



D3.8 Paradata and sustainability report

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LIST OF ACRONYMS

Acronym	Description
AAT	Getty Art & Architecture Thesaurus
AR	Augmented Reality
CARE	Collective, Authorisation, Responsible, Ethical, data principles
CH	Cultural Heritage
CUT	Cyprus University of Technology
E57	3D Point File format - ASTM E2807 standard
EASA	European Union Aviation Safety Agency
EDM	Europeana Data Model
FAIR	Findable, Accessible, Interoperable, and Reusable data principles
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMU	Inertial Measurement Units
IP	Ingress Protection
IPR	Intellectual Property Rights
ISO	International Organization for Standardization
LiDAR	Light Detection and Ranging
PPH	Pre-Processing Hardware
PPS	Pre-Processing Software
RMS	Root Mean Square Deviation
SHM	Structural Health Monitoring
TLS	Terrestrial Laser Scanning
UAV	Unmanned Aerial Vehicle
VIGIE 2020/654	The EU Study on quality in 3D digitisation of tangible cultural heritage: mapping parameters, formats, standards, benchmarks, methodologies, and guidelines [Contract number: LC-01549024- VIGIE number: 2020/654] and https://doi.org/10.2759/471776
VR	Virtual Reality
XR	Extended Reality
Z+F	Zoller + Fröhlich

EXECUTIVE SUMMARY

This report underscores that paradata is defined as the detailed record of the processes, decisions, tools, parameters, and conditions involved in creating 3D digital assets in Cultural Heritage and is essential to ensuring the reliability, transparency, and long-term value of 3D digitisation of tangible cultural heritage. Drawing on the EU Study VIGIE2020/654, it argues that high-quality digitisation is not only about the final 3D model or dataset, but equally about documenting how that output was produced, including acquisition methods, equipment settings, environmental conditions, data processing workflows, levels of intervention, and interpretative choices. Paradata enables reproducibility, critical assessment, and informed reuse of digital heritage assets across disciplines, supporting research integrity and trust. It also facilitates interoperability by linking datasets to standards, formats, and benchmarks, allowing institutions to evaluate quality against agreed methodologies and guidelines.

Moreover, paradata plays a crucial role in long-term preservation, as it provides future users with the contextual knowledge necessary to understand, migrate, or reprocess data as technologies evolve. A key best-practice example highlighted in the report is the Cypriot pilot, *Enkleistra of Saint Neophytos*, which demonstrates how comprehensive paradata documentation can be systematically integrated into the digitisation workflow, from initial data capture through to processing and dissemination, ensuring both scientific rigor and cultural authenticity. The study emphasises that without structured and standardised paradata, even technically precise 3D outputs risk becoming opaque, unverifiable, or unusable over time. Therefore, integrating paradata capture into the project's digitisation workflows, from the planning through acquisition to post-processing and Use/ReUse, is presented as a fundamental requirement for sustainable, high-quality digital documentation of cultural heritage, reinforcing accountability, comparability, and meaningful access within the broader European digital heritage ecosystem.

The document is composed of the following sections:

1. Introduction
2. Paradata
3. Project case study: the Enkleistra of Saint Neophytos
4. Paradata in EDM evolutions
5. Paradata as a foundation for sustainability
6. Conclusions

Annex 1: Images showing the results of the high-quality digitisation of the Enkleistra of Saint Neophytos

1. INTRODUCTION

Paradata captures and describes the processes used in the creation of a digital asset. This is conceptually different from metadata, which describes the data asset itself. While metadata provides strong functionality in making an asset findable and accessible, metadata alone is not sufficient to enable interoperability and reusability as it is objective in nature. Together with the data they relate to they form a “trinity” of data (Figure 1) which documents the life cycle of a digitisation effort that shows due diligence, authenticity and intellectual transparency to both the cultural heritage community , primary users and the secondary reuse sector.

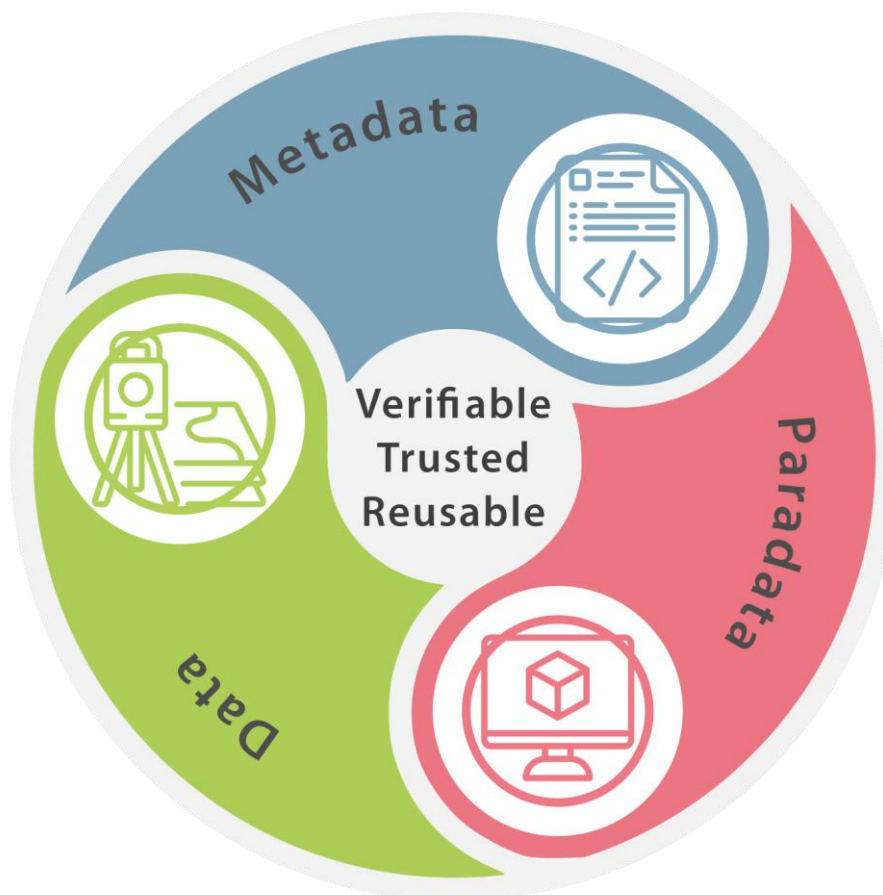


Figure 1: The Trinity of Data

As paradata attempts to capture the context of the process, including the research undertaken and decisions made when creating the final asset, it provides a degree of intellectual transparency, able to be reviewed and better understood and accordingly to be redeployed with greater confidence than an asset without paradata¹. This transparency enables the reuser to assess if the asset applies to their needs and if (or to what extent) the asset will need to be modified for their specific use case. The better the paradata, the more informed the reuser will be, whether that is in assessing alterations, looking for points of commonality to shorten development cycles or finding points of divergence where new research opportunities may lie.

¹ Baker, D. (2012). Defining paradata in heritage visualization. In A. Bentkowska-Kafel, H. Denard, & D. Baker (Eds.), *Paradata and transparency in virtual heritage* (pp. 163–176). Ashgate Publishing Limited.

There is no direct correlation between confidence, reusability, and quality; quality is a subjective term, and even when quantifiable in terms of resolution, polygon count, etc., this changes rapidly as digitisation technology advances. However, there is a tacit understanding that a well-documented, easily understood, and replicable data set is likely to have been created with care and attention to its use case and needs specification documentation. Through the paradata record this assumption can be audited, reviewed, and assessed; and like peer review, good work (i.e., quality) will be used and built upon (i.e., cited) over poor or undocumented assets. By focusing on the process rather than the bits and bytes of a digital asset, the quality of research and methods employed become more important than the raw data leading to enhanced routes to interoperability and reuse of the 3D asset. This is not to diminish the value of the raw data, far from it as data-set can be reused to generate new material, rather the paradata associated with a 3D model allows the reuser to decide if the asset is fit of the purpose of their use case without having to regenerate a model.

It is commonly acknowledged that the single best form of data preservation is wide dissemination and continual use. A digital asset with a paradata provenance is, therefore, more likely to survive within the digital ecosystem than one that does not, in the same way that a quality paper is more likely to remain in circulation than one that does not. Moreover, as the paradata record contains the context of an asset, the circumstances of its creation, development, and reuse are recorded within the paradata record, thereby increasing the chance that raw data can be reconstructed/recovered should the asset be compromised, either directly, for example, through emulation, or by replicating the documented process of creation.

2. PARADATA

2.1 WHAT NEEDS TO BE RECORDED?

The EU VIGIE Study 2020/654² and Eureka3D Guidelines³ consider two different aspects of paradata, 1) Complexity and 2) Quality.

Complexity is defined as a system characterised by multiple parameters whose interactions, interdependencies, and dynamics make the system difficult to fully understand, predict, or control. of the tasks needed to successfully digitise the tangible object. Complexity assessment attempts two tasks first to focus the understanding of what the digitisation effort aims are, and second to identify (and thereby mediate) risk. Complexity assessment therefore reduces both project drift by establishing the parameters of the documentation and ensures that the documentation is undertaken under the best possible optimised conditions according to a set of known metrics.

Quality is an indication of how accurately and precisely the digital representation (geometry, texture, materials, etc) matches the physical object, including its structural anomalies in accordance with the metrics specified in the Complexity assessment.

It is important to note here that Quality assessment is tightly bound to the Complexity assessment: recording the paradata of both is vital to successful reuse as one output will differ from another based on the objective of the digitisation parameters. Therefore, two different documentation efforts may both produce high quality assessments but the reusability of one or both will be dependent on the reuse case. The decision whether or not to reuse the outcomes of a digitisation effort (from raw data to 3D asset) can only be assessed through the paradata record by the reuser based on their confidence in being able to fulfil their use case on existing documentation. If the paradata record does not exist the sustainability, reuse and return on investment is limited, and may adversely affect the reuse scenario as assets are.

Paradata describes the processes undertaken to digitise a CH object and its context, and the resulting 3D representation of the data - Paradata is therefore subjective, whereas metadata is (or is intended to be) objective. It is a companion to both the data created (either through data acquisition or data transformation) and complementary metadata, enhancing its findability, accessibility, interoperability and reusability by others. By describing the context of digitisation long-term preservation and sustainability strategies can be better established - simply put by providing transparency in the process of digitisation the data user (and subsequent re-user) has a record of provenance and trust which can be evaluated for their own use-case applicability.

Paradata for Digital Data Acquisition

Data acquisition establishes a “ground truth” data-set (images, meshes, point clouds etc., depending on the method used) for the generation of 3D models. These data sets are the primary source from which geometric data is derived as a 3D model. Yet there has been until quite recently with the publication of VIGIE 2020/654 that a structured approach to recording the process and the factors that affect data acquisition has been widely adopted. Despite the significance of the circumstances surrounding the data acquisition process there

² European Commission. Directorate General for Communications Networks, Content and Technology. Study on quality in 3D digitisation of tangible cultural heritage: mapping parameters, formats, standards, benchmarks, methodologies, and guidelines : executive summary. Publications Office. DOI: <https://doi.org/10.2759/581678>

³ <https://eureka3d.eu/wp-content/uploads/2024/06/3D-digitisation-guidelines-Eureka3D.pdf>

is still no accepted metadata schema that offers the possibility to record this information. There are historic reasons for this⁴ and with the first functional 3D models ingested into Europeana in 2023 as part of the Twin it! Initiative⁵ (in response to *EU Commission Recommendations on a common European data space for cultural heritage*⁶), the Europeana Data Model (EDM)⁷ is undergoing a transition to accommodate aspects of 3D data including parts of the data acquisition process.

While this is both laudable and needed it does not, as yet, address how data acquisition paradata can be codified into a schema. Indeed while VIGIE 2020/654 lays the foundation for paradata collection through a series of 75 variables in 12 parameters used to algorithmically assess the quality of digital documentation of tangible cultural heritage, its remit was not to produce a schema for metadata/paradata serving as a best practice guideline. Nevertheless VIGIE 2020/654 is still the only significant, EU approved, guide on the information needed for recording data acquisition paradata and its use.

The output of data acquisition is a preliminary 3D model, intended to visualise the data collected. It is seldom the final production and dissemination output. Nevertheless it is important serving as a *prima facie* view on the underpinning data acquisition and test bed for Quality Assessment.

2.2 PARADATA FOR 3D ASSETS

3D assets are created from the “raw materials” of data acquisition⁸. There may be many assets derived from the original source depending on the use case defined in a project: for example the specification for a model to run on a mobile platform will be different to that used for high fidelity 3D printing yet both will use the primary data source. The creation of a 3D asset is a transformative process and may include non geometric data from traditional geometry based data acquisition. This approach is more holistic in nature, requiring attention to intellectual transparency as well as practical details on process. To make the analogy with hard archaeology: for archeology it is important to record each layer investigated before it is destroyed in the pursuit of discovering new data, digital reconstruction must record each layer in the creation of new understanding represented by the asset.

3D Asset Metadata

It is perhaps a good place to describe what is *not* paradata before we examine the paradata requirements for a 3D asset. Metadata describes what the 3D asset is. Each separate component of the 3D asset has its own unique set of metadata, while, depending on the processes used, these components may share a single paradata record. Typical 3D asset metadata may include

- File size

⁴ Baker, D. (2024). Paradata: The Digital Prometheus. In Lecture Notes in Computer Science (pp. 12–23). Springer Nature Switzerland. DOI: https://doi.org/10.1007/978-3-031-78590-0_2

⁵ Europeana. (n.d.). Twin it! 3D for Europe’s culture. Europeana PRO. Retrieved April 29, 2026, from <https://pro.europeana.eu/page/twin-it-3d-for-europe-s-culture>

⁶ European Union: Commission Recommendation (EU) 2021/1970 of 10 November 2021 on a common European data space for cultural heritage. In Official Journal of the European Union (OJ) L 401, 12.11.2021, pp. 5–16 2021

⁷ Europeana. (2017). Definition of the Europeana Data Model v5.2.8. Europeana Pro. https://pro.europeana.eu/files/Europeana_Professional/Share_your_data/Technical_requirements/EDM_Documentation/EDM_Definition_v5.2.8_102017.pdf

⁸ Baker, D., Ioannides, M., Cassar, A., & Siegkas, P. The Multidisciplinary Cultural Heritage Community: Towards a Definition of Roles. In Proceedings of EVA Berlin 2026 Berlin, Germany, 18-20 March 2026. https://eva-berlin-conference.de/Conference_Programme_and_Proceedings/EVA_Berlin%202026_Tentativ%20Conference%20Proceedings_23.03.2026.pdf

- Dimensions (and unit of measurement)
- Embedded properties (e.g., colour per vertex data)
- Orientation
- Point of origin (e.g., centre the geometry, either literal in the case of a single object or offset where it is a component part)
- Number of vertices and triangles (aka, tris, polygons or faces)⁹
- If the mesh is a closed surface (i.e., “watertight”)
- External dependencies (e.g., texture files, and parent files in the case of component meshes)
- Author
- Copyright information
- Date of publication
- Version control

3D Asset Paradata

While metadata informs us of the “facts” about the asset, paradata tells us the circumstances of its creation. Typical paradata for a 3D asset will record

- The data input used to create the asset
- The purpose/intent of the reconstruction
- Hardware used in the creation of the asset
- Software used in the creation of the asset
- Process/methodologies employed in the creation of the asset
- Output formats and identifiers
- Citation method
- External administrative reference files

External administrative reference files are those which define the digitisation as a whole, these will include CARE data compliance, FAIR data compliance, Data preservation plan, Project specification, Complexity Assessment, Digitisation plan, Quality Assessment, Development plan and Exploitation plan. Each of these will affect the context and extent of the digitisation effort and therefore the resultant 3D asset, understand the primary use and its eligibility for secondary use whether through resume, repurposing, refactoring or recycling of components.

⁹ It should be noted that while terms like “low poly” and “high poly”, are used to describe “quality”, this is a fallacy. The number of polygons is however important to know for speed of rendering to screen, graphical hardware capability and necessary granularity of data to fulfil the intended use case.

3. PROJECT CASE STUDY - THE ENKLEISTRA OF ST NEOPHYTOS

The digitisation of the Enkleistra is part of a wider ranging holistic programme involving earth observation, digitisation of artefacts and scholarly research. However as each subject of a digital documentation has its own requirements, purpose and techniques each must have its own Complexity (and Quality) assessment to accurately portray the creation of the 3D asset under study. In this section we present the example of the paradata record for the Enkleistra considered under the extended VIGIE 2020 654¹⁰.

3.1 SITE CONTEXT

The Enkleistra of Saint Neophytos (literally meaning the place of seclusion) is one of the most celebrated Byzantine twelfth-century monuments worldwide, given the high quality and the unique iconographic program of its frescoes, encountered nowhere else in the Byzantine world, as well as the fact that the whole complex was cut in rock by hand into the living rockface (Figure 2).



Figure 2: External view of the Enkleistra from below the cliff face (note the entrance to the Naos is shown in the second arch from the left)

¹⁰ Ioannides, M., Baker, D., Agapiou, A., Siegkas, P., & Cassar, A. (2025). Quality Certification in Data Acquisition for Cultural Heritage: The Power of Paradata for High Quality Digital 3D Cultural Heritage Assets. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVIII-M-9-2025, 623–628. <https://doi.org/10.5194/isprs-archives-xxviii-m-9-2025-623-2025>

The monument is connected with important religious intangible heritage for the Cypriot Greek Orthodox church and is a site of pilgrimage and veneration as well as a significant tourist attraction.

Saint Neophytos the Recluse (1134-ca.1214) is one of the most important Cypriot Saints and historic figures. He was a prolific writer who composed his biography, an account of the first years of the Latin conquest of the island, as well as several theological treatises. At the age of 17, he became a monk at Koutsoventis Monastery. In search of a solitary life, he quit this Monastery two years later. After many adventures, he decided to become an ascetic in the mountainous area above the city of Paphos. In 1159 he started building his cell, by enlarging and modifying an already existing cave, which was expanded into a complex comprising three caves shown in Figure 3: the Naos the Bema, and the Cell (as shown in Figures 4, 5 and 6 respectively).

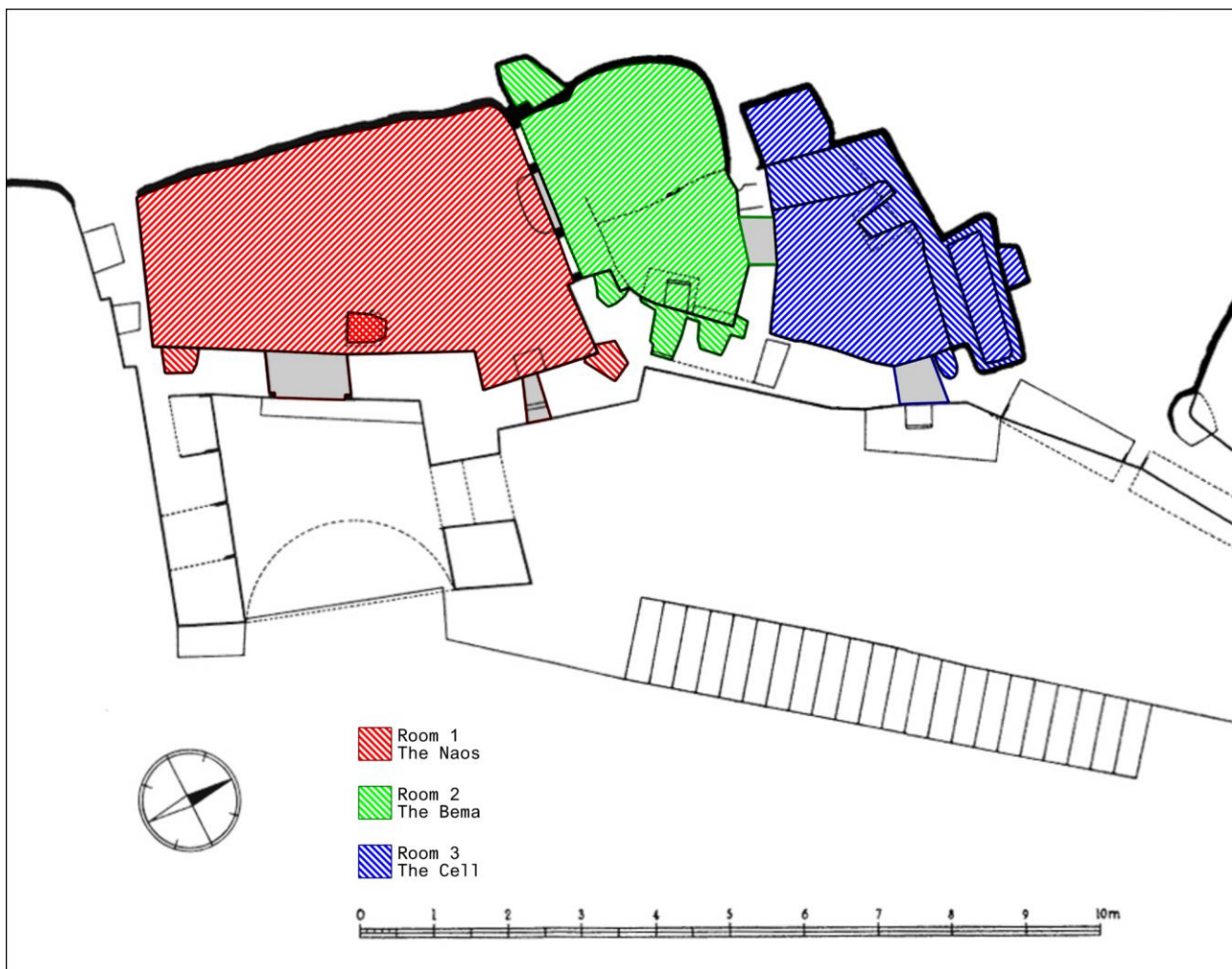


Figure 3: Floor plan of the Enkleistra showing the layout of the three cave rooms, adapted from Mango, C., and Hawkins, E.¹¹

¹¹ Mango, Cyril A., and Ernest J. W. Hawkins. *The Hermitage of St. Neophytos and Its Wall Paintings*. *Dumbarton Oaks Papers* 20 (1966): 119–206.



Figure 4: View of the Naos looking north to the Bema (reconstructed)



Figure 5: View of the Bema looking West (Reconstructed)



Figure 6: View of the Cell looking West (Reconstructed)

Neophytos soon became a well-known spiritual figure and in 1170 he was forced by Basil Kinnamos, the bishop of Paphos at the time, to accept a disciple. During this same period, the Enkleistra began to be extended and adorned with paintings, while the whole cliff was excavated for the creation of additional cells. This extension phase included possibly as well the Refectory, which was also adorned. According to Neophytos' testimony, however, the Naos was excavated in 1183. The increasing number of pilgrims visiting him obliged Neophytos to dig another cave above the first one (the so-called New Zion), in search of solitude and inner peace. This latter cave was completed and painted by the end of 1197. According to written testimonies, the Enkleistra was painted in 1183 by Theodoros Apseudis, likely a Constantinopolitan painter who came to Cyprus at the instigation of the bishop of Paphos Basil Kinnamos. To the same painter are also attributed the Bema and the Naos of the church of the Virgin at Lagoudera (UNESCO World Heritage monument in Cyprus, dated ca. 1192), as well as at least seven icons currently owned by different ecclesiastical institutions in Cyprus.

The community that was built and organised around Neophytos has been the centre of intellectual production with strong connections to the Byzantine elites of the island and the capital of the Byzantine empire (Constantinople), during the tumultuous period spanning the last decades of the Byzantine era -which ended with the conquest of the island by Richard the Lionheart in 1191- through the first decades of the Frankish period of Cyprus.

The intellectual production at the Enkleistra is evidenced by the writings of Neophytos and the composition of the pictorial narratives of the frescoes. The latter has been studied extensively in the past, whereas the writings of Neophytos, as well as the artefacts produced by or connected to the members of the circle of Neophytos both monks and laymen, have made the object of far less study.

3.2 DIGITISATION CONTEXT

The purpose of the 2025 digitisation of the Enkleistra was to provide the biennial data for the long-term monitoring of the site, which is declared as a “monument at risk”. The scheduled data acquisition for 2025 aligned well with the EUreaka3D-XR project, not only to fulfil the requirement for a 3D model for the staging of the case study scenario and use of the Avatar Creation tool, but also a prime opportunity to show how, with correct paradata, the output of a digitisation effort can be reused with confidence.

In this case, the digitisation of the Enkleistra was undertaken by a team from Cyprus University of Technology, while the XR components were developed in Switzerland by partners MiraLab. The trinity of data (both raw and pre-processed), metadata and paradata would therefore be a test of the increased robustness offered by the project’s approach to re-use and sustainability of CH digital assets. Of specific significance was the implementation of the mixed reality application, which required precise documentation of the Enkleistra, requiring synchronisation between both sets of digital assets, the avatar of St Neophytos and the 3D model of the Enkleistra, which would serve as a proxy for the physical space during development of the scenario.

This additional complexity required a root and branch review of the previously determined Complexity and Quality assessment for the Enkleistra; from redefining stakeholder requirements regarding the use of the digital asset and representation of the saint, to developing more streamlined pipelines to prepare assets within the project timeframe. It also sharpened focus on how the VIGIE 2020 654 guidelines have responded to the needs of the multi-disciplinary cultural heritage community, as its recommendations are adopted into wider CH practice, notably those parts that have been included, or are being considered for inclusion, in the EDM.

3.3 COMPLEXITY ASSESSMENT

The purpose of the Complexity Assessment is twofold; first it provides the record of the “why, what, who, when and how” for the digitisation that forms the basis of the 3D asset’s digital provenance. Second when used pre data acquisition as part of the planning process it significantly aids identification, and mediation, of risks and identification of areas where challenges may arise. The Complexity Assessment therefore, is both a record of the documentation process and a statement providing evidence that the digitation was undertaken under the best possible circumstances at the time. Paradata within this record supports the future use of the 3D asset allowing those circumstances, and their limitations, to be understood by data reusers, and in turn allowing the reuser to assess the need and scope or any re-digitisation that might be required minimising duplication of effort. Figure 7 illustrates the overview of all the parameters in place for the estimation of Complexity in the 3D data Acquisition.

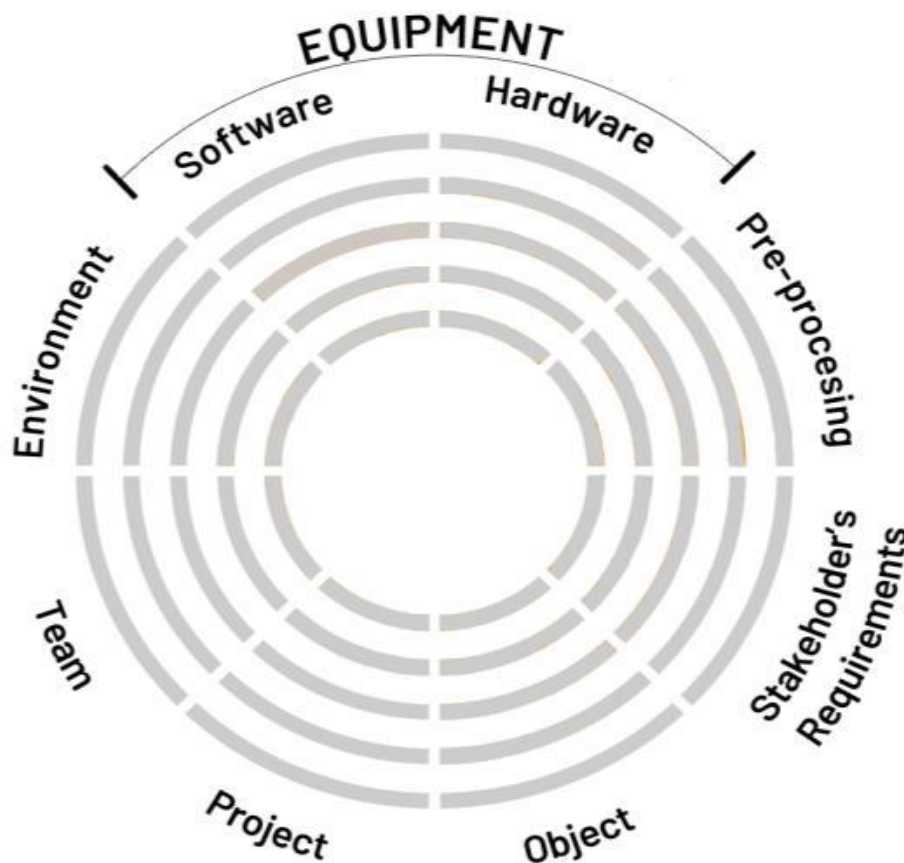


Figure 7: Overview diagram of Complexity

Stakeholder Requirements

The Stakeholder Requirements parameter records those preconditions and constraints placed on the digitisation by the stakeholder(s). The definition of who a stakeholder is will depend on the project but normally include a primary stakeholder as commissioner/organiser of the digitisation. CUT has defined a stakeholder as “an actor with an investment in the cultural heritage resource, which may be prejudiced through its digitisation. This investment may be financial, legal, moral, or ethical.”¹². Figure 8 shows an example of the structure of the Stakeholder Requirements parameter as defined in VIGIE 2020/654

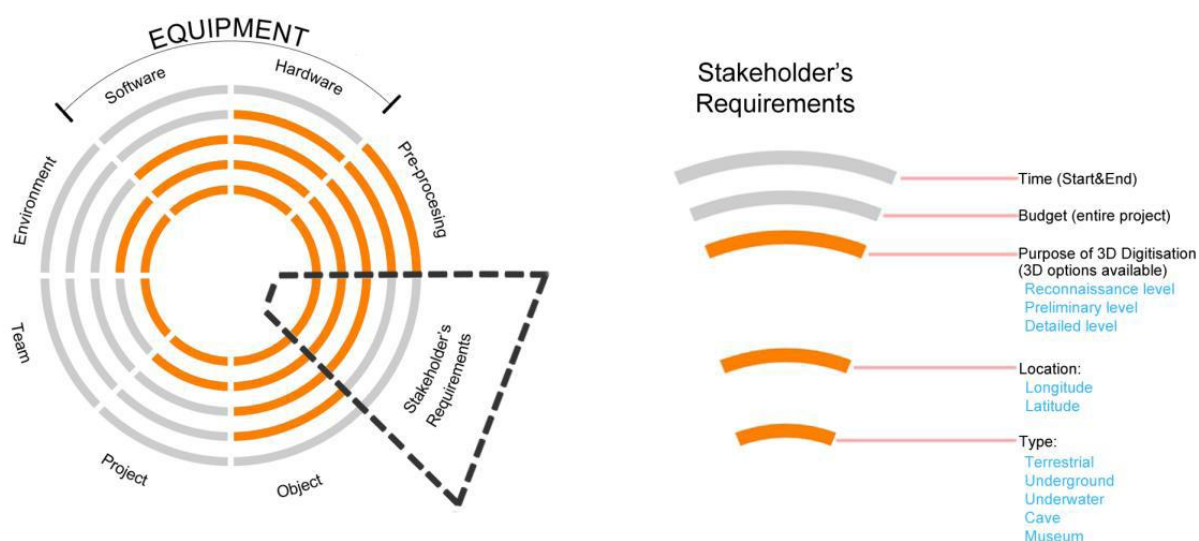


Figure 8: Example of the Stakeholder Requirement parameter structure.

Type

The EU VIGIE 2020/654 has five different classifications to help evaluate the complexity of the type of digitisation needed, Terrestrial, underground, underwater, cave and museum. The intent of this variable is to identify what kind of CH resource the digitisation will be documenting.

The Enklystra is designated as a cave type as all three areas (the naos, bema and cell) are caves. This part of the data acquisition programme does not require external or artefact digitisation which have their own assessments. As a partially enclosed subterranean immobile object the Enklystra type complexity was assessed as 80%.

Location

The location variable establishes where the stakeholder intends the digitisation to take place. This may differ from the **Object Location** which provides a more granular location specifically for movable CH resources (i.e., artefacts). VIGIE 2020/654 requires representation of a geographic point location by

¹² Baker, D., Ioannides, M., Cassar, A., & Siegkas, P. The Multidisciplinary Cultural Heritage Community: Towards a Definition of Roles. In Proceedings of EVA Berlin 2026 Berlin, Germany, 18-20 March 2026. https://eva-berlin-conference.de/Conference_Programme_and_Proceedings/EVA_Berlin%202026_Tentativ%20Conference%20Proceedings_23.03.2026.pdf

coordinates latitude, longitude and altitude record in ISO 6709 format¹³. It is also recommended that the paradata record includes a GeoNames reference (if available) to help with disambiguation and in support of the EDM.

The location for the Enklystra is 34.84686712875565, 32.44508854160252, 427.9 and the GeoNames id is 146714¹⁴. As the location of the Enklystra in all three dimensions and GeoNames entry is available the location variable is assessed as being 0%.

Purpose

This variable defines the specification for the digitisation effort. VIGIE 2020/654 has three levels of purpose: Reconnaissance, Preliminary and Detailed. The intent of this variable is to identify the expected granularity of data to be documented by the digitisation, augmented by any specific requirements. For example a detailed documentation may require “high resolution”, however what this term means needs to be clarified against the purpose of the digitisation being undertaken (detailed satellite imaging may provide information at a scale of tens of centimetres, terrestrial laser scanning at centimetres, and close range data captures in the millimeter range yet all can be considered high-resolution depending on the purpose and intent of the documentation).

The purpose of the 2025 digitisation of the Enklystra was to provide the biennial data for the long term monitoring of the site as a “monument at risk”, specifically in the case of this part of the digitisation the interior of the Enklystra which has a higher granularity requirement than the external parts of the monument. Previous digitisations in the series have employed terrestrial laser scanning therefore for consistently this is the preferred approach. As the 2025 digitisation would also be used to provide the 3D model for the Eureka3D-XR case study implementation this was noted and the requirement for both geometric and colour data acquisition was noted. The initial assessment for the parameter was placed at 75% complexity as “detailed”, however taking into consideration that the method had already been established previously (and knowing the risks and limitations) this was reduced to 60%.

Budget

This variable defines the funding allocated to the digitisation effort, or portion thereof. The purpose is to establish that the available funding can cover the established costs. Any shortfall increases the complexity of the variable; it is expressed as a percentage of the overall budget allocated to the task e.g, if the budget available only covers 70% of the total estimated budget required the complexity would be 30%.

This specific part of the Enklystra’s documentation process as set out in the **Stakeholder Purpose** description was allocated 2 person days for data acquisition and another for pre-processing to undertake data acquisition and prepare the preliminary model. No purchase or hire of new equipment or travel costs were considered for inclusion. For the 2025 Enklystra digitisation using the TLS the allocated budget

¹³ International Organization for Standardization. (2022). Standard representation of geographic point location by coordinates (ISO Standard No. 6709:2022). <https://www.iso.org/standard/75147.html>

¹⁴ GeoNames entry Ágios Neófytos <https://www.geonames.org/146714/>

covered the entirety of the assigned members of staff in the Project/Team parameter therefore the Budget complexity variable was assessed as 0%

Time

The final variable in the Stakeholder segment is Time. The intent here is to establish the time available for the digitisation process covered by the VIGIE 2020/654 to be fulfilled according to the Stakeholder and project timeline ensuring that the correct resources are available at the right time. Any shortfall increases the complexity of the variable; it is expressed as a percentage of the overall time allocated to the task e.g, if the estimated time required to complete the digitisation process is 8 person days but the allocation of resources is 6 person days the shortfall and resulting complexity assessment would be 20%. It should be noted that the Time variable may be constrained by available daylight when outdoor digitisation is being undertaken and should be cross referenced with the Location parameter to calculate daylight dependent operations.

In the case of the digitisation of the Enklystra the most significant factor was access to the site which was restricted between the hours of 08:00-20:00 on 13 May 2025 for data acquisition including set up and clear down activities. As noted in Stakeholder Purpose the digitisation preference was to use TLS at a high quality/high resolution setting (see **Equipment Hardware**) a single scan would require approximately 6 minutes to complete with additional time allocated for repositioning, etc. an estimated 15 minutes total per scan. While the total access to the site would be 12 hours the site would need to be prepared and restored (i.e., removal and replacement of non-scanned items such as furniture see **Object Remedy Options**), other activities related to the overall digitisation of the site would also be being undertaken (photo documentation, aerial photography etc), and the probability of interruption based on previous experience (see **Access**) a more realistic time to complete the TLS survey was placed at 3 hours, or 12 scans. Based on the opinion of the member of staff assigned to undertake the scanning (see **Team**) this was considered adequate to ensure good data collection. The time complexity assessment variable was set to 0% on this basis.

Object

The variables of the Object parameter are concerned with defining and recording aspects of the digitisation of the cultural heritage resource under documentation (i.e., the “object” may refer to a landscape, site, monument or artefact). Figure 9 shows an example of the structure for the Object parameter in VIGIE 2020/654.

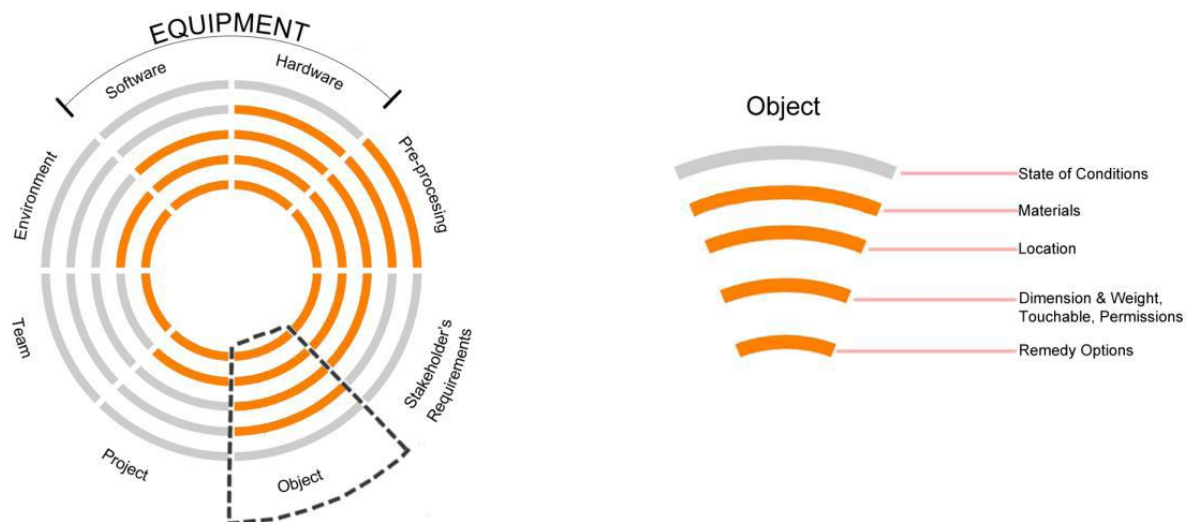


Figure 9: Example of the structure of the Object parameter.

State of Condition

This variable is used to describe the current condition of the object under documentation- specifically to identify areas of concern that may affect the digitisation process- for example whether the object is fragile, broken or in a state of collapse. VIGIE 2020/654 requires an appraisal of any hazards both to the object and staff from the digitisation process are taken into account before work is undertaken. VIGIE 2020/654 offers no direct guidance on how this might be structured, however the Museums and Galleries of New South Wales provides a simple and concise guide Condition Report - Essentials¹⁵. The guide implies five different categories to which we can assign a 20% base range for condition assessment starting at 0% with "Excellent" to 80% for “Very poor”

- [0%] Excellent (as new condition with little or no sign of use)
- [20%] Good (some signs of wear but physically sound)
- [40%] Fair (minor damage, some losses/ deterioration more aesthetic than physical)
- [60%] Poor (wear, damage, deterioration and loss to a large proportion of the item)
- [80%] Very poor (extremely deteriorated, weakened condition with very extensive loss/damage which greatly impacts the integrity of the object).

Additional observations may be used to modify these base values in regard to conditions that may affect the digitisation of the object in accordance with the Stakeholder Requirements and project specification document. Examples this include furniture, scaffolding or similar obstructions that may inhibit digitisation, additional components connected to the object (e.g., latter additions either through anastylosis,

¹⁵ Museums & Galleries of NSW. (n.d.). *Condition reports – the essentials*.

<https://mgsw.org.au/sector/resources/online-resources/collection-care/condition-reports-essentials/>

reconstructive conservation or aesthetics) which may be superfluous to the documentation or the inverse where the “object” consists of multiple parts each which may require different assessment.

For the Condition complexity assessment of the Enklystra was set at 60%, “Poor”; the structure is sound, however much of the lower part of the frescoes have been lost, while evidence of restoration activities are visible. Several items of furniture not included in the digitisation plan but obscuring the surface of the object were noted.

Materials

The Materials variable attempts to list the primary material types of the object to identify potential challenges to the digitisation process. For example high reflectance surfaces, transparent materials or fur may require additional preparation or techniques to obtain satisfactory results from data acquisition. The VIGIE 2020/654 provides a non-exhaustive list of common material types reflected in the EUreka3D Data Hub and adopted in the EDM. It is strongly recommended that wherever possible standard vocabulary is used (e.g., The Getty Research Institute Art & Architecture Thesaurus¹⁶) for interoperability when describing an object’s materials. At least one (the primary) material should be with other significant object material included.

In the case of the Enklystra three primary materials were identified, limestone (AAT ID: 300011286), plaster (AAT ID: 300014922) and paint (coating) (AAT ID: 300015029). None of these materials were considered as problematic for digitisation, however it was noted that the *Iconostasion* (the wooden panel separating the naos from the bema) contained two icons with reflective gold foil, behind glass, and in the cell the tomb has a protective glass- door, which may affect local data acquisition at those points. Overall the materials complexity score was set at 10%.

Location

The Object Location variable establishes the deposition of the object. For immobile objects, like the Enkleistra this is likely to be the same as the **Stakeholder Location** variable, however for movable objects these may be held in storage or may require specific laboratories where digitisation will take place. The purpose of the Object Location variable is to ensure that the location of the object is known in advance and can be scheduled for retrieval if necessary without having to be “found”. Such delays increase the complexity of the digitisation process. Variable details should follow the requirements as the **Stakeholder Location** variable with augmentation to identify specific local arrangements such as arrival space, stack, box etc.

As the Enklystra is an immobile cultural heritage resource this is the same as **Stakeholder Location** variable and was assigned a value of 0% for its complexity assessment.

¹⁶ Citation: Getty Research Institute. (n.d.). *Art & architecture thesaurus online*.
<https://www.getty.edu/research/tools/vocabularies/aat/>

Dimensions

The Dimensions variable is used to describe the physical properties of the object that may impact the digitisation process, the intent is to ensure that both the object and the setup required match. For example if the proposed digitisation method is a light box based photogrammetric documentation the object must be able to fit within the light box with the appropriate distance for photography and the turntable/surface used to manipulate the object must be able to bear the weight of the object itself to ensure smooth operation and avoid potential failure or stability issues that may pose a risk to the object itself. Physical dimensions of the object should be described in X, Y, Z coordinates using a right-handed coordinate system (where the positive x axis points to the right, the positive y axis points upwards and the positive z axis points forwards)¹⁷, it is often easier to think of this as a “box” in which the entire object can fit (see Figure 10). The unit of measurement must also be included; this should be in consistent metric units. It is good practice to include information on the object's orientation identifying the “up” axis.

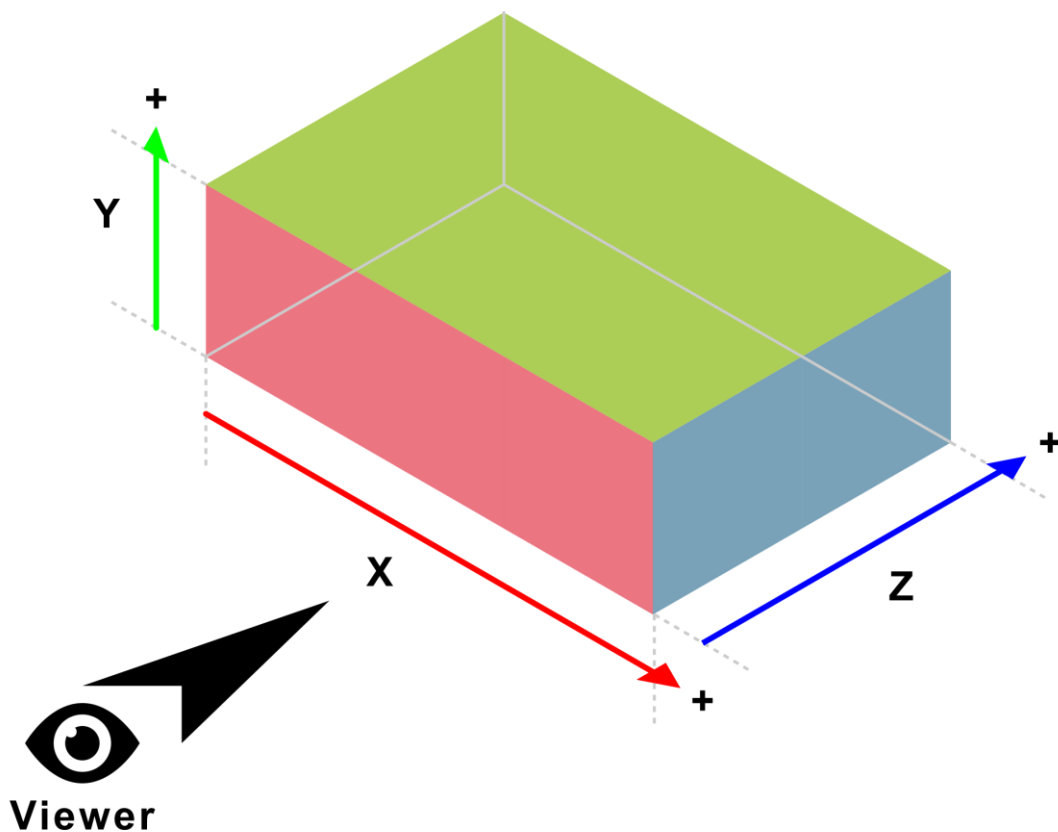


Figure 10: Dimension coordinate system.

¹⁷ This is inline with the IIIF specification for 3D objects as reported in Rossenova, L. (2023, November 13). IIIF for 3D – making web interoperability multi-dimensional. Data Space for Cultural Heritage. <https://www.dataspace-culturalheritage.eu/en/news/iiif-for-3d-making-web-interoperability-multi-dimensional> and previous standard for interoperability like VRML (Virtual Reality Modelling Language) ISO/IEC 14772-1:1997 International Organization for Standardization & International Electrotechnical Commission. (1997). Information technology — Computer graphics and image processing — The Virtual Reality Modeling Language — Part 1: Functional specification and UTF-8 encoding (ISO/IEC Standard No. 14772-1:1997). <https://www.iso.org/standard/25508.html>

From a museological viewpoint Y can be understood as Height - the maximum vertical measurement of the object when in its natural resting position (Up orientation) needed to enclose the object, Length - the longest maximum horizontal measurement needed to enclose the object - the X axis, and Width - the shortest maximum horizontal measurement needed to enclose the object. Depending on the object it may be necessary to consider concavity, depth (the internal vertical measurement) and breadth of any aperture (for example digitising the interior of a ceramic vessel will require knowing the dimensions of any aperture to fit the data recording device through, or the expected coverage available externally)

The weight of the object should be entered in standard metric units, for immobile objects this can be set to 0% as it can not de facto be moved. Lacking information for the dimensions may seriously impact on the ability to digitise the object correctly.

Two other factors considered by VIGIE 2020/654 to be part of the Dimensions sector are Touchable and Permissions. Touchable encompasses two aspects: first, can the object be physically touched both manually and/or supported during the digitisation? Second, does the object need to be moved/repositioned or otherwise handled by authorised personnel (e.g., a museum curator, conservator or custodian)? Both of these considerations are connected to the **Condition** and **Material** parameters and may significantly impact the digitisation process. For example in photogrammetry it is common practice to invert an object to capture the underside, if this is not possible - e.g. the object condition cannot support the weight on the inverted surface or there is no point of stability for the object when inverted - this will add complexity, if the object can only be handled by authorised personnel they will need to be on hand to handle the object during the digitisation process and be able to take instruction from the digitisation team, if this is not possible this will add complexity.

The final factor to be considered is the so-called Permissions variable. This specifically deals with ensuring that the correct authorisations are in place and understood to digitise the object. This covers both the legal and ethical considerations and the extent of what can be digitised. While such permissions will be part of the overall project plan it is important that they are referenced by the object not only for authentication of provenance and compliance to CARE data principles but to ensure that specific details including method of digitisation have been accounted for and that the team has proof of a “licence to digitise” on the day. It cannot be understated that without permissions related to the object and its digitisation no digitisation should take place. Examples where lack of clear permissions have severely impacted digitisation include: Overflying/over photography on restricted air space, misunderstanding of what is to be digitised, specific restrictions on secret/sacred object or parts thereof and use of equipment (including ancillary equipment such as ladders) during the digitisation process. Data which has been obtained without securing appropriate permissions should not be disseminated or used outside of the project.

In the case of the Enklystra the physical dimensions are known (X:11m, Y:6m, Z:5m), as an immobile object weight is not applicable. However, the object consists of three interconnected spaces with half height doors, multiple irregular niches in the walls and in situ carved features (notably the altar in the naos and table in the cell) which presents significant challenges for digitisation. Vertically the caves have highly irregular heights and morphology with spot height measurements ranging from 1.7-6m. Based on this the complexity assessment was put at 90%.

Restrictions were placed on touching the painted frescoes but otherwise no Touchable considerations were considered, as the pre identified method of data acquisition did not require physical contact with the frescoes; this was assessed with a complexity of 0%. A note was made in the field briefing that extra

cases should be made while working on site to avoid contact with the frescoes due to the cramped conditions.
Permissions were in place with no restrictions on digitising the Enklystra and a complexity of 0% was assigned.

Remedy Options

This variable relates to the tasks and options available to the digitisation team when considering improvements to the success of digitisation, considering the observations of the **Condition** variable- it also notes remedial work previously undertaken (Figures 11 and 12 show examples of this complexity variable in the Enkleistra). This variable does not reduce overall complexity, but rather intends to estimate the complexity of taking remedial action to improve the digitisation process. For example a site which is partially overgrown may restrict what can be captured, however it may be possible to have the vegetation removed or an artefact which has an- unstable surface may be able to be stabilised during digitisation through supports or a different method of data acquisition, e.g. for photogrammetry moving round the object rather than using a turntable. Complexity assignment should be considered on what is possible to achieve/put in place before the team arrives and what may need to be done on the day.

In the case of the Enklystra several options were identified, the removal (and return) of furniture not considered to be part of the digitisation, requesting internal lighting to be turned off during scanning, the securing of external doors to prevent light spill and accidental entry when scanning was taking place. Previous conservation work was noted and not considered to impact the digitisation of the object. It was determined that any removal of furniture would be the responsibility of the team on the day and that the coverings of bed and table in the cell were not to be removed. In the initial planning the removal of the “poor box” in the naos and the glass window to the tomb in the cell were considered as potential remedial options, however it was determined that both were impractical. Overall the complexity assessment for undertaking remedial options was placed at 25%.



Figure 11: Southern wall of the naos showing the two types of Remedy Options.

Remedy Options: items of furniture to be removed prior to digitisation, lighting complexity caused by open door and artificial lighting - and previous conservation work - stabilisation of frescoes using conservation tape (seen running across the fresco and at the top and right side intersections) and consolidation replastering above.



Figure 12: Photograph detailing previous conservation work.

Project

The Project parameter contains a set of variables that should be understood and documented relating to the project itself. The intent of this paradata is to supplement and identify additional items that may affect the Complexity of digitisation based on the project documentation (i.e., the project specification document, data acquisition plan, FAIR/CARE data policy etc). Figure 13 shows an example of the Project parameter for Complexity using VIGIE 2020/654

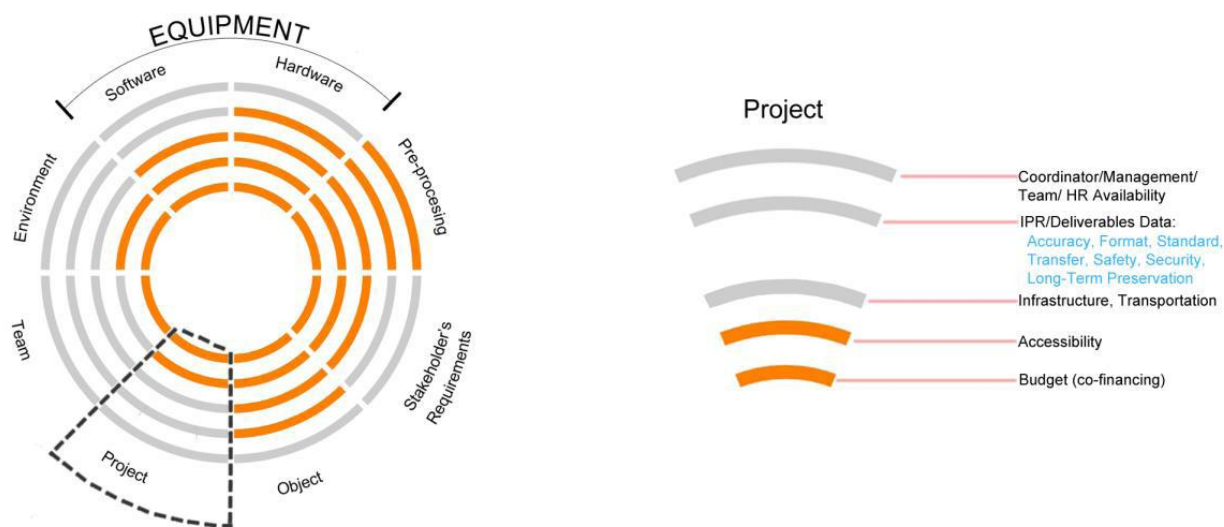


Figure 13: Example structure of the Project parameter.

Management

The purpose of the Management variable is to clarify the role and responsibilities for the specific digitisation task. Its intent is to capture data relating to the planning and resource allocation which may impact the complexity of the digitisation. VIGIE 2020/654 requires the identification of the digitisation coordinator, local management arrangements, potential team members and availability. For example, without knowing who the contact point at the digitisation location is, whether they will be available during the duration of the digitisation is high risk - and therefore increase in Complexity - when the team arrives to start work and the site is locked or security has no knowledge of the activity scheduled. The variable does not explicitly require names and contact detail (in line with General Data Protection Regulation guidelines¹⁸), but rather ensures that these are documented in the digitisation plan and included in the Fieldwork Documentation accompanying the team.

Regarding team composition this does not necessarily relate to individual members of staff but to the skill sets needed to accomplish the digitisation. For example if the project requires a qualified conservator to be present the record should note this and whether or not the pool of team members has an individual available to fulfil that requirement - if that team member is not present or unavailable then complexity increases as the role must be filled externally. Actual team composition is detailed in the Team parameter, reflecting those directly involved in the digitisation process.

For the digitisation of the Enklystra the coordinator was identified as the DHR Lab, Cyprus University of Technology, with appropriate contact details provided. Local management was identified with both a local contact and deputy's details documented. The skills required for undertaking this part of the digitisation were identified as competence in TLS operation (for data acquisition) and preparation of data in the pre-production component of the digitisation. Existing staff profiles and availability were consulted to ensure that these requirements were able to be sourced internally. Having confirmed these the complexity assessment was set to 0%

¹⁸ Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016. <https://eur-lex.europa.eu/eli/reg/2016/679/oj/eng>

IPR & Deliverables

This variable is concerned with the expectations for the delivered data and its status. The intent is to document factors including the expected accuracy, the format(s) in which it will be delivered, standards adhered to, how data will be transferred, and data security. It also considers the responsibility for long term digital preservation of the data and intellectual property right considerations. As such the variable is made up of a number of sub values which must be considered individually and reconciled to achieve an overall value for the variable

Accuracy in terms of deliverables is the difference between the data collected during the data acquisition process and the preliminary 3D mesh produced from the pre-processing stage of digitisation. This is expressed as the root mean square deviation (RMS) between the two data sets. The RMS comparison between two data sets is based on the unit of measure as specified in the Object **Dimension** variable, thus a RMS of 1 would be a divergence of 1m if using meters, 0.5 would be 50 centimetres, 0.01 one centimetre etc. Theoretically a RMS of 0 would be perfect but is unlikely in practical terms. If the expectation is that the accuracy of the delivered mesh is to be highly accurate (i.e., the raw data point cloud and the mesh are well aligned) the complexity assignment should be equally high i.e., an accuracy of 1cm would be 99% complexity.

Specified formats and standards will depend on specific output from data acquisition hardware/software (if raw data is required) and the use case. Wherever possible these should conform to recognised or *de facto* standards. It is strongly recommended that open source be used over proprietary formats to provide a more robust long-term preservation and sustainability pathway. As a minimum any standard of format used should be referenced including version where applicable. Formats should be investigated to ensure that the requirements are supported. For example, if the expectation is that the output will be colourised then the format selected must be verified as supporting colour information, further is that information embedded within the data structure (e.g. colour per vertex assignment) or referenced to external files? If external files then what formats are available and functionality are available (e.g., are files compressed which may result in data loss, does the format support transparency etc.). The less that is known about a format the more complex the transformation from data acquisition through preprocessing to delivery will be.

When considering data storage and safety, both short and long term higher accuracy generally means a higher allocation of resources. When will data be backed up, is there provision for storage space, what are the policies (and/or restrictions) for data storage and management in the projects Data management Plan, FAIR and CARE Data policy and requirements for long term digital archiving of data? Similar to the Management variable VIGIE 2020/654 does not require duplication of data already in project documentation but provision of references to those documents and an analysis that the promised delivery is achievable within the allocated resources.

Finally the question of intellectual property rights must be addressed. This includes clearances to digitise the object itself and what conditions are placed on the digital output delivered. As both permissions, copyright and subsequent IPR will have been negotiated and set in the project contract/project specification document this variable is intended as a confirmation check that the digitisation process and delivered outputs comply with those agreements. As a minimum this should include a rights statement for the delivered data and

where necessary and indicate if non disclosure agreements are in place. It is recommended that a recognised standard such as Creatives Commons¹⁹ be adopted to clearly indicate the status of the delivered data.

For the Enkleystra the expected Accuracy subvariable was set at 98% for the delivered preliminary 3D mesh (i.e. within 2cm). Expected formats were .e57 for LIDAR Point Cloud data files²⁰ and companion reference panoramic images in .PNG²¹ (RGB 8bit compressed 20000x10000px) for raw data and Wavefront .OBJ²² format with .PNG (RGBA 8bit uncompressed 8192x8192px) diffuse texture. All three of these formats are well established and documented and are considered *de facto* standards and within the capabilities of data acquisition equipment and pre-processing stage - consequently a complexity assessment of 0% was allocated to this sub variable.

Data backup was taken immediately after data acquisition to an 2TB external hard drive and retained on the scanner. Further backups of the data were made to the EUreka3D Data Hub and Basecamp cloud services. Pre-processing was undertaken at the auspices of the DCHR Centre at CUT working from local workstations and incremental version control and staged backups to offline media. The Data security sub variable complexity was assigned a value of 10%.

Within the framework of the EUreka3D-XR retention of data both in terms of access and preservation is guaranteed for 5 years and a complexity of 0% for this subvariable assignment.

The IPR for the digital resources created though the digitisation were assigned to Cyprus University of Technology under a preexisting agreement with the Monastery as CC BY-NC-SA 4.0²³; However this was amended to CC BY-NC-ND 4.0²⁴ the least permissive of the CC licences, at the request of Monastery prior to ingestion into Europeana subsequently complexity for IPR was increased from an initial 0% to 10%. The total for the IPR & Deliverables variable was set at the average of the five subvariables at 24%

Infrastructure

The Infrastructure variable of the Project variable is used to detail any infrastructure requirements that need to be accounted for during the project planning. VIGIE 2020/654 contains only one variable for consideration that of transportation. The intent of the variable is to ensure that transport arrangements have been put in place to get staff and equipment to the appointed place where data acquisition will take place at the correct time and for the planned duration. For example, do flights/trains need to be booked? What are the institutional rules for use of private vehicles or public transport? Is accommodation needed? What financial support is available for out of office expenses etc. This is most pressing when work is conducted internationally and it is advisable to also consider staff restrictions on international travel. The more complicated the logistics are to ensure that the right people and at the right place at the right time with the right equipment the higher the variable complexity will be.

¹⁹ Creative Commons. (n.d.). About CC. <https://creativecommons.org/>

²⁰ ASTM E2807-11(2019)e1 (2019). Specification for 3D Imaging Data Exchange, Version 1.0. ASTM International. <https://doi.org/10.1520/e2807-11r19e01>

²¹ World Wide Web Consortium. (2025). Portable Network Graphics (PNG) specification (third edition). <https://www.w3.org/TR/png-3/>

²² "Library of Congress. (2024). Wavefront OBJ File Format (fdd000507). <https://www.loc.gov/preservation/digital/formats/fdd/fdd000507.shtml> ".

²³ Creative Commons (n.d.) Attribution-NonCommercial-ShareAlike 4.0 International Deed <https://creativecommons.org/licenses/by-nc-sa/4.0/>

²⁴ Creative Commons (n.d.) Attribution-NonCommercial-NoDerivatives 4.0 International Deed <https://creativecommons.org/licenses/by-nc-nd/4.0/>

As the Enklystra is a static object the team would need to travel to the site with equipment to undertake digitisation. Cyprus has no trains and the bus service can be erratic. For example Limassol has a bus route to the Monastery, duration ~2hours 15mins with one change - however the first available bus is advertised as departing from Limassol at 07:40 connecting at Paphos and arriving at the Monastery 09:48, with the the last bus from the monastery advertised as departing at 16:17 connecting at Paphos and arriving in Limassol at 18:08 this would cut into the available time to undertake the digitisation activities and limit what could be taken in terms of equipment on public transport. Private transport for staff and equipment was the preferred solution enabling both flexibility in terms of arrival and departure, car sharing and transportation of equipment. The variable was assigned a complexity of 10% reflecting the potential for traffic delays.

Accessibility

The accessibility variable considers those aspects surrounding the digitisation event which may hamper successful or efficient data acquisition. Its purpose is to identify health and safety considerations that may exist during planning and potential routes to mediation. VIGIE 2020/654 takes into account four factors Obstacles, Hazards, Ethics and Approachability. Obstacles are those physical barriers which may impede access to the object not only for staff but also equipment. Examples include stairs, narrow spaces or low ceilings, restricted working areas or movement between transportation and location. Hazards are those challenges which may pose a risk to staff and equipment during the digitisation event. Examples of these include, poor ventilation, lighting, lack of shade, amenities and trip or fall hazards. Ethics covers both restrictions set out in the permissions and cultural observance. Examples may include expected conduct on site, handling of objects, mode of dress etc. Approachability is a mark of how the digitisation is likely to be received by those on site, while at first glance this may seem an odd variable even if the correct permissions and authorisations are in place this does not necessarily mean that site staff will be cooperative or happy with the disruption digitisation may cause to their routines. The complexity will increase depending on the challenges identified.

The Enklystra has good access in terms of obstacles with the monastery granting permission for carparking close by the site itself, the site is elevated and reached by a flight of steps adequate for the movement of equipment and staff. The site itself presented a number of trip hazards due to uneven floors, change in levels between the naos and the bema, external door threshold and raised surfaces. No additional ethical considerations were identified. Exclusive access to the Enklystra during data acquisition period had been promised by the Monastery, however previous experience had identified a risk of unexpected visitors, tourists and pilgrims. This is a Approachability issue, to help in the management of such visitors a member of staff was assigned to keep watch ensuring that no entry was made during scanning. The member of staff would be briefed to explain what was occurring, the objectives of the mission and the EUreka3D-XR project both verbally and with related materials. Communication with the digital acquisition team allowed for the potential of visitor access to the Enklystra during reset of positions. Overall the accessibility variable was assessed as 20%

Co-Financing

While the overall budget for the project is discussed in the **Stakeholder Budget** the specific allocation of staff and where funding for their time comes from is a consideration. This parameter intends to identify those members of staff whose time may need to be “bought out” or otherwise traded from other projects or duties,

this is more than an *internal* accounting exercise as it requires staff coordination including those who may have additional calls on their time. For example a part time member of project staff time allocation will need to be agreed across other projects commitments, staff may be subject to priority calls (e.g. senior staff being on standby for institutional needs). The co-financing variable therefore is used in planning to minimise the risk of complications arising from a Human Resources perspective and potential absence of staff due to institutional external demands. The more unaddressed co-financing issues identified during the planning of the project the higher the complexity assessment.

For this specific data acquisition activity at the Enklystra two members of staff were assigned. One staff member was directly funded at 50% by the project, the other fully funded. Pre-production assignment was fully covered by the project funds. No other co-financing issues were identified. The complexity for this variable was therefore set at 23%

Monitoring

The Monitoring parameter is part of the extended VIGIE 2020/654 and only included for completeness and as an example of how the recommendations are evolving. The Monitoring parameter was added in 2025 as a direct result of needs identified by the EUreka3D-XR project and deals specifically with the increasing demand and use of remote sensing technologies (*in-situ* sensors, uncrewed vehicles, and satellite based earth observation) within cultural heritage. The additional complexity taken into account here is the dimension of time. In the classic approach to cultural heritage documentation (whether digital or not) a one off event (all be it one in a services if, for example a site is undergoing long term study). Monitoring however deals with the complexities involved in documenting realtime and longterm data collection.

As these methods provide their own unique challenges to technical, deployment, data management, sustainability and application complexity this new parameter was developed to accommodate the recording of paradata where such techniques are employed.

Observation Area

The Observation Area variable describes the observation domains under monitoring. It intends to classify the domains to be monitored, land water atmosphere, climate, etc. It is similar to but distinct from **Stakeholder Requirements Type**.

Topic Area

Topic Area is the variable in which the paradata regarding the specific intent of the monitoring i.e. land cover, land use, vegetation, surface deformation etc. It is similar to but distinct from **Stakeholder Requirements Purpose**.

Sensor & Data Type

The Sensor & Data Type variable contains information on the sensors used and the data types available e.g. level of processing. It is intended to document specific deployment of remote sensing technologies aligned to the Observation and Topic Area. For example, optical sensors can provide colour photography for visual monitoring, multi/hyperspectral sensors are used to analyse details of material composition and degradation, thermal infrared sensors and record temperature identifying thermal stress and moisture retention etc.

Time

The Time variable is the indication of the period of monitoring required. While this appears straight forward - monitor starts and ends - this is not necessarily the case, factors including temporal dilation (the rate of data collection), the span of the service (which may include historic data) and continuity of monitoring (for example switching between services) need to be taken into account.

Service Provider

This variable identifies the type of service being considered for data collection and the implications for data use. The intent is to provide an understanding not only of who the service provider is - self owned, other privately owned, publicly accessible or commercial but the rights to an extent to which data is extracted and can be used.

For this specific data acquisition activity (the internal scanning of the Enkleistra) Monitoring was not a requirement. All of variables in the Monitoring parameter were set to 0%

Equipment Hardware

The Equipment Hardware parameter is closely connected with the **Equipment Software** parameter. Specifically this parameter documents the hardware specifications of equipment used during the data acquisition process.

Licence

The Licence variable notes if any specific licences are required to operate the equipment selected for the data acquisition task. The intent is to note what licences may be required and ensure that staff allocated hold the appropriate licences to operate the devices. The variable also notes the date of the last hardware calibration and maintenance and expiry of any certification. For example, operation of an uncrewed aerial vehicle (aka drone) in Europe must comply to regulations published by the EASA²⁵ and local laws, depending on the location, weight category, classification etc.

For the data acquisition of the Enkleistra the Zoller + Fröhlich 5016 phase-based terrestrial 3D laser scanner was used²⁶. No licence for the operation of this equipment is required and the complexity was set to 0%

Precision

The Precision variable records the stated precision of the instrumentation used in the data acquisition. Precision is a mark of how close measurements are to each other, not accuracy which is a mark of how close they are to a target. Precision of data acquisition should be recorded from the technical specification of the equipment used under different conditions and ranges. Using the published information such as range noise and paradata from other parameters, such as Object Dimension (for maximum range), colour and absorbency information from materials and conditions the RMS value for precision can be obtained.

²⁵ European Union Aviation Safety Agency. (n.d.). Drones (UAS). <https://www.easa.europa.eu/en/the-agency/faqs/drones-uas>

²⁶ Zoller + Fröhlich. (2021). Z+F IMAGER 5016: Datasheet [Data sheet]. https://zf-usa.com/wp-content/uploads/2021/06/ZF-IMAGER-5016_Datasheet-E_compr.pdf

For the data acquisition of the Enkleistra using the Zoller + Fröhlich 5016 laser scanner the maximum distance expected for data capture based on the Dimensions would be ~14m the highest published RMS noise at 25m is 0.39 mm i.e., an RMS of 0.00039. Complexity was assessed as being 0%.

Usability

The Usability variable captures details regarding the communication, transfer of data, power supply for equipment operation and data storage devices. The intent of the variable is to ensure that scan times are validated, that battery life and provision are adequate if fixed power sources are not available/applicable and that enough storage is provided either device or external in line with the data management plan noted in the **Project IPR & Deliverables** variable. For example if the data acquisition takes 15 minutes per scan (Based on Efficiency and including reset time) and the estimated required scans to cover the object is 10 a total of 2.5 hours minimum power supply must be available. If this is based on batteries (either removable or fixed) then the battery life must match, if not then either additional power must be provided by extra batteries or time to recharge internal batteries must be taken into account. Likewise if the data provision on the recording device is inadequate for the predicted data collected or a stepwise backup procedure is required the time to swap out storage devices or download data should also be accounted for. The complexity assessment is the total time for the data acquisition permitted in the **Stakeholder Time** variable.

For the task of digitising the Enkleistra using the Zoller + Fröhlich 5016 laser scanner the decision to use battery over direct power supply was made. Reviewing the specifications for the scanner scan time, battery life and expected results relying on a single fully charged battery set would be achievable using the High-Resolution/High-Quality setting. However this would be very close to the published battery life of 2.5hours. To mediate this a spare set of batteries was prepared to cover any depletion of battery before data acquisition completion. The on-board 128 GB of internal storage was considered as being adequate for the number of scans planned. Complexity was assessed at 20%.

Efficiency

The Efficiency variable is a mark of the speed of data acquisition in relation to the demands of time and accuracy of results. It is related to the Usability variable. The intent of the variable is to estimate the optimal balance between data acquisition time and data collection requirements. For example the recommended overlap rate for photogrammetry is 90% (see Pre-Processing Software Overlap) however if the data acquisition pipeline will take longer than the available time the overlap rate may need to be dropped or an alternative solution implemented. Efficiency calculations should also take into account the time needed to reset equipment (moving of scanners to the next location, repositioning of objects, change of camera positions etc.), transfer data etc. The complexity assessment is made on the estimated risk in being unable to fulfill the digitisation within the allotted time.

For the Zoller + Fröhlich 5016 laser scanner a number of different options are available depending on the balance between resolution and quality (clarity) of data desired. The setting High-Resolution/High-Quality was selected for digitisation. The published time to scan at this setting is ~6 minutes with repositioning a total of 15 minutes was assigned to complete a single scan. As noted in the Stakeholder Time the estimated time available to undertake the specific task was three hours or 12 scans. Based on the digitisation plan it was estimated that 10 scans would be required to survey the object, indicating that the task could be fulfilled. Complexity was therefore assessed at 0%.

Sensor Integration

The Sensor Integration variable is a mark of how well the different sensors required to capture the specific data are in line with the project requirements. The intent here is to identify any bottlenecks in pipeline efficiency, harmonisation of protocols and formats, calibration status etc between the different sensors. For example if geolocation data is part of the requirement of the digitisation does the data acquisition system record this (and in what format) or will a secondary piece of equipment be required to record the positions of each scan? Each digitisation requirement should be assessed and the level of integration determined. For highly integrated systems (for example where geolocation is natively supported) complexity should be assessed as 0% for each applicable output. Where sensors are less integrated the hardware necessary to complete the task should be individually assessed and this may affect the overall complexity assessment of the variable. As a rule of thumb each poorly integrated sensor used during the digital acquisition process should be considered a 10% complexity increment.

The Zoller + Fröhlich 5016 laser scanner used for the data acquisition of the Enklystra is a highly integrated system including HDR camera & lighting, barometer, accelerometer, compass, altimeter, and GPS. The overall assessment for this variable was set at 0%.

Equipment Software

The Equipment Software parameter is closely connected with the **Equipment Hardware** parameter. Specifically this parameter documents the software (and firmware) specifications of equipment used during the data acquisition process. This is of specific importance where the hardware is separate from the software i.e., poorly integrated within one single unit.

Licence

The Licence parameter notes if any specific licences are required to operate the software selected for the data acquisition task. The intent is to note what licences are in effect and includes where appropriate clearance notices for operational frequencies, registration method etc. By recording the paradata for software it is possible to identify where licences have expired (or may expire during the period of the event), whether the most recent, or stable, version of the software is applied (and therefore known issues/challenges which may affect data acquisition), ensure that the software is being used adheres to terms and condition of its use and its operation complies with data security needs (for example uploading to third party cloud services). For example, licensed, industry standard software, well documented and supported and designed to be compatible with the selected hardware is likely to be assessed as having a lower complexity than multiple software applications being employed to achieve the same result, undocumented/supported software or ad-hoc coding/pipelines. For assessment of complexity purposes the higher the number of licences that are missing the higher the complexity should be scored. Licences which are legally required must be available for digitisation to take place, for those that may be of concern a rule of thumb is 10% per licence can be made.

The data acquisition of the Enklystra required no additional software operational licences. The Zoller + Fröhlich scanner used has a perpetual licence and critical updates were checked before the event commenced. Complexity was assessed as 0%

Precision

The Precision variable for this parameter reflects the ease that the software variables used in equipment operation can be entered, saved and recalled. The intent is to ensure that the same settings can be used to repeat and/or replicate the digitisation software ecosystem. In an ideal situation digitisation should take place in one uninterrupted session, however systems may need to be shut down for operational reasons (overheating, movement, changing of batteries etc) or the digitisation may take several sessions (if the planned digitisation is over multiple days or part of a long term study). Consideration is also made to how easy it is to establish system settings after shutdown as this may impact on allocated time. For well integrated systems where setup details are stored on device and can be recalled, complexity will be low for multiple software setups or different setups for poorly integrated systems this will be higher. As a rule of thumb each additional software set up should increase complexity.

The Zoller + Fröhlich scanner used in the digitisation of the Enkleistra has both on-device and usb link to PC for entering, recalling and saving multiple settings depending on project use. No additional software was required to manage this operation. Complexity was assessed as 0%

Usability

The Usability variable is an assessment of how easily and effectively respondents can understand, navigate, the software employed in the digitisation and complete a survey, ensuring high-quality data collection. Software that is well designed and scalable across devices (i.e., can be used on device, or externally by mobile device or computer), and feedback or alerts will have a lower complexity than those which do not. The complexity assessment is subjective and depends on the familiarity and experience with the software and linked to the team members assigned to undertake digitisation.

For the digitisation of the Enklystra the assigned team members were very familiar and at ease with using and operating the software components of the scanner. Complexity was assessed at 0% (see Figure 14)

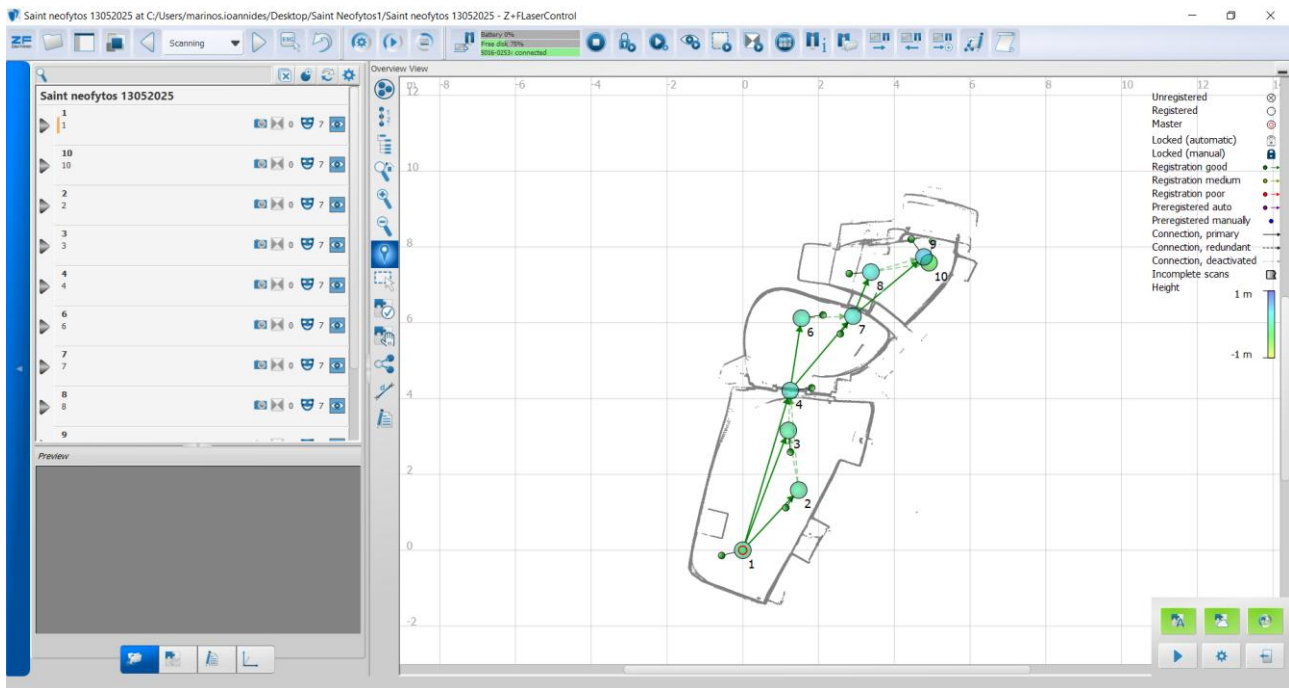


Figure 14: Screen shot of the user interface to the Zoller + Fröhlich 5016 laser scanner control and integrated work flow software for the digitisation of the Enkleistra.

Efficiency

The Efficiency variable represents how efficiently the device combines different data types recorded by the sensors (e.g., point cloud data, photography, GPS etc) and can transfer these. This is increasingly important for optimising pipelines and implementing “field-to-office” workflows and backups as part of data security. Software that can combine multiple data types, and formats and optimise workflows are more efficient than those which do not and are therefore considered more complex as data may be missed, lost or incomplete during multiple transfers. As a rule of thumb, for each additional combination of device/data the software must download from complexity will increase by 10%

The scanner used for the digitisation of the Enkleistra is well integrated in terms of sensor/software and combines the critical data for processing in a single format. Complexity was assessed as 0%

Sensor Integration

The Sensor Integration variable considers the software needed to ensure the different sensors are coordinated and work together to achieve optimal results. Sensor integration in surveying combines multiple technologies—such as GNSS, Inertial Measurement Units (IMUs), cameras, and LiDAR—to produce accurate, comprehensive geospatial data. This fusion increases efficiency and allows for high-precision mapping even when GPS signals are unavailable, but at the cost of increasing complexity as software may have to coordinate, synchronise and align both sensors and their data output to realise this potential. As a rule of thumb, for each additional software application required in the coordination of sensors complexity will increase by 10%

As noted the Zoller + Fröhlich scanner used in the digitisation of the Enklystra is a highly integrated system combining sensors and software coordination in a single unit, no other software was required for the data acquisition and therefore complexity for this variable as assessed at 0%

Team

The Team parameter is used both in the planning of the digitisation and as the paradata record taken at the time of digitisation. There is no maximum number to the team composition however the documentation should record only those who undertook the digitisation not the total number of persons present. Price's Law²⁷ suggests that 50% of the work is done by the square root of the total number of people involved in a task. If true then the optimal number for a team undertaking digitisation would be no more than four - two contributors each with a supporting team member. VIGIE 2020/654 suggests the distinction between "professional" and "amateur" be made, however this is an artificial delineation used in the planning phase, as the **Project Team** variable will have specified the team's level of competence and training requirement, ethical standards to be met, and expected remuneration. Figure 15 shows an example structure of the Team parameter used in assessing Complexity in VIGIE 2020/654

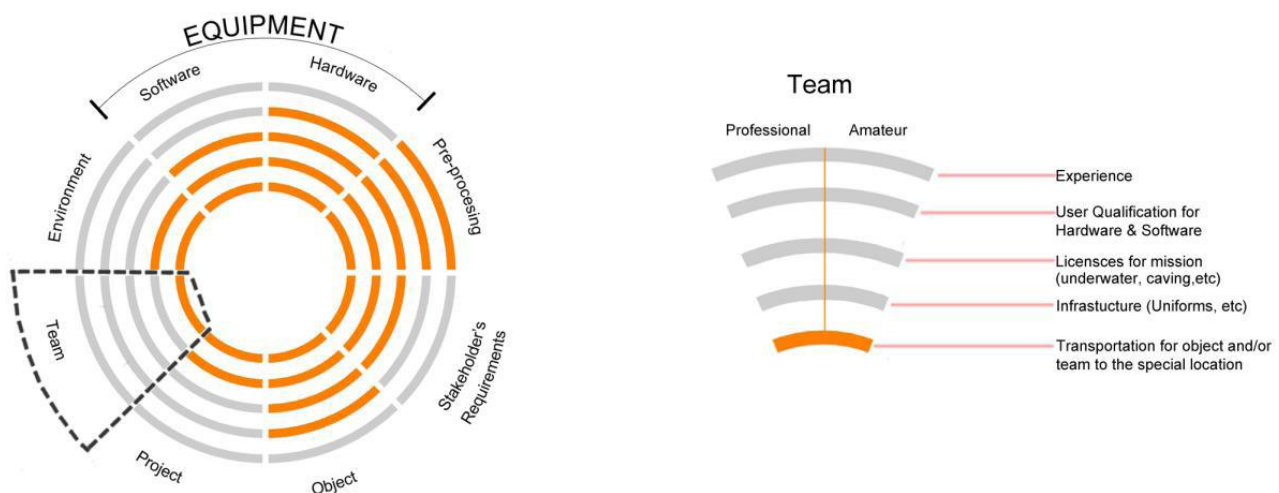


Figure 15: Example of the structure for the Team parameter Complexity assessment.

Experience

The Experience variable is a consolidated value based on the average experience for those engaged in the digitisation task. Its intent is to indicate the level of competence with the digitisation process, data acquisition and familiarity with the equipment. Complexity is assigned at 100% minus the average experience in years x10 i.e. the more experience the team has the less the complexity is implied. For example a team with two veteran staff with over ten years experience each would be assessed as 0% while the same veterans including two less experienced members in support with 3 years experience (e.g. a postgraduate) and no experience

²⁷ Price, D. J. D. S. (1963). Little Science, Big Science. Columbia University Press. <https://doi.org/10.7312/pric91844>

at all (e.g., a student being trained) would be assessed as having a complexity of 43%. As a guideline for assessment of individuals experiencing the following scale may be useful

- 0–2 Years (Undergraduate/Junior/Entry-level): Individuals with minimal to no experience.
- 2–5 Years (Mid-level/Associate): Individuals who can work independently and have demonstrated proficiency in their assigned role.
- 5–10 Years (Senior): Experienced individuals, often with specialised knowledge.
- 10–15+ Years (Expert/Lead/Principal): Individuals with extensive, in-depth experience.

The data acquisition team assigned to this portion of the digitisation of the Enklystra consisted of two, with a total of 15 years experience on the data acquisition method employed. The complexity was therefore set at 25%

Qualifications

The Qualifications variable specifically relates to the need for qualification on elements of the Equipment Hardware and Equipment Software specified in the Project Team variable. The intent is to ensure that qualified staff have been assigned to the team during planning, and show that the requirements were fulfilled during the digitisation event. For example if the requirements set out in the project stipulates that the Team must include a person who has a recognised qualification in UAV operations this will add complexity as the right team member must be found and allocated to the task during the project planning phase. VIGIE 2020/654 makes no distinction between what constitutes academic, vocational or informal (i.e., in house training) qualification.

Assessment is not based on individual team members but on the qualifications held in common - a requirement for four different qualifications may be fulfilled if four different members of the team hold one specified qualification each or if one team member holds all four. It is assumed that if a qualification is required this represents a challenge to the digitisation process that can only be overcome by an individual who has the competency to resolve this through specialised knowledge gained through qualification. This does not mean that the challenge can be overcome by a non qualified individual, rather it is more likely that the qualified individual will be able to resolve the challenge more rapidly than one who is unqualified thus reducing risk (and complexity) in the digitisation process.

Complexity is assessed on the total required qualifications identified in the project plan less those qualifications present in the team during the digitisation as a percentage (e.g., if the project has identified a requirement for four different qualifications on equipment and only three were present in the team the complexity would be 25%).

For the Enklystra digitisation no requirements for specific certification on equipment was required. Complexity was set to 0%

Licences

If licences are required and not present digitisation must not take place. For example, if permissions are not present with the team on the day of the event access to the object may be delayed or refused. This variable is either 0% compliant or 100% non compliant. Data which has been obtained without appropriate licences should not be disseminated or used outside of the project.

For the Enklystra digitisation no licences for operation of the Z-F laser scanner were required. Complexity was set to 0%

Infrastructure

The Infrastructure variable is concerned with ensuring that the required equipment to undertake the digitisation is in place, this includes both actual digital acquisition equipment and peripherals as well as additional resources in support of the event. The intent is to record that necessary equipment was present as planned to undertake the digitisation. For example if photogrammetry has been planned to use a specific camera set up but the necessary lighting is not present this may impact the data acquisition process and quality of images collected as as-hoc lighting is implemented. This variable should also consider the infrastructure needed to support the digitisation for example, protective clothing for staff (hard hats, weather resistant clothing, shade provision, hi-vis jackets etc), power provision (extension cables and convertors -essential when working outside of national boundaries where plugs may be different), power loading (ensuring that their power supplies are not overloaded), appropriate protection for transportation of equipment (cases, boxes, crates etc) and so on. It is strongly recommended that a check list of equipment be produced to assist in ensuring the correct load out is planned, enacted, checked before digitisation begins and that all equipment accounted for during take down.

For the Enklystra digitisation no specific infrastructure beyond the digitisation equipment was required to support the data acquisition team. A load-out list was compiled before travel to the site, checked on arrival and before departure. Complexity was set to 0%

Transportation

This variable is concerned with the provision of transportation of the team and equipment to the digitisation location (or under some circumstances the object to the digitisation location). The intent is to ensure that all selected members of the team and equipment have adequate transport to the location where digitisation will take place and that the object will be available for digitisation. This variable references **Project Infrastructure**.

Digitisation at the Enklystra did not require the transportation of the object as it is immobile and coordination for transportation by private cars had been agreed and executed within the team. Complexity was assessed as being 0% as all staff allocated were present for the event.

Pre-Processing

Pre-processing 3D data involves cleaning, transforming, and organising raw data obtained from the data acquisition process into a structured format suitable for visualisation. The output is the preliminary model ready to be further developed to fit the project's use case. It is not the final model but one which can be used in conjunction with the raw data, metadata and paradata to create the final 3D component of the end product (in the context of the EUreka30-XR project an XR/AR or VR implementation).

The Pre-Processing parameter records the information necessary for the combination of hardware and software to process the data collected during data acquisition. If the pre-processing infrastructure can not process a large volume of data or the quantity is too small to create the preliminary model then the whole

endeavour is at risk and either the aspirations of the digitisation effort must be reviewed and scaled to the pre-processing capabilities or the pre-processing capacity must be increased to achieve the task. This has implications for the project budget, the ability to deliver results in a timely manner and ultimately the level of quality that can be achieved. Figure 16 shows an example of the structure of the Pre-Processing variable described in VIGIE 2020/654

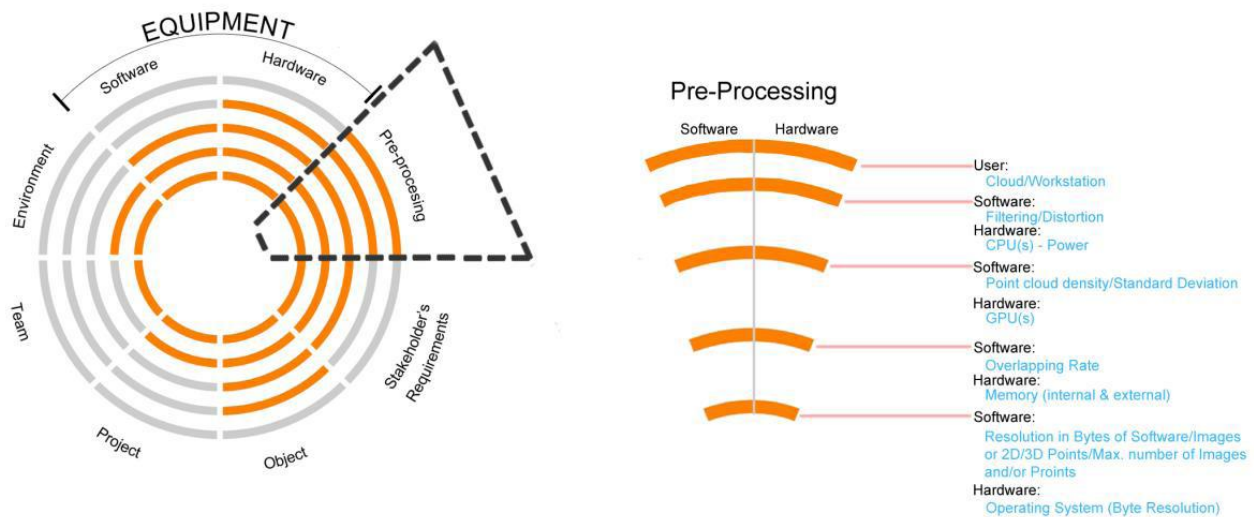


Figure 16: Example of the Pre-Processing parameter structure.

The parameter is split into two parts one dealing specifically with Pre-Processing Software requirements (PPS) the other with Pre-Processing Hardware capabilities (PPH), the complexity of each of these variables is determined by a series of subvariables. While each subvariable may be assessed for complexity based on required steps or features for each candidate PPS for comparison, ultimately the selection of PPS comes down to a) does the PPS support the requirements of the data (and vice versa) and b) Can this be achieved within the project constraints of time, funding and skill sets?, with complexity identifying where issues may occur (for example where minimum recommendations are met but recommended settings are not exceeded).

VIGIE 2020/654 places a division between PPS and PPH for complexity assessment during project planning and selection purposes. This is very useful for planning but less so when compiling the final Complexity Assessment radial chart as PPH is a binary assessment i.e. it will always equal 0% as non-compliance to PPS requirements will automatically exclude the candidate hardware.

Overall the review of both pre-processing software and hardware available and fulfilling the specified requirements the selected PPS was RealityScan 2.1²⁸ and Blender 4.5²⁹, and the PPH software running on a ROG Zephyrus G16 (2023) GU603³⁰ high performance laptop.

²⁸ Epic Games. (n.d.). RealityScan 2.1 documentation. Epic Games Dev Community. <https://dev.epicgames.com/documentation/realityscan/realityscan-2-1>

²⁹ Blender Foundation. (2025). Blender 4.5 LTS release notes. <https://www.blender.org/download/releases/4-5/>

³⁰ Asus. (n.d.). ROG Zephyrus G16 (2023) GU603 - Tech specs. Retrieved 2026/04/16, from <https://rog.asus.com/us/laptops/rog-zephyrus/rog-zephyrus-g16-2023-series/spec/>.

Pre-Processing Software

The Pre-Processing Software variable measures various aspects of the data collected and compares this with the selected PPS. The intent is to ensure that the PPS is sufficiently “strong” enough to produce the desired results highlighting shortfalls which may require alternative PPS solutions and/or expectations of results.

User

The User variable is a misnomer within VIGIE 2020/654, does not refer to the personnel assigned to the task of pre-processing but to the PPS which will be “using” the data. The intent is to establish the inputs from the data acquisition and align these with the most appropriate PPS to fulfil the pre-processing activity. For example if the data acquisition will produce point cloud data can the PPS use the format provided, or will an intermediate step be required to convert the data into a usable format? Complexity assessment is based on the number of steps needed to accomplish the task of producing the initial 3D mesh as each step carries the inherent risk of data loss - in a perfect world scenario a closed loop “magic box” system that has no reliance on external software (i.e., it collects the data, processes the data, internally and delivers the initial 3D mesh) would be assessed as having a complexity of 0%.

It should be noted that cloud processing is considered as an additional step and while VIGIE 2020/654 predates the proliferation and accessibility to generative Artificial Intelligence this should also be considered a factor in complexity assessment.

As specified in the **Project IPR & Deliverables** the expected input for pre-processing from the Enklystra data acquisition was .e57 point cloud data and the expected output from the pre-processing was a .OBJ file with accompanying .PNG texture files. Each of the pre-processing pipelines implemented at the DCHRC were assessed on this basis to find the least complex path. These ranged from 2 to 5 steps (equating to 20-50% complexity) with the final complexity assessment being placed at 20% informed by the other variables of the Pre-Processing parameter.

Filtering

The subvariable Filtering considers the ease and level each candidate PPS offers in filtering - or cleaning - of the input data. Filtering includes techniques such as distortion correction, masking, duplicate data and statistical outlier removal and noise reduction. The intent is to establish whether or not filtering is supported by the PPS and the degree of manual intervention required to produce a usable 3D mesh. For example a PPS that supports automatic filtering of data will have a lower complexity than one which requires manual selection and deletion of individual points, likewise PPS that offer better support for filtering operations e.g, mass selection of points by properties (location, colour assignment, proximity etc) will have a lower complexity than those which do not. Complexity assessment for filtering is subjective and can only be assessed by those conducting the pre-processing task who will be able to estimate the impact of filtering within their established workflows.

Initial assessment of the .e57 files indicated that some filtering would be required, mostly to remove superfluous overscan data (e.g. points external to the object but still recorded through the Enklystra’s unglazed windows). Further the irregularity, orientation and accessibility of data points (meaning the ease of which data points could be selected while working “inside” the Enklystra volume) strongly supported the need for automatic filtering. The PPS candidates were assessed against these criterion and

complexity assigned informing the decision on PPS selection.

Point Cloud Density

The Point Cloud Density subvariable describes the maximum number of points the PPS is capable of handling, not necessarily the number of points per cubic unit. The intent is to establish if the number of expected points in (or created from) the data acquisition will be able to be processed using the candidate PPS in its entirety or whether the multiple parts must be created and or point reduced then recombined to allow a final unified model to be reconstructed. Most PPS will express this as points or vertices. It should be noted that performance almost always drops significantly the closer the points reach the limit. For native point cloud data acquired from scanning this is relatively straightforward as the number of points are known, for photogrammetry this is more problematic as modern photogrammetry software approaches 1 point per pixel (although this is theoretical).

Most photogrammetry software will provide a recommended number of photographs to perform a reconstruction on which is probably a better metric to assess the variable. (see Overlap below however). Best practice for photogrammetry requires a 90% overlap between photographs. In context turntable based data acquisition would require 72 photos for one rotation (1 every 5°), with three rows (rotations) of photographs taken from a camera angle of 0° (straight on), 45° and 65° angles, plus a straight down photograph - a total of 271 for one orientation - if underside recording was required the same number of photographs would be required for a total of 434.

For the purpose of the assessment of complexity, if the candidate PPS can easily handle the number of points within the cloud (or is below the recommended photograph range) the complexity is assessed as 0%. If the number is higher then the data will need to be segmented, processed and recombined, each time this needs to occur to fulfil the target will add 10% to the complexity i.e. segmenting the data into two operations will be assessed as 20% complexity three operations 30% etc.

Examining the .e57 files (9 in total) the total number of points within the Enklystra's point cloud was reported as 27,673,399 by CloudCompare. The candidate PPS specifications were consulted and appropriate complexity assigned.

Overlapping Rate

The Overlap Rate variable references the minimum overlap required by the PPS to perform registration tasks and reconstruct the object, it is not the overlap protocol implemented during data acquisition of itself although this is part of the process. The intent is to ensure that the data acquisition overlap rate is adequate for the PPS to perform the reconstruction process. In principle the higher the overlap the more points are available to conduct registration and alignment leading to better reconstruction potential.

As noted best practice for photogrammetry recommends a 90% overlap while other sources cite 70%. For LiDAR a 20–30% overlap - the physical area where both clouds coexist - of scans is generally considered acceptable but the two are not comparable as the registration has already occurred. If needed tools like

CloudCompare³¹ can provide statistics on overlap rates for scanned data. It is recommended that the scanning position plan be included as a record with the data.

Complexity assessment is based on any shortfall between the overlap protocol implemented during data acquisition and that specified by the PPS.

The Enklystra data acquisition method LiDAR and format .e57 includes a scanning position plan for reference. No overlap consideration was required complexity was set at 0%

Resolution

The Resolution variable refers to the resolution of images needed by the PPS to reconstruct the object. The intent here is to ensure that the images used do not fall below the minimum or exceed the maximum resolution for the candidate PPS. It is important to note that resolution does not necessarily relate to image pixel size - a 4k image will have the same resolution whether it is compressed or not but may have implications on effective resolution depending on the compression ratio used. The recommendation for photogrammetry is to use lossless formats or recording of the compression ratio used during data acquisition independently of stored Exif metadata in the images themselves.

If LiDAR data may not necessarily utilise images relying on colour information per point, if needed this can be approximated using calculate a projected 2D surface area without manual mesh reconstruction with tools like CloudCompare.

As PPS depends on images complexity is binary, either the resolution falls within the requirements of the PPS (assessed as 0%) or they do not (assessed as 100%). LiDAR data using embedded color data should be assessed at having 0% complexity

The Enkleistra data acquisition method LiDAR and format .e57 with colour did not require separate image resolution consideration and the candidate PPS were not assessed. Complexity was therefore assessed as 0%

Pre-Processing Hardware

The Pre-Processing Hardware variable is a compound variable consisting of five points weighted equally. The intent of the variable is to ensure that the candidate pre-processing hardware (PPH) is capable of running the pre-processing software identified, most of these are self explanatory. Any subvariable failing to meet the requirements is assessed at 100% complexity (i.e., it will not support the PPS specification).

User

Like the Pre-Processing Software variable the Pre-Processing Hardware User subvariable does not refer to the personnel assigned to the task of pre-processing but to the PPH which will be “using” the data (i.e., processing the data using the PPS). The intent is to establish that the candidate PPS can run on proposed/available computer hardware. Like PPS the both cloud systems and local hardware should be considered.

³¹ CloudCompare Software <https://www.cloudcompare.org/>

Assessment for available PPH was made with the available PPH candidates. The final selection was a ROG Zephyrus G16 (2023) GU603³² high performance laptop capable of performing all of the pre-processing requirements (Complexity was therefore assessed as 0%).

CPU Power

The CPU Power subvariable is a mark of the candidate PPH CPU ability to run the PPS. The intent is to simply establish if the CPU specification will run the expected software.

The specification for the PPH GPU is a 13th Gen Intel Core i7-13620H Processor 2.4 GHz (24M Cache, up to 4.9 GHz, 10 cores: 6 P-cores and 4 E-cores). The minimum specification for the pre-processing software is a 64-bit processor that supports the SSE4.2 instruction set. Comparison was made using the first compliant CPU (i7-920) with the i7-13620H using the PassMark Software online CPU Benchmark comparison tool³³ confirming that the CPU was able to run the software.

GPU

The GPU subvariable is a mark of the candidate PPH GPU needed to run the selected PPS. The intent is to ensure that the GPU requirements of the PPS are met. Notice should be taken not only for the recommended chipset but also the amount of Video RAM that is required. For photogrammetry special notice should be made if the PPS requires NVIDIA's CUDA chipset capabilities to process images.

The specification for the PPH GPU is the NVIDIA GeForce RTX 4070 Laptop GPU (321 AI TOPs) 8GB GDDR6. The minimum specification for the pre-processing software is an NVIDIA card with at least 1GB VRAM, supporting CUDA Compute Capability 3.5 or higher. Comparison was made using the first compliant GPU (GeForce GTX Titan X) with the GeForce RTX 4070 Laptop GPU using the PassMark Software online GPU Benchmark comparison tool³⁴ confirming that the GPU was able to run the software.

Memory

The Memory subvariable refers to the RAM available on the candidate PPH. The intent is to ensure that the RAM requirements of the PPS are met.

The specification for the PPH Memory 48GB DDR4 on board. The minimum specification for the pre-processing software is Minimum 8 GB, recommended 16 GB.

³² Asus. (n.d.). ROG Zephyrus G16 (2023) GU603 - Tech specs. Retrieved 2026/04/16, from <https://rog.asus.com/us/laptops/rog-zephyrus/rog-zephyrus-g16-2023-series/spec/>.

³³ <https://www.cpubenchmark.net/compare/5283vs834/Intel-i7-13620H-vs-Intel-i7-920>

³⁴ <https://www.videocardbenchmark.net/compare/3162vs4756/GeForce-GTX-TITAN-X-vs-GeForce-RTX-4070-Laptop-GPU>

Operating system

The final subvariable refers to the specified Operating System required to run the candidate PPH. The intent is to ensure that the OS requirements of the PPS are met.

The PPH operating system was 64-bit Windows 11 Home with the minimum specification required for the pre-processing software being 64-bit Windows 10.

Environmental

The Environmental parameter is important in two ways; first in the planning of the project, predicted weather can be useful in ensuring deleterious conditions are avoided and/or moderated. This goes beyond the simple question of “will the equipment work”, but has implications for provision of additional infrastructure needs (e.g., tents for shade and protection for staff and equipment in high heat or protective clothing in cold weather). Second recording of environmental conditions for the digital acquisition period will help in remediating/identifying potential errors in data resulting from unfavorable environmental factors. Figure 17 shows the structure of the Environmental parameter from VIGIE 2020/654

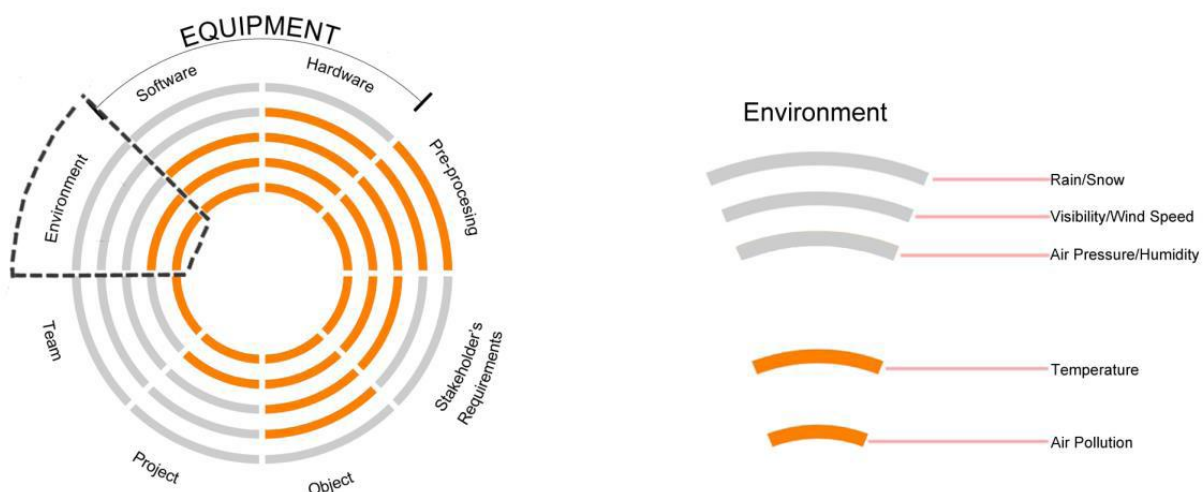


Figure 17: Example of the structure for the Environmental parameter.

Precipitation

Precipitation (Named Rain and Snow in VIGIE 2020/654) has two major effects on data acquisition.: First there are operational constraints - both in terms of actual data acquisition which may be affected (deflecting laser beams and blocking scanners) but also the equipment's vulnerability to water intrusion and damage. Second precipitation can alter the colour and reflectivity of surfaces which may cause incorrect values to be recorded. Any equipment used Ingress Protection (IP) rating (defined by IEC 60529³⁵) should be checked before use in the field for both liquid and particulate (see following) protection ratings.

³⁵ International Electrotechnical Commission. (2013). Degrees of protection provided by enclosures (IP Code) (IEC Standard No. 60529:1989+AMD1:1999+AMD2:2013 CSV) [Consolidated version]. <https://webstore.iec.ch/en/publication/2452>

Using the Location and Time variables of the Stakeholder parameter, the place and duration of digitisation, the nearest weather station was identified as LCPH - PFO Paphos International Airport (~14km). As the digitisation was conducted undercover no precipitation consideration was required (the station reported 0mm precipitation and none was observed on site). Complexity was set to 0%.

Visibility/Wind Speed

Fog, mist and other precipitation or particulates (dust and smoke) scatters light, increasing noise in Lidar scanning and can obscure detail in photogrammetry. Wind speed may also increase noise as flexible items (e.g., vegetation) may move distorting the appearance of the object. Although obvious it is important to state that UAV operation is affected by wind speed and their use should only be undertaken in line with the published guidelines for the device.

As the data acquisition was conducted under force within the Enklystra wind speed and visibility were not a consideration (the station reported visibility of 4-8km, and Wind speeds of between 4-26km/h. Complexity was set to 0%

Air Pressure/Humidity

High relative humidity (e.g., above 70-90%) can increase noise in 3D data capture by LiDAR and decrease accuracy, as water particles in the air can cause scattering of laser light. Air pressure can also affect calibration of sensitive equipment and rapid changes may cause UAV flight stability. In all cases high humidity can affect electronic components of digitisation equipment. Humidity may also affect the characteristics of the object itself causing swelling, something that should be considered based on the **Object Materials** variable. High humidity and temperature may also contribute to heat stress in staff.

During the digitisation air pressure ranged from 10006.57-1008.56 hPa and relative humidity between 64-83%. The Zoller + Fröhlich 5016 laser scanner technical documentation advises against use in condensing humidity, which did not occur. Complexity was set to 0%

Temperature

Both high and low temperatures (and rapid changes) can affect digitisation equipment ranging from fluctuations in sensor performance, battery life and even failure. Operation should conform to the technical specifications for the equipment used. Working temperatures may be set by institutional or national laws especially when working outside, these must be complied with.

During the digitisation temperature ranged between 20-24°C within the operational parameters of the equipment (-10 °C to +45 °C) and heat index for staff comfort. Complexity was set to 0%

Air Pollution

Air pollution/quality can affect both the operation of data acquisition equipment and the data recovered, as noted in Visibility/Wind Speed.

No data was available for air pollution/quality at the time of data acquisition. It is noted that the scanning took place undercover in a semi closed space. The complexity assessment could not rule out the potential air pollution affects, however none were observed complexity was placed at 25%

Complexity Assessment Analysis

Using the Complexity assignments for each of the nine segments VIGIE 2020/654 implements a radial chart to visualise the overall Complexity of the digitisation process. In Figure 18, the Complexity Assessment is shown, with each sector- shown as a wedge consisting of five arcs representing the parameter described. Each arc represents the assessed complexity for the parameter shown as orange over grey, the more orange the higher Complexity assessment for the parameter.

COMPLEXITY

Complexity assessment should be read clockwise with each orange block representing a 10% increase



Figure 18: Radial chart for the Complexity assessment of the Enkleistra of St Neophytos

3.4 QUALITY ASSESSMENT

The quality assessment of the results of the digitisation process is an additive process. That is to say all output from the data acquisition process is considered as having a starting Quality Assessment of 0% - it is just data, something given as is without context. The aim of the Quality Assessment is to show by reference to the paradata record created by the Complexity Assessment that they can be trusted and are fit for purpose whether that is for wholesale data reuse or integration. Further as VIGIE 2020/654 recognises the need for a holistic approach to contextualising data, the digitisation process must reference other domains that may require access to, and use of, data sets. Therefore data salience and usability is as important as visual quality in terms of sustainability.

Material

The Material parameter is a record of those physical aspects of the objects composition that may have affected data acquisition fidelity. The intent of the parameter is to help inform data users about the materiality of the object under-pin the three dimensional representation and which may constitute non-tangible information. The assessment of Quality for the parameter is closely tied to parameters exposed in the Complexity assessment. VIGIE 2020/654 evaluates five variables connected with the Material parameter.

Chemical Composition

The Chemical Composition variable is a deeper description of the materials identified as being significant during the Complexity assessment. While the Complexity variable **Object Materials** identifies potential challenges to the digitisation process from a material the Chemical Composition describes specific details that may help to explain anomalies or misrepresentation of geometric data. Quality assessment is made against each material identified in the **Object Materials** variable. For each claim made (i.e., the material identified) the Chemical Composition variable requires evidence to back up that claim. For example if the **Object Materials** identifies a material as “Silver”, the expectation is that evidence will be available to confirm that the material is Silver (i.e., significantly chemical Ag) and not a Silver like material (for example Nickel Silver which has no Ag content but consists of Copper, Nickel and Zinc - CU, Ni and Zi respectively). Quality assessment increases with each material that can be verified chemically. For each material claim that can be verified through published sources (including those taken as part of the data acquisition process if appropriate) the assessed quality will increase. The resulting assessment is the percentage of supported claims over total claims made.

In the case of the Enklystra three significant materials are noted. Limestone, plaster and paint (coating). No chemical analysis was conducted directly as part of the data acquisition, however as part of the wider holistic approach to documentation emphasised by VIGIE 2020/654 documented sources confirming the chemical composition for the plaster and a number of paint/pigments can be cited. The claim for limestone, while attested to in several sources as being limestone (and therefore likely to be of at least 50% Calcium Carbonate), has no chemical analysis published to identify which kind of limestone the cave matrix is, something significant for conservation/preservation purposes. In this instance two of the three claims can be supported and the quality of the variable is therefore assessed as 66%

Moisture

The Moisture variable is a measure of the object’s exposure to moisture and related to the **Complexity Environmental** parameters of Precipitation and Humidity. As previously noted both surface and internal moisture can affect data quality resulting in both visual misrepresentation and physical deformities due to

swelling or shrinkage. The variable is therefore valuable to both conservation/restoration efforts and to authenticity of visual reproduction. The more data available to understand the potential effect on the object the higher the quality assessment will be. Moisture quality assessment can be based on the following:

- 100% - Gravimetric measurement: While the most accurate this is a destructive method requiring a sample of the object to be taken, dried and compared to determine moisture content.
- 75% - Direct data acquisition using a moisture meter. Either pin-type (considered destructive as pins are inserted into the object to measure internal moisture content) or pinless (non destructive to measure surface moisture) based on measuring electrical resistance.
- 50% - Indirect local reading of precipitation and humidity. This is not object based but measures the moisture of the immediate location of the object. This must be done at the time of the data acquisition and in close proximity to the object.
- 25% - Indirect remote record of precipitation and humidity. This is based solely on the data available from remote sources i.e., weather stations at a distance from the object. It is only indicative of the general conditions but may still be useful.
- 0% - No data.

No provision for direct data acquisition was made for recording moisture content of the Enklystra. General data was made available from the environmental record setting the quality assessment of the variable at 25%

Corrosion

The Corrosion variable explicitly indicates observations relating to the presence of corrosion on objects. Corrosion is the deterioration of material, usually metallic artefacts and structural materials (like iron, copper, and bronze), caused by environmental factors. Measurement of corrosion can be conducted using non destructive techniques e.g., Raman spectroscopy and should comply with the appropriate heritage monitoring standards for the object under documentation. Quality assessment is not based on the results obtained from the digitisation but the contribution made to the holistic approach of VIGIE 2020/654 documentation. Four values can be used for quality assessment,

- 0% no corrosion measurements were undertaken and no published corrosion data was found.
- 33% no corrosion measurements were undertaken but previous published corrosion data record exists
- 66% corrosion measurements were undertaken as part of the digitisation
- 100% corrosion measurements were undertaken as part of the digitisation and a previous published corrosion data record exists

The Enkleistra has no metallic objects identified as requiring corrosion measurement. No corrosion testing was undertaken during the digitisation of the Enkleistra and no published record is publicly available for inclusion in the documentation. Quality assessment is therefore 0%

Carbonation

The Carbonation variable explicitly indicates observations relating to the effect of the chemical reaction between atmospheric carbon dioxide - CO₂ - on calcium hydroxide - Ca(OH)₂ - present in mortars, plasters and concrete. Testing for Carbonation is a destructive process and described in the EU Standard EN

14630:2006³⁶. Quality assessment is not based on the results obtained from the digitisation but the contribution made to the holistic approach of VIGIE 2020/654 documentation. Four values can be used for quality assessment,

- 0% no carbonation testing was undertaken and no published carbonation data was found.
- 33% no carbonation testing was undertaken but previous published carbonation data record exists
- 66% carbonation testing was undertaken as part of the digitisation effort
- 100% carbonation testing was undertaken as part of the digitisation and previous published carbonation testing data records exist

No carbonation testing was undertaken during the digitisation of the Enkleistra and no published record is publicly available for inclusion in the documentation. Quality assessment is therefore 0%

Porosity

The Porosity variable explicitly indicates observations relating to the porosity, (both open porosity and pore size distribution) used to assess the decay state of materials like stone, brick, mortar, and ceramics. Measuring porosity depends on the object under documentation. Data assets created with a specific use case requiring porosity measurement should comply with the appropriate heritage monitoring standards for the object under documentation and the correct reconstruction methods applied to fulfil these standards. Quality assessment is not based on the results obtained from the digitisation but the contribution made to the holistic approach of VIGIE 2020/654 documentation. Four values can be used for quality assessment,

- 0% no porosity measurements were undertaken and no published porosity data was found.
- 33% no porosity measurements were but previous published porosity data exist
- 66% porosity measurements were undertaken as part of the digitisation effort
- 100% porosity measurements were as part of the digitisation and previous published porosity data exist

No explicit porosity measurements during the digitisation of the Enkleistra and no published record is publicly available for inclusion in the documentation. Quality assessment is therefore 0%

³⁶ European Committee for Standardization. (2006). Products and systems for the protection and repair of concrete structures - Test methods - Determination of carbonation depth in hardened concrete by the phenolphthalein method (EN 14630:2006)

Structural Health Monitoring

Structural Health Monitoring (SHM) may be a specific requirement for data acquisition as defined in the **Complexity Stakeholder Requirements Purpose** variable. The parameter generally is only used for built heritage conservation purposes and has longitudinal timeframes. The quality assessment only is applied if the specific heritage monitoring standards for the object under documentation are met and the correct reconstruction methods applied to fulfil those standards. Quality assessment is not based on the results obtained from the digitisation but the contribution made to the holistic approach of VIGIE 2020/654 documentation. All five variables use the same metric for assessment of quality.

- 0% the digitisation was not intended to support SHM and no published data was found
- 33% the digitisation was not intended to support SHM but published data was found
- 66% the digitisation was undertaken to support SHM
- 100% the digitisation was undertaken to support and previous published data exist

State of Conservation

The state of conservation of materials refers to the current physical and chemical condition of an object or structure, assessing its degree of deterioration, stability, and integrity.

The digitisation of the Enkleistra was not intended to record SHM data, however it did identify previous published work on the State of Conservation that may be informative to those working in the field and able to reuse parts of the digital record. Quality was therefore assessed as 33%

Diaphragmatic Action

Diaphragmatic action (or diaphragm action) in surveying and structural engineering refers to the ability of a horizontal structure—such as a floor slab, roof decking, or bracing system—to act as a rigid, deep beam that transfers horizontal lateral loads (wind or seismic forces) to vertical structural elements like shear walls, columns, or frames.

The digitisation of the Enklystra was not intended to record SHM data, and no references were found in relation to Diaphragmatic Action in the published literature. Quality was therefore assessed as 0%

Connectivity of Structure

the physical links (connections/joints) that bind individual members (beams, columns, trusses) into a stable, load-resisting system. Proper connection design is critical for maintaining overall structural integrity and determining how forces, such as gravity and lateral loads, are transferred throughout the structure.

The digitisation of the Enklystra was not intended to record SHM data, and no references were found in relation to Connectivity of Structure in the published literature. Quality was therefore assessed as 0%

Quality of Materials

Quality of Material variable is specifically concerned with the fitness of substances (such as steel, concrete, or timber) for their intended use, ensuring they meet specific design strength, durability, and safety

standards. It involves compliance with technical specifications, regulations, and resistance to environmental factors over time, rather than just initial strength. It is not directly related to **Complexity Object Materials**

The digitisation of the Enkleistra was not intended to record SHM data, and no references were found in relation to Quality of Materials in the published literature. Quality was therefore assessed as 0%

Strength & Integrity of Foundation

ensure the safe transfer of structural loads (dead, live, and environmental) to the ground, preventing collapse, excessive settlement, or tilting. A robust foundation combines high-quality materials (reinforced concrete), proper design based on soil investigation, and precise construction techniques, typically involving shallow footings for good soil or deep pile foundations for weak soil.

The digitisation of the Enklystra was not intended to record SHM data, and no references were found in relation to Strength & Integrity of Foundation in the published literature. Quality was therefore assessed as 0%

Geometry 2D

The Geometry 2D parameter is an expression of the replicability of the results claimed. It uses the variables from the Complexity to achieve this. Given a set of circumstances, i.e., this data set, this software and this hardware the following results were obtained. By replicating the circumstances the claim can be verified. However this can be a long process depending on how many images have significant changes in distance from the object.

The digitisation of the Enkleistra did not use photogrammetry. Complexity was set to 0% for all variables in the Geometry 2D parameter

Point Density

The Point Density variable is a numeric representation of the number of points within a specific unit (e.g. points per m²). The higher the Point Density the increased likelihood that reconstruction algorithms will be able to detect similar features or clusters across multiple images or scans. These 2D configurations, or “tie points” increase the chance of a complete reconstruction with more accurate results and allow for the capture of finer surface textures and sharp geometrical edges. Points are not the same as vertices or pixels.

To calculate the Point Density the Ground Sample Distance (GSD) for the image will first need to be calculated to provide a theoretical maximum point density. The Point Density is $1/GSD^2$. To get the actual Density or P_{2D} value the mesh would need to be calculated and the two compared. The quality is assessed as the percentile difference between the two numbers.

Completeness (% lack points)

Completeness attempts to estimate points have been used from the image in reconstructing the mesh cloud. This can be calculated using CloudCompare, rastering the mesh and counting the number of occupied cells and dividing the total by the total number of cells. The result is the indicative Completeness percentage and assessment for quality.

Resolution

The P_{2D} value describes how many points fall within a 2D square unit (e.g., 1m²), resolution describes the average distance between those points. Resolution can be calculated as the square root of $1/P_{2D}$. This provides the Point Spacing which can be divided by the GSD to provide the Quality Ratio. For quality assessment the inverse of the Quality Ratio expressed as a percentage should be used.

Geometrical Accuracy

Without a Reference Cloud to act as a Ground Truth absolute accuracy can not be measured. The most common way to check accuracy in this case is to examine the photogrammetry software for statistics for a Maximum Preprojection Error value. However the “3-Pixel Rule” in photogrammetry states that the final 3D error will be 3 times the GSD due to triangulation.

Geometrical Precision

Without a Reference Cloud to act a Ground Truth absolute precision cannot be measured. Precision can be approximated in CloudCompare by using a Roughness as a proxy for local precision. However, the “3-Pixel Rule” in photogrammetry states that the final 3D error will be 3 times the GSD due to triangulation.

Geometry 3D

The Geometry 3D parameter is an expression of the replicability of the results claimed. It uses the variables from the Complexity to achieve this. Given a set of circumstances, i.e., this data set, this software and this hardware the following results were obtained. By replicating the circumstances the claim can be verified.

Point Density

The Point Density variable (P_{3D}) is a numeric representation of the number of points within a specific volumetric unit (e.g. points per m^3). The higher the P_{3D} the increased likelihood that reconstruction algorithms will be able to detect similar features or clusters across multiple images or scans. These 3D configurations, or “tie points” increase the chance of a complete reconstruction with more accurate results and allow for the capture of finer surface textures and sharp geometrical edges. Points are not the same as vertices or pixels. The intent is to show the difference between the raw data collected and the preliminary mesh. Point cloud density can be computed using CloudCompare’s Compute geometric features Volume density tool (ensuring that both clouds use the same Local neighbourhood radius for comparison).

P_{3D} ranges depend on the type of reconstruction intended and what determines high or low (dense or sparse) clouds varies according to the use case application. The level of accuracy inferred is described in the U.S. Institute of Building Documentation Level of Accuracy (LOA) Specification Version 3.1³⁷ and is helpful as a guide for heritage documentation. P_{3D} is only an indicator of overall density and must be considered in context with other quality measures fulfilment of the Stakeholder Purpose and Complexity Project IPR & Deliverables Accuracy variables when interpreting what this means in reality. Quality is assessed in regard to the overall LOA level and is intended to provide guidance for its applicability for reuse, assessment can be made by multiplying the LOA level by 2.

The point density for the initial mesh was evaluated at 618,013 points per m^3 by CloudCompare using M3C2 and Volume Density (Radius 0.2m) suitable for detailed building surface documentation and structural verification equivalent to LOA 30. Quality assessment was therefore set at 60%

Completeness (% lack points)

Completeness is an attempt to assess how much of the raw data has been used in the reconstruction process to create the preliminary mesh, and identify incomplete reconstructed areas. This can be calculated by estimating the intersection between the raw data point cloud and the mesh point cloud, sometimes called the “Hit Rate”. It is recommended that a sample rate be set to 1M points for the reference cloud (the raw data) and the tolerance be set to the root mean square deviation (RMS) value specified in the **Complexity Project IPR & Deliverables Accuracy** variable. Completeness may be assessed by examining the extracted point count.

Using the described method the count of points remaining from the sample was 948,753 indicating an estimated Completeness of ~95%. The assessment of quality for the preliminary mesh was therefore set to 95%

³⁷ U.S. Institute of Building Documentation. (2025). Level of accuracy (LOA). <https://usibd.org/level-of-accuracy/>

Resolution

If P_{3D} measures how tightly packed points are within a cloud then resolution is a measure of the mean distance between points in the point cloud (Approximate distance to neighbours). Resolution can be derived from the Point Density value as the square root of P_{3D} . For assessment of quality the Value for the RMS can be used.

Overall resolution for the initial mesh was calculated as approximately 1.27 mm. Quality assessment was placed at 93.65%

Geometrical Accuracy

Mean Distance: This represents Bias (Accuracy). If the mean is not zero, one scan is systematically shifted or scaled compared to the other, the greater the number the less consistent the accuracy is. Tools like CloudCompare can be used to perform this calculation. The quality is assessed as the difference between 0 (a perfect match) and 1 (the unit of measurement) e.g. if the unit of measure is meters and the mean distance is 0.05 or 5cm the quality of the accuracy is 95%

Distance between the points of the raw scan and those of the mesh was measured using CloudCompare Cloud to Cloud Distance. The average distance was reported as 0.00309967m or ~3mm. The assessment of quality for the preliminary mesh was therefore set to 99%

Geometrical Precision

Standard Deviation: This is the representation of Precision, the spread of the error, the smaller the number the more precise the points are. It tells you the spread of the error. The quality is assessed as the difference between 0 (a perfect match) and 1 (the unit of measurement) e.g. if the unit of measure is meters and the mean distance is 0.05 or 5cm the quality of the precision is 95%

Standard deviation between the points of the raw scan and those of the mesh was measured using CloudCompare Cloud to Cloud Distance. The reported standard deviation was 0.0302631 or ~3cm over 1m. The assessment of quality for the preliminary mesh was therefore set to 97%

Texture

Texture refers to the material properties being digitised not the image being produced. The intent of the Texture parameter is to inform the data user (and re-user) of specific conditions which should be taken into account when interpreting the data set and the initial mesh. This is significant if as it places the materiality of the object in a context and identifying or highlighting areas where special attention should be paid. Quality in this regard is a mark of the additional information provided to assess the digitisation and the resulting outputs.

Opacity

Opacity refers to the inherent characteristics of the object being digitised that may affect how light (either thorough photography or laser measurement) collects data. Basic physics dictates how much light is absorbed, scattered, or transmitted. A simple example would be a brick wall absorbs light while the glass of a window allows light to pass though, more complicated examples include high specular surfaces like metals or polished surfaces, reflectance from wet surfaces or absorption/scattering caused by surface coverings like dust or other particulates. Data recovered may therefore be compromised creating "ghost" points especially at higher levels of density required for heritage digitisation and may cause holes, shifts in features or fake geometry to be created. Recording absence of opacity concerns is equally as important as this provides "Evidence of Absence". The assessment for quality is subjective based on the experience of the digitisation team in identifying areas where opacity may impact data collection.

The digitisation team identified several points where the materials of the Enklystra may affect opacity. These included glass (the icons cover and protective door to the tomb), areas of "polish" notably the altar in the bema and high absorbance of the coverings of the desk and bed in the cell. The team also recorded general observations noting that the surface of floor and walls were not overly dusty or otherwise compromised and no visible wet spots were present. These were documented and the quality of information provided was assessed at 60%

Granularity

Granularity refers to the overall continuity of the object's surface, its cohesion and changes in materials. A flat smooth plaster finished wall will have a lower granularity than a wall constructed of rough cut stones in poor condition. Surfaces which possess significant, irregular variations in texture, depth, and shape (macro- and micro-texture) that require higher point-cloud density to capture accurately. Documenting the changes and observed conditions adds to the quality of the data helping the user to interpret what is being shown. The assessment for quality is subjective based on the experience of the digitisation team in identifying areas where granularity may impact data collection.

The digitisation team identified several points where granularity changes occurred, notably from the relatively smooth floor to natural wall surface and from wall surface to plaster render. These were documented and the quality of information provided was assessed at 60%

Contrast

Contrast is the change in lighting across the object being digitised, areas of light and shade or dramatic colour shift can affect both laser scanning and photogrammetric techniques. For laser based systems high contrast areas can cause edge noise or bleeding making areas “fuzzy” or creating ghost points and lead to drifts in accuracy due to lower return signal and higher sensor noise. For Photogrammetry the opposite is true, areas of high contrast are used to identify key points where images overlap, areas of low contrast like a plain white vase will be more difficult to digitise unless contrast is added, for example by using high contrast scale mats. In this case contrast may result in sparse clouds and high reprojection error and possible failure in the reconstruction process. Documenting the areas of high contrast assists the data user interpret data, identify anomalies and cross reference to other paradata (for example **Complexity Object Remedy Options**). The assessment for quality is subjective based on the experience of the digitisation team in identifying areas where contrast may impact data collection.

The digitisation team identified several areas of high contrast, notably where light spill from the Enkleistra external apertures could produce oversaturation or reflectance and areas of shadow (within the niches) which may cause significant contrast change. Particular attention was made to assessing areas where materials change including colours of the frescoes and while these were not considered to be overly problematic the observations were recorded. These were documented and the quality of information provided was assessed at 60%

Resolution

As noted Resolution is a mark of how closely points are arranged within an area (either in two dimensions or three). Matching resolutions between different systems or even different point clouds (for example patching a space with a higher resolution to improve detail) needs to be recorded as part of the process of digitisation to avoid misinterpretation of data. If, how and why data sets of different resolution were combined should be recorded drawing on the specifications of the Complexity Equipment Hardware and Equipment Software parameters. The quality assessment is subjective based on the experience of the digitisation team in undertaking such tasks and communicating any processes implemented to future users.

As digitisation at the Enkleistra used one single source the Zoller + Fröhlich 5016 scanner and a single resolution determined by the settings established in the paradata record, no further documentation regarding resolution was considered necessary in describing the established workflow. These were documented and the quality of information provided was assessed at 100%

Colour Depth

Colour Depth (or Bit Depth) is the amount of information stored for the color or intensity of each point in the cloud. Colour Depth is important in visually distinguishing between different materials that might have similar geometry. Most 3D scanners and photogrammetry capture color in 8-bit (256 levels per channel) or can capture "High Dynamic Range" (HDR) at 10/12-bit which can help in resolving problems of shadows. Specifically for LiDAR based systems Intensity Bit Depth represents the strength of the laser return, usually recorded in 16-bit (65,536 levels) which can improve capture of high granularity objects and show hidden details. Knowing which Colour Depth was used during digitisation and where they were used is significant especially where different sensors or techniques are being used and combined. The specification for this will be part of the **Complexity Equipment Hardware** and **Equipment Software** parameters and these are used to

describe the processes of combining different Colour Depths during digitisation. The assessment for quality is subjective based on the experience of the digitisation team in describing the different sensors and software implementations to collect data to provide clear understanding of process and applicability.

As digitisation at the Enklystra used one single source the Zoller + Fröhlich 5016 scanner there was a single Colour Depth used during the data acquisition, the documentation for Colour Depth and the process of data capture is self contained. This was recorded to prevent ambiguity and quality was estimated as 100%

Scale

The Scale parameter attempts to establish a relationship between the physical camera and the virtual camera to assess the visual quality of the images used to colorise the mesh. This technique is particularly relevant for accurate simulation of lighting conditions and types.

No Quality assessment was undertaken for the Scale parameter of the digitisation Enklystra based on the scope of the use-case specification and time limitations.

Sensor Size

The Sensor Size variable documents the process of matching the physical sensor type with the digital counterpart. This includes matching horizontal and vertical fit, cropping factor, aspect ratios and so forth..

Radimetric Resolution Colour Depth

This variable records the process of duplicating the light intensity and color variations within the virtual camera. For precision calculation comparison matches must be made to the input image Bit Depth, luminescence calibration and colour space.

Pixel Size

The Pixel Size parameter details the process of matching the physical and digital camera pixel pitch. This is used to determine the amount of aliasing - digital artifacting used to blur pixels to produce a more visually harmonious result. It considers texture map resolution, anti-aliasing setting and the need for noise injection to approximate the physical camera's ISO settings.

Resolution

The Resolution parameter records the method implemented to map the input image's optical resolution to the mesh's spatial resolution and the resulting texture used.

Distance

The Distance parameter records the methods by which the distance between the camera and the object was duplicated in the digital proxy. This requires both alignment checking and scale verification.

Spectral

Spectral imaging may be a specific requirement for data acquisition as defined in the Complexity Stakeholder Requirements Purpose variable. The quality assessment only is applied if the object under documentation has been surveyed using spectral techniques beyond the visible spectrum and documented accordingly.

Quality assessment is not based on the results obtained from the digitisation but the contribution made to the holistic approach of VIGIE 2020/654 documentation. All five variables use the same metric for assessment of quality.

- 0% the digitisation did not include specialised spectral imaging and no published data was found
- 33% the digitisation did not include specialised spectral imaging but published data was found
- 66% the digitisation was undertaken with specialised spectral imaging
- 100% the digitisation was undertaken with specialised spectral imaging and previous published data exist

The digitisation of the Enkleistra did not undertake any special spectral imaging. During the whole process no documentation specifically relating to multispectral imaging of the Enkleistra that could be combined with the data set was identified from the published record. Consequently this parameter and variables were set to 0%

Spectral Range

The Spectral Range variable should record the specific range, or ranges, for data collected by the survey as described in the Purpose variable. Typical ranges for CH documentation are

- 315-400nm - Ultraviolet
- 400-700nm - Visible
- 700-1100 nm - Near-Infrared
- 4100-2500nm - Short-Wave Infrared
- 2500-15000nm Mid-Infrared

Image Fusion

Image Fusion is the process of combining multiple spectral ranges into a single image. The aim is to provide a composite image that provides more information that is seen under normal conditions (i.e., visible light).

Absorptance

Absorptance is the measure of how much light energy (for the specific wavelength) is absorbed by the object or part of the object material rather than reflected or transmitted.

Transmittance

Transmittance is the measure of light energy (for the specific wavelength) that passes through the object or part of the object material rather than being absorbed or reflected.

Reflectance

Reflectance is the measure of light energy (for the specific wavelength) that is reflected back from the object or part of the object material compared to the light energy hitting it.

Quality Assessment Analysis

Using the Quality assignments for each of the seven segments VIGIE 2020/654 implements a radial chart to visualise the overall Quality of the digitisation process. In Figure 19, the Quality Assessment is shown, with each sector- shown as a wedge - consisting of five arcs representing the parameter described. Each arc represents the assessed quality for the parameter shown as orange over grey, the more orange the higher Quality assessment for the parameter.

QUALITY

Quality assessment should be read clockwise with each orange block representing a 10% increase

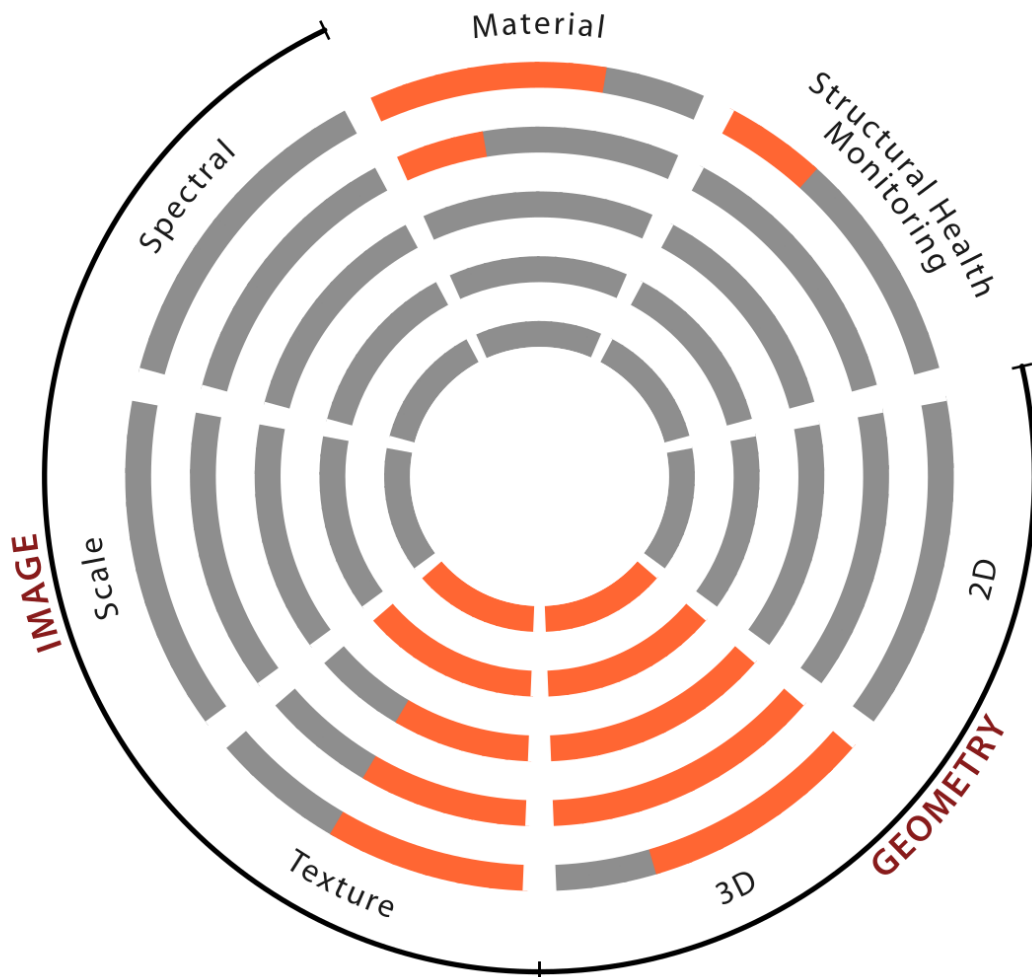


Figure 19: Radial chart for the Quality assessment of the Enkleistra of St Neophytos.

4. PARADATA IN EDM EVOLUTION

Work has been ongoing since 2024, in the context of a Europeana-led 3D Working Group, to provide an extension of the Europeana Data Model. The main scope was to provide an analysis of the EDM from the perspective of improving, expanding and enhancing representation of 3D in Europeana, both in terms of accommodating a larger quantity of items and representations, and higher quality of information.

The 3D Working Group gathers representatives from the Europeana Initiative and also from data space projects focused on 3D, including Eureka3D and Eureka3D-XR. In the process, the WG looked at relevant, related works such as EC 3D studies, deliverables of past projects, earlier Europeana outcomes and work like the report of the EuropeanaTech task force on 3D content in Europeana³⁸, and concrete examples of metadata of 3D items. As a result, a roadmap for EDM extensions was produced in mid 2024, and also presented in a paper³⁹ published in December 2024.

The EDM extensions are based on the modelling schema that informed the EDM since the beginning, with 3 main classes: *ProvidedCHO* (the cultural object), *WebResource* (its digital representation) and *Aggregation* (additional properties about aggregation processes like the providing institution, the aggregator and others). The extensions of EDM to improve representation of 3D records build upon this structure, adapting and upgrading it to meet new needs and requirements. This is a work ongoing that reflects the novelty and complexity of this research field, and its developments.

The first implementation of the new EDM was presented to data space partners and Europeana Aggregators in December 2025 and the test-bed for the new structure and additional fields was the TwinIt! Part II campaign, where the objects offered by Member States would need to comply with the new requirements.

Specifically noteworthy and impactful are new requirements relating to using an oEmbed compliant viewer that allows users of Europeana to visualise the model; enabling direct download of the model; to provide information on its intended usage of the model; and to add paradata information.

Viewer: the 3D models must be visible directly in Europeana platform, by the use of an oEmbed compliant viewer, like the Eureka3D Viewer.

Direct download: in the light of facilitating access and reuse of 3D models, a direct link to the files of the model (e.g. .GLB, .OBJ, etc) must be provided in the dataset, so that the user can download it if they want. Depending on the characteristics of the file and the relation to the view of the model, this link is provided in *edm:hasView* or in the *dcterms:isFormatOf* of *WebResource* class.

Intended usage: it is acknowledged that, when sharing 3D models in a context like that of the data space, it is important to be transparent and clarify if a representation is meant for a specific (technical) purpose, such as preservation or research, or just for viewing and dissemination, and this distinction is represented in

³⁸ Fernie, K., et al. (2020). 3D content in Europeana task force: Final report (Version 1.0). Europeana Network Association.

https://pro.europeana.eu/files/Europeana_Professional/Europeana_Network/Europeana_Network_Task_Forces/Final_reports/3D-TF-final%20report.pdf.

³⁹ <https://link.springer.com/book/10.1007/978-3-031-78590-0>, Isaac A., Fernie K., Bachi V., Tsoupra E., Medici M., Alkemade H., Münster S., Charles V., Heslinga L., (2024). **Making the Europeana Data Model a Better Fit for Documentation of 3D Objects**. In: Ioannides M., Baker D., Agapiou A., Siegkas P. (Eds) "3D Research Challenges in Cultural Heritage V: Paradata, Metadata and Data in Digitisation". Springer, Print ISBN: 978-3-031-78589-4, Online ISBN: 978-3-031-78590-0, DOI: 10.1007/978-3-031-78590-0_6

the new *edm:intendedUsage* field that content providers must deliver in the dataset from 2026 onwards. The field is supported with a controlled vocabulary from which the content provider can choose the option(s) that fits best the case:

Value of reference for <i>edm:intendedUsage</i>
http://data.europeana.eu/vocabulary/usageArea/Knowledge http://data.europeana.eu/vocabulary/usageArea/Research http://data.europeana.eu/vocabulary/usageArea/Education
http://data.europeana.eu/vocabulary/usageArea/Infotainment http://data.europeana.eu/vocabulary/usageArea/Tourism http://data.europeana.eu/vocabulary/usageArea/Gaming http://data.europeana.eu/vocabulary/usageArea/Exhibition
http://data.europeana.eu/vocabulary/usageArea/Creativity http://data.europeana.eu/vocabulary/usageArea/Design http://data.europeana.eu/vocabulary/usageArea/Art
http://data.europeana.eu/vocabulary/usageArea/Curation http://data.europeana.eu/vocabulary/usageArea/Maintenance http://data.europeana.eu/vocabulary/usageArea/Restoration http://data.europeana.eu/vocabulary/usageArea/Documentation

Paradata: this is the most important area where extensions of EDM are needed, to inform on the provenance of 3D content, providing insights into a digitised object's authenticity, usage conditions and copyright, and technical aspects linked to its creation process. Information about the digitisation process can be of high interest for data space users, especially for the quality of the final results of the digitisation for research or re-use purposes (Quality Certificate). Although it is not envisioned to include every category of paradata (ranging from basic to complex information) in EDM, a subset of this detail - also including appropriate grounding for the copyright status of a 3D object and relevant technical aspects of the model and its creation process - can be beneficial, even in basic access/re-use scenarios. Additional basic fields like *edm:polygonCount* and *edm:vertexCount* can be directly added in the EDM datasets, and content providers are also enabled to provide direct links to paradata reports and other detailed documentation, again via the *edm:WebResource* class.

While the first iteration of EDM extensions is currently being tested and validated, the WG still meets regularly under coordination of the Europeana Foundation, and will continue the reflections and dialogue with stakeholders to ensure that 3D models in Europeana are correctly and appropriately represented for the benefit of the different data space users.

At the same time, a collaborative effort is being deployed in updating the current Europeana EDM documentation, to provide capacity building to content partners, and to disseminate the extended EDM in the group of Europeana Aggregators, whose role is certainly evolving as the data space development progresses, but who remain one of the core elements that inform the Europeana Initiative and that support the data space itself.

5. PARADATA AS A FOUNDATION FOR SUSTAINABILITY

In the context of digitisation, sustainability requires more than the long-term preservation of data. We need to enable the maintenance, interpretation, validation, and reuse of digital assets over time. Paradata plays a key role in enabling this by documenting the processes, conditions, and decisions that define the properties of the digital asset.

Paradata must be collected accurately and systematically at the time of digitisation, in accordance with established guidelines and best practices (e.g. VIGIE 2020/654). As it reflects the original acquisition and processing context, paradata serves as a reference record of the digitisation process. To support future interpretation, paradata must remain accessible, well-structured, and reliably linked to the corresponding digital assets.

From a sustainability perspective, high-quality paradata contributes to several key properties:

Verifiable

Paradata enables the verification of digitisation processes by documenting acquisition conditions, processing steps, and technical choices. This supports the validation of results and contributes to trust in the digital assets across different usage scenarios.

Repeatable and comparable

Digitisation captures a specific state of a physical or evolving object under particular conditions. To support meaningful comparison across time—whether for monitoring, re-digitisation, or technological evolution—it is essential to document these conditions in a consistent and structured manner. Paradata enables the reproduction of workflows and the interpretation of results within their original context, ensuring that comparisons are based on comparable conditions.

Refreshable

Paradata provides the context required to assess whether existing digital assets remain fit for purpose or whether new digitisation efforts are justified. By documenting both the capabilities and limitations of past workflows, it supports informed decision-making in the management and evolution of digital collections.

Interpretable and reusable

By recording assumptions, methodologies, and constraints, paradata enables digital assets to be understood and reused beyond their original context. This supports integration into different platforms, applications, and infrastructures, in line with broader requirements for interoperability and reuse.

Taken together, these properties illustrate how paradata contributes to the sustainability of digitisation workflows and outputs. Rather than relying solely on data preservation, sustainability is achieved through the combination of well-documented processes, consistent practices, and the ability to interpret and reuse digital assets over time. In this context, paradata provides a form of process transparency that supports trust, comparability, and long-term value.

6. CONCLUSION

Paradata has the potential to provide critical, actionable insight that helps reusers of cultural heritage content select assets suited to their specific needs. It addresses the fundamental questions any user asks: Can I trust this resource? Where does it come from? Is it safe and reliable? Will it serve my purpose? For research-oriented users, paradata offers a structured means to assess, verify, and validate existing datasets by reducing uncertainty, avoiding duplication of effort, and ultimately saving both time and resources.

Like metadata, paradata must continuously evolve to meet the expectations of a diverse, multidisciplinary cultural heritage community, while sustaining trust and encouraging uptake. In the context of tangible cultural heritage digitisation, the EU VIGIE 2020/654 study remains the most comprehensive effort to define and operationalise paradata within a holistic framework for data quality, management, and long-term sustainability. Rather than reinventing the wheel, this framework should be maintained, refined, and further validated through concrete implementations. For example, such as the case studies developed within Eureka3D and Eureka3D-XR.

This need becomes even more pressing as emerging technologies transition into standard practice, including remote sensing, the growing adoption of XR applications, and the integration of artificial intelligence. Ultimately, the central question is not simply “what are we digitising for,” but “who are we digitising for.” If the goal is to position cultural heritage as a driver of economic, social, and scholarly impact, then paradata plays a pivotal role: it equips users with the contextual knowledge: the “what,” “why,” “when,” “where” and “how” behind digitisation processes and datasets - enabling informed, confident reuse rather than presenting content as a decontextualised “take it or leave it” proposition.

A final point is essential: **without paradata** - in other words, a certificate of quality - what remains is uncertainty. Users are left to question the reliability, provenance, and fitness-for-purpose of digital assets, undermining trust, limiting reuse, and ultimately diminishing the value and impact of the digitisation effort itself.

ANNEX 1: IMAGES SHOWING THE RESULTS OF THE HIGH-QUALITY DIGITISATION OF THE ENKLEISTRA OF ST. NEOPHYTOS



Internal Orthographic Cross Section at the central horizontal axis towards the west wall of the Enkleistra



Internal Orthographic Cross Section at the central horizontal axis towards the east wall of the Enkleistra



Internal Orthographic Cross Section at the central vertical axis facing east looking upwards at the ceiling of the Enkleistra



View from the upper northeast looking at the centre point of the Enkleistra. The image depicts the frescoes as they would be seen if the surrounding cliff enclosing the Enkleistra was removed.



View from the upper southeast looking at the centre point of the Enkleistra. The image depicts the frescoes as they would be seen if the surrounding cliff enclosing the Enkleistra was removed.

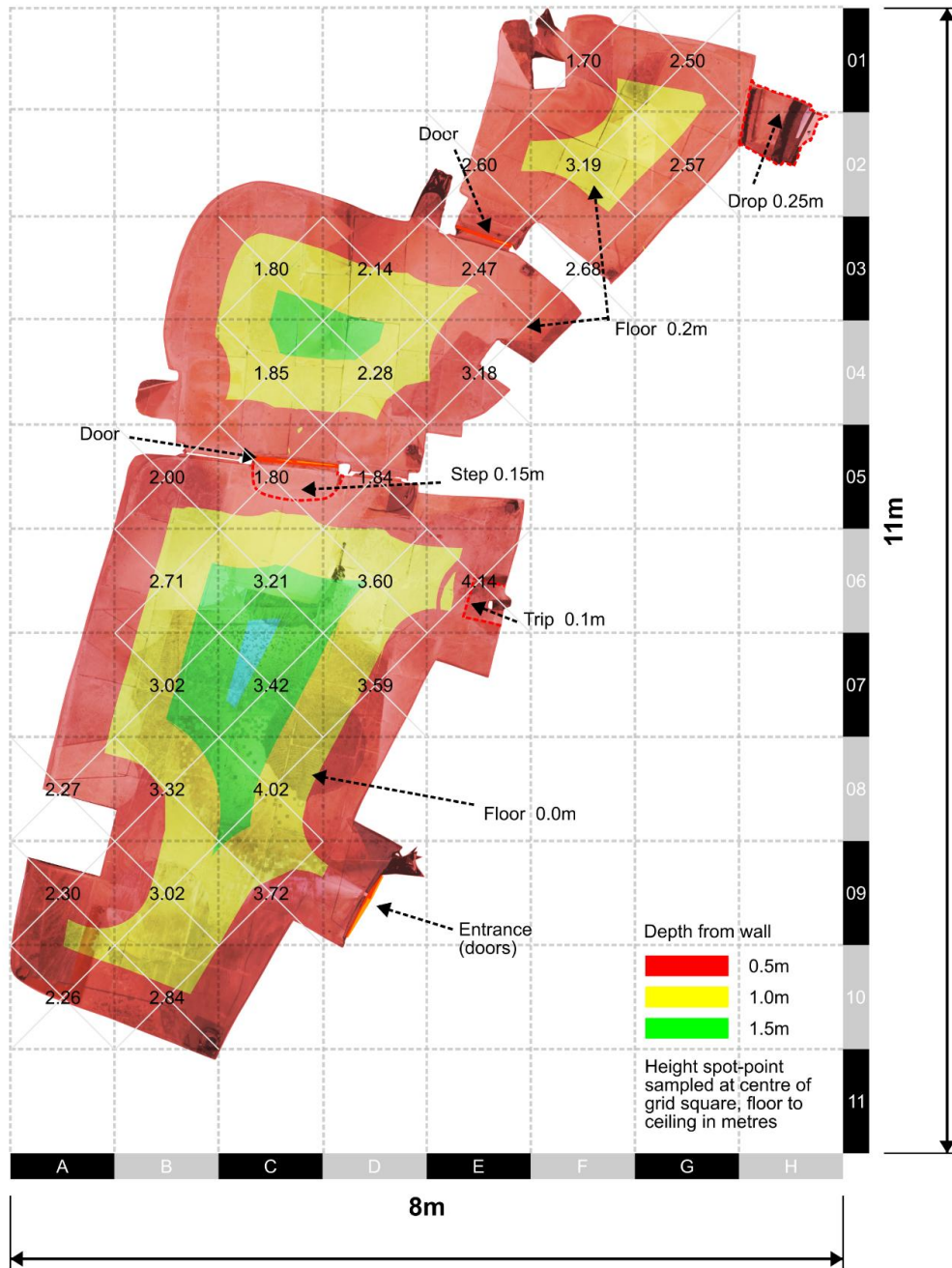


View from the upper southeast looking at the centre point of the Enkleistra. The image depicts the frescoes as they would be seen if the surrounding cliff enclosing the Enkleistra was removed.



View from the upper southeast looking at the centre point of the Enkleistra. The image depicts the frescoes as they would be seen if the surrounding cliff enclosing the Enkleistra was removed.

**St. Neophytos Enkleistra, floorplan grid out
Crossection of Neophytos_20250513_007**



An example of communicating paradata between partners. The image shows a scaled floor plan of the Enkleistra with coloured zones indicating the distance from the walls and spot heights to guide the placement of the avatar for optimal viewing in the mixed reality scenario. Additional notes show areas of concern including floor height changes, doors and potential trip hazards for visitors using the mixed reality implementation.