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Multitemporal SAR data for prospection, monitoring and preservation of Cultural Heritage

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Abstract **The present research proposes an interdisciplinary approach that integrates traditional archaeological investigation with advanced satellite remote sensing techniques, through the use of Synthetic Aperture Radar (SAR) data acquired from Sentinel-1 and COSMO-SkyMed missions. The objective is to assess the effectiveness of Earth Observation technologies in preventive archaeology developing a non-invasive methodology for the identification and prospection of buried remains, with the aim of identifying areas of potential archaeological interest for future monitoring activities to ensure the conservation of Cultural Heritage. The study area encompasses the territory of the lower Calore Valley in the Benevento province, with a focus on the site of the Roman city of *Telesia Vetere* (San Salvatore Telesino), and the Norman bell tower of Telese (Telese Terme). Through multitemporal processing and interferometric analysis of SAR data, the research aims to develop appropriate urban and infrastructural planning, through the creation of potential and risk maps to preserve and promote potential archaeological sites. The proposed model is intended as an operational tool to support public authorities to mitigate the impact of anthropogenic transformations on the historical landscape, while also reducing intervention time and costs. In parallel, the use of interferometric (InSAR and Persistent Scatterer Interferometry) techniques enables the monitoring of the structural condition of above-ground archaeological remains, facilitating the detection of structural instabilities and the activation of preventive measures. The integrated approach thus constitutes a concrete contribution to the advancement of sustainable practices for the protection and enhancement of archaeological heritage.**

Keywords: Archaeology, Cultural Heritage, COSMO-SkyMed, InSAR, Earth Observation, Monitoring, Remote Sensing

I. INTRODUCTION

In the last decades, the use of Earth Observation (EO) for monitoring and conservation of cultural heritage has significantly increased. In 2017, the European Commission established a Task Force with the aim of exploring the potential of Copernicus satellite data for the conservation, enhancement, monitoring, and management of Cultural Heritage (CH) (1–4). Furthermore, EO for cultural heritage is a growing topic of international cooperation as proved by projects such as SARchaeology under the Dragon-5 program promoted by the European Space Agency (ESA). Led by CNR-ISAC in collaboration with the LIESMARS center at Wuhan University, the Italian Space Agency (ASI), and the Chinese Academy of Sciences (CAS), the project fostered the use of satellite Synthetic Aperture Radar (SAR) data for archaeological applications and the protection of CH (5).

Of the Copernicus EO data portfolio, Sentinel-1 imagery already proved valuable, especially for interferometric (InSAR and Persistent Scatterer Interferometry) applications, given its ease of access, regular revisit time and millimeter-sclae precision of the quantitative estimates of the structural deformation that may affect monuments and historical buildings (6,7).

In Italy, a country with an extensive and rich historical-archaeological heritage, CH represents a key resource for sustainable development and thus EO-based solutions to support monitoring can benefit the organisation in charge of heritage conservation.

This research proposal is situated within this evolving scientific and technological framework. It is based on a methodology that integrates free access SAR data, such as those from Sentinel-1, with very high-resolution data provided by ASI's COSMO-SkyMed constellation.

II. AIMS AND OBJECTIVES

This research aims to develop an innovative methodology for detection, monitoring, and protection of cultural and archaeological heritage through the use of SAR data, with a specific focus on the Sentinel-1 and COSMO-SkyMed sensors. The overarching goal is to enhance preventive archaeology practices by promoting a non-invasive, sustainable, and replicable approach, grounded in the integration of EO technologies into territorial planning and heritage management processes.

By addressing both "subsurface" and "visible" heritage contexts, the study aims to highlight the versatility of the methodology and its applicability across different archaeological and cultural heritage scenarios. At the operational level, the research seeks to identify geospatial anomalies and signatures consistent with the presence of buried archaeological structures through the analysis of radar backscatter and multitemporal SAR data (5,8–12). In parallel, it aims to monitor the condition of historical buildings and monuments using advanced InSAR techniques, enabling the assessment of structural deformation and instabilities over time (13–19).

III. ARCHAEOLOGICAL CONTEXT

The selected case study focuses on a historically and archaeologically significant area located in the lower Calore Valley, in southern Italy. Together, the two case studies exemplify how the proposed integrated framework can be applied to both subsurface and visible heritage, thus covering the full spectrum of prospection, monitoring, and preservation.

The first case study is the ancient Roman city of Telesia Vetere, located near the confluence of the Calore and Volturno rivers, about halfway between the cities of Capua, Benevento and Venafro, in an area bordering Campania and Sannio (20,21). It currently occupies the southern part of the municipality of San Salvatore Telesino, bordering the municipality of Telese Terme, both in the province of Benevento. The remains of the ancient Roman city are today almost entirely buried in the flat area enclosed between the Portella and Truono streams. Telesia is mentioned for the first time in 217 BC and witnessed a prosperous economic condition. Documentary sources seem to attest to the abandonment of the city in the 9th century, when it was conquered by the Saracens. However, the archaeological material identified does not go beyond the 7th century. It would therefore seem that the Roman city was gradually emptied in favour of the localities of Putechelle and Episcopio, separated by the Grassano stream in modern Telese Terme. In fact, ceramic materials dating from the 7th and 8th centuries have been found in this area, suggesting a period of habitation (22). Furthermore, archaeological excavations have dated the remains of a cathedral church dedicated to the Holy Cross, flanked by a necropolis from the same period, to between the 8th and 10th centuries (23).

The ancient Roman city of Telesia Vetere is characterised by a high density of CH features, and the site offers a valuable testing ground for the integration of satellite SAR, optical, and LiDAR data for archaeological prospecting and monitoring. The urban layout of the city has been partially reconstructed through historical cartography and is still legible in the current rural landscape, as seen in high-resolution satellite imagery (Fig. 1 A-B). The combination of historical sources and modern EO technologies enables a comprehensive analysis of landscape transformations, settlement dynamics, and preservation challenges, making it a representative model for developing and validating preventive archaeology methodologies.

The second case study is the Norman bell tower of Telese (Fig. 1 C-D), dated to the 12th century and located on the side of Via Roma, on the edge of a narrow area bordered to the south by the Grassano stream (24). The bell tower appears to be the only remaining visible vestige of the ancient early medieval village of Telesia, in the Episcopio area. The bell tower has a quadrangular base and is divided into three orders distinguished by cornices made of different materials. The first is characterised by the use of large reused blocks dating back to Roman times. A projecting cornice separates the first and second orders, the latter characterised by brick bands, with rhombuses and cubes in different colours alternating with zigzag patterns. The last cornice, which introduces the crowning, is made of brick. The masonry work is rather disordered, but it would appear to have been carried out by skilled craftsmen (Fig. 1 E) (25).

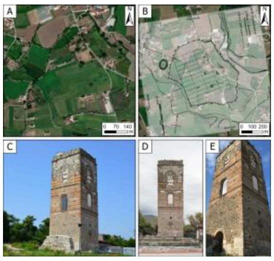

Fig. 1. A, ESRI satellite basemap and B, reconstruction of the urban layout of Telesia (after Quilici 1966, 87, fig. 2), georeferenced and overlain on the satellite image with 50% transparency. C, Norman bell tower of Telese from the east (https://sannio.guideslow.it/localita/telese-terme/) and D, from the north (https://divisare.com/projects/369720-mariano-de-angelis-giardino-archeologico-della-torre-normanna). E, Detail of the masonry texture of the tower (https://fondoambiente.it/luoghi/giardino-archeologico-della-torre-normanna?ldc).

IV. METHODOLOGY

The first methodological step focuses on identifying potential buried archaeological structures in the ancient roman city of Telesia Vetere (San Salvatore Telesino, Benevento). To this end, 3-m spatial resolution X-band COSMO-SkyMed data (StripMap) are employed, complemented by C-band Sentinel-1 and processing included speckle noise reduction through multi-looking and multitemporal averaging, as well as and the extraction of characteristic radar signatures indicative of anthropogenic subsurface anomalies.

The approach involved the selection of COSMO-SkyMed StripMap images at Level 1D, namely geocoded ellipsoid-corrected (GEC) and geocoded terrain-corrected (GTC) products. This product type employs a digital elevation model (DEM) to approximate the real Earth surface. In this study, the DEM used was the NASA Shuttle Radar Topography Mission (SRTM) global dataset, with a spatial resolution of 3 arc-sec (~90 m), available between latitudes 60° N and 56° S (10).

The choice of SAR images was guided by a set of optical data acquired between 2017 and 2022. These included medium-resolution multispectral Sentinel-2 data provided by the Copernicus Programme, high-resolution PlanetScope imagery, and very high-resolution optical data from Google Earth Pro. The analyses focused on the summer months, when vegetation cutting promotes faster regrowth in areas lacking buried archaeological material. This seasonal condition enhances the visibility of crop marks and soil marks associated with subsurface features. Such integration enabled an assessment of the potential of X-band COSMO-SkyMed SAR data in a landscape characterised by mixed land cover and land use (5)

For the first case study, six descending-orbit images acquired between July and September in the years 2017–2021 (Fig. 2 B) and nine descending-orbit images acquired between July and October 2017 (Fig. 3 B) were analysed. In both cases, speckle reduction was carried out using a multitemporal approach based on multi-looking and averaging techniques.

As a final component of the proposed approach, the project aims to develop a predictive model for preventive archaeology, capable of detecting geospatial signals indicative of buried archaeological features. This model is based on an iterative cycle of prediction, verification, and postdiction. The postdiction phase relies on retrospective analysis of SAR data from areas where subsequent excavations or survey confirmed the presence of buried elements, thereby enabling calibration and refinement of the model's predictive capabilities.

The research strategy therefore combines two complementary case studies. While the ancient city of Telesia Vetere serves to test the methodology in relation to subsurface prospection, the Norman bell tower provides a reference example for visible heritage, where the same approach is adapted for monitoring and preservation. This dual perspective demonstrates the capacity of the integrated framework to address both buried and standing heritage, ensuring broader applicability to different cultural heritage scenarios.

The second case study, the Norman bell tower of Telesia, was included with the aim to demonstrate the applicability of the proposed methodology to a visible cultural heritage, thus extending the approach from subsurface prospection to monitoring and preservation. In this case study, the methodological workflow started with the creation of a digital 3D model of the tower, obtained through parametric digitisation process. This model served as the reference system for the integration of satellite radar data and the spatial analysis of deformations. In particular, Sentinel-1 acquisition InSAR datasets, from the European Ground Motion Service (EGMS), were used. They provide multi-temporal displacement measurements at regular intervals from ascending and descending orbits across the entire European region. With this kind of data, it is possible to detect changes in structural stability on a millimetric scale, which is a fundamental tool for the preventive monitoring of monumental and historical buildings (Fig. 4, A).

The data integration involved the import and georeferencing of Persistent Scatterers identified in the EGMS products into the digital model of the bell tower, which had been generated through parametric digitisation. This process enabled the precise placement of Persistent Scatterers on the architectural surfaces of the structure, thereby linking the interferometric measurements to specific structural elements. The integration of InSAR from EGMS data with the digital model was also complemented by realisation in a GIS environment, where it could confront the PS dataset with historical cartography and technical surveys existing, thereby strengthening the validation of the interpretations and expanding the informational potential of the dataset (Fig. 4, B). Through this test case, the Norman Tower demonstrates the adaptability of the SAR-based approach for conservation purposes, complementing the prospection results obtained at the Roman city of Telesia Vetere and reinforcing the integrated framework of prospection, monitoring and preservation.

V. RESULTS

The analyses carried out confirmed the existence of some already known road axes and, at the same time, made it possible to identify new routes that connect to those previously documented. This has enabled a more detailed and accurate reconstruction of the city's road system in Roman period (Figg. 2 C, 3 C).

In particular, a connecting route between two of the main roads leading into the city through the southern gates was identified (Fig. 2 D, no 1). The continuation of a transverse road axis was also recognised, suggesting the existence of a western gate that has not been documented to date (Fig. 2 D, no 2). Two other linear traces, possibly pertaining to a building, also appear to have been identified in this area (Fig. 3 D, nn. 1-2). Another interesting feature is a road route that appears to be the continuation of the road that entered the city from the north-eastern sector (Fig. 2 D, no 3). Also in the north-eastern area, portions of a previously identified road and a possible linear structure interpretable as a canal were found (Fig. 2 D, nn. 4-5, 8). Other linear traces, of uncertain attribution (Fig. 2 D, no 7; Fig. 3 D, nn 4-5), were identified in south sectors of the site; some of them could also be related to canals (Fig. 2 D, no 6; Fig. 3 D, no 6).

The above results are preliminary, and need further verification and validation. From these results it is already clear how advantageous the availability of multi-temporal COSMO-SkyMed data collected in StripMap mode over the same area is. Despite the limitation in spatial resolution that does not allow for clear documentation of the more subtle archaeological traces, the time series allowed an effective speckle reduction and enhancement of the imaged scene. Nevertheless, higher spatial resolution imagery (e.g. SpotLight at 1 m resolution) is expected to improve the observation capability, although ad hoc collection will be required in absence of archive imagery. The evidence that has emerged demonstrates the potential of the methodology adopted and, more generally, the effectiveness of SAR data for archaeological prospecting. These results make a significant contribution to documentation and monitoring activities, with direct implications for preventive archaeology.

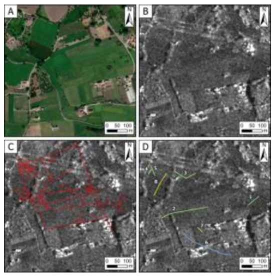

*Fig. 2. SAR image interpretation and preliminary archaeological mapping in the southern part of the ancient city of Telesia. **A**, Esri satellite base map. **B**, Multi-temporal averaged COSMO-SkyMed Enhanced StripMap SAR backscattering. **C**, with traces of archaeological features already known, in red. **D**, Archaeological interpretation, road and archaeological features (green), unclear (yellow), channels (blue).*

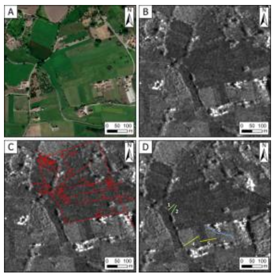

*Fig. 3. SAR image interpretation and preliminary archaeological mapping in the southern part of the ancient city of Telesia. **A**, Esri satellite base map. **B**, Multi-temporal averaged COSMO-SkyMed Enhanced StripMap SAR backscattering. **C**, with traces of archaeological features already known, in red. **D**, Archaeological interpretation, road and archaeological features (green), unclear (yellow), channels (blue).*

Furthermore, the analysis of the Sentinel-1 time series, integrated into the digital model of the Norman bell tower, highlighted the effective distribution of Persistent Scatterers along the main architectural surfaces, particularly on corners, cornices, and stone blocks. The projection of EGMS data onto the 3D model allowed for a structurally consistent interpretation of the interferometric measurements, linking radar signals directly to specific construction elements (Fig. 4, A-B). The integration of InSAR data into the digital and GIS environment therefore not only validated the reliability of the satellite observations, but also demonstrated the potential of the methodology for non-invasive monitoring, preventive conservation, and long-term management of historic architectural heritage. These outcomes, although different in scope from the prospection results obtained at Telesia Vetere, complement them by demonstrating how the same SAR-based approach can be effectively adapted to the monitoring of visible monuments, thereby reinforcing the integrated framework of prospection, monitoring and preservation.

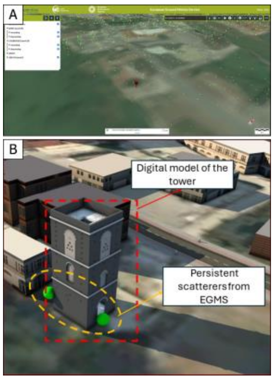

Fig. 4. A EGMS Persistent Scatterers located in the surrounding area of the Norman tower. B Data integration: incorporation of EGMS data into the digital model of the Norman tower.

VI. CONCLUSIONS

The research presented proposes an innovative methodological approach for the analysis and protection of archaeological heritage, based on the use of SAR satellite data and the integration of multispectral and LiDAR datasets. The application of EO techniques to an archaeologically significant area previously unexplored using such tools expands knowledge potential beyond the limits of traditional surface surveys, opening new avenues for preventive archaeology.

The adopted approach not only enhances the detection and documentation of archaeological sites through the analysis of proxy indicators visible in radar data but also represents a significant advancement over the current state of the art in predictive modeling. The combined use of open-source and proprietary software, together with the growing availability of high-resolution EO data, ensures the replicability of this methodology across different contexts, with potential applications at both regional and national scales.

This project is aligned with recent research initiatives developed in Southern Italy and marks a substantial step forward in understanding settlement dynamics and promoting the sustainable management of cultural landscapes. In particular, the use of SAR techniques for monitoring above-ground historical structures opens up new possibilities for the early identification of structural vulnerabilities, with significant implications for planned conservation strategies. This dual perspective reinforces the adaptability of the proposed methodology, confirming its value as an integrated framework for prospection, monitoring, and preservation of cultural heritage.

VII. ACKNOWLEDGEMENTS

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