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InSAR analysis of C-band data for transport infrastructure monitoring

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ABSTRACT: In recent years, successful applications of the Synthetic Aperture Radar Interferometry (InSAR) have been reported for the monitoring of subsidence and deformation in transport infrastructures. Compared to other non-destructive surveying methodologies, this technique can perform network-level analyses more rapidly and it can provide time-series of ground displacements by multi-temporal data acquisition. However, processing of satellite images by high-resolution sensors (i.e., X-band radars) is demanding in terms of computational resources and specialist skills. This aspect has contributed to partially hinder this technique to become a strategic infrastructure asset management tool. Parallel to this, it is important to emphasise that the use of middle-range frequency SAR sensors (i.e., C-band) allows for the acquisition of lighter datasets and, hence, more computationally affordable analyses. However, due to a lower system resolution and the challenges in identifying features of scattering objects with size below the resolution cell, the C-band imagery is usually not employed for infrastructure monitoring. This limitation could be compensated in rural environment areas, where transport infrastructures are usually the most stable scatterers.

This study aims to demonstrate the viability of the medium-range resolution SAR imagery in transport asset monitoring for the preliminary identification of sections affected by subsidence in rural areas. InSAR analyses of high (COSMO-SkyMed) and medium-resolution (Sentinel-1A) datasets are performed on a dual-carriageway rural motorway. A comparison between the Persistent Scatterers Interferometry (PSI) outcomes from data processed with the two resolutions demonstrates the viability of using Sentinel-1A images for multi-temporal subsidence monitoring in highway infrastructure.

Keywords: Remote Sensing, transport infrastructure monitoring, InSAR, Sentinel 1, COSMO- SkyMed

1 INTRODUCTION

Monitoring the structural integrity of transport infrastructure, such as railways, roads and bridges, is a priority for asset owners to ensure the operation and prevent damage and deterioration prior to rehabilitation or failures (Chang et al. 2003, Hosseini Nourzad et al. 2016).

Public awareness has been raised in many countries, where new guidelines and standards of practice were released in this area. This is the case of Italy, where guidelines on classification and risk management, and the safety assessment and monitoring of infrastructure and bridges have been published by the Italian Higher Council for Public Works and Ministry of

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Infrastructure and Transport (Italian Higher Council for Public Works et. al 2020). Currently, several on-site non-destructive testing (NDT) technologies and sensors are available for subsidence monitoring and displacement mapping. Amongst others, accelerometers (Kongyang et. al 2011), strain gauges (Olund et al. 2017), wireless network systems (Chae et al. 2012), Global Position System (GPS) and levelling (Mossop A et al. 1997, Sato et al.2003), Ground Penetrating Radar (GPR) (Alani et al. 2013, Benedetto et al. 2016) and the Ground-based Interferometer (Stabile et al. 2013), have been recognised as viable technologies to support ordinary and extraordinary asset management. However, these equipment can be expensive to acquire and they may be not fully proficient for use at the network level.

To overcome this limitation, various innovative satellite-based remote sensing technologies, i.e. the Interferometric Synthetic Aperture Radar (InSAR), Persistent Scatterers Interferometry (PSI) (Colesanti et al. 2003, Ferretti et al. 2000, 2001, 2011), and the Small Baseline Subsets (SBAS) techniques (Berardino et al. 2003, Lanari et al. 2004), have gained momentum in the last few years in the monitoring of transport assets. This is due to relatively affordable and high-frequently updated datasets that allow to reconstruct the historical time-series of displacements for vast territories, including infrastructure assets.

Despite the high-resolution of X-Band data allows for an accurate and dense detection of PS points, it is worthy of note that a minimum of 20 SAR images are required to reach a sufficient level of statistical significance of data. This can impact costs for image acquisition and can still be a factor that limits their application for routine structural monitoring. Furthermore, the time required for data processing of large areas increases drastically and requires important computational efforts. On the other hand, the use of C-Band data allows inherently to analyse vast areas in shorter time. However, there might be data resolution constraints that are not compatible with the level of detail required for infrastructure monitoring. New research has been developed that identify critical infrastructure areas at the network level by the processing of C-band data, and then uses high-resolution (X-band) data to make more detailed analyses (Wang et al., 2021). In this context, the use of C-band data is still to be explored, especially for application to roads and transport infrastructure.

This research aims to demonstrate the viability of using C-band SAR imagery for effective monitoring of linear transport infrastructure in rural environments. To this purpose, a C-band dataset, collected in the framework of the Sentinel 1 mission, provided by the European Space Agency (ESA), was processed for the monitoring of a section of a dual-carriageway rural motorway and one major exit ramp located in an area affected by known subsidence. The outcomes from the PSI analysis were compared to the Permanent Scatterers (PSs) obtained from the processing of high-resolution SAR datasets, acquired by the COSMO-SkyMed mission.

2 MULTI-TEMPORAL INSAR: WORKING FRAMEWORK AND MAIN APPLICATIONS IN TRANSPORT INFRASTRUCTURE MONITORING

The working framework of the multi-temporal Interferometric Synthetic Aperture Radar (MT- InSAR) technique relies on a statistical analysis of the signals emitted by the on-satellite sensor and back-scattered by a network of coherent targets on the ground, i.e., the PSs. This approach allows to estimate the displacements occurred between different acquisitions by a separation between the phase shift from the ground motions and the phase component related to atmosphere, topography and signal noise contributions (Berardino et al. 2003, Colesanti et al. 2003, Ferretti et al. 2000,2001, Lanari et al. 2004).

A main advantage of these techniques is the relatively lighter data-processing required for the assessment of displacements and the detection of critical areas, as opposed to the higher computational load needed in other approaches (Ferretti et al. 2000,2001). Therefore, the multi- temporal InSAR approach has proven ideal in monitoring transport infrastructure, as the high density of radar stable targets allows for more comprehensive measurements.

Several multi-temporal InSAR techniques were developed in the last few years for the detection of PS point targets, such as the PS- InSAR (Ferretti et al. 2000,2001), the SqueeSAR

(Ferretti et al. 2011), and the SBAS (Berardino et al. 2003, Lanari et al. 2004) techniques, all of which are based on different approaches.

To this effect, many works can be found in the literature that relate to the use of PS-InSAR techniques in transport infrastructure monitoring, such as railway networks (Bianchini Ciampoli et al. 2019 a, Chang et al. 2017, Qin et al. 2017, Tosti et al. 2020, Yang et al. 2014), highways and tunnels, (Barla et al. 2016, Koudogbo et al. 2018, Perissin et al. 2012), bridges (Alani et al. 2020, Bianchini Ciampoli et al. 2019 b, D'Amico et al. 2020, Gagliardi et al. 2020a, 2021a,, Jung et al. 2019, Milillo et al. 2019) and airport runways (Gagliardi et al. 2021 b,c, Bianchini Ciampoli et al. 2020, Gao et al. 2016, Jiang et al. 2010). This evidence confirms the effectiveness of satellite-based remote sensing techniques to these specific areas of application, and their potential to become strategic infrastructure asset management tools.

3 EXPERIMENTAL FRAMEWORK

3.1 *The case study*

To pursue the above-set objectives, datasets of SAR images from both the Sentinel 1A and COSMO- SkyMed missions in the time interval 2015–2019 were collected and processed by means of the PSI technique. A comparison between results from the PS analysis for both the operating frequencies was performed to assess the viability of the C-band data in the monitoring of highways.

In detail, the present study focuses on the monitoring of a road intersection connecting the A91 and the A12 motorways, located nearby Rome, Italy (Figure 1). This section has been selected due to a well-known subsidence affecting the whole area. The process has been monitored in the past (Delgado Blasco et al., 2019; Orellana et al., 2020), as it affects a strategic area connecting the "Leonardo Da Vinci" International Airport and other major industrial areas to the municipality of Rome.

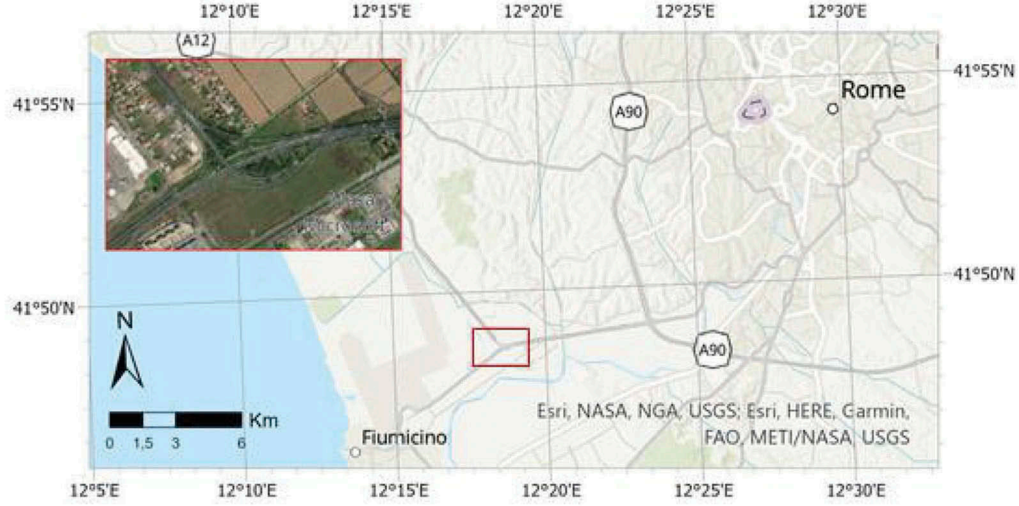

Figure 1. The road intersection investigated in this study.

3.2 *SAR datasets*

Multi-frequency SAR datasets (C-band and X-band) were collected and processed by the PSI technique to assess displacements associated with the investigated infrastructure. The C-Band SAR products were acquired by the European Space Agency (ESA) in the framework of the

Sentinel-1 mission which is the European Radar Observatory for the Copernicus joint initiative of the European Commission (EC) and the European Space Agency (ESA). The Sentinel-1 satellite, operates at a frequency of 5.4 GHz, which allows to detect displacements with a centimetre accuracy. A number of 23 Single Look Complex (SLC) SAR products collected in the time period from 2017 to 2019, were processed. Furthermore, 35 images of X-Band SAR data were collected by the COSMO- SkyMed mission (COSMO-SkyMed Product - ©ASI: Italian Space Agency, 2015-2019, All Rights Reserved), and delivered under the license to use. The Cosmo-SkyMed system operates at a frequency of 9.6 GHz corresponding to a wavelength of 3.1 cm. This allows to achieve a 3 m ground-resolution cell and, under ideal conditions, to reach a millimetre accuracy of measurements.

3.3 *PSI processing*

The SAR datasets were processed following the PSI method (Colesanti et al. 2003, Ferretti et al. 2000,2001) by means of the Interferometric Stacking Module of the Software SARscape (Sarmap, 2012) integrated in the Software ENVI, licensed within the framework of the ESA approved project “STRAIN2: Sensing Transport Infrastructures 2” (EOhops proposal ID 53071). More specifically, the PSI technique operates by the application of the following sequential stages (Colesanti et al. 2003, Ferretti et al. 2000,2001):

i. A statistical analysis of the amplitudes of the electromagnetic returns is developed on a pixel-by- pixel base to compute the Amplitude Dispersion Index (Da), reported in Eq.1, where μ and σ are the mean and the standard deviation of the amplitude values, respectively. This index is a measure of the phase stability over time for each pixel at least for high Signal-to-Noise Ratio (SNR) values.

$$\mathrm{Da} = \mu/\sigma \tag{1}$$

ii. Persistent Scatterer Candidates (PSCs) were selected by computing the dispersion index of the amplitude values relative to each pixel. These are pixels with a value of stability index that exceeds a fixed threshold of typically 0.25.;

iii. the interferometric phase $\Delta\phi i$ is computed for any PSC, at any i^{th} interferogram;

iv. the atmospheric phase contributions, the orbital and noise-related effects were identified and removed from the interferometric phase to identify the phase-shift related to the range variation only.

As a result of the above steps, the stable reflectors, i.e., the PSs, can be recognized over the inspected area. At the end of the processing stages, historical displacement trends can be produced for every pixel identified as the PS, providing an indication of the average ground motion over the time-period investigated. These steps were successfully completed using the two different SAR band datasets acquired in in this study (i.e., C-band, X-band).

However, SAR satellites can only detect displacements in the Line-of-Sight (LoS), with reference to the specific orbit-related incident angle. Consequently, the displacement detected is a component of the real displacement on the ground. Several research proposed different approaches, i.e., the vector- based approach, to overcame these occurrences and calculate the actual displacement-velocity-vector from datasets acquired in different acquisition geometries (i.e. Ascending and Descending). (Dalla Via et al. 2012, Gagliardi et al. 2020a, Wright et al. 2000).

For the area of interest investigated in this study, different SAR images in the ascending acquisition geometry have been collected and analysed for the same investigated period for the Sentinel 1A and the COSMO-SkyMed missions. Hence, in this work we refer only to displacements detected in THE LoS direction of the SAR sensors.

4 RESULTS AND SHORT DISCUSSION

To demonstrate the effectiveness of using C-Band imagery processed by the PSI technique for subsidence monitoring in transport infrastructure, results were compared to the data obtained by the processing of the high-resolution COSMO-SkyMed products.

Several PSs from the processing of both the datasets were identified in the investigated road intersection (Figure 2). The processing of C-Band dataset (Figure 2b) was effective in highlighting the deformation trends compared to the processing carried out on X-Band data (Figure 2a). To quantitatively assess the goodness of fit between the two datasets, data from a critical area (marked in yellow in Figure 2) were extrapolated and the corresponding time series of displacements were analyzed for any given PS in this area.

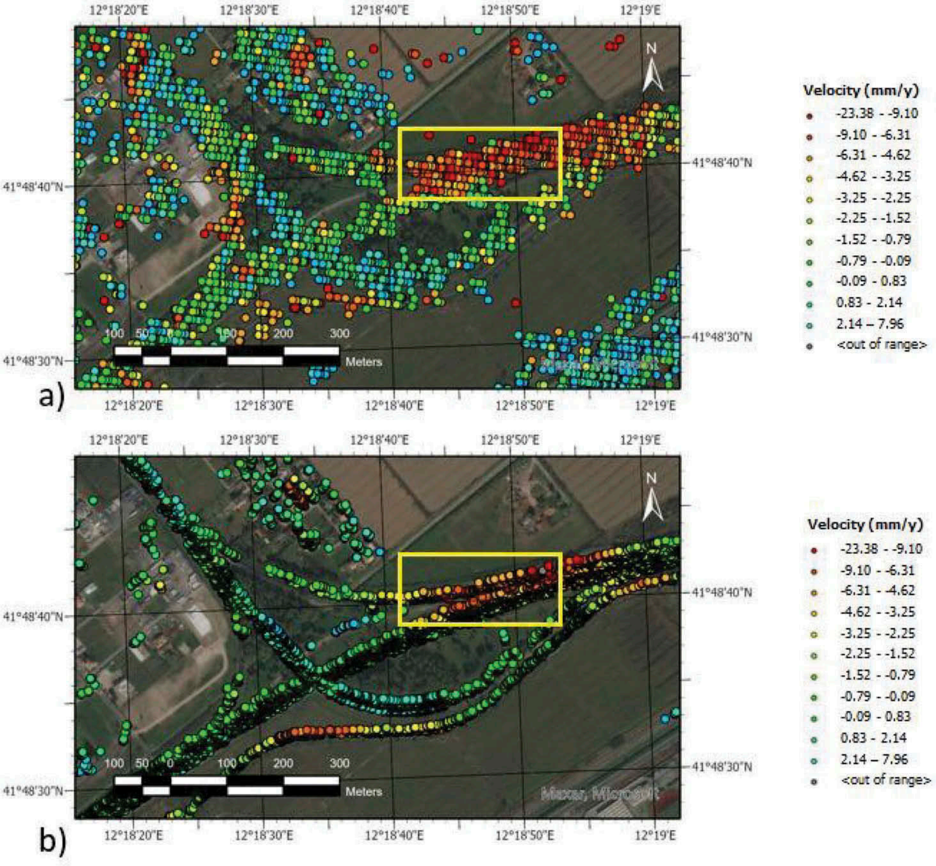

Figure 2. Comparison between the displacement velocity of PSs for a) COSMO-SkyMed and b) Sentinel-1 missions.

To elaborate, 753 PSs and 235 PSs were extracted from the processing of the COSMO-SkyMed and the Sentinel-1 datasets, respectively. The time series of displacements for individual PSs were then plotted against the acquisition time (Figure 3). As the Sentinel-1 dataset relates to a shorter period of observation time, this was related to the COSMO-SkyMed observation time by matching the zero time at the first acquisition (i.e., October 2017) with the value of displacement measured by the processing of COSMO-SkyMed data at the same period. The trend of the average displacements for COSMO-SkyMed and Sentinel-1clearly proves a good matching between the two datasets.

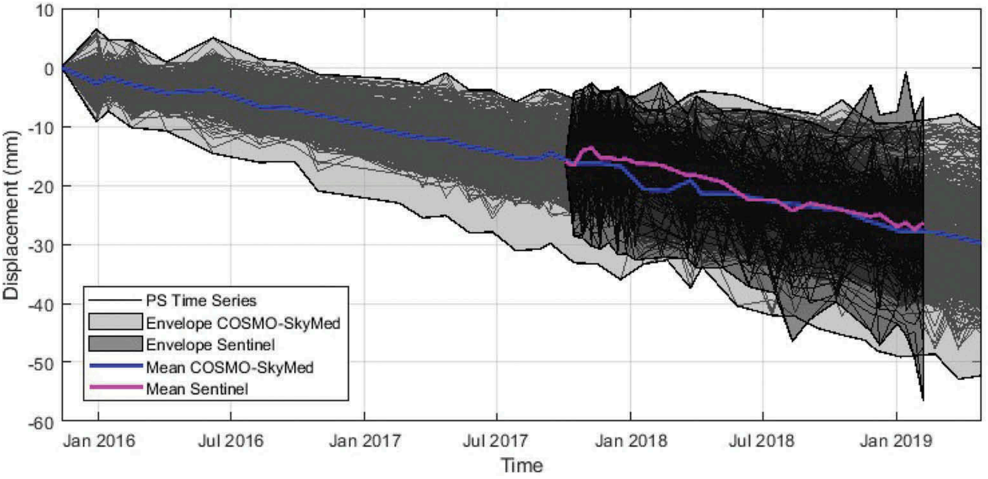

Figure 3. Comparison between displacement time series of PSs within the investigated area (i.e., the yellow rectangular area in Figure 2) for both Sentinel and COSMO-SkyMed data. The envelopes represent areas of maximum and minimum variations of each averaged displacement value across the period analysed.

Considering a linear regression fitting of the average deformation points for the two datasets, very close slopes of the fitting lines are observed. These indicate velocities of deformation equal to –8.43 mm/y and –9.78 mm/y for the COSMO-SkyMed and the Sentinel-1 data, respectively (Figure 4). The quality of the fitting is proven by very high values of R2, i.e., 0.96 (COSMO-SkyMed) and 0.88 (Sentinel-1).

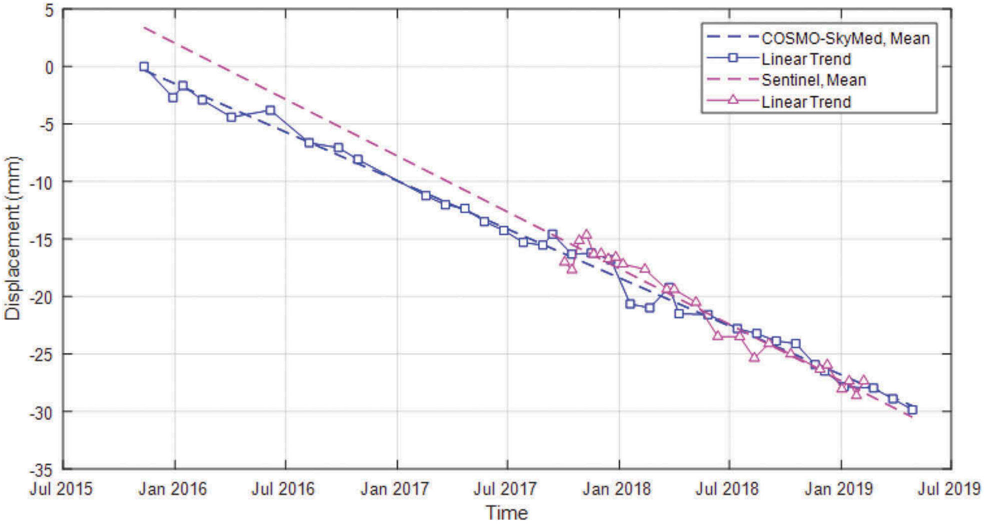

Figure 4. Linear fitting of average displacement time series for COSMO-SkyMed and Sentinel-1 datasets.

The analysis of the statistical distribution of the two populations of displacement velocities confirms a good agreement between COSMO-SkyMed and Sentinel-1 datasets (Figure 5), with COSMO-SkyMed being more centred around the mean value (i.e., a lower standard deviation). This is expected considering the lower resolution associated with Sentinel-1 images.

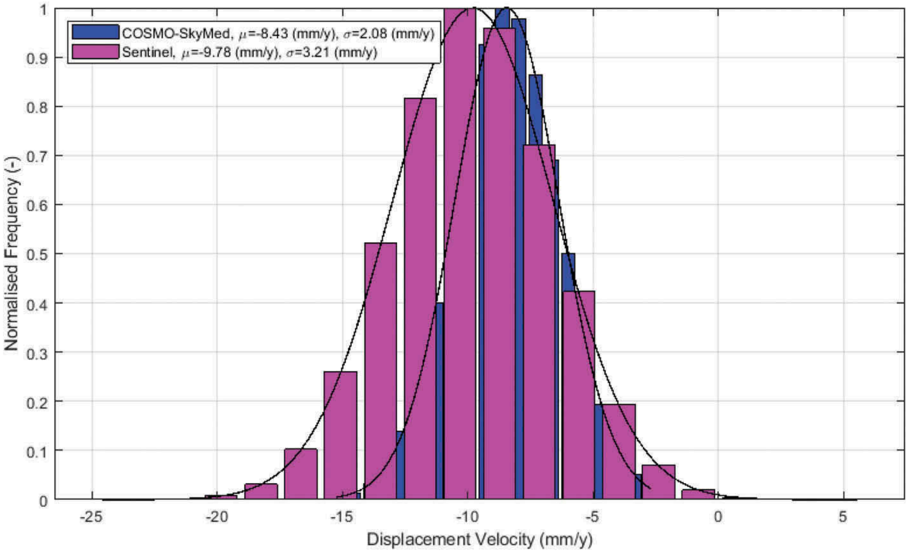

Figure 5. Normal probability density functions of displacement velocity for COSMO-SkyMed and Sentinel-1 PSs.

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

This work aims to demonstrate the viability of the medium-range resolution SAR datasets in transport asset monitoring for effective detection of subsidence. To this effect, InSAR analysis of high (COSMO-SkyMed) and medium-resolution (Sentinel-1A) datasets is performed on a dual- carriageway rural motorway and one major exit ramp located in an area affected by known subsidence. A comparison between the outcomes of the Persistent Scatterers Interferometry (PSI) processing with the two resolutions demonstrates the viability of using Sentinel-1A images for the monitoring of subsidence.

This information is crucial for integration into Pavement Management Systems (PMSs) to predict critical displacements and optimize maintenance prior to pavement degradation and failure. Results have proven that medium-resolution data could be used effectively to preliminarily identify areas of concern, where in depth analyses (e.g., using X-band data or ground-based non-destructive testing methods) could be carried out at a later stage. However, an integration with other specialist techniques must be mandatory for areas affected by natural hazards, such as subsidence or landslides.

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