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3D Documentation for Large Scale Monuments - The Roman Forum, Rome, Italy (2010-2025)

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Abstract

Analysis of point cloud data has been pivotal in advancing 3D scanning for heritage documentation. The Roman Forum project, initiated in 2010, exemplifies this evolution. Multiple expeditions amassed dense point cloud data that underwent rigorous processing comprising noise reduction, precise alignment, and the extraction of essential geometric features to produce a unified, fully rotatable 3D model. This digital reconstruction not only captures the intricate details of the Roman Forum monuments with high fidelity but also enables deliverables such as detailed terrain sections spanning nearly 800 meters, offering a refreshed analytical perspective on this ancient site.

1. Manuscript

1.1 Introduction

While numerous measured drawings have been made in the past to document the ruins of the Roman Forum, there has been no comprehensive urban and architectural documentation of the Forum until now since the plans were prepared by Giacomo Boni and his team over a hundred years ago (Fortini and Krusche, 2021). The Forum has been discussed and re-discussed, especially since its earliest excavations in 1536 and through the work various excavations from well into the 19th and 20th centuries (Watkin, 2009). The Digital Historic Architectural Research and Building Analysis (DHARMA) Lab from the University of Notre Dame was granted permission by the Ministry of Cultural Heritage and Activities and Tourism (MIBACT), and the Soprintendenza Speciale per il Colosseo e l'Area Archeologica Centrale di Roma, today better known as Parco Archeologico del Colosseo (P.AR.Co), to document the western half of the Forum, a part of the World Heritage site of the Historic Centre of Rome. The survey focused particularly on the most ancient of the fora, the Forum Romanum, from its westernmost edge at the Tabularium to the Temple of Vesta. When referencing the multiple layers of construction from the Late Republican and Imperial periods in ancient Rome, this work will use the terms 'Roman Forum,' 'Forum Romanum,' or simply 'the Forum' interchangeably (Gorski and Packer, 2015). The DHARMA Lab documentation of the Roman Forum began in July 2010. In 2012, this project expanded to cover the Forum in its entirety from the Colosseum up to the Tabularium (except for the Temple of Jupiter Capitolinus, which is partially embedded in the lower sections of the Capitoline Museum and beyond the scope of the area covered in this survey). Multiple expeditions in 2013, 2014, 2017 helped cover areas of the documentation that were needed to examine specific monuments in detail. This paper seeks to answer questions related to how long-term, multi-technology documentation is cleaned and combined to enhance urban-scale heritage interpretation.

The complex nature of the terrain of this *stratorum urbis* or layered city and the large variety of monuments found on the site necessitated careful and comprehensive documentation. No prior study had comprehensively documented the elevational relationships of Forum monuments using integrated 3D and

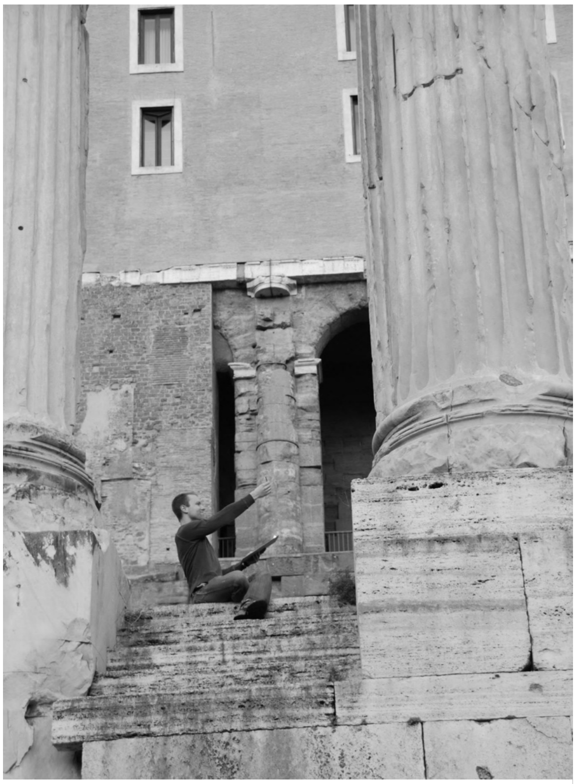

Figure 1. Hand Measure drawing for the Temple of Vespasian being produced by Mason Roberts. Source: DHARMA Lab.

archival methods. The difference in elevation between the present-day ground level and the imperial level, as excavated in the 20th century, added complexity to the nature of the site. The survey produced the most thorough data on the overall site and its terrain since its mapping during excavations by Boni. As the project took shape, it became apparent that the DHARMA team would be making a unique contribution both to the fields of architecture and archaeology. While the team’s primary objective remained in place about presenting with laser accuracy the locations and relationships of the monuments within the Forum; the efforts also introduced combined results of archival, digital, and hand-rendered visualization for a variety of outputs, including urban, architectural, and archeological studies. The present paper also acts as a precursor to the larger book publication composing a series of vertical and horizontal sliced and close-up studies on the architectural and typographical sections of the Forum in relation to its terrain and context, including the relative height of individual monuments with reference to the landscape. This precise study of the preserved remains of the Forum’s standing monuments enables a detailed examination of materials, surface textures, and architectural details, with a level of accuracy that is both comprehensive and consistently scalable across all drawings and plates with verified measurements. Moreover, a comprehensive strategy and best practice, to utilize digital and traditional surveying technologies, brings together the benefits of manual focus to the site with the precision of digital surveying. One such result is that the 3D scans from the last decade of study add newer information on the present condition of the site. While drawings and painted surveys from the Beaux-Arts period illustrate the relationships between various ruins in section, they do so through a conceptual and visually interpretive lens, often based on idealized observation rather than precise measurement (Massimiliano, 1999). In contrast, the new surveys offer a more current and accurate representation of the monuments as they were uncovered following the extensive archaeological excavations of the early 20th century. These updated studies reflect the actual conditions and configurations of the structures, grounded in empirical data rather than conjectural reconstruction.

1.2 Methodology for Survey

DHARMA represents the first-hand, full survey of the site since Boni's pioneering work in 1909, employing a range of cutting-edge techniques (Krusche 2020). The study meticulously captures the intricate sectional and planar urban and architectural relationships among the forum's various standing monuments. Crucially, such methodology and surveys can serve as a primary source of information for scholars engaged in reconstructing the forum and conducting analytical studies on its history (Packer 2016, Caradini 2017, Coarelli 2008). The DHARMA Lab has over 15 years of fine-grained, detailed data with up to 1mm accuracy on the Roman Forum. Due to the vast scale and size of the site, documentation efforts on the site required phased examination of areas requiring seven to ten years to complete by small, dedicated teams working in various stages of site documentation, data collection and processing.

Past expeditions have methodically investigated parts of the Roman Forum. Given its large area—measuring approximately 2447 feet (745 meters) in length and 850 feet (259 meters) in width—the site presented significant challenges because of its size and the interconnectedness of the monuments within it. The survey sought to conduct a continuous, comprehensive scan of the entire area without resorting to piecemeal documentation. The complexity of the terrain and the volume of data necessitated the support of 3D scanning technology and the integration of data from multiple scans to achieve the most accurate results with minimal errors.

For on-site documentation, the DHARMA team included three groups, each specializing in a unique documentation method: digital surveying with long-range scanners, ultra-high-resolution photography or Gigapan technology, and traditional surveying with hand measurements and notes. This section focuses on describing the three techniques of data collection on site.

1.2.1 3D Scanning with LIDAR

Figure 2. Documenting the Colosseum and the Temple of Venus and Rome terrain with a Leica P40 3D Scanner. The scans were kept at a maximum of 70 m range. The scanner has a maximum 300 m range. Source: DHARMA Lab.

Laser scanning, or Light Detection and Ranging (LIDAR), has revolutionized site documentation by offering detailed three-dimensional data collection. This method utilizes high-speed laser beams to capture spatial coordinates, creating a point cloud that accurately represents an object's shape. The use of "time of flight" scanners, ideal for large historical sites, allows for rapid data collection, significantly enhancing efficiency and accuracy over traditional methods (Smith, 2019). The scanning resolution, which can achieve millimetre-level precision, ensures that even the smallest details are captured (Brown, 2020). The on-site data is collected into a repository and then registered into a large 3D point cloud unified model. encompassing all datasets. This single source of 3D data is used to inform all plans, sections, and details, and can be segmented into multiple deliverables (Williams, 2018). This comprehensive model integrated data from various expeditions and created a dense point cloud that accurately represented the site's current state. With over 500 million data points and an average resolution of 1.5 cm x 1.5 cm, this model serves as the foundational layer for subsequent analyses and visualizations.

1.2.2 Gigapan Technology

Gigapan technology enables the creation of high-resolution panoramic images by stitching together hundreds or thousands of photographs. This method was originally developed by robotics scientists from Carnegie Mellon University in cooperation with NASA Ames Research Center for the Mars Rover program (Jones, 2010). The GigaPan system employs a programmable robotic mount to precisely control a DSLR camera, enabling it to take hundreds or thousands of pictures of a scene automatically (Smith, 2017). The practical resolution limit of the panoramic imagery created using GigaPan technology is directly related to the zoom lens resolution and the quality of the camera's CCD image sensor (Brown, 2012). The resulting digital images are then stitched into extremely high-resolution panoramas using GigaPan Stitch or Autopano Pro software. Autopano Pro utilizes image stitching technology developed as part of a research project at the University of British Columbia in Vancouver, Canada (Williams, 2013). This technology is highly valuable for obtaining zoomed-in, detailed information about the monuments. It allows for the creation of extremely high-resolution images, which are instrumental in studying cracks, material variations, and other hard-to-reach areas of the monuments (Roberts, 2015).

1.2.3 Hand-Measured Surveys and Field Notes

Traditional hand-measured surveys and field notes remain invaluable for capturing detailed information not accessible through remote methods. This technique, with roots in the Renaissance, allows for precise documentation of scale, proportion, and architectural details, which are essential for restoration and scholarly study (James, 2005). The comprehensive approach to documenting the Roman Forum using both advanced technological means and traditional methods has provided a rich, detailed understanding of this historical site (Green, 2018). This dual approach offers invaluable resources for future research, conservation, and educational purposes (Krusche 2018, Wilson 2020).

1.2.4 Methodological Workflow Overview

To manage the complexity of documenting a monumental site across a 15-year period with evolving technologies, the research followed a four-phase methodological model. This structure ensured coherence, reproducibility, and data integrity across all survey and analysis stages.

Table 1. Roman Forum Documentation Workflow

Phase	Key Activities	Tools/Standards Used
1. Data Acquisition	- LIDAR scanning (Leica P40) - Gigapan panoramic imagery - Hand-measured surveys and field notes	Leica Cyclone, Gigapan Epic Pro V, manual grid tracing
2. Data Cleaning	- Noise filtering (people, scaffolding, vegetation) - Outlier removal and range trimming - Image correction and stitching	CloudCompare, Autopano Pro, Photoshop
3. Multi source Data Integration	- Scan registration using GPS control points and physical markers - Gigapan-to-point cloud alignment via patented image-mapping interface - Georeferencing hand drawings using QGIS	QGIS, proprietary plugin (US Patent 9972120), CloudCompare
4. Visualiza-tion & Analysis	- Generation of sections, plans, elevations - Comparative overlays with historical drawings - Identification of structural/material changes	Rhino, AutoCAD, Photoshop, metadata-tagged PDF deliverables

1.2.4.1 Data Acquisition

The documentation of the Roman Forum relied on the integration of multiple acquisition methods to achieve both breadth and depth of data capture. Long-range LIDAR scanning was conducted using a Leica P40 scanner, with data collected across 75 scan positions to ensure coverage of all monument elevations and terrain contours. Scans were taken at a resolution of ≤1 cm to guarantee high geometric fidelity.

In parallel, Gigapan panoramic imaging was used to document surface textures, material deterioration, and fine architectural details. Using a robotic mount, hundreds of high-resolution photographs were stitched into panoramic views, offering contextual visual data at a granular level.

Complementing the digital data, hand-measured field surveys were carried out using grid paper and trace overlays. These provided detailed notes on structural joints, material types, surface conditions, and inaccessible areas—offering an analog layer of insight that digital scanning alone could not capture. All forms of data were catalogued daily during field expeditions to support the subsequent cleaning and integration process.

1.2.4.2 Data Cleaning

Given the volume and variety of data, rigorous cleaning protocols were applied to ensure clarity, accuracy, and usability. Raw point cloud datasets were first processed through CloudCompare and Cyclone to filter out "noise" such as human figures, vegetation, scaffolding, and ambient debris. Some of the details in the final edits were manually removed. Statistical outlier removal techniques and manual editing were employed to enhance geometric precision.

Gigapan imagery underwent exposure correction, lens distortion removal, and careful stitching using Autopano Pro, yielding seamless, high-resolution composites. These visual layers were then cross-verified with the point cloud data to confirm alignment and visual integrity.

Throughout the cleaning phase, emphasis was placed on preserving the original resolution and avoiding over-smoothing, ensuring that minute architectural features such as cracks, inscriptions, and weathering patterns remained legible in the processed outputs.

1.2.4.3 Multi-source Data Integration

The most technically demanding phase involved the standardization and fusion of datasets collected across multiple years and platforms. All point cloud data was normalized to a shared coordinate system using GPS control points and transformation matrices, aligning older scans with recent geometry.

To achieve format interoperability, scans were converted to .e57 or .las files, then unified into a master point cloud. Manual drawings were digitized and georeferenced in QGIS, using architectural landmarks (e.g., base corners, cornices, vault spring points) as control nodes for spatial anchoring.

A proprietary system (U.S. Patent No. 9972120) was used to integrate Gigapan imagery directly with point cloud data, avoiding surface meshing and preserving both geometric and visual accuracy. This allowed the team to correlate spatial structure with surface textures, effectively layering visual and geometric evidence in one analytical environment. The Potree open-source viewer was employed to visualize this integrated dataset, enabling high-resolution, web-based exploration of both the point cloud geometry and corresponding photographic detail in real time (Schütz, 2016).

Data integrity was maintained using a versioning system, where each iteration of processed data was archived with time stamps and metadata logs. Only validated and aligned versions of the dataset were used for subsequent analysis and plate generation.

1.2.4.4 Visualization & Analysis

The integrated dataset enabled a rich set of analytical outputs. Using Rhino, AutoCAD, and Photoshop, the team produced over 20 sectional drawings and 15 detailed monument studies that captured not only planimetric and elevational geometry, but also the topographic relationships across the Forum.

The ability to overlay modern scans with archival measured drawings from the 16th to 20th centuries allowed for comparative analysis, highlighting discrepancies in design, elevation, site phasing, and monument alignment. Structural inconsistencies, previously hypothesized but undocumented, were clarified through this layered visual and metric framework.

Furthermore, the detailed cross-sectional terrain profiles informed interpretations of urban development and excavation layers, offering scholars a new way to understand spatial planning across centuries. Plates were annotated with metric coordinates and material tags, creating a resource not only for academic research, but also for conservation, education, and virtual reconstruction efforts.

The diverse datasets obtained are meticulously cross-referenced with archival information, leading to a synthesis of outputs ranging from traditional architectural representations to comprehensive analytical insights (Johnson 2017).

Over recent years, DHARMA also fills a unique niche in a pioneering approach that combines large-scale surveying techniques with cutting-edge 3D scanning technology, including NASA – Carnegie Mellon's Gigapan technology, a patented collaboration with the Center of Research Computing (Patent number: 9972120). This methodology is further enriched through the integration of hand-measured drawings, developed in collaboration with Ph.D., graduates and undergraduate students from the School of Architecture and College of Engineering, Computer Science Department (Krusche et al., 2014). By seamlessly blending these methods, the field documentation process ensures not only meticulous data collection but also incorporates essential field notes crucial for comprehensive site analysis. DHARMA is also a major enterprise; over the years, the lab has benefitted from the expertise of 8 faculty, 3 archaeological site directors, 3 PhD students, and 49 graduate and undergraduate students.

2. Survey Structure

The methodological framework described above was implemented through a structured sequence of site-based actions designed to ensure continuity, accuracy, and depth of documentation. In practice, the entire survey was executed through a three-phase operational workflow—pre-site, on-site, and post-site—each building upon the outcomes of the previous phase. This structure translated the abstract methodology into field-ready strategies, enabling the team to manage the complexities of the Roman Forum's vast scale, temporal layers, and diverse monument typologies.

Each phase was essential not only to organizing data acquisition and analysis but also to fostering interdisciplinary collaboration among historians, architects, engineers, and digital technologists. The following sections detail the structure and logic of this phased approach, illustrating how research planning, on-ground execution, and post-processing were coordinated to produce high-fidelity outputs grounded in both historical scholarship and advanced digital methodology.

2.1 Pre-site:

The pre-site phase involved compiling all existing documentation of the site, including drawings such as plans, sections, sketches, details, and elevations, as well as written histories and theoretical perspectives. This created an elaborate library of information for reference during the on-site survey and post-processing (Smith 2019). The pre-site phase relies heavily on archival research. Here the existing studies, measure drawings done by other scholars over the centuries are collected, examined and analyzed for use by the team. The key aspects examined are, a) what information about the site's history, construction, materials used, and transformation is available; b) does it contain all the required drawings for the site c) what kind of a research question should be formulated to examine the site. Depending on how extensive the site information is the longer it may take to study and examine the work and create a collective understanding on how to proceed with the research to the next stage. The archival documents helped with establishing a specific research question for the study, and also formed the base material for the on-site notes and marking. It also gave the team a sense of scale of the site. Before each expedition to the Roman Forum, research was conducted to examine the area under consideration for study using previous scholarship on the site (Fortini and Krusche, 2021). Initially the work was done with large plans from Google Earth, Lanciani and others (Lanciani 1910). Before the project could begin, the need for a pre-site study quickly became clear. The team collected, reviewed, and analyzed previous scholarship in the field and then created a plan to complete an on-site survey that would form the basis of this project and provide a critical overview of the past documentation of the Forum. Along with archival research, one or multiple site visits to create strategic decisions regarding the placement of instruments, the number of days on-site, specific measurement locations, and areas of focus are made during this time. Additionally, preliminary site visits are conducted to examine the terrain, visibility of specific monuments, and to develop a detailed site survey plan (Brown 2020).

2.2 On-site:

The on-site phase is the most intense and critical period of the project (Krusche 2018). It requires high levels of coordination and ensuring that all team members have the necessary permissions to access the site (Williams 2018). The site survey is conducted daily from sunrise to sunset over a period ranging from ten to thirty days per expedition (Johnson 2017). The team, divided into groups, works according to the pre-site planning. Each evening, the collected data, in various forms, is cataloged and saved in a database to ensure ease of post-processing and quality control (Anderson 2021). During the Forum site expeditions, the overall site was divided into large parts. Each of the monuments are located between the sectional height of 0.00m at the base level of the Temple of Divus Iulius and up to the uppermost level of height of the Colosseum of 58.80m. The whole site spans a length of 745 meters and hence needed to be broken down in batches of scales that needed to be scanned, examined, and detailed before the next expedition was planned. The scans were made at a resolution of at least 1cm x 1cm accuracy. The scans are done in parts to focus on the monuments based on changing heights to ensure adequate scan accuracy and resolution at the topmost level of the scan (Krusche, Turner and Sweet, 2014). Each monument has multiple scans with at least 6 strategic locations or more based on form complexities. Along with the scans, Gigapan imagery was mapped for every monument at the same locations as the scans to create a compatibility between the point cloud and the image mapping. The individual monuments were drawn with hand measure drawings on graph paper or trace to collect information related to details, plan layout, material fieldnotes and any findings found on the site based on specific monuments ruins on site.

2.3 Post-site:

Finally, the post-site phase involves processing the collected data over months and years to create multiple deliverables (Taylor 2016). Based on the results, further expeditions are planned to gather additional evidence about specific parts of the survey that require further evaluation (Roberts, 2015). This phase also includes transforming the raw information, drawings, and field notes collected on-site into final outputs and deliverables (Fortini and Krusche, 2021). The post-site phase is the most extensive, as it integrates and analyzes all information from the previous phases to produce comprehensive results (Clark, 2022). Scan data was used to produce line drawings of plans, sections, elevations, and detail orders of the Forum monuments (Krusche, 2018).

Multiple expeditions were undertaken in 2010, 2012, 2014, and 2017 to survey, map, and document the existing conditions of the Forum. The final comprehensive dataset offers estimations of projected site layers in earlier periods based on the interpretation of previous archeological stratigraphic studies as well as the new work. Thus, the DHARMA Forum project presents a major advancement in the information now available in terms of both documentation and visualization.

The whole process from pre-site, on-site and post-site study was published in multiple articles and is comprehensively available in the most recent publication in 2021 titled, *From Pen to Pixel: Studies of the Roman Forum and the Digital Future of World Heritage*, L'Erma Di Bretschneider (Fortini and Krusche 2021). The book is part of a larger agreement with the P.AR.Co that also produced an exhibit titled, *Revisiting the Roman Forum: from Pen to Pixel, Methods of Documentation in the 20th and 21st centuries*, hosted in the Curia, the Senate house of antiquity in the Forum. This was also accompanied by a conference hosted in Rome titled *The Digital Future of World Heritage*. This included a paper by Irina Bokova, who was the Head of UNESCO at that time and was very keen on adapting digital heritage documentation as a form of evidence-based access for scholars, researchers, visitors, students, and future generations for World Heritage Sites. For the Forum project multiple deliverables have been produced in the post-site phase in the form of articles, book, book chapters, a 3D live interactive model interface and an app that can be used on site. The digital versions of the survey have also been published on an online portal (Brown 2023).

3. Survey Challenges

While the phased structure provided a clear operational framework, the implementation of this survey was not without significant technical, logistical, and environmental challenges. The Roman Forum's vast scale, stratified terrain, and restricted accessibility demanded innovative solutions and adaptive workflows. The following section outlines the primary obstacles encountered across expeditions—ranging from incomplete visibility and physical hazards to data overload and equipment limitations—and the strategies employed by the team to mitigate them while preserving the fidelity of the final outputs.

Even though a large amount of area was covered, certain areas of gaps in the study still remain due to non-accessibility to all angles of the ruins on site. At various times scaffolding or on-going excavation work would sometimes prevent full access to the monuments. Often the instruments were installed in precarious and difficult terrain environments to collect the ideal measure drawings. There should be a word of caution to the fact that this can often be a limiting factor on the site. The whole team got excellent access to the monuments that were extremely up-close and allowed for deeper, first-hand interaction with the ruins but also meant dangerous site conditions where we had to take high degree of precaution for their safety.

Over the past decade, the scanning efforts have yielded at least 75 scan sets and 30 digital panoramic Gigasets, encompassing several terabytes of data, in addition to the hand-measured data collected for many of the site's significant monuments. Data collection, storage and curation has been a learning curve in this process with changes in software and instrumentation causing several difficulties. Over time the efficiency of the teamwork was greatly improved as the workflow of the project was improvised with each on-going expedition. During the post-expedition phase, the DHARMA team meticulously compiled a vast point cloud dataset. This dataset required careful cleaning to remove 'noise'—unwanted data elements such as people, trees, and protective railings around monuments—that could obscure the clarity of the site's information.

Expeditions incorporated lessons learned from the initial survey to enhance site workflow and reduce the logistical challenges of transporting equipment. Technological advancements in scanning equipment facilitated more efficient data capture and reduced the reliance on external power sources, with later models offering improved battery life and scanning speeds.

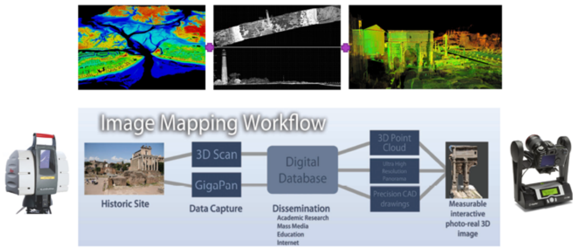

Figure 3. The patented technology of merging scan data sets with Gigapan images in a common database without mesh and direct surface application. Credit: DHARMA Lab.

Notably, at the start of the project Gigapan technology for panoramic imaging proved invaluable for creating comprehensive site captures. However, as scanning technology advanced, particularly with improvements in integrated camera capabilities, the necessity for separate Gigapan imaging diminished.

The approach was refined to data management and equipment utilization through later expeditions, leading to more effective on-site operations and post-processing efforts. The cumulative data collected—comprising numerous scans, gigapixel images, thousands of photographs, and detailed line drawings—is a rich repository of information that will serve as a valuable asset for future scholars and conservators.

3.1 Deliverables

The deliverables from this multi-year project extend beyond documentation into the realm of scholarly analysis. By transforming raw point cloud data into layered visualizations, detailed plates, and comparative studies, the survey has yielded new insights into the architectural, chronological, and urban context of the Roman Forum. The process of utilizing 3D scan data to create detailed plates involved several meticulous steps, each aimed at transforming the raw point cloud data into informative, accessible, and visually appealing representations. This preserved the intricate details captured by the scanning technology to facilitate a deeper understanding of the site's architectural and historical significance. The information collected during the survey of the Roman Forum can be a resource for future researchers. The plates include metric measurements for specific parts of the Forum, and each point on the drawings presents a coordinate that can be measured and geolocated to understand its relative measurement within the overall site. It is impossible to show all the measurements taken to achieve these results. Rather, the plates show all points visible on the individual facades of the monuments and a select number of points for the overall sections and plan of the site.

The study documented all visible monuments and ruins except features underground. Other surveys of underground areas have been done with hand-drawing techniques, stratigraphic studies, and 3D scans. In the future, these results can be combined with this study to create an even more comprehensive survey of the site. All plates were created out of one extremely large dataset that was reduced in scale to show the results without obscuring

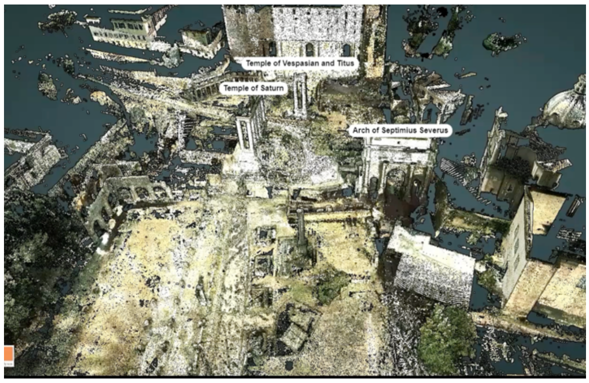

Figure 4. Visualization of the 3D data from the full-scale data model with tagged information with images, text and articles. Credit: Visualization Team @DHARMA Lab.

the information. Often the plates had to be layered to present large sets of information in the most understandable way.

The data collected was transformed, cleaned and unified into point cloud formats for various forms of representation, including detailed plates that highlight the architectural and historical features of the site. This transformation process involved several key steps:

3.1.1 Data Conversion and Visualization: The point cloud data was converted into formats suitable for traditional representation methods, such as plans, sections, and elevations. This conversion allowed the data to be visualized in more conventional architectural drawings, making it accessible to a broader audience, including preservationists, archaeologists, and students.

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3.1.2 Sectional Relationship of the Forum's Terrain: The cleaned and unified point cloud data was used to create detailed cross-sectional views of the Forum's terrain. These sections revealed the topographical variations across the site, illustrating how the landscape has been shaped by human activity over centuries. Analyzing the terrain's sectional relationships provided insights into the Forum's development, from its origins to its present form. It revealed the architectural planning and construction techniques adapted to the site's unique topographical challenges and the relationship of the various structures to each other.

Figure 5. Process drawings representing scan data, line drawings and watercolor plates in a sectional format from the Tabularium till the Temple of Faustina. Note the post processing of the same scan data to get improved clarity and results for the site information. Credit: DHARMA Lab.

3.1.3 Detailed Studies of Individual Monuments: The 3D scan data enables in-depth studies of each monument in the Forum. The data meticulously presents each monument's architectural features, detailed relief design, and historical modifications. The research reveals new information about construction methods, architectural styles, and historical usage. Piecing together the Forum's architectural narrative in this way contributes to a more comprehensive understanding of its historical and cultural significance.

3.1.4 Integration of Historical and Contemporary Data: The process integrated historical documentation and contemporary scan data to produce plates that reflect both the current state and the historical context of the Roman Forum. The results are resources for scholarly research, education, and public engagement, bridging the gap between technical documentation and the broader appreciation of cultural heritage sites. The data provides a solid foundation for scholarly research, offering precise measurements and high-resolution visualizations that can be analyzed to uncover new insights about the Roman Forum's architectural and historical development. The detailed sectional views and monument studies also support conservation efforts, helping to identify areas of deterioration or structural weakness that require attention. In addition, the visualizations and analyses produced from the scan data can be used to create educational materials that can make the complex history of the Roman Forum accessible to students and the general public.

3.1.5 Case Study: The Arch of Septimius Severus

One particularly significant outcome of the project is the updated documentation and analysis of the Arch of Septimius Severus, a triumphal arch constructed in AD 203. The new 3D scans, captured from eight positions and cross-referenced with Gigapan imagery, enabled the creation of highly accurate elevation and sectional drawings. These drawings revealed subtle but measurable misalignments in the original construction—particularly in the curvature of the entablature and the proportional irregularities of the inner archway pilasters.

Before/after comparison with 18th- and 19th-century architectural renderings (e.g., Desgodetz's 1742 elevation and Boni's early 20th-century surveys) exposed discrepancies in several key dimensions. These differences are not simply due to artistic stylization or observational error; one particularly significant outcome of the project is the updated documentation and analysis of the arch. Using high-resolution digital scans and photographic data captured through the DHARMA data, the team produced precise elevation and sectional drawings that correct long-standing inaccuracies in the monument's recorded dimensions. For example, the total height of the arch was confirmed to be 23.99 meters, and its width 23.37 meters, representing figures that include previously omitted exposed foundations. The central arch measures 12.52 meters high and 6.80 meters wide, while the side arches are 7.93 meters high and

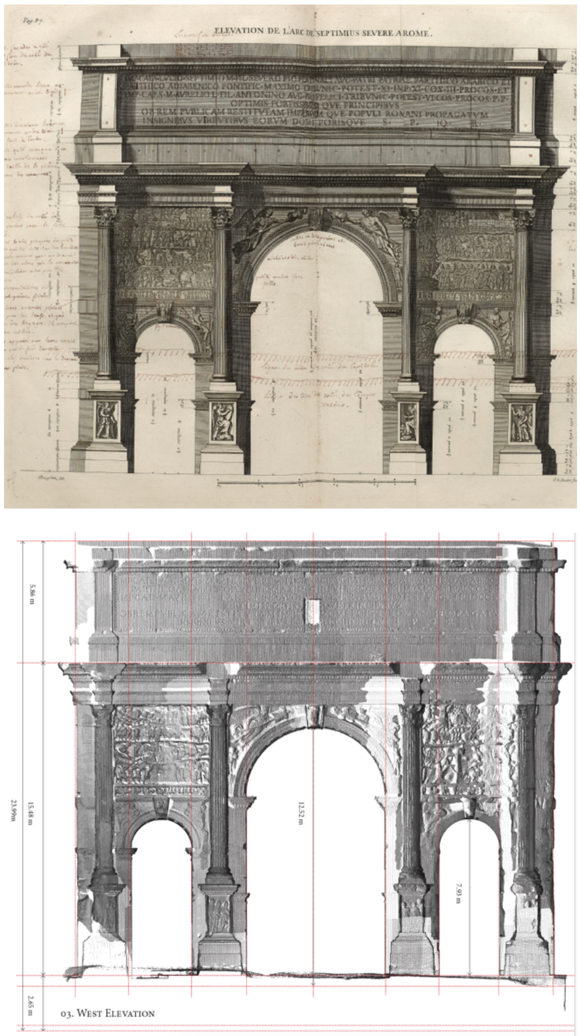

Figure 6. Up: Elevation de l'arc de Septimius Severe a Rome (plate 84) De l'Arc de Septimius, à Rome as drawn by Antoine Desgodetz. Credit: Paris, Claude-Antoine Jombert (De l'Imprimerie de Monsieur), 1779. Right: Latest measured drawings of the West Elevation of the Arch of Septimius Severus Credit: Krusche, DHARMA 2023.

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3.05 meters wide. The documentation also clarified the full height of the composite columns as 15.48 meters and the attic height as 5.86 meters.

A systematic comparison with Desgodetz's 17th-century elevation drawings revealed several critical discrepancies that have persisted in architectural scholarship. These include an overestimation of the total width due to a misplaced parapet and shallower entablature, incorrect proportions in the height of the attic and column shafts, and variations in the position of arch springing points. These are not simply errors of artistic stylization; rather, they illustrate the limits of previous centuries measurement techniques and underscore the necessity of modern digital verification. For instance, the pedestal bases are more elongated on-site than shown in historical drawings, and the relief panels, particularly the spandrel figures of Victory, are larger than Desgodetz depicted.

The updated documentation also revealed architectural anomalies on the southern and western sides of the arch. Notably, the south façade is elevated by 2.65 meters compared to the Forum-facing side, a feature previously undocumented with such precision. Beyond correcting individual measurements, this survey contributes to a broader reinterpretation of Forum planning. The comparative data indicate that adjacent monuments, such as the Temple of Saturn, the Rostra, and the Arch itself, were not aligned to a single unified imperial axis. Instead, their placement reveals adaptive responses to local topography, earlier constructions, and shifting political priorities. The DHARMA scan data thereby enables a more nuanced, phasing-based model of construction chronology, informed by measurable benchmarks in elevation, material transitions, and structural sequencing, offering a revised narrative of urban development in the heart of imperial Rome.

3.2 Conclusion

This study presents the most extensive and integrated digital documentation of the Roman Forum to date, resulting from 15 years of interdisciplinary effort. By combining LIDAR scanning, panoramic imaging, and hand-drawn analysis, we have developed a unified 3D dataset that captures the architectural, material, and spatial complexity of over 40 major monuments across 745 meters of terrain.

This project moves beyond visual documentation toward an analytical model that allows scholars, conservators, and planners to interrogate the Forum's built history with new precision. The resulting datasets reveal not only monument geometries, but also sectional relationships between buildings, topographical variations, and construction techniques across phases of development.

One of the key findings is the clarification of relative elevations across the Forum's layers—from the Tabularium to the Colosseum—which exposes inconsistencies in prior urban mappings and enables more accurate phasing of construction activities. In particular, the ability to correlate high-resolution surface imagery with structural scans reveals areas of material deterioration not previously documented, supporting preservation efforts.

Despite these contributions, the project faced limitations. Some portions of the site were inaccessible due to ongoing excavations, scaffolding, or terrain instability. As a result, certain datasets remain partial. Additionally, the integration of data collected over a long time span required overcoming technological incompatibilities, especially as software and file formats evolved.

Future work should address these challenges by incorporating subsurface scan data and further automating cross-platform data fusion. A key next step will be expanding the existing digital interface into a live comparative platform—allowing researchers to toggle between historical drawings, excavation maps, and current scans to enable layered interpretation of the Forum over time.

By creating a scalable and shareable archive of this complexity, the project not only enhances scholarly knowledge of one of antiquity's most iconic sites but also models best practices in heritage digitization for other large-scale monuments worldwide.

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