and cultural diversity. Across the wide-ranging European urban and rural cultural landscapes, many are characterised by the presence of standing monuments and buried structures belonging to more or less known archaeological sites. Historic cities, monuments, archaeological sites and cultural landscapes, in general, are increasingly affected by natural and anthropic pressures. Specifically, progressive loss of historical places is the primary result of floods, mudslides, fire, earthquakes, climate change and other hazards.

In the last decades, archaeology has benefited from the development of earth observation (EO) technologies, including optical multispectral, LiDAR and synthetic aperture radar (SAR) remote sensing (RS). In this context, RESEARCH will test new risk assessment methodology, by examining soil erosion, land movement and land-use change threatening archaeological sites using an integrated system of documentation and research in the fields of archaeology and environmental studies, combining advanced remote sensing technologies with GIS application for the mapping and the long-term monitoring of archaeological heritage. RESEARCH project addresses the design and development of a multi-task platform, integrating satellite and UAV aerial RS and ground-based RS technologies with GIS application for mapping, diagnostics and long term monitoring of archaeological heritage sites.

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As for land movement monitoring of archaeological sites, it requires high precision technologies to be achieved near real-time monitoring and preventive diagnosis of deformation threats, enabling the effective conservation and sustainability of cultural heritage and their surrounding areas. Different Synthetic Aperture Radar (SAR) techniques, (i.e Satellite SAR interferometry (InSAR), Differential Interferometry (DinSAR) and Persistent Scatterer Interferometry (PSI)), constitute an effective way of surface deformation monitoring and an essential tool in archaeology owing to a specific characteristic of its operational modalities (e.g. all-weather, penetration, polarisation and interferometry).

2. RESEARCH PROJECT

RESEARCH (REmote Sensing techniques for ARCHaeology) is a 4 year (2018-2022) H2020-MSCA-RISE project (grant agreement 823987). It aims at testing risk assessment methodology using an integrated system of documentation and research in the fields of archaeology and environmental studies. It will introduce a strategy and select most efficient tools for risk assessment and harmonisation of data, criteria, and indicators, to be used to assess and monitor the impact of environmental changes on tangible cultural heritage assets. The project addresses the design and development of a multi-task thematic platform, combining advanced remote sensing technologies with GIS application for mapping and long-term monitoring of archaeological heritage in order to identify changes due to environmental factors, climate change, and anthropic pressures.

The broad spectra of Satellite Earth Observations (EO) provide the ideal platform to undertake a wide range of effective, cost-efficient and up-to-date programmable analysis and monitoring of archaeological sites, as a support to the remote sensing technology today applied in archaeology. This valuable information will be complemented, calibrated and tested with ground-based data (e.g. geotechnical information, geophysics, and field survey), site scale monitoring (e.g. ground monitoring stations, laser scanners etc.) and risk forecasting models (soil erosion, land use, land movement) to derive end-user driven products (e.g. hazard, vulnerability and risk maps).

The remote sensing data processing chains developed by the project will address some of the major risks affecting archaeological heritage, such as soil erosion, land movement, land-use change and, as part of the latter, vegetation growth.

In order to carry out the demonstration and validation of the Platform, six case study sites have been selected namely the Falerii Novi (Italy), Amathùs (Cyprus), Almyriotiki (Greece), Itanos (Greece), Vaitsi Mill (Greece) and lawno-Darlowo area (Poland).

3. BACKGROUND OF SYNTHETIC APERTURE RADAR (SAR)

3.1 Definition of SAR

Synthetic Aperture Radar (SAR) is an active microwave device capable of recording the electromagnetic echo backscattered from the Earth surface and of arranging it in a 2D image map, whose dimensions are the sensor-target distance (slant range or Line of Sight direction, LOS) and the platform flight direction (azimuth). Concerning radar sensors, SAR offers several unique opportunities but also presents considerable data processing and interpretation difficulties. Being an active system, SAR is independent of Sun illumination. Moreover, microwaves can penetrate clouds, and, to some extent (up to several cm, depending on the operating frequency) even soil, vegetated canopies, and snow. [1]

Different from optical, SAR remote sensing actively transmits signals and then receives backscattering of observed scenarios for imaging. Generally, there are two components in a SAR image [2,3]

- ✓ the backscattering amplitude
- ✓ the phase

The backscatter amplitude is influenced by speckle, layover, shadow and fore-shortening, and the phase, by the variation of backscattering and movements. Exploiting the backscattering in terms of intensity or polarization, information can be retrieved on the surface characteristics (revealing in some cases the presence of archaeological features)[4]; whereas exploiting the phase information, topography and subtle deformations from interferometric analyses can be obtained, based on multiple data acquisitions, such as tandem configuration or a multi-temporal dataset. The topography is an important factor influencing the detection and discovery of heritage targets[5], whereas, the identification of subtle deformations has potential relevance for preventive diagnosis of the vulnerability of monuments and surrounding environments and providing early-warning risks[6].

3.2 SAR parameters

The most relevant SAR observation parameters include:

i. the wavelength range (band),
ii. the polarization, and
iii. the incidence angle

These three parameters are analysed below:

i. Frequency

Synthetic aperture radars are active sensors operating in the microwave electromagnetic (EM) range. As for optical imaging, the frequency is selected according to the mission aims, target and phenomena under investigation. Different frequencies are characterized by different ‘penetration capabilities’ as shown in Figure 1.1. From a theoretical point of view, according to basic physical principals, the signal is backscattered by a target with a geometrical dimension comparable with the frequency. Therefore, higher frequencies exhibit greater penetration capabilities. Moreover, for a given frequency the ‘real’ penetration capability into the soil is linked to a number of factors. Among them, the most relevant is the presence/absence of vegetation, the moisture content and the soil porosity. Actually, the penetration capability is strongly limited by surface characteristics and significantly by moisture content. This is the main reason why early applications of satellite SAR were focused on desert areas. Nowadays, multi-frequency, multi-sensor and multi-temporal data sets are available and they can be used alone or integrated with optical imagery, geophysics and ancillary data (such as meteorological records), to conduct investigations over diverse geographical regions, land cover and varying moisture content.[7]

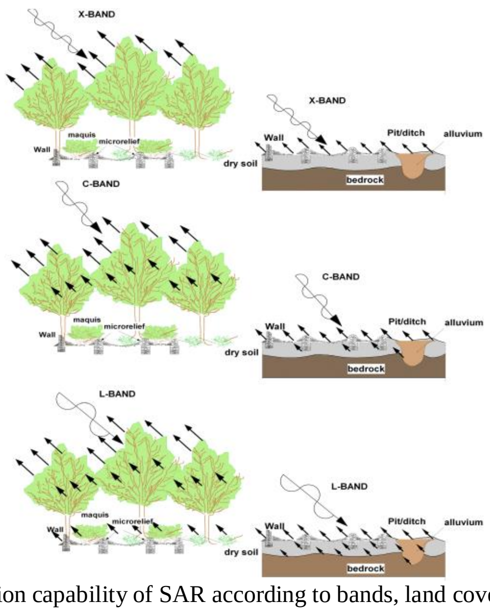

Figure 3.1. Different penetration capability of SAR according to bands, land cover and surface characteristics[7]

ii. Polarization

Polarization indicates the orientation of the electric field of an electromagnetic (EM) wave. Imaging SARs can have different polarization configurations. The most commonly used are the linear polarizations indicated as HH, VV, HV and VH where the first term refers to the emitted radiation and the latter to the received radiation. The SAR systems can have different polarization levels:

- single polarization, HH or VV or HV or VH
- dual polarization, HH and HV, VV and VH, or HH and VV
- four polarizations, HH, VV, HV, and VH.

The acquisition mode HV or VH are termed cross polarization, whereas HH and VV mode are denoted as standard polarization. Quadrupole polarization (i.e. polarimetric) SAR provides the four polarizations HH, VV, HV and VH, and also measures the difference in the magnitudes and phase between channels. Fully polarimetric sensors provide images that can be created using all possible combinations of transmitting and receiving orientations, not just the standard HH and VV. [8, 9]

Polarimetric information plays an important role for data processing and interpretation, as it can improve information extraction relating to:

- target shape and orientation,
- different layering and
- diverse moisture content (VV polarization enhances moisture response).

The polarization state of an EM wave, changes when it strikes an object, or is scattered by a surface or passes through one medium to another. Differences in the backscatter of targets at different polarizations of the incident wave depend on the geometrical structure and orientation of the target as well as on its geophysical properties. The amount of backscattered energy depends on the target as well as on the relative orientation of the incident electric field. The polarization state can be expressed mathematically as a combination of transmitted and received polarizations, for each pixel of the polarimetric SAR image.[9]

A multiband SAR dataset can be obtained varying several parameters including frequency and polarization. Polarimetric multifrequency models provide increased capacity for target discrimination, classification and analysis, but obviously require more sophisticated processing, including multiband, scatter modelling. The RGB visualization of multiple channels of polarimetric data can help in a visual interpretation, to enhance features of interest and make them recognizable.

iii. Incidence angle

The incidence angle refers to the angle between the perpendicular to the imaged surface and the direction of the incident radiation. Backscattering may vary with the incidence angle. The selection of the most appropriate SAR incidence angle is very important for target recognition and mapping because the effects of terrain and surface roughness on SAR backscatter vary with different viewing geometry.[7]

3.3 SAR Satellites

Satellites equipped with Synthetic Aperture Radar (SAR) sensors are almost circumpolar, and side-looking (travelling from south to north in ascending orbit and from north to south in descending orbit), and they can measure only the component of movement along their line of sight (LOS). The combination of both ascending and descending LOS measurements permits decomposition of the movement into its vertical and E–W horizontal components, in order better to discern subsidence from landslide movements. Even with a single available acquisition mode, it is still possible to obtain the vertical and the horizontal components of the motion when a priori information is present about the true vector of movement. The SAR satellites orbit the Earth in a sun-synchronous LEO polar orbit and data acquisitions can be made at any time of day or night and independent of cloud coverage, collecting both amplitude and phase data. These satellites have repeating paths which, using two-phase datasets for the same location at different times, allows for interferometric SAR (InSAR) showing relative ground displacements between the two datasets along the direction of the radar beam. The SAR satellites operate at designated frequencies with L-band, C-band, and X-band being the predominate wavelengths. Figure 3.2 presents the past, present, and projected SAR satellite missions.[10]

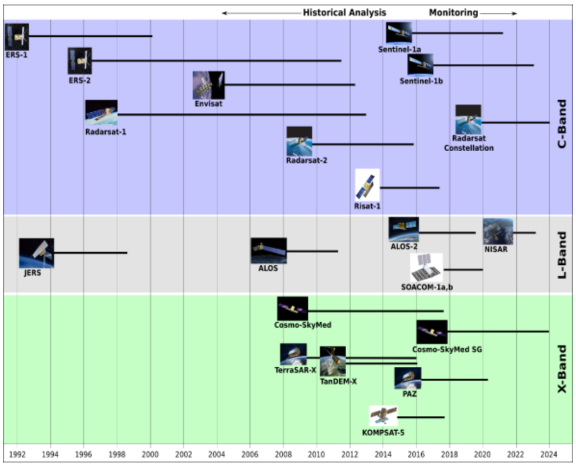

Figure 3.2: Past, present and projected SAR satellite missions [11]

The different SAR missions are supported by various agencies as it can be seen below:

- European Space Agency (ESA): ERS-1, ERS-2, Envisat, Sentinel-1
- Japan Aerospace Exploration Agency (JAXA): JERS-1, ALOS-1, ALOS-2
- Canadian Space Agency (CSA): Radarsat-1, Radarsat-2, Radarsat constellation
- Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR): TerraSAR-X, TanDEM-X
- Indian Space Research Organization (ISRO): RISAT-1, NISAR (w/ NASA)
- Comision Nacional de Actividades Espaciales: SAOCOM
- Italian Space Agency (ASI): COSMO-Skymed
- Instituto National de Técnica Aeroespacial (INTA): PAZ
- Korea Areospace Research Institute (KARI): KOMPSat-5
- National Aeronautics and Space Administration (NASA): NISAR (w/ ISRO)

4. SATELLITE SAR INTERFEROMETRY (INSAR)

Space-borne radar interferometry is a technique that can measure ground movement between two radar images acquired at different times on the same area, on a pixel-by-pixel basis.[12] Interferometry allows for the monitoring of even slight ground movement- down to a few millimetres, across wide areas.

The basic principle of interferometry relies on the fact that the phase of SAR images is an ambiguous (modulo- 2π) measure of the sensor-target distance. Distance variations can, therefore, be determined by computing on a pixel by pixel basis the phase difference (interferometric phase) relative to two SAR images. This is actually performed as pixel by pixel product of the reference image (master) times the complex conjugated secondary (slave) image. Each SAR image pixel represents the coherent sum of all scattering elements within a resolution cell. Moreover, each element contributes both with its own complex reflectivity (amplitude and phase) and with its individual distance from the sensor. The coherent image formation mechanism coupled with the high phase sensitivity prevents the phase value relative to an individual pixel of a single SAR image from being directly exploitable.

On the other hand, as long as the complex reflectivity of the pixel as a whole (i.e. the reflectivity of the elementary scatterers and their differential sensor-target path) does not change in the time span between successive radar acquisitions, it is cancelled out from the interferometric phase. This is the basic assumption for carrying out interferometric measurements and is referred to as the absence of decorrelation (or full coherence). In reality, a residual differential reflectivity term always affects the interferometric phase and is referred to as decorrelation noise. In particular, vegetated areas are often afflicted by temporal decorrelation because of a complex reflectivity varying with time and/or position of the elementary scatterers within the sampling cell (e.g. leaves and small branches of a tree).

Conversely, geometric decorrelation is due to a complex reflectivity that changes with the acquisition geometry.[13] Geometric decorrelation is mainly due to the presence of plural comparable (in terms of the backscattered radiation) scatterers within a single sampling cell. Their differential travel path varies with the acquisition geometry. The principal orbital parameter controlling this effect is the so-called normal baseline Bn, i.e. the projection perpendicular to the LOS direction of the distance of the satellite orbits relative to the two images involved in the interferogram, as shown in Figure 4.1.

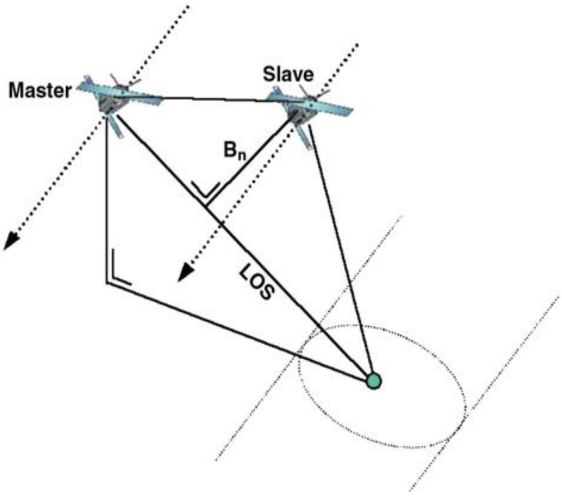

Figure 4.1: Simplified geometry of interferometric measurements[14]

The main contributions to the interferometric phase are the following:

- Possible ground deformation Δs, affecting the sensor-target travel path directly. Only the projection of the deformation occurring along the sensor-target LOS (ΔsLOS) is appreciated by a SAR system:

$$\Delta\varphi_{def,LOS} = (4\pi/\lambda)\ \Delta s_{LOS} \quad (4.1)$$

The sensitivity is very high: a LOS displacement of λ/2 causes a full phase cycle.

- Topographic profiles, in particular the height difference Δq1,2 between couples of image pixels. The interferometric sensitivity to topography is much lower and is proportional to the normal baseline of the interferogram:

$$\Delta\varphi_{topo1,2} = \frac{4\pi}{\lambda r_M sin\theta}\ B_n\ \Delta q_{1,2} \quad (4.2)$$

where $\Delta\varphi_{topo1,2}$ is the topographic contribution to the interferometric phase difference between two arbitrary pixels (named 1 and 2), r_M is the sensor-target, Bn is the normal baseline of the interferogram and $\Delta q_{1,2}$ is the topographic height difference of pixels 1 and 2. The topographic sensitivity of an interferogram is usually quantified by the height of ambiguity.[12]

- Phase noise (both temporal and geometric decorrelation).

- Atmospheric artefacts. Although SAR systems are capable of penetrating the cloud cover, the SAR phase signal is significantly influenced by the atmospheric conditions, in particular by the water vapour distribution in the troposphere.[15, 16] The atmospheric phase distortion (atmospheric phase screen, APS) is strongly correlated in space within each individual SAR image (i.e. it varies smoothly as a function of range and azimuth).

- Possible imprecisions in the orbital data (in particular baseline errors) translate into a further spatially correlated phase term[17].

Finally, the main advantages of InSAR are the capability of providing spatially "continuous" data (with the exception of low coherence areas) directly in digital format and suitable for ground surface feature extraction and the optimal characteristics for covering wide-areas (thousands of square kilometres) at low costs when compared to ground-based conventional topographic or GPS surveying and photogrammetric applications.[1]

5. SATELLITE SAR DIFFERENTIAL INTERFEROMETRY (DINSAR)

InSAR techniques can be applied to detect and measure ground deformation, provided that the topographic phase contribution is removed from a sufficiently long time span interferogram in which interferometric phase surface displacement is recorded. This involves the generation and subtraction of the so-called synthetic interferogram and leads to Differential SAR interferometry (DInSAR).[1]

DInSAR uses two InSAR interference patterns from different times, one named as topographic pair indicating the elevation of the Earth's surface and the other named as deformation pair containing both terrain effects and surface deformation. The two interference patterns are then differentiated to remove the terrain effect, and the ultimate result represents the phase difference caused by deformation of the earth surface. This technology provides relatively good accuracy at the centimetre scale. Because different types of topographic pairs exist, DInSAR offers three processing methods: two-pass, three-pass and four-pass. [18,19,20] The processing of SAR interferometric data is a complex procedure. Based on the quality of the data sets, the performance of each processing step is crucial. Consequently, the interferometric processing consists of three steps, the image registration, the calculation of modulate phase difference and the phase unwrapping and geocoding. [12,21,22] It is worth noting that the displacement measured by DInSAR is in the line-of-sight direction, not vertical direction.

As for the DinSAR principles, considering a single-pixel footprint on the ground P, the sensor acquires a first SAR image from a satellite position M, measuring a phase φ_M:

$$\varphi_M = \varphi_{geom\text{-}M} + \varphi_{scatt\text{-}M} = \frac{4\,\pi\,MP}{\lambda} + \varphi_{scatt\text{-}M} \quad (5.1)$$

where MP is the sensor to target distance, φ_{scatt} is the phase shift generated during the interaction between the microwaves and the target P, λ is the radar wavelength, and the factor 4π is related to the two-way path, radar-target-radar. Assuming that the sensor acquires a second image from a satellite position S, measuring the phase φ_S over the same pixel footprint P, then:

$$\varphi_S = \varphi_{geom\text{-}S} + \varphi_{scatt\text{-}S} = \frac{4\,\pi\,SP}{\lambda} + \varphi_{scatt\text{-}S} \quad (5.2)$$

The Interferometric SAR (InSAR) technique exploits the phase difference φ_S - φ_M:

$$\Delta\varphi_{Int} = \varphi_S - \varphi_M = \frac{SP - MP}{\frac{\lambda}{4\pi}} + \varphi_{scatt\text{-}S} - \varphi_{scatt\text{-}M} \quad (5.3)$$

This phase is called interferometric phase and is related to the distance difference SP - MP, which is fundamental for Digital Elevation Model (DEM) generation, i.e. to estimate the topography of the observed scene.[12,23]

The InSAR sensitivity to topography depends on the satellite baseline SM, and more specifically on the projection of SM in the direction perpendicular to the SAR Line-Of-Sight (LOS), called perpendicular baseline. In the case of DInSAR deformation measurement, considering a single-pixel footprint P and a first acquisition from the satellite position M, as shown in Fig. 5.1, a phase φ_M is measured. Then, assuming that the target moves from P to P_0 and that, afterwards, the sensor acquires a second image from the satellite position S, φ_S is estimated:

$$\varphi_S = \varphi_{geom\text{-}S} + \varphi_{scatt\text{-}S} = \frac{4\pi SP'}{\lambda} + \varphi_{scatt\text{-}S} \quad (5.4)$$

In this case, the interferometric phase $\Delta\varphi_{Int}$ is given by:

$$\Delta\varphi_{Int} = \varphi_S - \varphi_M = \frac{SP' - MP}{\frac{\lambda}{4\pi}} + \varphi_{scatt\text{-}S} - \varphi_{scatt\text{-}M} \quad (5.5)$$

By adding and subtracting the term $\frac{SP}{\frac{\lambda}{4\pi}}$, the following equation is obtained:

$$\Delta\varphi_{Int} = \varphi_S - \varphi_M = \frac{SP - MP}{\frac{\lambda}{4\pi}} + \frac{SP' - SP}{\frac{\lambda}{4\pi}} + \varphi_{scatt\text{-}S} - \varphi_{scatt\text{-}M} \quad (5.6)$$

where the first term is the topographic phase component φ_{Topo}, which includes the so-called reference ellipsoidal phase component, and the second term is the displacement phase component φDispl, related to the LOS displacement d shown in Fig 5.1. Assuming that the last two terms of Eq. (5.5) cancel out, if a DEM of the imaged scene is available, φ_{Topo} can be simulated and subtracted from $\Delta\varphi_{Int}$ (this is the inverse operation performed in InSAR DEM generation), obtaining the so-called DInSAR phase $\Delta\varphi_{D\text{-}Int}$:

$$\Delta\varphi_{D\text{-}Int} = \Delta\varphi_{Int} - \varphi_{Topo\_simu} = \varphi_{Displ} \quad (5.7)$$

where φ_{Topo_simu} is the simulated topographic component, which implicitly contains a flat-earth phase component. The orbital errors affect this simulated topographic component, even if the flattening process is not explicitly done. Eq. (5.7) summarizes the DInSAR working principle, which allows the displacements of the imaged scene to be derived from two complex SAR images.[24]

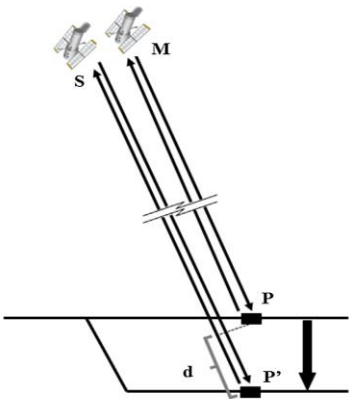

Fig.5.1 Scheme of the DInSAR deformation measurement[24]

6. PERSISTENT SCATTERER INTERFEROMETRY (PSI)

6.1 Definition of PSI

Persistent Scatterer Interferometry (PSI) is a radar-based remote-sensing technique to measure and monitor land deformation. It is the most advanced class of Differential Interferometric Synthetic Aperture Radar techniques (DINSAR) based on data acquired by spaceborne SAR sensors.

Theoretically, PSI techniques can be used with data from terrestrial,[25,26] or airborne SAR sensors. However, spaceborne SAR sensors are by far the most essential PSI data source.[24] PSI started with the so-called Permanent Scatterer technique proposed by Ferretti et al.[27] After this initial work, other approaches were introduced in the following years. Although these techniques were initially called "Permanent Scatterer techniques," now all of them, including the original Permanent Scatterer technique, are usually called "PSI techniques," while the term "Permanent Scatterers" is exclusively associated with the original method patented by Ferretti et al.[28]

6.2 PSI products

The main outcomes of a PSI analysis include the deformation time series and the deformation velocity estimated over the analysed PSs or DSs. Another outcome of a PSI analysis is the so-called residual topographic error (RTE), which is the difference between the true height of the scattering phase centre of a given PS and the height of the DEM in this point. The RTE is a key parameter in order to achieve an accurate PS geocoding.[14]

6.2.1 Deformation time series

The deformation time series represents the most advanced PSI product. They provide the deformation history over the observed period, which is fundamental for many applications, e.g. studying the kinematics of a given phenomenon (quiescence, activation, acceleration, etc.), correlation with driving factors, etc. In order to properly use, interpret and exploit the deformation time series it is important to consider that they are a zero-redundancy product. In fact, they contain one deformation estimate per each SAR acquisition, i.e. per each observation. For this reason, they are particularly sensitive to the phase noise. This aspect was highlighted in the Terrafirma Validation project analysing C-band ERS and Envisat data. X-band time series show a remarkable quality improvement over C-band time series**.**[24] It is important to be considered that, if used, the linear deformation model can considerably dominate the time series patterns and this issue needs to be carefully considered during data interpretation.

6.2.2 Average Displacement Rates

The average PS displacement rates have been the most important PSI product so far, mainly for the C-band studies. From the intercomparison of results from different teams, computed over large sets of common PSs, the estimated standard deviation of the displacement rates or velocities has been estimated:

$$\sigma_{velo} = 0.4 – 0.5 \text{ mm/y} \quad (6.1)$$

This value provides information on the global behaviour of PSI velocities. However, it is the only representative of areas with characteristics similar to those of the Terrafirma Validation Project test sites, e.g., urban areas with moderate deformation rates, etc. An example of average displacement rates is shown in Fig 6.1. The benefit of getting a high PS density is the fact that it allows to properly sample the deformation induced by construction works of an underground parking garage that affects a narrow area of about 200 m x 25 m.[24]

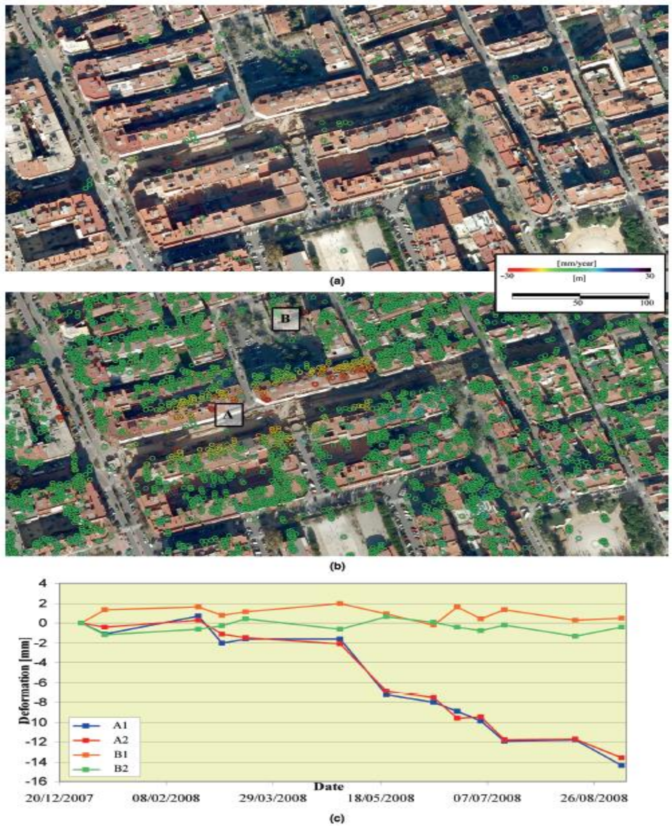

Fig 6.1. (a) Average displacement rates over an urban area: Envisat C-band, from November 2007 to January 2009, (b) TerraSAR-X, from December 2007 to September 2008, (c) the plot showing four TerraSAR-X TSs whose PS location is indicated by two squares in the middle image.[14]

6.2.3 Residual Topographic Error

The importance of the residual topographic error (RTE) is two-fold: it plays a key role in the accurate modelling of the PSI observations (i.e., the PSI phases), and in geocoding. The magnitude of the topographic phase component of the PSI phase is usually reduced by simulating a synthetic topographic phase using a DEM of the observed scene. However, any difference between the actual height of a PS and the DEM height generates the so-called residual topographic phase component, which has to be adequately modelled, estimated, and separated from the PSI deformation phase component.

Additionally, the estimated RTE is used to get an improved geocoding of the PSI products. In fact, the standard PSI geocoding only employs the external DEM (used in the processing) to geocode its products: it does not consider the difference between the true PS height and the DEM height, resulting in geocoding location errors. By using the estimated RTE this kind of error can be largely reduced, and more precise geocoding achieved. The C-band PSI performances were assessed for RTE in the Terrafirma Validation Project. The inter-comparison of results from different teams, computed over large sets of common PSs, gave a standard deviation of the RTE differences ranging from 1.3 to 2.8 m. Assuming that all inter-compared results have the same precision and are uncorrelated, can be derived an estimate of each team's standard RTE deviation: [24]

$$\sigma_{RTE} = 0.9 - 2 \text{ m} \quad (6.2)$$

7. APPROACHES OF RADAR INTERFEROMETRY FOR CULTURAL HERITAGE MONITORING

Cultural heritage, encompassing the archaeological and historical built environment, from cultural landscapes and sacred sites to archaeological complexes, individual architectural or artistic monuments and historic urban centres. Such places are often impacted by several geological disasters and potentially devastating natural events which may result in different degrees of damage or, less commonly, total destruction. The former includes two types of deformation threats for cultural heritage:

i. slow deformations at the mm-level caused by long term environmental influences, for example, surface subsidence, ground displacements or land movements; and

ii. rapid deformation such as earthquakes, volcanoes, floods may cause more significant, i.e., at least cm-level, shifts[6]

Thus, high precision technologies are urgently required to achieve the early recognition of potential risks, monitoring and preventing diagnosis the deformation of structures and their surroundings, and for consequent planning of proper hazard – reduction resources and actions. In general, cultural heritage sites have their own particularity concerning spatial scales, geometric characteristics, material properties and constituent structures. Different approaches can be applied in deformation monitoring cultural heritage sites and monuments according to their specific characteristics including levelling, GPS surveying and geophysical prospecting.[29,30,31]

Satellite SAR is a rapidly evolving remote sensing technology that offers a great potential for detecting, documenting and monitoring heritage targets. SAR is gaining the attention of an expanding community of scientists and archaeologists due to the increasing availability of multi-platform, multi-band, multi-polarization and very high-resolution satellite SAR data. It is increasingly becoming an important tool in archaeology owing to the specific characteristic of its operational modalities, e.g. all-weather, penetration, polarization and interferometry.[10]

Different approaches of differential radar interferometry can be applied in deformation monitoring over cultural heritage sites according to their specific characteristics. The DinSAR technique can provide excellent observations in flat area with high temporal correlation (e.g. man-made buildings, bedrocks). However, in the regions with dense vegetation (e.g. rice field) or high relief (e.g. mountains), the conventional DInSAR is unable to obtain reliable signals in these regions due to the lower correlation between acquisitions.

Differential Interferometric SAR (DInSAR) techniques date back to 1989 when L-band SEASAT SAR data was first exploited for this purpose.[32] Since 2001, the capability of DInSAR has been considerably improved by using Multi-Temporal Interferometric SAR (MT-InSAR) adopted to reduce noise and retrieve consistent estimation. In the last decade, growing interest has been directed towards the exploitation of remote sensing for monitoring cultural heritage using DInSAR as relevant tool for deformation monitoring and preventive diagnosis of monuments and surrounding environments. For instance, Parcharidis et al.[33] focused on the ancient Olympic site (Greece) to monitor ground subsidence; Tapete et al.[34] tested the capabilities of MT-InSAR techniques for preventive diagnosis of deformation threatening the structural stability of archaeological monuments in Italy. UNESCO has recommended InSAR for World Heritage site preservation and management. For instance, based on a request from UNESCO, DLR-Germany acquired high-resolution interferometric TerraSAR-X data for monitoring ground subsidence in the ancient Mexico City due to impacts of a complex of anthropogenic activities. Owing to the occurrence of multi-platform and high-resolution data, fine structural monitoring and preventive diagnosis of ancient monuments have become increasingly feasible with the development of the Differential Tomography SAR (D-TomoSAR) and Ground-Based Interferometric SAR (GB-InSAR) technologies. Fornaro et al.[35] applied D-TomoSAR into 4D imaging experiment (3D positioning and 1D deformation velocity) in Rome. Fratini et al.[36] assessed the vibration reduction on the Baptistery of San Giovanni in Florence after vehicular traffic block by analyzing data from a GB-InSAR system. Also, Cigna et al.[37] carried out a comprehensive study focused on SAR-based investigations on Rome over time. In particular, outputs from X-band COSMO-SkyMed time series processed using the Stanford Method for Persistent Scatterers (StaMPS), confirms the persistence of ground motions affecting monuments, and subsidence in southern residential quarters adjacent to the Tiber River, as shown in fig 4.4.[10]

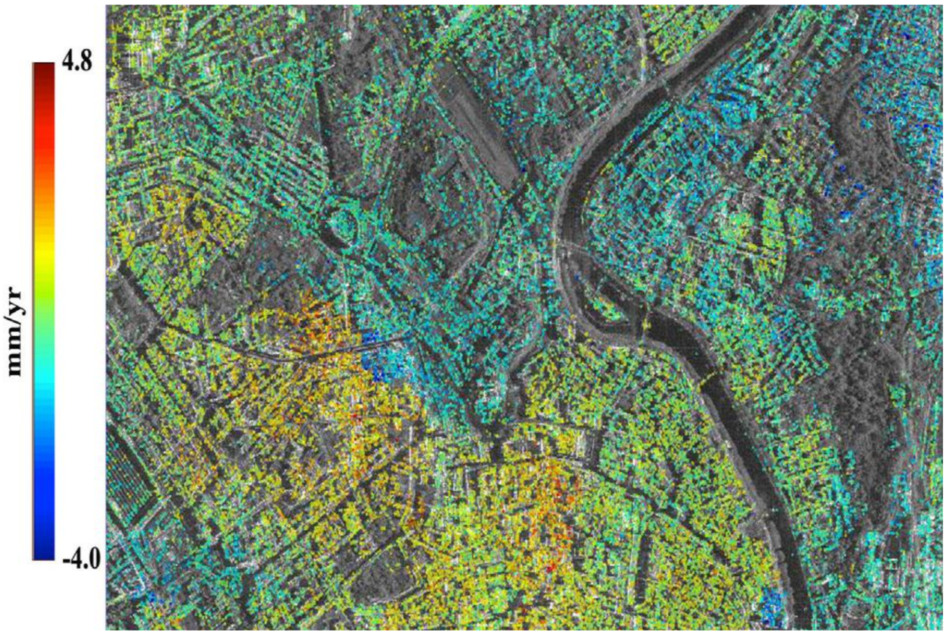

Fig. 4.4. Historical Centre of Rome: Velocity maps obtained by processing a data set of two interferometric stacks of COSMO-SkyMed Stripmap from March 2011 to June 2014[10]

Last but not least, the persistent scatterers (PS) InSAR is an advanced technique in comparison with conventional InSAR technique, which is able to overcome the problems of decorrelation when generating a time series of phase changes without atmospheric and DEM residual effects by computing only on sparsely distributed PSs who are pixels coherent over long time series.
In summary, the different approaches that are commonly used for deformation monitoring in cultural heritage sites are presented in table 7.1.

Table 7.1: The main characteristics of differential radar interferometry for deformation anomaly monitoring in cultural heritage sites. [6]

	Characteristics Approaches	**Description**	**Monitoring of**			
			Site	**Monument**	**Slow Deformation**	**Rapid Deformation**
	Persistent Scatterers SAR Interferometry (PS-InSAR)	applicable to heritage sites with an abundance of structures and archaeological remains on the ground	recommended	feasible	recommended	limited
	Small Baseline SAR Interferometry (SB-InSAR)	applicable to heritage sites in non-urban areas characterized by bare soil, debris concentrations and non-cultivated land	recommended	limited	recommended	limited

Space-borne differential radar interferometry	Combined MT-InSAR	applicable to heritage sites in both urban and non-urban areas, especially in archaeological sites characterized by a low density of exposed structures on the ground or archaeological remains widely spread over rural landscapes	recommended	feasible	recommended	limited
	Differential SAR Tomography (D-TomoSAR)	applicable to cultural heritage sites with a large density of vertical structures	feasible	recommended	recommended	limited

8. CONCLUSIONS

RESEARCH project is a MSC Marie Sklodowska Curie action of the European RISE Research and Innovation Staff Exchange programme (H2020-MSCA-RISE-2017), which promotes the exchange of innovative knowledge through the international and intersectoral participation of researchers and technical staff. RESEARCH is an ongoing project promoting and reinforcing the archaeological sites monitoring for management and prevention through the analysis using state of the art remote sensing technologies with the design and development of tools focused on archeology. SAR methods will be used for existing archaeological heritage monitoring and land movement detection taking into consideration the advantages of SAR techniques in terms of penetration, polarization and interferometry. The final output will be the creation of a risk map, concerning land movement, for the selected case studies of RESEARCH project.

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