

Remote Sensing Techniques for the Monitoring of the Villa of Sette Bassi Archaeological Site

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Abstract – This paper examines the application of high-resolution satellite remote sensing and vegetation index analysis for the non-invasive investigation of the Villa of Sette Bassi, a major Roman archaeological site located on the outskirts of Rome. Utilizing Pléiades Neo satellite data and a suite of eleven vegetation indices, the study identifies subsurface anomalies indicative of buried architectural features. The methodological framework integrates rigorous image preprocessing, index derivation, and correlation with geophysical and historical datasets. The findings underscore the efficacy of select indices in complex Mediterranean landscapes. This work advances the methodological discourse in archaeological remote sensing, offering a scalable and replicable protocol for cultural heritage monitoring and landscape archaeology.

I. INTRODUCTION

Recent advances in satellite-based remote sensing have significantly transformed non-invasive archaeological prospection [1, 2, 3], enabling the detection of subsurface features through indirect indicators such as vegetation stress and soil reflectance. Among these tools, the use of vegetation indices (VIs) calculated from high-resolution multispectral imagery has become central to identifying buried archaeological structures without disturbing the terrain [3, 4]. In particular, the Pléiades Neo satellite constellation, with its superior spatial and spectral resolution, offers new opportunities [5, 6] for detecting subtle anomalies in vegetation that may correspond to anthropogenic features beneath the surface.

When applied across different environmental and cultural settings, VIs such as NDVI, SAVI, and GNDVI have proven effective in revealing traces of historical land use, architecture, and infrastructure. These methods are especially relevant in Mediterranean landscapes, where seasonal vegetation dynamics interact closely with the buried stratigraphy. Multitemporal analysis enhances interpretive reliability by accounting for phenological cycles and environmental variability, thereby increasing

the probability of identifying archaeologically meaningful patterns.

The present study adopts this methodological framework to investigate the Villa of Sette Bassi, one of the largest Roman villa complexes in central Italy. Located along the ancient Via Latina and extending over 36 hectares, the site includes a rich array of architectural and agricultural components that remain only partially documented. The application of non-invasive remote sensing techniques in this context aims to improve the identification and mapping of subsurface remains, contributing to ongoing heritage management and conservation strategies.

A. Historical Context and Site Degradation

Constructed during the 2nd to 3rd centuries CE, the Villa of Sette Bassi stands as one of the largest and most elaborate suburban villa complexes in the Roman Empire [2, 7]. Its strategic location along the Via Latina, one of Rome's most important consular roads, facilitated both administrative control and agricultural exploitation of the surrounding countryside (Fig.1).



Fig. 1 Villa of Sette Bassi location, in south-eastern suburbs of Rome, along the via Latina

The villa likely served not only as a luxurious rural retreat but also as a hub for agricultural production, integrating residential, thermal, and storage facilities with landscaped gardens and water management systems (Fig. 2).



Fig. 2 Villa of Sette bassi complex: A - Residential and representative building; B - Residential and representative building; C - Bathing Complex; D - Formal Garden (so-called Hippodrom); E - Nymphaeum, so-called Temple; F - So-called Pars rustica; G - Aqueduct; H - Cistern; I - So-called Dependence

Over the centuries, the site has undergone multiple phases of transformation and degradation. Following the collapse of the Roman Empire, spoliation of building materials, natural decay, and later agricultural use altered the topography and destroyed many surface structures [2, 6]. The 20th century brought additional threats, including bombing during World War II and unregulated urban expansion. These cumulative processes have rendered much of the archaeological record fragmentary and difficult to interpret solely through traditional excavation.

Documentation of the site began in earnest in the 18th and 19th centuries with the work of antiquarians and topographers, yet comprehensive mapping remained

elusive until modern survey techniques were introduced [1, 5]. In recent decades, the area has benefited from renewed interest thanks to its inclusion within the Appia Antica Archaeological Park. Here, interdisciplinary collaboration among archaeologists, remote sensing specialists, and conservators has aimed to stabilize key structures and explore the villa's broader spatial organization using non-invasive methodologies.

This renewed attention has highlighted the need for systematic approaches to monitoring and interpretation that minimize disturbance while maximizing data acquisition. In this context, high-resolution satellite imagery and vegetation index analysis offer a promising avenue for identifying buried architectural elements and for guiding future excavation and conservation strategies.

B. Remote Sensing and Archaeological Application

Remote sensing technologies have become indispensable tools in modern archaeological research, providing high-resolution, non-invasive means for detecting and monitoring buried cultural features. Satellite-based multispectral and hyperspectral imagery, in particular, have enabled archaeologists to investigate extensive landscapes with unprecedented efficiency and accuracy. By analyzing differences in surface reflectance and vegetation health, remote sensing can detect patterns indicative of sub-surface architecture, infrastructure, and land use without the need for direct physical intervention.

One of the most significant contributions of remote sensing lies in its ability to support heritage monitoring in contexts where excavation is not feasible due to legal, financial, or preservation constraints. Techniques such as vegetation index analysis, thermal imaging, and Synthetic Aperture Radar (SAR) have been successfully applied in various parts of the world to detect roads, temples, necropolises, and settlement structures. For instance, in the Bekaa Valley (Lebanon), NDVI and aerial surveys revealed previously undocumented Roman and Hellenistic sites [3]. In the Italian region of Apulia, SAR and VIs helped delineate the full extent of the Roman city of Egnatia buried beneath modern fields [4]. Comparable applications at Villa Adriana and Villa dei Quintili near Rome demonstrated the utility of high-resolution indices in detecting wall lines, cisterns, and portico alignments [8]. Similar results were obtained at the Etruscan-Roman city of Veio, where multispectral satellite imagery and NDVI analysis were used to reconstruct the layout of sacred and domestic zones within a densely vegetated plateau [9, 10, 11].

The present study builds on this well-established foundation by tailoring remote sensing workflows to the unique environmental and archaeological conditions of the Villa of Sette Bassi. The integration of Pléiades Neo VHR satellite data with targeted vegetation indices allows for the detection of subtle anomalies that align with historical

documentation and prior geophysical surveys. This site-specific application demonstrates how standardized remote sensing techniques can be refined and adapted to yield meaningful results even in densely vegetated and morphologically complex contexts. The integration of Pléiades Neo VHR satellite data with targeted vegetation indices allows for the detection of subtle anomalies that align with historical documentation and prior geophysical surveys. This site-specific application demonstrates how standardized remote sensing techniques can be refined and adapted to yield meaningful results even in densely vegetated and morphologically complex contexts.

II. METHODOLOGY

A. Satellite Imagery Acquisition and Processing

A total of six Pléiades Neo satellite scenes were procured, encompassing acquisitions from various seasons between 2021 and 2023. Each image was selected based on strict quality criteria, including cloud cover under 5%, minimal off-nadir displacement ($<10^\circ$), and optimal solar angle [4, 6]. Images were subjected to pansharpener, radiometric normalization, and orthorectification using OrthoEngine software, with elevation corrections based on the TinItaly digital elevation model.

Table 1. Dataset

Date	Pleiades Neo	off-nadir angle	Cloud-cover
20-08-2021	3	7.2°	0%
12-12-2021	3	10°	0%
16-07-2022	4	5.8°	0%
01-09-2022	4	7.5°	20%
02-08-2023	3	9.6°	0%
17-11-2023	4	7.9°	0%

B. Vegetation Index Computation

A total of eleven vegetation indices (VIs) were selected for analysis based on their documented performance in Mediterranean climatic conditions and their sensitivity to variations in vegetation health. Indices such as NDVI, SAVI, and OSAVI have a well-established record in semi-arid archaeological settings [2, 4], while others such as GNDVI and MCARI were selected for their heightened responsiveness to chlorophyll dynamics [12], which often correlate with anthropogenic soil disturbances. Each VI was generated in QGIS using Raster Calculator, followed by contrast enhancement and unsupervised classification to facilitate pattern recognition.

Table 2. Vegetation Indices selected

Vegetation index	Formula
NDVI (Normalized Difference Vegetation Index)	$(\text{NIR} - \text{red}) / (\text{NIR} + \text{red})$
SR (Simple Ratio)	NIR / red
RDVI (Renormalized Difference Vegetation Index)	$(\text{NIR} - \text{red}) / \sqrt{(\text{NIR} + \text{red})}$
NDRE (Normalized Difference Red-edge)	$(\text{NIR} - \text{red edge}) / (\text{NIR} + \text{red edge})$
GNDVI (Green Normalized Difference Vegetation Index)	$(\text{NIR} - \text{green}) / (\text{NIR} + \text{green})$
SAVI (Soil Adjusted Vegetation Index)	$[\text{NIR} - \text{red}] / (\text{NIR} + \text{red} + \text{L}) \times (1 + \text{L})$
OSAVI (Optimized Soil Adjusted Vegetation Index)	$(\text{NIR} - \text{red}) / (\text{NIR} + \text{red} + 0.16)$
TCARI (Transformed Chlorophyll Absorption Ratio Index)	$3 \times ((\text{red edge} - \text{red}) - 0.2 \times (\text{red edge} - \text{green}) \times (\text{red edge} / \text{red}))$
MCARI (Modified Chlorophyll Absorption in Reflectance Index)	$((\text{red edge} - \text{red}) - 0.2 \times (\text{red edge} - \text{green})) \times (\text{red edge} / \text{red})$
Chred-edge (Chlorophyll Red-edge)	$(\text{NIR} / \text{red edge}) - 1$
Chlgreen (Chlorophyll Green)	$(\text{NIR} / \text{green}) - 1$

C. Integration with Archaeological and Archival Datasets

To enhance interpretive reliability, VI outputs were cross-referenced with historical excavation data, geomagnetic surveys conducted by the German Archaeological Institute [13], and 19th- and 20th-century cartographic materials. All results were georeferenced and integrated into a GIS environment to allow for spatiotemporal comparison and hypothesis testing

III. RESULTS

A. Detection of Subsurface Features

The analysis of vegetation indices (VIs), panchromatic imagery, and historical documentation revealed a diverse array of subsurface anomalies indicative of anthropogenic activity. Key findings can be grouped by area of occurrence:

Complex A and B: Linear and semicircular anomalies identified in panchromatic imagery align with known architectural orientations and were validated through archaeological excavation by the Appia Antica Archaeological Park. These features are interpreted as foundational remains, apsidal structures and exedra (Fig. 3)

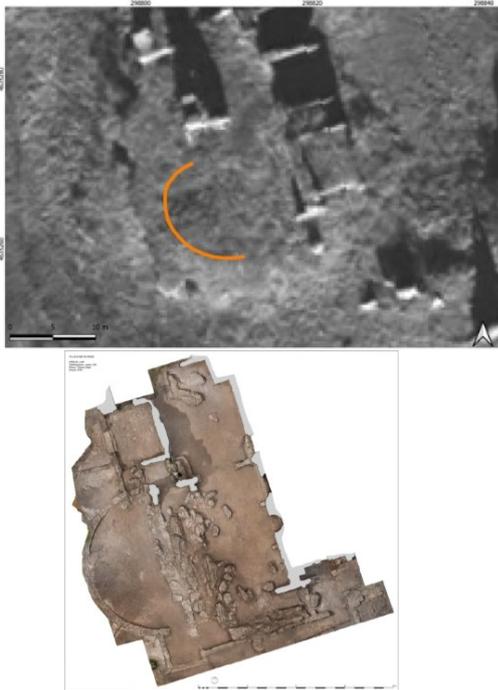


Fig. 3 Semicircular anomalies identified in panchromatic imagery Pleiades Neo 3 12-12-2021 Panchromatic validated through archaeological excavation in Complex B (archaeological orthophotograph of D. Nepi, Parco Appia Antica Archive)

Via Latina Segment: A linear depression detected in SAVI (Fig. 4) and OSAVI maps coincides with the hypothesized path of the ancient Via Latina. Though undocumented in previous surveys, this feature aligns with expected trajectory and width [14].

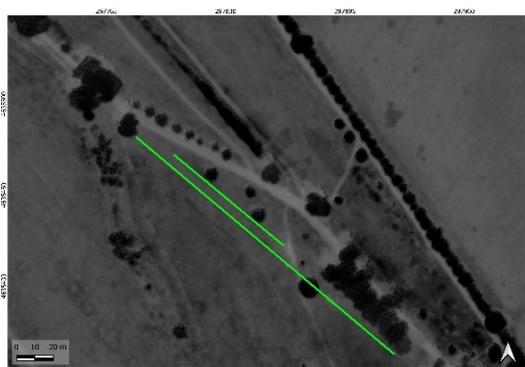


Fig. 4 Linear depression detected in SAVI VI map Pleiades Neo 3 02-08-2023, coincident with Via Latina path

Northern Sector: A broader anomaly—detected by multiple vegetation indices (SR, NDVI, SAVI, and GNDVI) and magnetometry—could be interpreted either as a Roman-cut road or a canal (Fig. 5)



Fig. 5 Anomaly detected in NDVI VI map Pleiades Neo 3 02-08-2023 that could be interpreted either as a Roman-cut road or a canal

Hippodrome Zone: Repetitive negative anomalies at 4–6-meter intervals were visible in NDVI, SAVI, and GNDVI outputs. These align partially with foundations identified through geophysics, though a trench near the barn revealed that some anomalies correspond to plow scars still evident as of 2005 (Fig. 6).

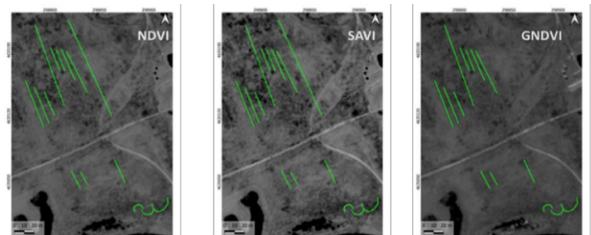


Fig. 6 Negative anomalies at 4–6-meter intervals detected in NDVI, SAVI, and GNDVI VI maps Pleiades Neo 3 02-08-2023

Terrace Niche: RDVI, OSAVI, and NDVI maps from December 2021 revealed a semicircular anomaly consistent with a 9-meter niche, originally shown in early reconstruction plans and confirmed by geophysical data. The feature is no longer visible at the surface.

These multisource observations highlight the diagnostic value of VHR imagery and vegetation indices, particularly when correlated with stratigraphic and geophysical datasets.

B. Seasonal Variation and Index Efficacy

The performance of VIs was notably modulated by acquisition season. Late autumn and early winter imagery provided optimal chlorophyll contrast, allowing GNDVI to outperform baseline NDVI. In contrast, summer scenes—though less effective in vegetative contrast—

highlighted shallow microtopography through shadow enhancement in panchromatic bands. These results reinforce the necessity of a multitemporal approach, wherein phenological cycles are leveraged to enhance feature detectability.

C. Comparative Performance of Vegetation Indices

Each VI exhibited context-specific efficacy:

NDVI, while widely adopted in archaeological remote sensing, demonstrated general reliability but was moderately impacted by soil reflectance in areas with sparse vegetation. Its performance was therefore solid but not exceptional under the site's summer conditions.

SAVI and OSAVI outperformed NDVI in stabilizing soil-vegetation contrast, proving particularly effective across marginal and irregular vegetation zones. These indices were better suited to the wild and patchy vegetation typical of the study area, especially during low-growth periods.

GNDVI, which substitutes the red band with green to increase sensitivity to chlorophyll, produced unexpectedly strong signals in some contexts, offering enhanced visibility of crop stress patterns above subsurface features.

MCARI, designed to maximize chlorophyll discrimination, also delivered consistent and interpretable outputs, particularly during early winter acquisitions when chlorophyll activity was more discernible.

RDVI, a refined version of NDVI, showed reliable enhancement of crop mark expression, while SR performed well in summer imagery with reduced biomass, highlighting differential vegetation-soil reflectance. However, SR's performance diminished under dense canopy conditions.

Overall, the results demonstrate that substantial archaeological information can be extracted even from phenologically suboptimal datasets. The accuracy and interpretability of the results are conditioned by a complex interplay of factors—including vegetation phase, feature morphology, and the nature of buried materials. These findings reinforce the need for a context-specific, multitemporal strategy in vegetation index selection and highlight the value of integrating multiple VIs to compensate for seasonal and ecological variability.

IV. DISCUSSION

The analytical framework developed in this study confirms the diagnostic power of very high-resolution multispectral satellite imagery when calibrated through vegetation indices tailored to Mediterranean ecological conditions. The successful detection of features otherwise invisible to the naked eye, including linear foundations and hydrological infrastructure, reinforces the interpretive value of remote sensing for complex Roman villa contexts. Comparative analysis with other case studies—such as

Villa dei Quintili, and Veio—demonstrates a consistent pattern in which GNDVI and MCARI indices outperform traditional NDVI in highly vegetated or morphologically ambiguous areas.

Moreover, the clarity afforded by Pléiades Neo data—due to its exceptional spatial resolution and low off-nadir acquisition—enabled the precise localization of anomalies with minimal geometric distortion. This level of detail is crucial for planning non-invasive field verification strategies and for updating heritage databases with georeferenced, multi-temporal information.

These findings also highlight a broader methodological implication: remote sensing for archaeological applications must be context-sensitive, adapting index selection, acquisition season, and processing protocols to specific site conditions. The flexibility of the approach, especially when validated through historical and geophysical datasets, supports its replication across other threatened or partially excavated archaeological landscapes. Future research should expand on this foundation through UAV and thermal imaging integration, machine learning classification, and the inclusion of long-term deformation monitoring via InSAR.

The integration of panchromatic sharpening, accurate DEM correction, and targeted seasonal imagery proved instrumental in achieving consistent detection outcomes. While satellite imagery offers limitations in depth resolution compared to ground-based geophysical methods, its efficiency and areal coverage represent significant advantages in preliminary site assessments.

The integration of remote sensing outputs with independent sources—including historical cartography, geomagnetic prospection, and archival excavation data—proved critical for validating spectral anomalies and reducing the likelihood of misinterpretation. This triangulated methodology enabled the identification of consistent spatial patterns across distinct datasets, enhancing interpretive robustness. For instance, several anomalies identified through GNDVI and MCARI corresponded with structures mapped in early 20th-century surveys and aligned with magnetometric results produced by the German Archaeological Institute.

This convergence underscores the value of multi-source validation as a best-practice approach in archaeological metrology, especially when investigating sites affected by landscape modification, modern development, or incomplete documentation. By synthesizing heterogeneous data types within a geospatial framework, the methodology not only increases confidence in non-invasive detection strategies but also establishes a replicable model for future surveys at comparable archaeological sites.

VI. CONCLUSIONS

This research underscores the transformative potential of

high-resolution remote sensing technologies in archaeological prospection and site monitoring. By leveraging the spectral and spatial capabilities of Pléiades Neo imagery and a targeted suite of vegetation indices, we have demonstrated the viability of a cost-effective, replicable methodology for non-invasive site analysis. The Villa of Sette Bassi serves as an exemplary model for applying digital archaeological metrology to both interpret buried features and inform heritage conservation strategies. The integrated approach presented herein contributes to the methodological advancement of remote sensing in cultural heritage and offers significant implications for future landscape-scale archaeological investigations.

Pending flight authorization from ENAV, UAV-based thermal and multispectral surveys will be conducted to complement satellite datasets. These will focus on detecting thermal inertia contrasts and subsurface moisture anomalies. Furthermore, automated classification using machine learning algorithms will be implemented to streamline anomaly detection and reduce analyst subjectivity.

The GIS platform developed in this project will also incorporate InSAR data for deformation monitoring, providing a dynamic and integrative framework for long-term site management and conservation.

Author Contributions: Conceptualization, J.C., V.S., S.R., M.R., P.M.; methodology: J.C., V.S.; data acquisition and analysis: V.S.; writing - original draft preparation, review, editing J.C. §I - VI; images: V.S.; funding P.M.

Aknowledgment: This study was made possible thanks to the collaboration of several institutions. We acknowledge the Parco Archeologico dell'Appia Antica for granting access to the archaeological and cultural heritage sites. Satellite data were made available through the agreement between the CERI Research Center and the Italian Ministry of Culture, within the framework of the National Extraordinary Plan for Monitoring and Conservation of Cultural Heritage.

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