High-Resolution TLS and LiDAR Integration for the 3D Mapping of the Villa del Casale Bath Complex

Ktisis
Journal of Late Antique Housing

Davide Tanasi, *Institute for Digital Exploration (IDEx), University of South Florida, USA*
dtnasi@usf.edu

Stephan Hassam, *Randolph-Macon College, USA*
StephanHassam@rmc.edu

Laura Harrison, *Access 3D Lab, University of South Florida, USA*
harrisonl@usf.edu

Alex Fawbush, *Access 3D Lab, University of South Florida, USA*
fawbusha@usf.edu

Abstract
This study presents some of the results of a longitudinal digital documentation project focused on the western bath complex of the Villa Romana del Casale (Piazza Armerina, Sicily). By integrating terrestrial laser scanning (TLS) and LiDAR datasets acquired between 2017 and 2024, the study demonstrates the analytical value of reunifying legacy and newly collected 3D data into a single, metrically accurate digital surrogate. The resulting high-resolution point cloud supports precise volumetric and spatial analyses of the bath complex, one example of which is presented here. The study tracks the methods used and challenges faced in the digital documentation of the villa using TLS and suggests avenues of further research in its use for analysis on heating systems, water management, and architectural function. Beyond the potential for analytical use, the methods used in the study also establishes a framework for long-term condition monitoring and conservation planning. The project highlights both the technical challenges and methodological benefits of multi-sensor, multi-temporal integration, and argues for the treatment of 3D documentation as a cumulative research infrastructure rather than a series of isolated recording campaigns.

Keywords
Terrestrial Laser Scanning (TLS); LiDAR; Digital Archaeology.

https://ktisisjournal.unibo.it
ISSN: 3103-5566

DOI: https://doi.org/10.60923/issn.3103-5566/23664

1. Introduction

The Villa Romana del Casale, a UNESCO World Heritage Site in Sicily, is a renowned Roman residence constructed between 330 and 350 CE. It is a major cultural heritage tourism destination, welcoming over 200,000 visitors each year who come to the site to experience a labyrinth of interconnected spaces decorated with expansive in situ mosaic compositions such as The Great Hunt and the Bikini Girls. Yet although the site is indisputably impressive in its scale and craftsmanship, it has come under scrutiny due to the deteriorating state of its mosaics since it was inscribed on the UNESCO World Heritage List in 1997. That year, a report from the World Heritage Centre urged the State Party to address concerns expressed about the drainage of the site and the climatic conditions within the cover buildings, noting that these threats could damage the mosaics adorning the "supreme example of a Roman luxury villa". In the decades since, some minor upgrades to a protective canopy structure have been made, but major concerns about heritage loss and damage remain, especially as tourism at the site expands.

Researchers from the University of South Florida began working at Villa Romana del Casale in 2017, returning to the site again in 2022, 2023, and 2024. Over the years, the project incorporated a range of interrelated methodologies broadly aimed at digitally documenting and analyzing the remains of Villa Romana del Casale, given the challenge of promoting site preservation amid natural and anthropogenic threats. In this paper, we detail a longitudinal digital heritage approach that aimed to integrate earlier datasets into later datasets, produced in 2024, to provide a more comprehensive, analytical tool – rather than simply treating each year's data as a standalone "snapshot"[1]. The two primary areas in which this approach was implemented include the creation of an accurate, complete 3D digital surrogate of the villa, consisting of a mosaic of aligned and registered point clouds from multiple sensors and fieldwork campaigns, along with volumetric analyses of several spaces within the built environment. Together, this work provides a comprehensive overview of site conditions which will help land managers proactively develop data-driven conservation plans in the future that account for tiny shifts in the placement and condition of mosaic tesserae and archaeological structures at the scale of +/- 4 millimeters. The availability of metrologically accurate 3D models allows for the calculation of the volumes of certain rooms, that becomes of utmost importance for the study of energy expenditure related with the usage of the baths.

2. Previous Research

The resumption of archaeological activities at the Villa del Casale in 2021, under the auspices of the ARCHLabs project (Archaeological Heritage in Late Antique and Byzantine Sicily), marked the beginning of an ambitious digital project integrating advanced 3D survey technologies and geospatial investigations. This new phase of research not only revitalized a substantial body of earlier 3D visualizations, many of which had remained unused since their initial creation but also introduced the systematic production of new digital assets. The overarching goals were threefold: to document ongoing excavations with high precision, to update and expand the technical documentation of the villa, and to initiate a comprehensive program of virtual recontextualization of artifacts recovered during previous archaeological campaigns[2].

A central element of this initiative has been the strategic reuse of existing 3D datasets, a practice that lies at the heart of current academic debates regarding digital archaeology,

[1] For a definition of longitudinal project in digital heritage see: Cligget 2015, 233-238.

[2] These efforts were done alongside the "excavation" of legacy data of both documentation of past excavations and archaeological finds recovered from them. For initial results, see Marsili, Hassam 2025.

Fig. 1. 3D colored point cloud of the interior of the Villa generated by terrestrial laser scanning.

particularly due to its ethical and methodological implications[3]. In the new context of ARCHLabs, a large-scale 3D mapping project carried out in 2017 by the Institute for Digital Exploration (IDEx) of the University of South Florida provided a treasure of information well positioned for new scientific applications. This dataset included terrestrial laser scanning of the interior of all architectural spaces (**Fig. 1**), a comprehensive ortho-photo mosaic (**Fig. 2**), 3D digitization of all the mosaic pavements (38 rooms) through terrestrial photogrammetry (**Fig. 3**), and aerial photogrammetry documenting both the villa complex and the surrounding Arab-Norman settlement (**Fig. 4**).

These extensive data formed the foundation for producing updated and metrically accurate technical documentation, including architectural plans, sections, and elevations of the architectural remains[4]. They also made possible the development of monitoring systems for mosaic surfaces through Digital Elevation Models (DEM), allowing researchers to detect and assess subsidence, bulging, and other forms of structural instability (**Fig. 5**). This integration of legacy and newly acquired data has provided the project with a high level of analytical precision.

During the 2022 excavation season, 3D survey activities focused primarily on the documentation of Trench A, opened in 2021, and on the digitization of a selected group of artifacts. Multiple acquisition methodologies were employed, including terrestrial laser scanning, digital photogrammetry, and structured-light 3D scanning, to ensure optimal results according to the morphological characteristics and preservation conditions of the materials. This season

[3] For a discussion of digital data and its cycle of reuse, see: Harrison 2022. For a larger discussion of the importance of the reuse of digital data, see Faniel *et alii* 2018.

[4] Gabellone *et alii* 2020.

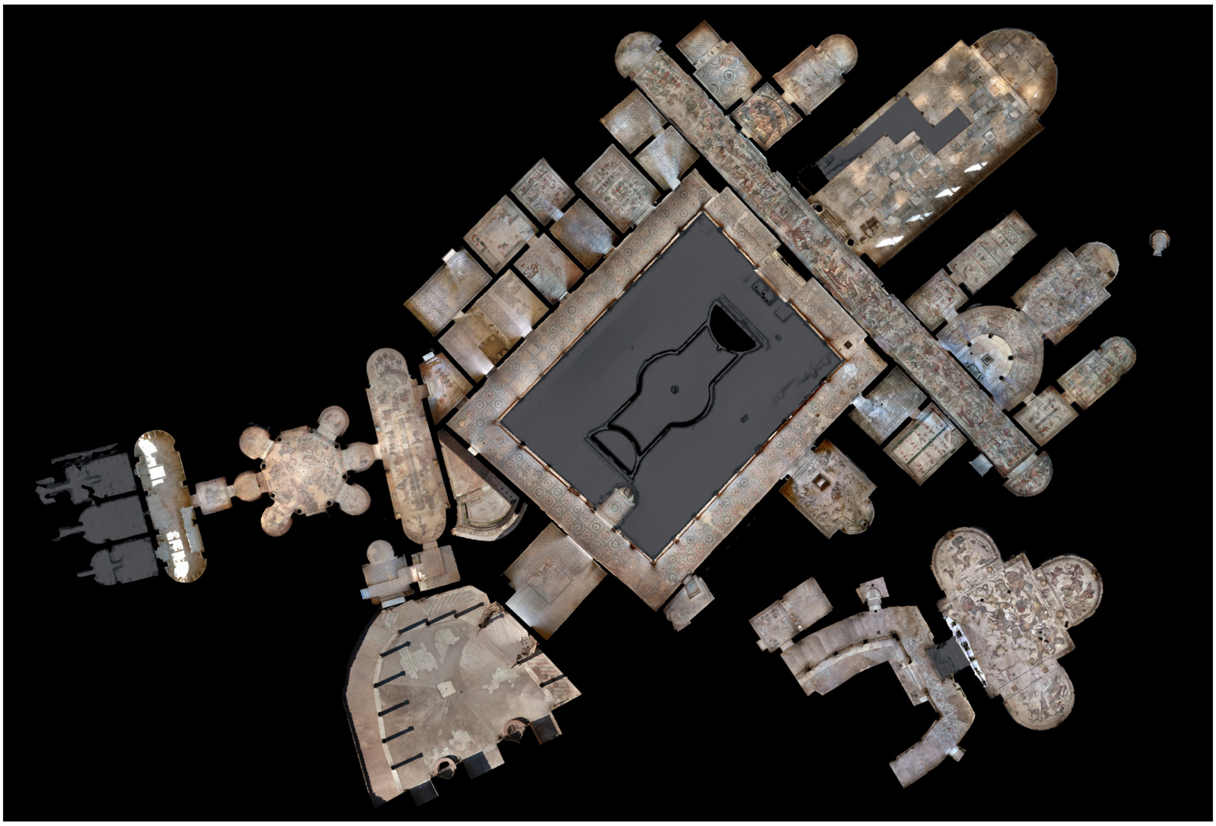

Fig. 2. Orto-photomosaic of the rooms of the Villa with mosaic floors.

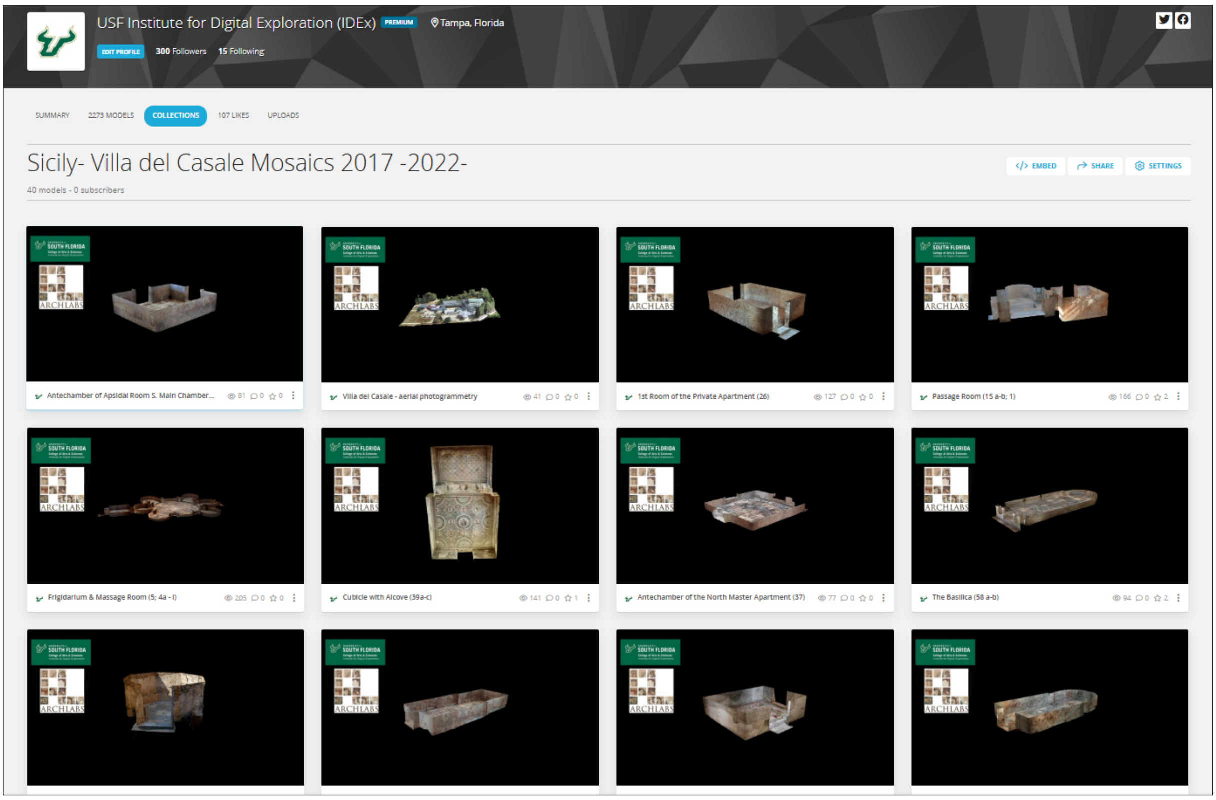

Fig. 3. Sketchfab collections of the 3D models of the 38 rooms: https://sketchfab.com/usfidex/collections/sicily-villa-del-casale-mosaics-2022-90bdd8045a17487f9a363b8faf6416ab

Fig. 4. Drone Photogrammetry 3D models of the entire site of the Villa del Casale.

represented a significant step toward aligning newly generated datasets with the larger digital framework established in 2017.

The 2023 campaign was considerably more complex and ambitious in scope[5]. As a continuation of the earlier large-scale mapping, the entire exterior of the villa complex was surveyed using terrestrial laser scanning, producing 93 scans at regular intervals of 6–9 meters (**Fig. 6**). Particular attention was devoted to documenting the bath complex, where interior and exterior scans were integrated into a unified 3D model. This integrated model now serves as a foundation for virtual simulations, including assessments of thermal energy requirements for heating hypocaust floors, an example of how digital archaeology can bridge architectural documentation and functional interpretation. In addition, a comprehensive photogrammetric survey of the eastern façade of the monumental entrance and the long adjacent wall was completed (**Fig. 7**). This high-resolution dataset supports detailed studies of the surviving frescoes, many of which present complex conservation challenges and require precise three-dimensional contextualization. One of the most significant components of the 2023 work was the 3D digitization of 61 artifacts from secure archaeological contexts associated with Gentili's earlier excavations in the eastern baths (**Fig. 8**). The materials included intact lamps, tableware ceramics, mosaic tesserae and pavement fragments, and metal objects. Twenty-six of these were acquired using an Artec Spider structured-light scanner, while the remaining thirty-five were digitized through terrestrial photogrammetry in controlled lighting conditions. The dual-method approach not only ensured high-quality models but also provided comparative insights into the performance and suitability of different acquisition technologies for diverse classes of artifacts. A further advancement in 2023 was the systematic processing and integration of pre-existing interior and exterior 3D datasets into unified volumetric models, particularly for the bath complex. This allowed for updated calculations of room areas, volumes, and structural relationships, producing a more reliable and dynamic digital representation of the architectural spaces.

[5] Baldini *et alii* 2024a; Baldini *et alii* 2024b; Baldini *et alii* 2025.

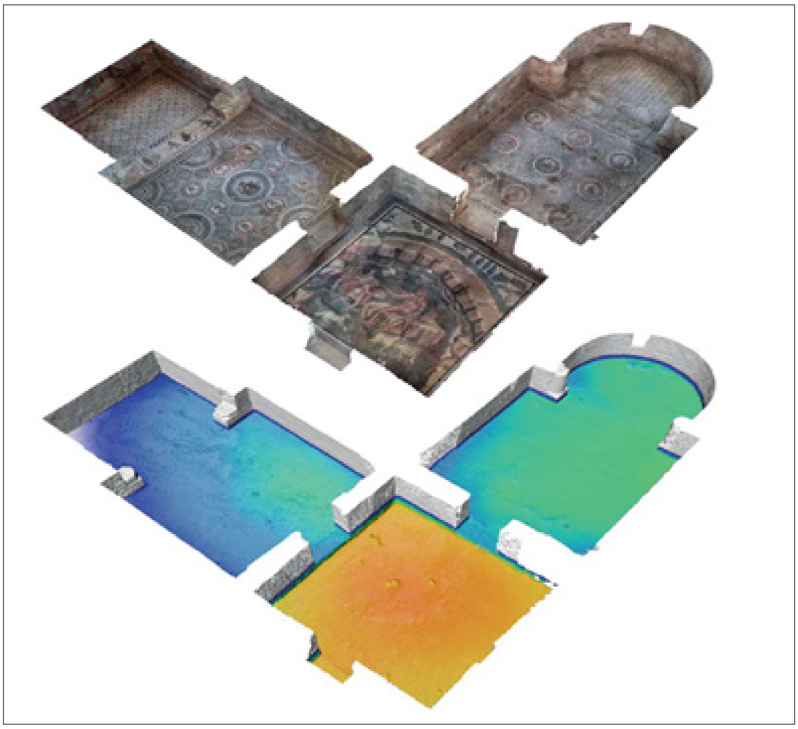

Fig. 5. Example of an altitude map and photogrammetric reconstruction (Gabellone *et alii* 2020).

Fig. 6. 3D colored point cloud of the exterior of the Villa generated by terrestrial laser scanning.

Additionally, to develop a public outreach interface to make user friendly the interactive experience with the 3D models of the rooms with mosaic floors, a HTML script was developed to create a web-based visualization platform where the individual 3D models residing in the Sketchfab collection are mapped on the orthophoto of the site and arranged in a catalogue fashion **(Fig. 9**).

Taken as a whole, the digital documentation activities undertaken between 2021 and 2023 constitute an essential foundation for reconstructing the architectural evolution and functional history of the Villa del Casale. The combination of legacy data and new 3D acquisitions has enabled the creation of a coherent, high-resolution digital corpus, which now serves both research and conservation goals. This corpus supports continual monitoring of mosaic pavements, facilitates complex architectural simulations, and establishes a replicable digital workflow for future archaeological work at the site.

Fig. 7. 3D model of the eastern façade of the monumental entrance and long adjacent wall (https://skfb.ly/pEFQs).

3. Data Collection and Processing

In 2024, a team from the University of South Florida's (USF) Institute for Digital Exploration (IDEx) carried out a terrestrial laser scanning mapping (TLS) of the water tank and the aqueduct serving the bath complex of the Villa Romana del Casale (**Fig. 10**), embedding in a final colored 3D point cloud model data previously obtained in 2017 and 2023 (**Fig. 11**) to generate an overall metrologically accurate plan (**Fig. 12**). In particular, for the last two campaigns, our team used a Faro Focus Premium TLS (2023), and a Matterport Pro3 (2024) scanners mounted on tripods to collect measurements at the villa. All scanners are time-of-flight scanners equipped with class one lasers that capture up to 976,000 points per second (100,000 for Pro3), with a range of 0.5m to 350m (Premium), 0.6m to 150m (s150), and 0.5m to 100m (Pro3). The scanners are equipped with a built-in camera for texturing and a GPS for accurate positioning. They generate 3D point cloud datasets with a maximum distance accuracy of +/- 4mm (Faro) and +/- 20mm (Matterport). All scanners were calibrated to industry standards by the manufacturer. A scan plan was developed to distribute scan points (3D measurements) evenly over the interior, exterior, and aqueduct of the villa, and to ensure good overlap between scan positions. Phase I focused on the villa's interior, with special attention to capturing the mosaics with as much detail as possible. Phase II of scanning captured the exterior structure of the villa. Lastly, Phase III captured the aqueduct and tested the feasibility of using the Matterport Pro3 to capture LiDAR data on large-scale heritage sites and integrating that data with Faro scans in Faro Scene.

The data from the Faro TLS scanners was processed at University of South Florida's Access 3D Lab at USF. First, a new project was created in Faro Scene 2024.0.1 and the raw scan data was imported from the Faro scanners as .FLS file. Each scan was processed with a dark point filter and a stray point filter. Next, the individual scans were organized into clusters based on the date of scanning and the individual scanner. Each cluster was registered using cloud-to-cloud registration, which was registered in clusters. Any outlying scans that were not registered automatically were registered manually. Each of the clusters was then registered together to create a single scan cluster for the entire project. The data was cleaned by manually removing

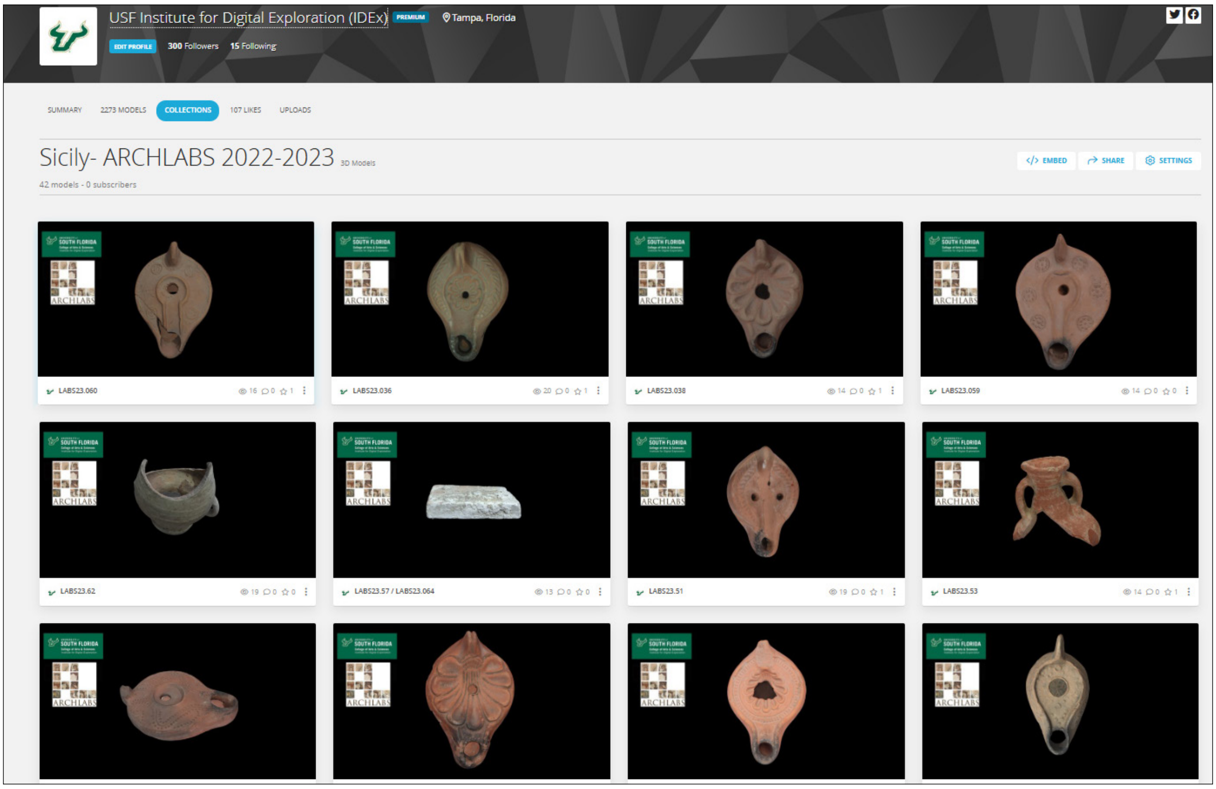

Fig. 8. 3D models of the artefacts from the Gentili excavations (Sketchfab collection: https://sketchfab.com/usfidex/collections/sicily-archlabs-2022-2023-16bc82ba247e4b9586a0b5e36d357357).

Fig. 9. USF IDEx-designed web-based visualization platform (https://usf-idex.github.io/Villa-del-Casale).

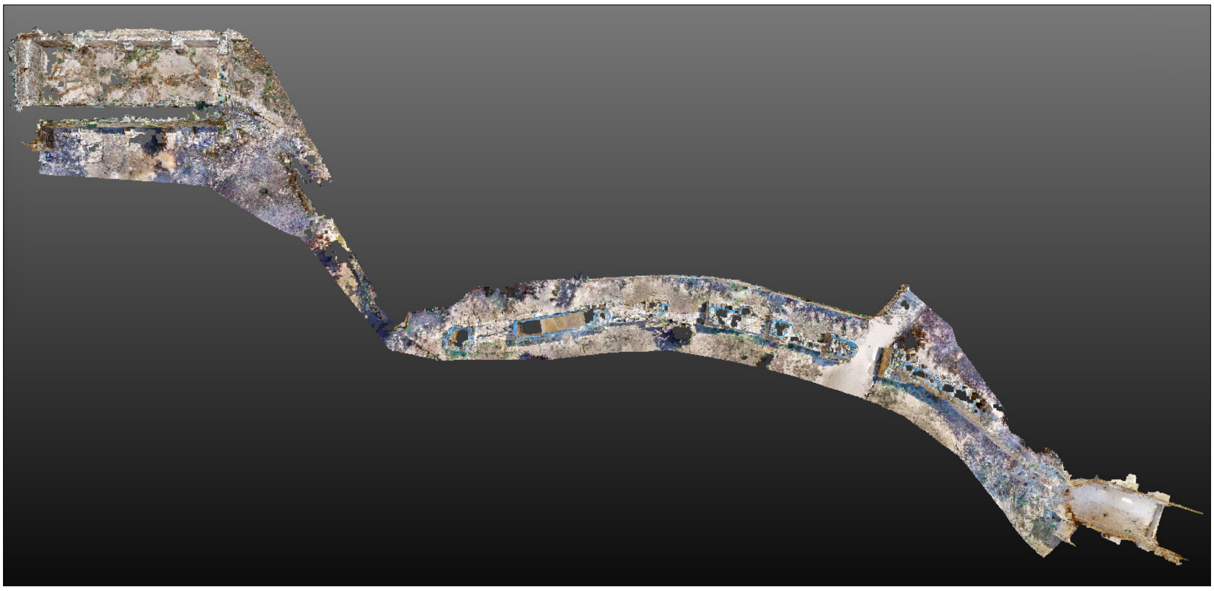

Fig. 10. 3D point cloud of the aqueduct and the water tank generated by merging Faro and Matterport terrestrial laser scanning datasets.

floating data, obstructions, and noise. The data from the Matterport Pro3 was processed via Matterport Cortex AI but was already registered when imported to Scene. Preparing each cluster separately and then merging the Faro and Matterport data was less demanding on hardware resources as smaller project files are easier to process. Once the areas were registered together, a project point cloud was created with parameters to eliminate duplicate scan points, homogenize point density, and apply color balancing. These processes resulted in a final 3D point cloud dataset that offers an accurate representation of the Villa Romana del Casale bath complex and meets 3D metrology industry standards for quality and precision (**Fig. 13**). This final product consists of 687,508,318 points, 260 scans, and occupies 470 GB of storage space.

4. Methodological problems and technical solutions

The project was processed on an Alienware Aurora R14 desktop with an AMD Ryzen 9 5900X 12-Core Processor, 128 GB of DDR4 RAM, 4 TB of total storage space, and an NVIDIA GeForce RTX 3080 graphics card. Alignment of the scans in the interior of the villa was particularly successful due to the use of 150mm Koppa target spheres. These target spheres act as stationary reference points within the space and are easily identified during processing to align scans quickly. However, these spheres were not used in the 2023 exterior scans causing that area to be registered through cloud-to-cloud registration and, when necessary, manual registration. The 2024 Matterport scan of the aqueduct is self-registered in real-time, so when importing into Scene as an .E57 file it only needed to be visually registered to the other two areas. The max point error, mean point error, and scan overlap are related to the accuracy of the scan project. (**Tab. 1**). That said, the overlap percentage listed in a registration report directly correlates to point error. If the scans are further apart there is less overlap and more error.

The reunification of variegated data introduced methodological issues that are present in many digitization projects[6]. Differences between approaches taken by different scanning teams

[6] For a longer discussion of challenges in digitization of cultural heritage see Chatzistamatis *et alii* 2023.

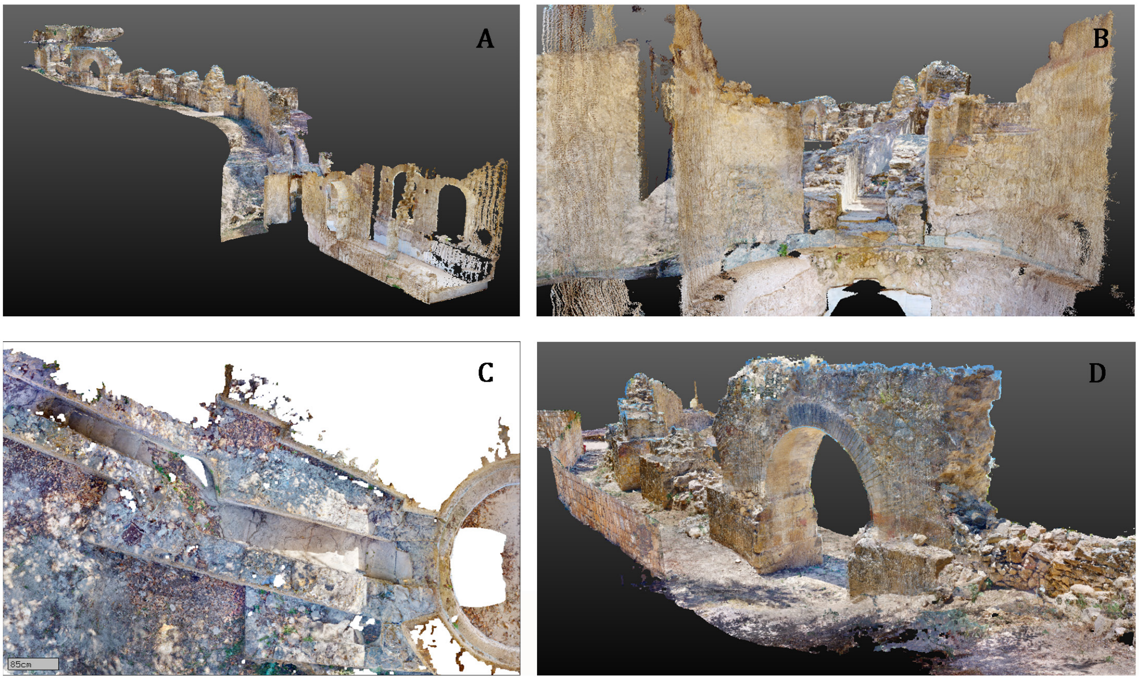

Fig. 11. Details of the combined colored 3D point cloud model, A) overall area, B) connection of the aqueduct to the natatio as viewed from inside the natatio, C) tope view of the point of connection, D) extant arch of the aqueduct.

and available hardware and software complicated the registration process. The difference in the environmental conditions of the terrain and the site, alongside the employment of different devices and calibration in the campaigns of 2017, 2024 and 2024 caused some methodological problems in the process of generating the unified 3D point cloud model.

Human error is the one common factor that all digitization projects face. For example, in one instance a team member was stationary against the wall of the aqueduct causing them to be 'baked' into the texture (**Fig. 14a**), which also commonly occurs on sites open to the public, like the Villa del Casale. This issue can be corrected by removing the section of the bad texture from the individual scan. After the problem area has been removed the texture from an adjacent scan will fill in the void (**Fig. 14b**). Fort this reason, it is important to ensure a great deal of scan overlap in the project, to prevent the need for additional scanning to fix the issue. Natural and anthropogenic features on the landscape also impacted scan quality by obscuring the villa. Areas of dense vegetation caused holes in the model, most notably the area north of the Salone del Circo. Anthropogenic factors such as netting, plastic sheeting, signage, downspouts, and modern 'protective' structures also obstruct portions of the villa. The removal of extensive pedestrian traffic, other anthropogenic factors, and vegetation lengthened the processing time.

Area	Scanner	Number of Scans	Raw Data Size (GB)	Max Point Error	Mean Point Error	Overlap
Aqueduct	Matterport Pro3	48	1.08	32.3 mm	13 mm	8.2%
Exterior	Faro x330	111	26.5	18.1 mm	3.4 mm	10.8%
Interior	Faro x330	101	41.4	1.8 mm	1.7 mm	49.7%

Tab. 1. Scan point statistics and cluster properties.

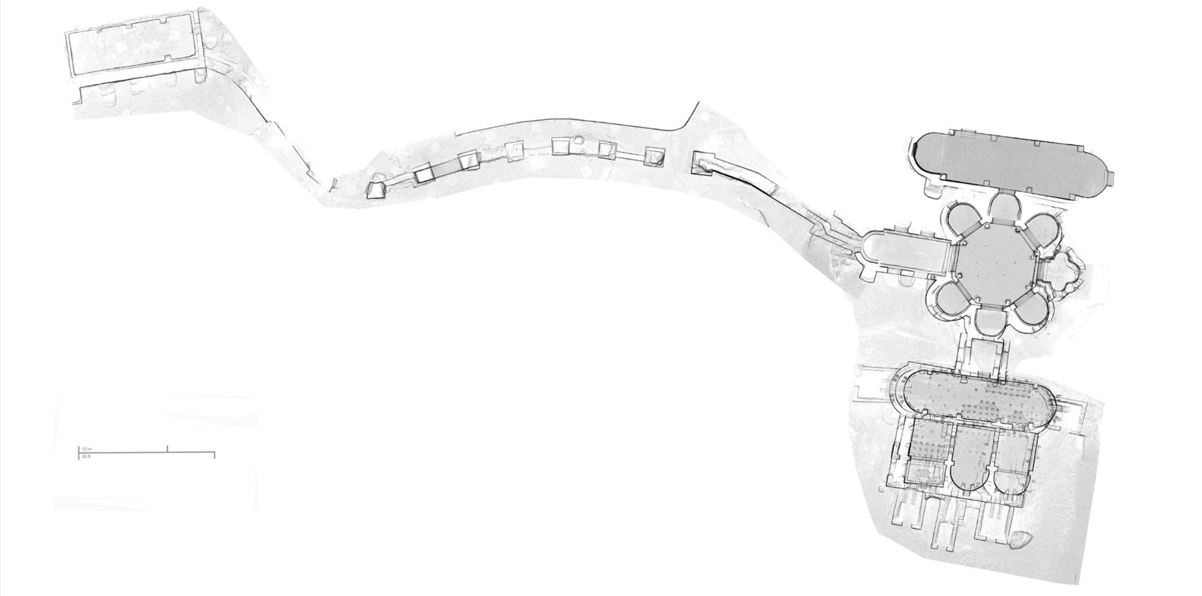

Fig. 12. Overall plan of the Villa's baths and related aqueduct and water tank extrapolated from the reunified 3D point clouds from the 2017, 2023 and 2024 campaigns.

It is important to point out that while the Matterport can complete a scan in 30 seconds and auto register versus the Faro x330 ~10 minutes and lack of auto registration, there are nevertheless important tradeoffs between the two. The Matterport Pro3 has a significant max point error of 32.3 mm versus the x330s 18.1 mm and a mean point error 5 times that of the x330 (**Tab. 1**). It is clear that the Matterport sacrifices point density and accuracy to meet its price point and speed. There is also a texturing issue with the Pro3 where objects meet the sky. It seems to confuse the texturing in those areas and applies a blueish hue. However, having used it successfully in the project, it should be considered an excellent tool in the context of digitally preserving and disseminating cultural heritage sites.

5. 3D visualization and analysis

The availability of the overall 3D model of the bath complex including interior and exterior allowed us to experiment with the calculations of the volumes of the individual rooms. We generated a unified 3D point cloud in Faro Scene and used tools within the software to extract quantitative spatial measurements directly from the 3D data. Area measurements were derived by defining planar boundaries within the point cloud. The process involved selecting representative points around each room footprint and finalizing the selection to generate a closed area. Faro Scene automatically recorded each measurement within a dedicated measurements directory. We renamed these entries to maintain clear correspondence with individual rooms. Volume measurements were calculated from the previously defined area boundaries. The software extruded each area vertically to create a three-dimensional bounding frame. We adjusted the frame to match the spatial extent of each room. Faro Scene then computed volumetric values based on the finalized bounding geometry. We applied this method consistently across the bath complex to obtain comparable spatial metrics for each room. The resulting area and volume measurements provide a quantitative basis for interpreting the scale and organization of the complex. These results are summarized in **Tab. 2** and illustrated in **Figure 15a–d**.

Fig. 13. Overall 3D model of the interior and exterior of the Villa's bath complex generated by terrestrial laser scanning.

Fig. 14. A) Faro scan with a person burned into the texture; B) Corrected texture with Matterport Pro3 scans.

Location	Area (m^2)	Volume (m^3)	Description
1	112.326	431.4727	*Dressing Room*
2	120.0287	585.3595	*Frigidarium*
3	9.7696	12.2541	*Small pool*
4	28.7885	37.0687	*Large pool*
5	11.6378	59.7895	*Sala delle frizioni*
6	73.9823	333.0557	*Tepidarium*
7	18.5008	54.0844	*Southern calidarium*
8	7.3746	25.4168	*Hot bath*
9	27.4156	88.7415	*Middle calidarium*
10	17.8988	61.1249	*Northern calidarium*
11	6.7786	20.5816	*Laconium*
12	60.8498	98.9407	*Aqueduct basin*
13	2.2743	2.5774	*Aqueduct to large pool*

Tab. 2: Area and volume measurements of the Casale bath complex.

The ability to calculate the precise volumes of the bath rooms through high-resolution 3D visualization and analysis is fundamental for advancing simulation studies on energy expenditure, particularly in relation to the heated spaces of the complex. Accurate volumetric data provide a quantitative foundation for modeling the thermal behavior of hot rooms such as the *calidarium,* and *tepidarium*, and *laconium*, where heat production, retention, and circulation were critical to the functioning of the baths. By anchoring these calculations in a metrically reliable 3D environment, it becomes possible to move beyond hypothetical reconstructions and to test energy demands in relation to room size, ceiling height, and spatial connectivity. This approach allows for more realistic assessments of fuel consumption, heating efficiency, and operational costs, while also offering insights into architectural choices and technological investment. Ultimately, volumetric analysis transforms 3D documentation into an interpretive tool that bridges digital archaeology and the study of ancient engineering and energy management.

6. Conclusions and Research Agenda

In conclusion, this study demonstrates the value of treating digital documentation as a longitudinal research effort rather than as a sequence of isolated recording campaigns. Building on past fieldwork, the reutilization and reunification of TLS and LiDAR datasets acquired over multiple field seasons has enabled the creation of a metrically precise, high-resolution digital surrogate of the Casale bath complex. The unified point cloud provides a three-dimensional source of data from which spatial relationships and other analyzable factors, such as volumetric properties, can be assessed with a level of precision that is otherwise difficult to achieve for a site of the scale and complexity of a monumental late Roman villa like that of the Villa del Casale.

The volumetric analyses presented here contribute directly to the functional interpretation of the bath complex, which can be particularly useful with regard to calculations involving the cost of heating the space and water management. By anchoring these measurements in a fully registered 3D environment, the results of these digitization campaigns provide tools with which hypothetical reconstructions can be grounded in spatial data. At the same time,

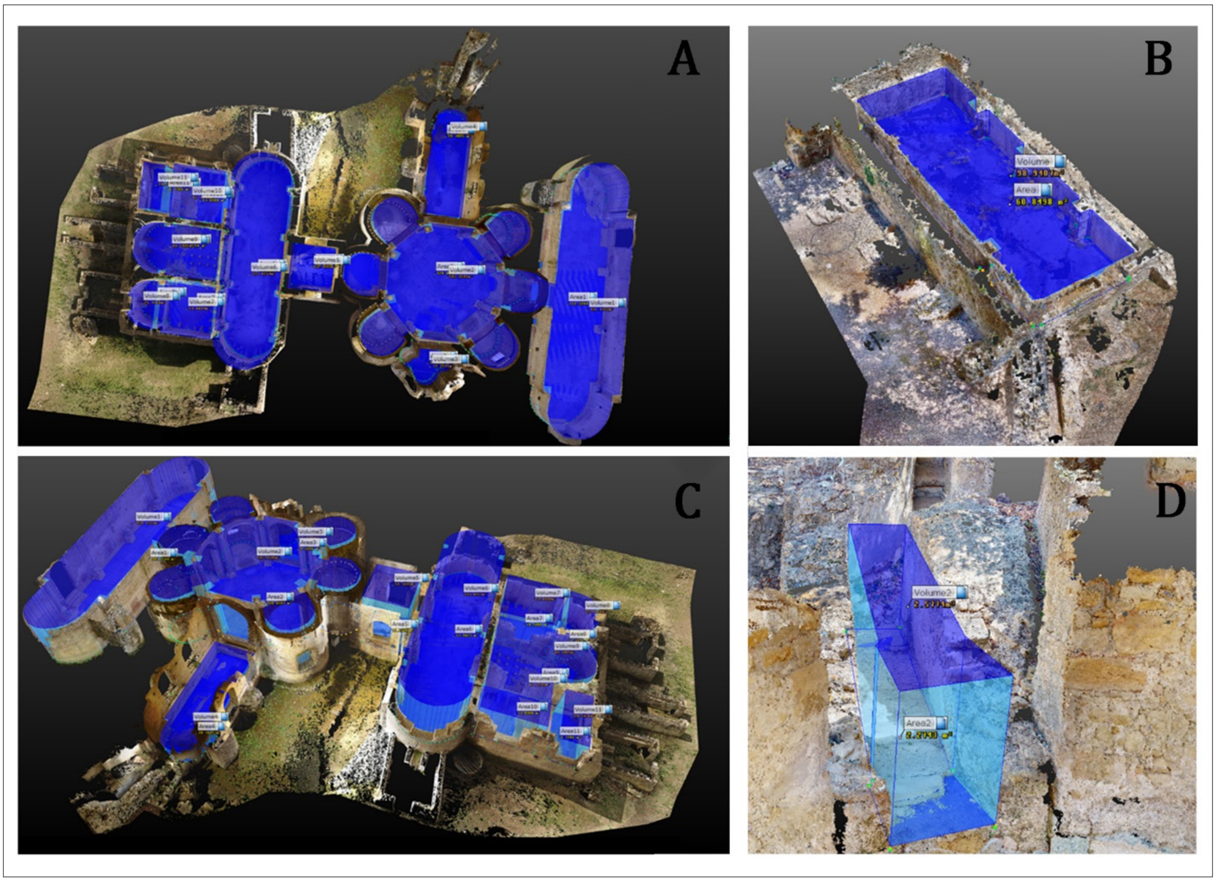

Fig. 15. Volume and Area measurements of the A) and C) bath complex; B) water tank, D) aqueduct basin; C) aqueduct connecting with the *natatio*.

the integration of "legacy" datasets shows how 3d data can be used and reused for more than the original scope they were intended for, preserving their interpretive value when they are recontextualized through updated workflows and analyses.

From a conservation perspective, the unified point cloud establishes a framework for condition monitoring and comparative analysis over time. Millimetric precision allows for the detection of subtle structural shifts and surface changes, supporting proactive, data-driven decision making by managers at the *Parco Archeologico di Morgantina e della Villa del Casale*. More broadly, the methodological approach outlined here offers a replicable model for other complex heritage sites facing similar challenges of preservation, scale, and public accessibility.

Looking forward, future research will build upon this foundation by integrating the data into a GIS and engaging in 3D modeling of reconstructions of the site. Planned work includes the integration of the 3D dataset into a geospatial framework to examine the bath complex in relation to broader water management systems, including water supply from aqueducts off the site. Additional modeling efforts will focus on simulating thermal performance and hydraulic behavior within the baths, allowing quantitative testing of architectural hypotheses. Together, these avenues of research will further situate the Villa del Casale's western bath complex within both its social, functional, and environmental contexts, while continuing to refine the role of digital data capture methodologies in the study of Late Antique housing.

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