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Transport infrastructure monitoring by data fusion of GPR and SAR imagery information

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Abstract

In order to maintain the highest operational safety standards, it is crucial that surface and structural deformation caused by geophysical natural hazards and human-related activities in linear transport networks (such as highways and railways) are monitored and evaluated. Today, Ground Penetrating Radar (GPR) is a well-established technology among the available non-destructive testing (NDT) methods for the collection of ground-based information. Concurrently, the space-borne Interferometric Synthetic Aperture Radar (InSAR) is another well-known viable methodology for large-scale investigations of road network surface deformations. However, it is fair to comment that the potential of this method in the area of transport infrastructure monitoring has not yet been sufficiently explored. Within this context, this research demonstrates the viability of integrating InSAR and GPR for monitoring transport assets at network level. The main theoretical and working principles of the two above-mentioned methodologies have been presented and discussed, and the advantage and drawbacks of each technique have then been analysed. The final section of the paper examines a recent experimental activity carried out on a real-life railway located in Puglia, Southern Italy. Test outcomes prove the viability of the proposed data fusion methodology for monitoring the health of transport assets at network level.

Keywords: ground penetrating radar (GPR); non-destructive testing (NDT) methods; space-borne Interferometric Synthetic Aperture Radar (InSAR); transport infrastructure monitoring; data fusion

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1. Introduction

The accurate assessment of the health conditions of linear transport infrastructures such as roads and railways, and the surrounding environment, is a crucial task to ensure safety, functionality and resilience standards over time. Typically, the assessment of the resilience features of an infrastructure asset against major natural hazards or human-related events (i.e., exogenous events) is conducted separately from the monitoring activities carried out for the control of safety conditions and strength properties over time (endogenous events). The latter are usually related to the maintenance of an infrastructure.

However, a progressive decrease in funds allocated for maintenance and prevention, along with a lack of advanced technologies for sufficiently accurate network-scale analyses, may affect both the assessment activities. Furthermore, a number of dramatic events, such as viaduct collapses (e.g. Polcevera Bridge in Genoa, Italy) and convoy derailments, recently occurred in transport infrastructures, emphasised the need to provide a more effective monitoring of the actual health conditions over a transport asset.

To that effect, the integration of multi-source information collected using different non-destructive testing (NDT) methods within a “data fusion” logic, can stand as an innovative and viable approach to cover specific technology-related gaps, as well as to ensure a more comprehensive assessment of the infrastructure (Grasmueck and Viggiano, 2007; Maser, 2009).

In addition to the above, monitoring the planning of a transportation asset is crucial to preserving and maintaining proper serviceability standards over time, and to preventing the risk of collapse during normal operations. Enormous investments have been made over the last decades in research and development within the context of an early-stage assessment of decay. To this effect, NDT methods are nowadays well-established for the health monitoring of civil engineering infrastructures.

This research proposes a novel approach to improving the collection of information about the transport asset conditions at network scale, with a special focus on the asset resilience, in both exogenous and endogenous events. Specifically, the proposed methodology is based on a data-fusion concept capable of integrating datasets collected using the space-borne Interferometric Synthetic Aperture Radar (InSAR) and the Ground Penetrating Radar (GPR) technologies.

The paper is structured as follows: a focus on the main features of the inSAR and the GPR methodologies is given in Sections 2 and 3, respectively; the data fusion approach is discussed in Section 4, where an experimental activity carried out on an existing railway track-bed is also presented; and conclusions are provided in the final section.

2. Satellite radar remote sensing systems

2.1. Background

Transport networks are inherently extensive and complex systems. To this effect, satellite remote sensing can be effectively applied to assess their condition and provide a continuous monitoring of the overall infrastructure and the surrounding environment. Several techniques have been developed in the last decades to exploit space-borne data from both SAR and Multispectral sensors for Earth surface monitoring. In more detail, SAR Differential Interferometry (DInSAR) techniques are capable of detecting ground deformation patterns at different ground resolutions and frequencies associated with local failures and natural hazards (e.g., earthquakes or slow-moving landslides) as well as human-related occurrences (e.g. excavations, settlements) impacting the network.

Within this context, the main benefits from satellite remote sensing are a large spatial coverage (tens of square kilometers) at different ground resolutions (tens of meters to sub-metric resolutions), and a low revisit time (weekly to daily surveys). The latter is true especially for applications that require frequent imaging and independence from weather conditions, as SAR is capable of collecting data through clouds as well as in nighttime conditions. In view of these features and a higher cost-effectiveness compared to conventional in-situ techniques and aerial surveys, satellite remote sensing has emerged as an innovative and promising technique for infrastructure monitoring purposes.

The deformations of linear infrastructures, including bridges and viaducts, can be measured by SAR interferometry with sub-centimetric accuracy using a multi-image approach. This approach identifies features providing robust and stable radar reflections back to the radar sensor. Many of these electromagnetic stable features can be effectively recognised over manmade linear tracks due to their scattering behaviour and the high radar reflectivity. To this effect, velocity and time-series of displacements can be obtained and provide a contribution to i) prompt a proactive asset maintenance, ii) optimise in-situ monitoring, and iii) increase network resilience.

2.2. Permanent Scatterer Interferometry (PSI) for transport infrastructure monitoring

Permanent Scatterer Interferometry (PSI) is a remote sensing technique capable of measuring displacements of the Earth's surface over time and collecting data at different time intervals and scales (Ferretti et al., 2000, 2001). The technique is very suitable for the investigation of displacements in linear infrastructures, as these can typically generate numerous permanent scatterers, especially in non-urban areas. In this work, PSI interferometry and non-destructive ground-based monitoring techniques have been used to assess and monitor a railway stretch located in Puglia, Southern Italy.

The application of the PSI technique for the monitoring of road and railway infrastructures has not yet been comprehensively investigated in the literature (Yang et al., 2014; Barla et al., 2016; Koudogbo et al., 2018). This technique, relying on the statistical analysis of the signals backscattered from a network of phase-coherent targets, can collect displacements between different acquisitions by calculation of the phase shift related to ground motions (Ferretti et al., 2000, 2001). Within this context, stable reflectors (i.e., the permanent scatterers) are defined as the points on the ground that return stable signals to the satellite sensor. These points can be detected over an inspected area, thereby allowing surface displacement velocities to be measured with a millimeter accuracy (Ferretti et al. 2001; Colesanti et al. 2005).

In addition, the possibility of creating a historical series of displacements stands as an innovative feature of this technique, and allows a likely prediction of the deformation trend. In this regard, it is worth mentioning that available ground-based sensors, such as inclinometers and GPS stations, allow only a partial prediction of this feature. Although the reliability of these systems is well-acknowledged, these sensors can provide a documented series of deformations only at the time/space collection point. In addition, the cost of installation is typically very high.

Conversely, the use of the InSAR technique allows an entire transport network to be investigated in a relatively-short time, compared to current monitoring systems. In addition, it does not require any on-site installation, as it uses reflection points already on the ground working as reflectors, and it does not affect the operation of road and rail infrastructures. However, its limitations have been identified in terms of a limited stand-alone applicability of the technique. Tab. 1 lists the advantages and drawbacks of the use of the InSAR technique to linear infrastructure monitoring.

Tab. 1. Advantages and drawbacks of the use of the InSAR technique to linear infrastructure monitoring

Advantages	**Limitations**
High resolution and accuracy	Size of database to handle
High productivity	Dependency on PS availability
Multi-scale datasets	Need for experienced surveyors
Repeatability of the measurements	
No interference with local traffic	

3. Ground Penetrating Radar

3.1. Background

GPR has found an increasingly wide applicability as an electromagnetic device for the assessment of the subsurface features of transport infrastructures (Alani et al., 2013; Alani and Tosti, 2018).

In general terms, GPR allows information about the bodies or structures hidden within a surface, typically the ground, to be inferred by means of a transmission/reception of EM waves. These travel through lossy media up to their ultimate attenuation. When a physical discontinuity is encountered, EM waves are partially back-reflected to the receiver, which allows for the reconstruction of the features of the subsurface (Annan, 2002).

Frequencies typically used to monitor transport infrastructures allow for a centimeter resolution, although limited information on the surface conditions can be inferred.

3.2. GPR for transport infrastructure monitoring

The GPR technology has proven high applicability for the monitoring of transport infrastructures (Tosti et al., 2014; Benedetto et al., 2016). This is mostly related to a number of advantages that GPR possesses over other traditional inspection techniques and NDTs (Alani et al., 2014). Despite a huge number of successful applications reported in the literature, some drawbacks are still noted, which limit its stand-alone applicability. The advantages and limitations of using GPR technology are summarised in Tab. 2.

Tab. 2. Advantages and limitations of using GPR for linear infrastructure monitoring

Advantages	**Limitations**
High flexibility	Need for calibration
Cost-time effectiveness	Need for expertise of a surveyor
Assessment of the causes of distress	Partial diagnosis
Low interference with local traffic	

4. Integration of InSAR and GPR techniques: a data fusion approach

Despite the above methodologies are capable of collecting a considerable amount of data on the conditions of a transport asset, the relevant outcomes are incomplete if considered singularly. Analyses of satellite data are hardly expected to assess hypogeal occurrences; on the other hand, GPR is scarcely effective for inferring information about superficial distress. The integration of these techniques allows the flexibility, high resolution and capacity to identify the causes of shallower defects of GPR, to be combined with the possibility to model the evolution trend of distresses at a larger scale of InSAR. Indeed, the enhanced accuracy arising from this integrated approach can contribute to increasing the resistance of an infrastructure to both major external events and internal decay, and might lead to an extended concept of infrastructure resilience.

5. An experimental application

A large dataset of SAR images from both the Sentinel 1A and the COSMO-SkyMed missions was gathered in the time interval 2016-2017and processed using the PSI technique. The aim of the application was to assess potential subsidence occurring on a railway stretch located in Puglia, Southern Italy. In addition, a dedicated on-site GPR survey over the same railway track was carried out for integration purposes. A total length of 9.8 km of a railway stretch was investigated. The site location for the field surveys and a flow-chart of the used methodology are illustrated in Fig. 1, and Fig. 2, respectively.

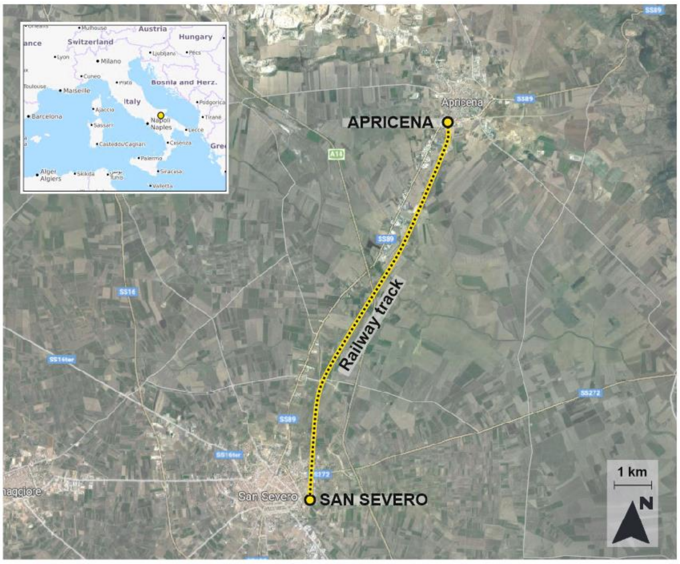

Fig. 1 The survey site nearby San Severo, Puglia, Italy.

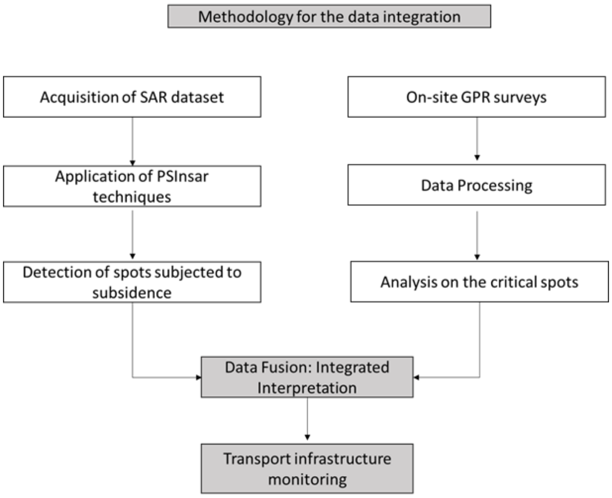

Fig. 2. Methodology used for the data integration.

6. Test Equipment and InSAR imagery

GPR acquisitions were carried out by using two horn antenna systems with operating frequencies of 1000 MHz and 2000 MHz. The GPR systems were mounted on an inspection convoy and suspended in the air at 45 cm of height from the ballast surface. The connection support and all the testing devices were mounted on an ETR 330 convoy (Fig. 3).

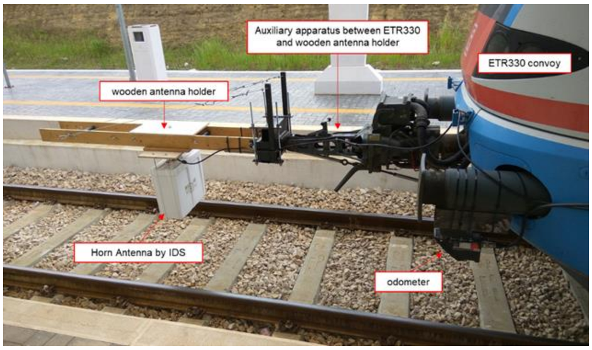

Fig. 3. Equipment used for the GPR tests on the railway track-bed.

The datasets used for interferometric analyses are an amount of 21 and 23 images collected in ascending and descending geometry from Sentinel 1A mission, respectively. The survey period spans from April 2017 and January 2018. Furthermore, an amount of 27 and 29 images collected in ascending and descending geometry from the COSMO-SkyMed mission, respectively, were taken into account. In this latter case, the observation period ranges from March 2016 to January 2018. In regard to the data processing, GPR data were elaborated in the Matlab™ environment according to a standard processing sequence (Benedetto et al., 2017; Bianchini Ciampoli et al., 2019), including: i) dewow; ii) time-zero correction; iii) band-pass filtering; iv) signal gain. On the other hand, the interferometric analysis of the imagery from the Sentinel and the Cosmo SkyMed missions has been developed using the ENVI SARscape® software. This allowed to locate the permanent scatterers and, hence, to apply the PSI technique. Such PS were finally represented over the inspected territory in a GIS environment.

7. Results

With reference to the methodology in Fig. 2, the technique was found to be effective at detecting potential areas subject to an evolving subsidence and a down-lifting occurrence over the inspected track. In turn, the analysis of the GPR datasets confirmed the presence of subsidence spots, as the potential causes of damage were identified. This is crucial to providing railway managers with useful information, and helps to prioritise maintenance interventions effectively.

In more detail, several permanent scatterers (PSs) were identified on the railway track and several of these were observed to be affected by down-lifting occurrences in the first kilometer of inspection (Fig. 4).

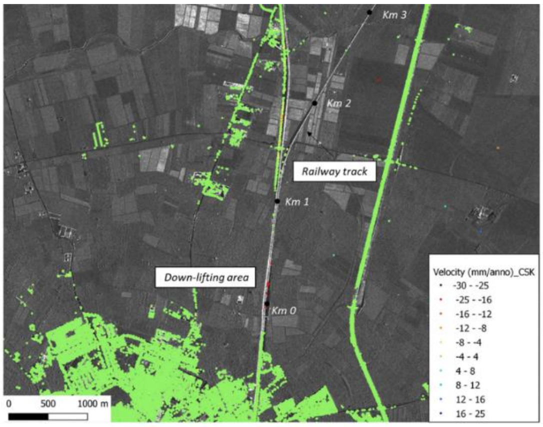

Fig.4. PS dataset from a PSI application; average trend of subsidence observed on the first kilometer. Copyright: "COSMO-SkyMed Product – ©ASI – Agenzia Spaziale Italiana – 2018. All rights reserved".

By analysing the GPR data, it was possible to observe various spots affected by a high attenuation of the signal This happened in the first half-kilometer, and especially in the first 500 m. In these areas, reflections occurring below the interface between the ballast and subballast layers are observed to be lower (Fig. 5) (Benedetto et al., 2017; Tosti et al., 2018). Such an occurrence is likely to be related to the uprising of highly conductive fine particles from the subgrade (Al-Qadi et al., 2008; Bianchini Ciampoli et al., 2017). This hypothesis seems to be confirmed by a video analysis, which highlighted the presence of clayey materials at the edges of the track-bed, and a geological investigation of the area, that has identified clayey subgrades over the first kilometer of inspection. These information would explain both the subsidence observed by InSAR and the attenuation of the GPR signal below the subbase, as the presence of clay is the major source of plasticity of subgrades (InSAR) and high attenuation coefficients (GPR).

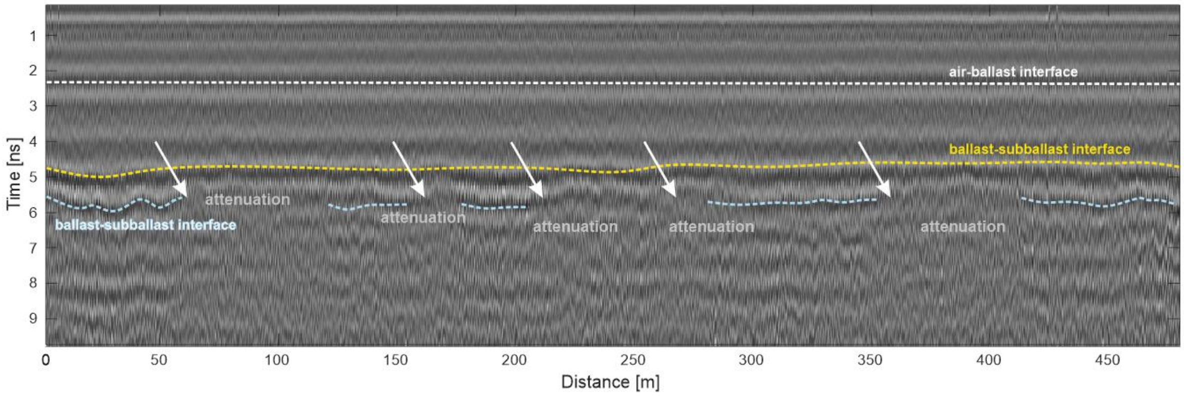

Fig. 5. GPR data collected at the subsidence spot detected from InSAR analysis over the first kilometer of railway track.

8. Conclusion and future prospects

This study reports an overview of major advantages and limitations of non-destructive testing (NDT) methods for transport infrastructure monitoring. In this context, the integration of datasets collected with different NDT methods can stand as a potential solution to technology-specific gaps arising from the stand-alone application of the singular technology. A data fusion rationale would ensure a more comprehensive assessment of the infrastructure elements, and more advanced data interpretation from the merging of different information.

In more detail, this study reports on two of the most promising non-destructive methodologies for the assessment of linear infrastructures, i.e., the Synthetic Aperture Radar Interferometry (InSAR) and the Ground Penetrating Radar (GPR). The focus is on the integration between remote sensing and ground-based high frequency investigations.

In view of the above, the proposed approach was tested over a 10 km long existing railway track-bed, located nearby San Severo, Southern Italy. The inspected stretch was subject to both InSAR and GPR surveys. As a preliminary result, the analysis of space-borne data was found to be very effective in rapidly identifying spots subject to deformations and subsidence, over the monitored length. In turn, the analysis of ground-based data collected by GPR allowed to effectively diagnose potential causes of decay. The integration of the datasets allowed for a comprehensive monitoring of the actual condition of the assets and a significant increase of the efficiency of the GPR data interpretation phase. This is due to the detection of critical spots using the InSAR technique.

Further efforts have to be dedicated to the application of the proposed approach at network level, involving the management of extensive datasets and the need for automating the processes of detection and diagnosis.

Acknowledgement

In this research, a stack 44 images of Sentinel 1A are processed ("produced from ESA European Space Agency, remote sensing data"). 56 images collected in both an ascending and a descending geometry from COSMO-SkyMed stripmap images have been processed (COSMO-SkyMed Product - ©ASI: Italian Space Agency, 2016-2017, All Rights Reserved). These products have been acquired and processed using the PS technique of SARscape Interferometric Stacking Module in the framework and under the license of the project “STRAIN: Sensing Transport Infrastructures” (proposal ID 46829), approved by ESA: European Space Agency. The license is from the project mentioned above.

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