

"Best practices for the 3D documentation of the Grotta dei Cervi of Porto Badisco, Italy",

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Best Practices for the 3D Documentation of the Grotta dei Cervi of Porto Badisco, Italy

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ABSTRACT

The Grotta dei Cervi is a Neolithic cave where human presence has left many unique pictographs on the walls of many of its chambers. It was closed for conservation reasons soon after its discovery in 1970. It is for these reasons that a 3D documentation was started. Two sets of high resolution and detailed three-dimensional (3D) acquisitions were captured in 2005 and 2009 respectively, along with two-dimensional (2D) images. From this information a textured 3D model was produced for most of the 300-m long central corridor. Carbon dating of the guano used for the pictographs and environmental monitoring (Temperature, Relative humidity, and Radon) completed the project. This paper presents this project, some results obtained up to now, the best practice that has emerged from this work and a description of the processing pipeline that deals with more than 27 billion 3D coordinates.

KEY WORDS: 3d imaging, large 3d models, best practices, rock art, texture mapping

1. INTRODUCTION

1.1. Grotta dei Cervi, (Apulia, Italy) a Neolithic cave and a solution to the site closure

The Grotta dei Cervi project aims at recording the shape and appearance of the cave system for multi-target applications. The level of resolution and complexity of the site created an opportunity to push three-dimensional (3D) technology to higher levels. The site is composed of three main corridors where the walls are decorated with pictographs made of bat guano and red ochre. Some petroglyphs are also present. The Grotto, discovered in 1970 by local speleologists, is situated in South-eastern Italy near Porto Badisco, Italy. The cave is of karstic origin and contains the largest, as well as the most important, set of pictographs from the European Neolithic period⁴⁷. Hundreds of pictures painted on the walls of its galleries and in the many chambers compose this site^{1,2}. Some of these chambers have a maximum cross section of about 8 m wide × 5 m high. The main entrance is situated at about 26 m above sea level and the greatest depth is about 26 m. The Grotto contains a rich stygobitic fauna^{3,4}. The average temperature is fairly constant at 16°C and the relative humidity (RH) hovers between 92%-98% during the year. To preserve the delicate environmental balance inside the site, the cave is closed to the public and only a limited number of experts are allowed in every year. The response by local authorities to the closure of the site was to allow its representation through a detailed digital 3D model draped with color images. The result will allow virtual visits without traumatic consequences to the site.

1.2. Tackling a large project

The 3D documentation of large sites (i.e., those that require expertise from different fields so employ large teams, have safety-related restrictions) requires the adoption of a set of best practice guidelines in order to deliver the intended results. We have drawn from our own past experience a set of guidelines that we have applied to the 3D documentation of the Grotta dei Cervi. This documentation includes two sets of high-resolution two-dimensional (2D) images, detailed acquisition of three-dimensional (3D) images and 3D modeling with texture draping of most of the 300-m long central corridor, carbon dating of the guano used for the pictographs, environmental monitoring (Temperature, Relative humidity, Radon-222), and a series of multi-target products.

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1.3. Organization of paper

This paper presents the project, results obtained up to now, the best practice that has emerged from this work and a description of the processing pipeline that can deal with more than 27 billion 3D coordinates. The paper first reviews, in Section 2, current literature on best practices in 3D documentation. Section 3 surveys some large rock art 3D recording projects. Section 4 presents some details about the planning of the project and shows an overview of the multi-resolution 3D imaging and processing approach used and the results obtained up to now. This paper ends with concluding remarks.

2. INFORMATION AVAILABLE ON BEST PRACTICES

The topic of best practices is an important one when the technology in a given field matures enough that many users, who were not among the technological innovators or the early adopters, decide to make that technology mainstream. Interestingly enough, it is only in the last few years that best-practice-related information has appeared in the field of 3D cultural heritage. Other areas, like dimensional contact metrology, have been advocating best practices and standards for many years. This is due to requirements in industry for the interchangeability of manufactured components coming from different plants. Best practices ensure, or at least increase, the chance of performing quality data acquisition and subsequent use in a given field. Quality data and results are the product of careful planning with a strong understanding of the determining factors. On the other hand, a standard is as per ISO/IEC Guide 2: 'A *document established by consensus and approved by a recognized body that provides for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context*'⁵. Any standard should be based on the consolidated results of science, technology and experience, and it should aim at the promotion of optimum community benefits. Charters are also in use in certain communities. We now review some initiatives regarding best practices for 3D with a focus on cultural heritage.

2.1. National Measurement Institutions (NMI): NPL good practice guide

According to reference⁶, a Good Practice Guide was written for metrologists to make better measurements of the size or shape of an object. The reference provides an introduction to good practice in dimensional metrology and highlights the fundamental principles that allow experienced metrologists to make precise and accurate measurements. The report uses as a basis six guiding principles to good measurement practice. They are:

- The Right Measurements: Measurements should only be made to satisfy agreed and well-specified requirements,
- The Right Tools: Measurements should be made using equipment and methods that have been demonstrated to be fit for purpose,
- The Right People: Measurement staff should be competent, properly qualified and well informed,
- Regular Review: There should be both internal and independent assessment of the technical performance of all measurement facilities and procedures,
- Demonstrable Consistency: Measurements made in one location should be consistent with those made elsewhere
- The Right Procedures: Well-defined procedures consistent with national or international standards should be in place for all measurements.

2.2. ASTM committee E57.03: Best Practices

The American Society for Testing and Materials (ASTM) Committee E57 on Three-dimensional (3D) Imaging Systems was formed in 2006^{7,8}. This committee addresses issues related to 3D imaging systems, which include, but are not limited to systems based on time-of-flight (TOF) technology and optical triangulation. ASTM E57 consists of four subcommittees: Terminology, Test Methods, Best Practices, and Data Interoperability. Of particular interest to the present project, we find some information in current working documents and publications from committee E57.03 on *best practices*⁹. This subcommittee defines a best practice as a process or method that, when executed effectively, leads to enhanced project performance. The scope of this subcommittee is to develop, validate, document and communicate best practices (BPs) in the successful and consistent application of 3D imaging technology. These include BPs focused on guidelines specific to an application area, common across all projects and common to all projects across all applications. Using these best practices and guidance, end users will be capable of specifying application requirements and associated deliverables traceable to accepted standards. Practitioners will be able to determine instrumentation, procedures, and quality control processes yielding work products suited to their application requirements. Their primary focus was concentrated on bottom level requirements (e.g., safety, quality metrics, etc.) which are common to all

projects across all applications. E2641, Practice for Best Practices for safe application of 3D imaging technology, was developed as a first step towards the committee’s goals. It presents a practical approach to the safe operation of 3D imaging systems as well as information on the development of safety plans specific to an industry or site¹⁰. The next step in the committee’s work will be to develop a work document that will lead to a standard: WK28005, Guide for the Definition of 3D Image Data Requirements Necessary to Meet Project Objectives¹¹. Other organizations, like the ISPRS, are working on best practices in close range sensing¹².

2.3. The *Heritage3D.org* project

A report has been generated as part of the *Heritage3D* project^{13, 14}. *Heritage3D* was sponsored by English Heritage’s Historic Environment Enabling Programme and was undertaken by the School of Civil Engineering and Geosciences at Newcastle University. The two-year project developed and supported best practices in laser scanning for archaeology and architecture. The project was guided by five objectives:

- to produce a guidance note that demonstrates the products that can be generated from laser scanning,
- to update the current Addendum to the Metric Survey Specification to take into account continuing advances in technology,
- to increase the knowledge base of English Heritage by forming partnerships with external survey practitioners/equipment manufacturers within the UK,
- to promote synthesis between disciplines within English Heritage by publishing and maintaining a project website, and,
- to provide workshops on the use of laser scanning to educate archaeologists, architects and engineers from within English Heritage.

The reader finds useful information on defining a typical project work flow. For instance, after confirming the need for a given survey, a *project brief* should be established by the client. It includes information that helps the contractor understand the site-specific needs and requirements of the survey. It is then put out to tender for survey contractors to provide a method statement giving details of how they intend to undertake the survey. During this work, the contractor is guided by the method statement and refers to a standard specification for guidance. Upon completion, the client uses the project brief and standard specification to undertake a quality assurance (QA) check before accepting the survey. We select one of the key factors in specifying a survey, i.e., what point density and measurement accuracy is required to generate the level of ‘deliverable’ required in a given project. The authors of the guide based the results shown in Table 1 on standard mathematics used to determine appropriate minimum sampling intervals and on the collection of a regular grid of data¹⁴. Other aspects for specifying a survey are listed in their report along with several test cases.

Table 1. Point density as a function of minimal feature size (adapted from Barber¹⁴).

Feature size	Example of features	Point density (Note 1)
1000 mm	Small earth work/ditch	50 mm
100 mm	Large stone masonry	5 mm
10 mm	Large tool marks	0.5 mm
1 mm	Weathered masonry	0.05 mm

Note 1: Density required giving 95% probability that the feature will be visible.

2.4. E-curator research project

The application of 3D scanning and e-Science technologies to museum work and artifact analysis (important for Art and Humanities research) is the main goal of the E-Curator project¹⁵. The research project aims at

- developing a traceable methodology for recording the surface detail and color quality of a range of object types and materials,
- exploring the potential for producing validated datasets that would allow closer and more scientific, examination of groups of objects, the processes involved in their manufacture, and issues of wear and deterioration,
- examining how the resulting datasets could be transmitted, shared and compared, and,
- building expertise in the use and transmission of 3D scan data as a curatorial tool.

This research project contributes to the field of cultural heritage by alleviating some of the practical barriers to the movement of people and objects, enhancing international scholarship, facilitating the safe movement of artifacts, and a better understanding of best practices for small to medium size museum artifacts¹⁵.

2.5. London charter

The London Charter is concerned with the use of 3D visualization in the research and communication of cultural heritage. It seeks to establish what is required for 3D visualization to be, and to be seen to be, as intellectually rigorous and robust as any other research method¹⁶. According to the charter, "transparency" is an issue of importance in the cultural community and it must be upheld. The Draft document adopted the format and style of the International Council on Monuments and Sites (ICOMOS) ENAME Charter¹⁷. Other related Charters exist, such as the Venice Charter on conservation and restoration¹⁸.

2.6. Other literature on best practices

A recent book published in Italy summarizes the methodology and decisions taken to model a large site like the one in Pompeii, Italy¹⁹. The authors bring to this book their own best practices that were put to use on The Forum of Pompeii (approximately 150 m long and 80 m wide) and the state-of-the-art described in current literature. A publication by Guidi et al. in 2009 on the same project describes the 3D scanning and texture mapping work²⁰. The Conservation Technologies of the National Conservation Centre in Liverpool²¹ have produced a body of knowledge (BOK) related to 3D recording and replication that exemplifies the importance of these technologies in the cultural sector. The center has developed extensive experience in using the latest laser scanning techniques to undertake quality three-dimensional recording of cultural artifacts. Their activities include large 3D projects commissioned by many different clients, scientific publications and training for those working within the heritage field. Training is a key component in a maturing technology. Their course includes teaching a basic understanding of laser scanning and its uses. It is aimed at museum curators, conservators, conservation officers, archaeologists, virtual reality providers, exhibition designers, surveyors and other commissioners of 3D recording work²¹. Pavlidis *et al.* discuss the issues affecting the whole life cycle of the digital cultural content²². They identify and describe five main processes in digital recording that require new advances: digitization in 3D, processing and storage of 3D data, archiving and management of 3D data, visualization and dissemination of 3D data, replication and reproduction of 3D data. According to Rennison *et al.*²³, although many different technologies for 3D data capture are available today, the field of archaeology has yet to formulate and achieve a standard, or common, approach to 3D scanning documentation. This implies that each documentation project is compared against projects belonging to a restricted set of data and, hence, no 'yardstick'. Usually, a given group will keep the data to themselves. The team decided to compare data sets and assess a number of approaches and results of other people's work in the same field²³. They created a collaborative scanning project with four other institutions (academic and cultural). Each partner scanned the same artifact, utilizing the 3D scanning technique available at their respective facility, recorded their approaches, and then the results were compared. As a result of this pilot project, they concluded that the establishment of methodological guidelines for assessing 'best practice' is a difficult target to achieve. Quantifying and understanding the variability of the results achieved would be the start of a discussion that eventually could lead down the road of achieving a standard approach and common language with regard to 3D data recording in archaeology. In the near future, the authors want to increase the number of artifacts, scanners and calibration tools (e.g VDI 2634)²⁴ to better cover current state-of-the-art 3D reconstructions and to ensure effective comparison of 3D models.

3. 3D DOCUMENTATION OF ROCK ART AND CAVE SITES

The accurate recording of rock art sites, ancient crypts and cave sites is a challenging task. The sites have either formed naturally or been carved from the surrounding rock, typically the walls, floors, and ceilings have an irregular surface shape, and the paintings (pictographs) or carvings (petroglyphs) follow the contours of the rock surface over large areas. These features, particularly the shape of the rock surface and speleothems (wall concretions, stalactites), are difficult to record with a high level of detail, measure, compare and display using conventional recording techniques, such as survey methods, rectified photography, distance meters, etc. For conservation applications, once a 3D digital model is prepared, all the resources of computer graphics and computer vision can be used to display and analyze the results. We now summarize some large 3D documentation projects of cave sites.

3.1. Early work performed with triangulation-based scanners

As early as 1994, laser scanning was used for cave recordings²⁵. Electricité de France and Mensi undertook the modeling of the Cosquer cave that was discovered in 1985 by a diver near Marseille (France). The cave walls are decorated by paintings that are between 19,000 and 27,000 years old. Access to the cave is treacherous: the entry is 37 meters below the water level with a 175 meter long passage tunnel. This cave is now closed. A triangulation-based laser scanner was transported in a water-proof case into the cave. The computer was positioned on the coast and connected directly to the scanner via a 300-meter cable. The laser scanner was described as having an acquisition speed of 100 points/s and a useable range from 0.5 m to about 10 m. Though considered slow acquisition by today's standards, the team succeeded in creating a 3D model with data from 28 different scanner positions. In its final version, the model contains 4.7 million 3D points at a lateral resolution of 30 mm. In 1996, in collaboration with the Israel Antiquities Authority, the National Research Council of Canada (NRCC) undertook a pilot project to demonstrate the application of a triangulation-based large-volume laser scanner for conservation documentation of the Arcosolia Room of the Tomb of St. James in Israel. This laser scanner was described as having an acquisition speed of 10 000 points/s and a useable range from 0.5 m to about 10 m. The tomb, which measures approximately 2 m x 2 m x 1.8 m, was carved in the rock, and its interior surfaces are rough and irregular. The interior was recorded with a lateral resolution of 0.2 mm and a depth uncertainty of about 0.3 mm. A total of 65 range images were taken. The final model had 1.75 million polygons, which at the time created some difficulties for real-time manipulation²⁶. The Altamira cave, located in Spain, was a popular stop for tourists until 1970. It was then closed because of the large number of visitors that had resulted in an increase in temperature and humidity, which is known to cause the prehistoric cave paintings to flake off the walls. The cave authorities decided to reconstruct the whole cave true-to-size so that the public could view the prehistoric paintings without risking damage to the original. A close-range triangulation-based laser scanner recorded three-dimensional images of more than 2600 m² of painted walls²⁷. No indications of spatial resolution were found.

3.2. Multi-sensor approaches to the rescue!

El-Hakim et al.²⁸ present an approach to create detailed and realistic 3D models of Aboriginal pictographs of the Baiame cave in New South Wales, Australia. They used a combination of long-range time-of-flight laser scanning, bundle adjustment, and surveying. The technique performed texture mapping without extracting common points between the texture images and the 3D geometric model. A total station was used to "tie" the data together by measuring the coordinates of points that were discernable in the data. The standard deviations of the computed 3D coordinates were 13mm (X), 9mm (Y), and 11mm (Z) and the model contained 400 000 textured polygons. Although the site is small in size compared to the following examples, it shows the impact of the arrival of time-of-flight-based systems on the market in the late 90's. Larger sites could now be done in a reasonable amount of time. The archaeological site of Wonderwerk Cave (South Africa) was documented using laser scanning, conventional survey, digital photogrammetry and 3D modeling technologies²⁹. The cave is 140 m long and ranges in width from 11 m to 24 m with a height of about 3 m to 10 m. A comprehensive laser scan of the entire interior of Wonderwerk Cave was deemed necessary for current archaeological research at the site, as well as for historical documentation of the cave. It was scanned by a two-member team using a Leica HDS 3000™ terrestrial scanner and Cyclone™ software operated on a laptop computer. This natural site presented a number of challenges for the team, which included:

- the impossibility of obtaining watertight scans due to the complexity and detail of the surface and difficulty of finding suitable vantage points to cover all missing surfaces,
- the immense amounts of time taken to register, clean, create a triangulated model, fill scan holes in the model, and texture it,
- finding software solutions for manipulation and storage of the immense volume of data that resulted,
- the need to enhance software for modeling, feature extraction, texturing and presentation²⁹.

Point intervals or scan resolutions were chosen to have a minimum spacing of 30 mm horizontally and 20 mm vertically. The authors chose this point interval as a compromise between high resolution on the one hand and increased scan time and difficult-to-process point volumes on the other. Draping photographic images over large areas of the surface was used to increase surface detail. Two Paleolithic caves located in northern Spain have been modeled: 'Las Caldas' and 'Peña de Candamo' caves (ca. 14,000 BP)³⁰. The authors summarize the planning stage (client requirements, project goals, cave features and limitations, cave environment, technique and instrument selection, number of stations, scan resolution, and reference system), the data collection stage (global scans - 20 mm at 10 meters, detailed scans - 2 mm at 10 meters, independent images for textures and, panoramic images), and, the data processing stage (scans registration, segmentation and filtering, mapping textures, geo-referencing, derivate products). A terrestrial laser scanner, Trimble

GS200™ and a 2D camera, Sony™ DSC F828 were used. They used several artificial targets (planar targets and spheres) placed inside the caves. These served a dual purpose, i.e., register all the 3D scans in a common reference system and geo-reference the 3D model into the archaeological reference system.

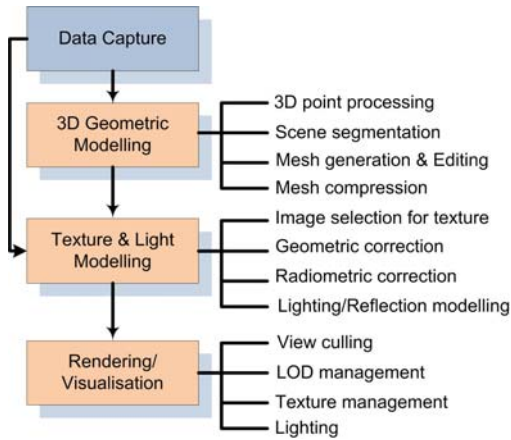


Figure 1. Modeling and rendering pipeline typically found in a 3D documentation project. LOD: Level of details.

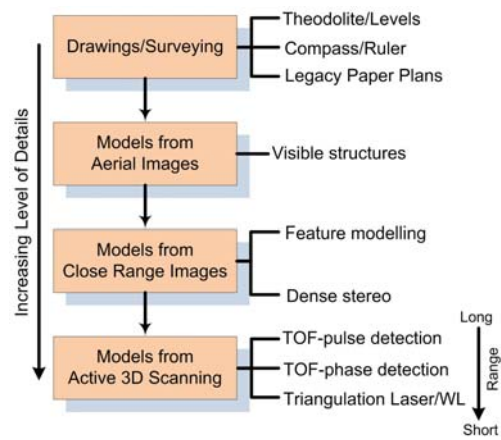


Figure 2. Model assembly hierarchy found in a typical 3D documentation project. TOF: time-of-flight, WL: White-light.

3.3. Summary of 3D modeling pipeline and What's next?

All of the projects described above follow very closely a typical modeling and rendering pipeline, and, a hierarchy for model assembly shown schematically on Figure 1 and Figure 2 respectively³¹. With the recent advent of modern terrestrial laser scanners (TLS) which generate between 10 and 50 million 3D coordinates per minute, we can easily foresee an increase in the demand for faster processing capabilities to visualize larger 3D models and increased storage (reliable) on regular commodity computers. Currently, when one combines the acquisition of high-resolution texture images to 3D scanning, three-dimensional modeling projects lasting several hours generate enough information to choke high-end PCs running commercial software packages. We will describe later a framework for the processing, visualization and analysis of such very large 2D/3D datasets i.e. in the billions of polygons.

4. BEST PRACTICES FOR MODELING THE GROTTA DEI CERVI

Best practices are vital to those that commission a project and to those that actually execute the work according to pre-defined specifications. The main objective of best practices (BP) is to increase the chances of success of a given project. For instance, proper project planning will aim at minimizing the impact of measurement uncertainties, maximizing the amount of information available (proper spatial resolution), and reduce both costs and time. Back in 2005, we adopted a best practices structure similar to the current documentation published by the ASTM E57.03 committee⁹. Figure 3 shows a block diagram with the main elements of the project (see also Section 2.2). Without going in the details of each block in Figure 3, we now describe some elements in this two-layer BP structure that was used for the Grotta dei Cervi project.

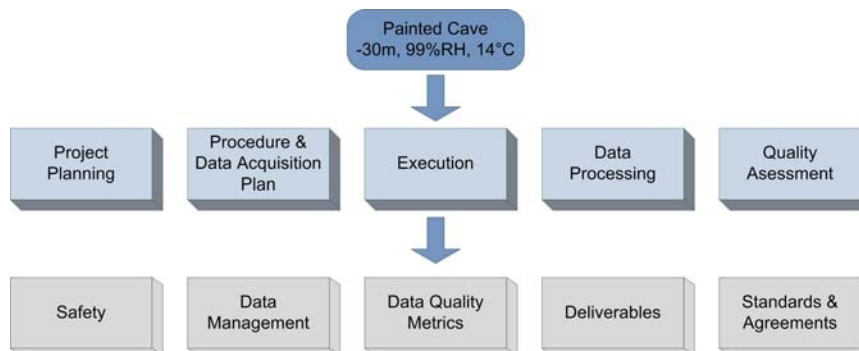


Figure 3. Best practices structure used for the project. (Diagram adapted from the ASTM E57⁹).

4.1. Procedure & data acquisition plan

A key question in any dimensional measurement project is linked to minimizing the impact of measurement uncertainties on the amount of information desirable (fit for purpose) for a given deliverable. This question brings both the service provider and end-user to understand the level of spatial resolution necessary given a budget and time frame and, at the same time, what is achievable by the physics of the measurement process.

4.1.1. Lateral resolution – surface sampling

The authors of the 3D Heritage guide¹³ published some results in that direction and they are shown in part in Table 1. These figures help determine the appropriate minimum sampling interval on a regular grid of data for a given feature size. For the Grotto, we determined that crack formation on the walls of the cave would be described accurately by a feature size of 1 mm. From that table, one finds a point density of 0.05 mm in order to yield a 95% probability that the feature will be visible. This figure is interpreted as a lateral resolution and, in the case of a laser spot scanner, can be linked to an estimated depth of field³² under Gaussian beam propagation. The equivalent depth of field (DOF) for a spot radius of 0.05 mm is approximately 23 mm which is the domain of close-range triangulation systems. From a practical stand point, this depth of field is very restrictive for work in a complex environment like a cave. Our experience in 3D is dictating instead a lateral sampling of about 0.2 mm in order to resolve a crack of about 1 mm (1/5 of the feature of interest = spot radius = 0.2 mm). Incidentally, a DOF of almost 500 mm is achieved with 0.2 mm. For larger features, like concretions, stalactites, stalagmites and lacunas, a lateral resolution of 5 mm to 10 mm was deemed satisfactory. Using the same rule of thumb, (i.e., 1 mm to 2 mm spot radii for those features sizes) the DOF is in the meters to tens of meters range. This is the domain of time-of-flight laser scanners. These calculations lend themselves to using an approach that entails a combination of 3D data from different 3D sensors and information from different sources in order to meet set resolution and accuracy targets. To complete the analysis, one needs to verify, for a given scanner, the pointing resolution and uncertainty in order to assess the final surface sampling step size achievable. Figure 4a shows the curves necessary to estimate: the surface point density as a function of laser spot radius, the pre-set points per degree from the scanner software, and the scanner angular pointing uncertainty for the TOF phase-based Surphaser HSXTM scanner.

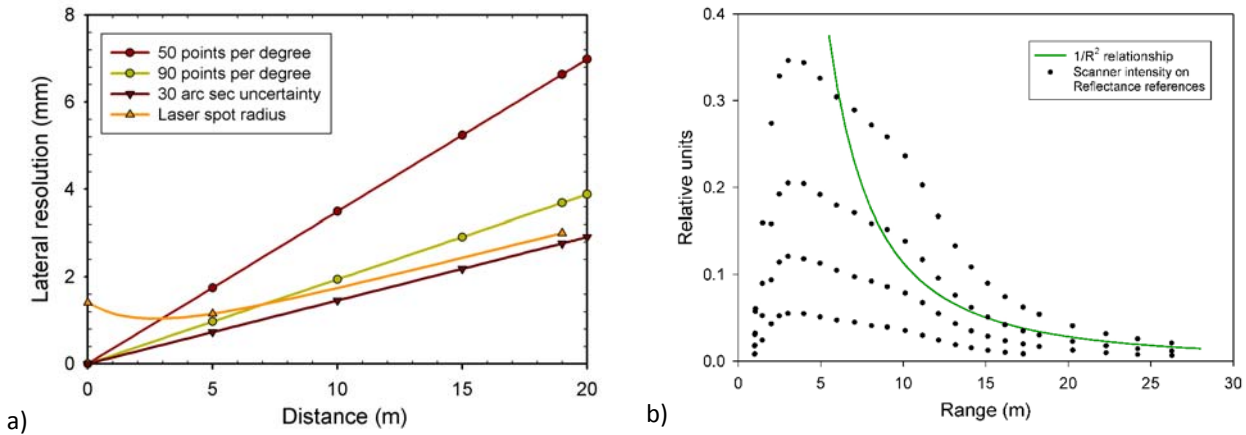


Figure 4. a) Laser spot radius compared to the point density at 50 points per degree (ppd) and 90 ppd, and, the angular scanning uncertainty of 30 arc sec as a function of distance, b) Laser intensity return curves (the compression of the dynamic range in intensity is clearly visible on the graph) for the Surphaser HSXTM scanner.

4.1.2. Depth uncertainty – accuracy

The measurement principles, the surface reflectance, opaqueness of a surface, and distance all have a direct impact on the depth uncertainty^{32,33}. Theoretical considerations can enlighten us on some aspects of a particular laser scanner technology. Experimentation, on the other hand, can be tailored to estimating a certain aspect of a system without performing long mathematical derivations. To allow comparison of different laser scanners, we used 3D artifacts that have different surface reflectance, surface details, and size. They were located at known distances and orientations. Their physical dimensions were selected depending on a system's measurement principle and the practicality of the situation. An object that is distinct from the calibration equipment, and for which the accuracy is 4-5 times (rule of thumb) better than that of the laser scanner, was employed in such an evaluation.

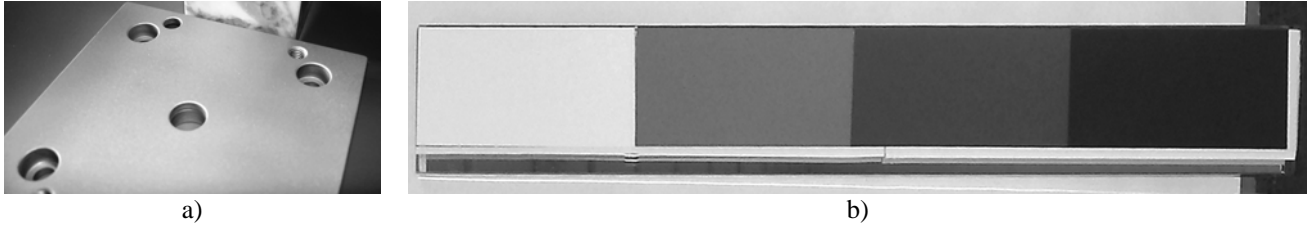


Figure 5. Artifacts used to quantify the range uncertainty as a function of distance and reflectance: a) vapor-blasted X95 structural rail end-plate from Newport™, b) Munsell™ reflectance material glued on a flat mirror. From the calibration certificate, the response is flat from 450 nm out to 750 nm (89.2%, 19.2%, 9.3%, 3.1%).

We report the standard deviation of a best-fit plane obtained from the software Innovmetric PolyWorks/IMInspect™ v11³³. Experimentation indicates that Total Least-squares Regression is used to obtain the best-fit planar model. For the reflectance target, small patches were selected for that particular target. **Figure 6** presents the results. Five time-of-flight (TOF) laser scanners were tested in the course of one year. The results are reported only for the scanner that was selected for the project. One can see the effect of a decreasing SNR as the distance increases and the reflectance is lowered. **Figure 4b** shows the response curve for radiometric calibration of the TOF laser scanner.

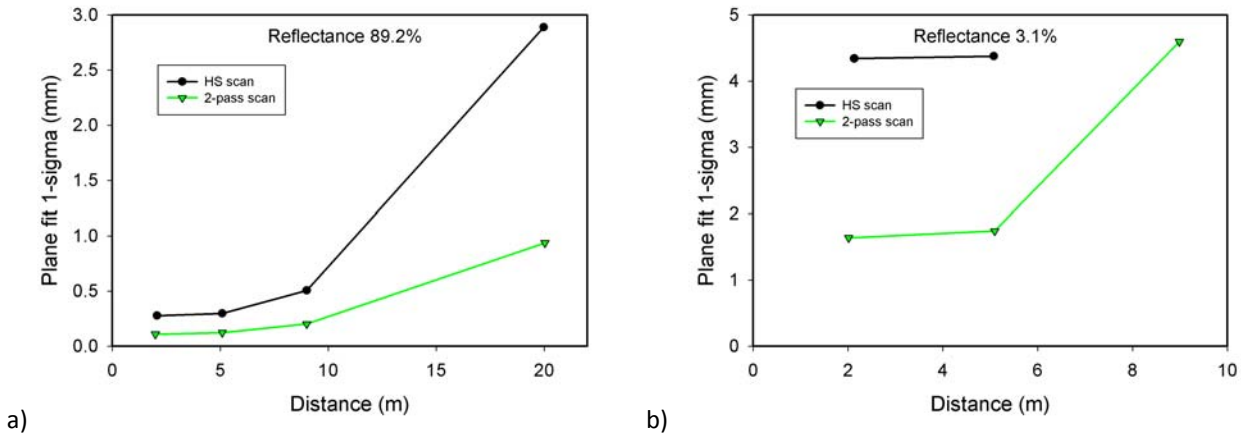


Figure 6. Estimated uncertainty (plane fit 1- σ value) at different distances to the scanner Surphaser HSX™. The reflectance value a) R=89.2%, b), 3.1%. Scanning modes: HS=high sensitivity, 2-pass scan=system scans the scene twice.

It has been observed by some authors that TOF systems may produce a bias in the range data when two surfaces with different reflectance are measured at the same location³⁴. We conducted an experiment using the object shown on Figure 5b on the five TOF systems we short listed. We first made sure that there was no penetration of the laser onto the target. Plane equations are fitted using the same method discussed above. The Surphaser HSX™ scanner gave no noticeable bias at in the range 1 m to 20 m and with surface reflectance from 3.1% to 89.2%.

4.1.3. Summary of specifications of the two laser scanners used in the project

We used two laser scanners to acquire the inside walls and some of the external structures. The first scanner used in 2005 was a prototype triangulation-based multi-resolution 3D laser imaging scanner that made it possible to acquire the shape information of the three main chambers (important pictograms) with a spatial resolution that improved with shorter standoffs³⁵. The system could record 3D data at a camera-to-object distance which ranged from 0.5 m to 10 m. At a standoff of 0.75 m, it provided a depth uncertainty of 0.08 mm on cooperative surfaces and a lateral resolution of 0.2 mm. These specifications were sufficient to describe crack shape as per Section 4.1.1. The second scanner used in 2009 was a commercially-available system that recorded 3D data at a range from 0.5 m to 19 m (Surphaser® phase-based scanner model 25HSX). The estimated depth uncertainty was about 0.25 mm from 0.5 m to 7.5 m on cooperative surfaces (see Figure 6a, 2-pass mode) and the laser spot radius was about 1.15 mm at 5 m (see Figure 4a). These specifications were adequate to describe larger features (e.g. concretions, stalactites, stalagmites) and the overall shape of the cave.

4.1.4. Acquisition sequence

The acquisition sequence was based on the fact that permission to enter the cave entitled the team 10 days of work inside the cave and 3 days outside. In reality, only 8 days could be used inside the cave. It, therefore, dictated a strategy to acquire as much 3D data as possible. As mentioned above, the triangulation scanner was used for close-ups in the first campaign in 2005³⁵ and the TOF phase-based scanner for the whole cave in the second in 2009. The TOF system is capable of scanning a FOV of $360^{\circ} \times 270^{\circ}$ and the data rate is about 90,000 3D points per second. Figure 7a shows the results of half of a scan in the vertical direction. The laser intensity data from the scanner is displayed. Using the information from Sections 4.1.1 and 4.1.2, the distance between positions of the scanner was set to about 9 m which yielded a good overlap region between scans. Figure 7b shows some of the actual scanner positions. The initial scan resolution was set to 100 points per degree (ppd). This had to be readjusted because of the shorter daily schedule that was communicated only when the project started. We therefore reduced the resolution to 50 ppd in most areas and 90 ppd for one chamber. Digital photographs provided the texture images that were mapped onto the 3D model resulting from both 3D data sets. A similar discussion on lateral resolution (Section 4.1.1) can be made with photographs. The interest reader can refer to Blais & Beraldin 2005 for more details³⁶.

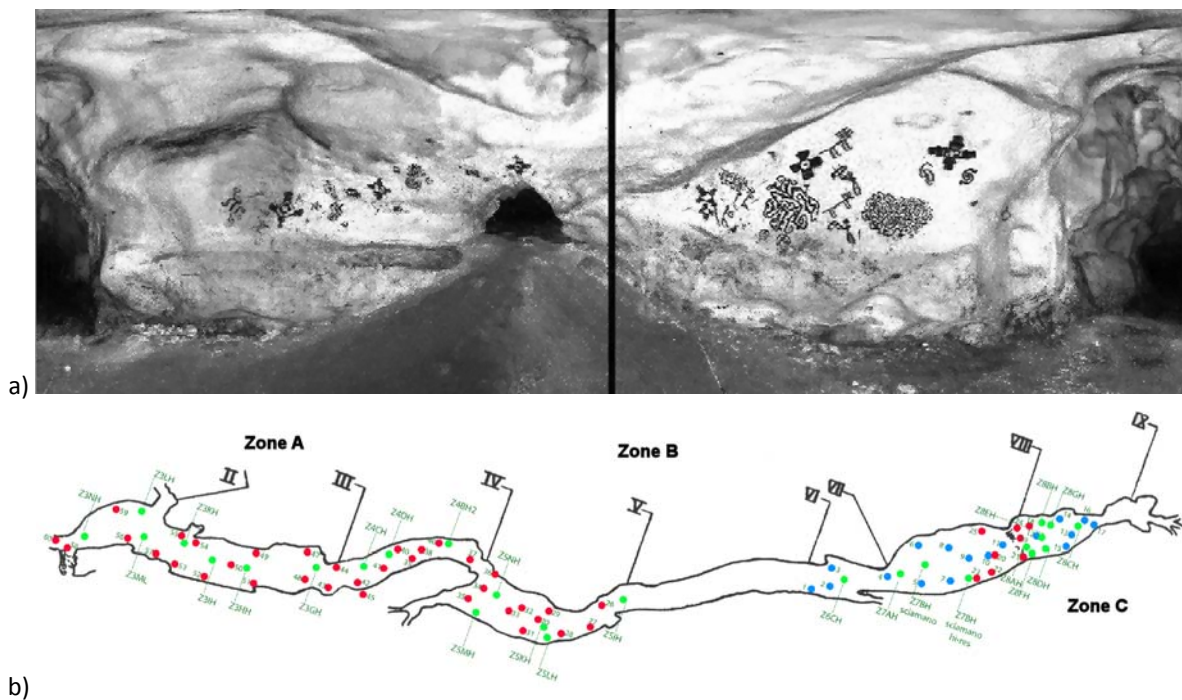


Figure 7. Acquisition sequence: a) Hemispherical scan showing the natural parameterization of the laser scanner: vertical scan angle $180 \text{ deg} \times$ horizontal scan angle 360 deg , b) the green dots are some the positions of the scanner; the blue and red dots are the sphere locations.

4.2. Execution of the second phase of the project (May 2009)

The second phase of the project took place in May 2009 and it generated 82-3D spherical images for a total of 26.4 Giga 3D points (106.7 GBytes of raw binary data) and 2481 2D images for a total of 35.5 GBytes of texture. Some statistics about the two campaigns are shown in Table 2. Video information was used to document the work. Four teams worked on the project during the two campaigns: a two-person team for the acquisition of the 3D data, a four-person team for the digital photography, a two-person for safety, and a two-person team located above the cave in a camper. The last team was responsible for coordinating all communications amongst team members and for pre-processing of data. A LAN assured an uninterrupted video/audio link and data backups. Two separate electrical cables connected to a low noise gas-powered generator provided electricity to the 3D and photography teams respectively.

Table 2. Project “Grotta Dei Cervi” in numbers.

	Campaign year	
	2005	2009
Number of rooms scanned	4 rooms	All 250 m
Smallest spatial resolution	0.2 mm	1 mm
Number of 3D images acquired	716	82 hem.
Number of 3D points acquired	0.63 Gpts	26.4 Gpts
Number of 2D images acquired	3500	2500
Length of electrical cables:	2 × 300 m	
Length of Ethernet cables:	300 m	
Scanner weight	3 kg	11 kg
Narrowest passage	0.6 m ×	0.6 m

hem.: Hemispherical; Gpts: giga-points.

4.3. Data processing

Due to the sheer quantity of data generated by the 2D and 3D acquisition campaigns, the development of new tools for modeling and managing very large textured polygonal meshes was necessary. This was achieved in a number of steps that saw the creation of progressively more complex models, e.g. Mona Lisa^{37,38} and the Erechtheion³⁹ projects. NRCC developed efficient and robust algorithms for 3D image processing, management, and real-time visualization of multi-Giga-triangle meshed models of large and complex sites⁴⁰. These algorithms are part of Atelier3D.ca, a general framework developed for the acquisition, modeling, visualization, and analysis of very large, multi-scale 3D datasets built from data gathered with 3D and color sensors⁴¹. This suite of tools is compatible with Innovmetric Polyworks Modeler™. The use of this commercial package made it possible to speed up the development of the tools and helped us to streamline operations that didn’t need reimplementation. Atelier3D.ca facilitates or fully automates many of the tedious operations necessary in the typical modeling pipeline (e.g. registration of the multiple scans, processing the photographs before texture draping, accurate registration of texture images with the geometric model, interactive visualization of the full resolution 3D model). Figure 8 shows a block diagram of the data processing for the Grotto project.

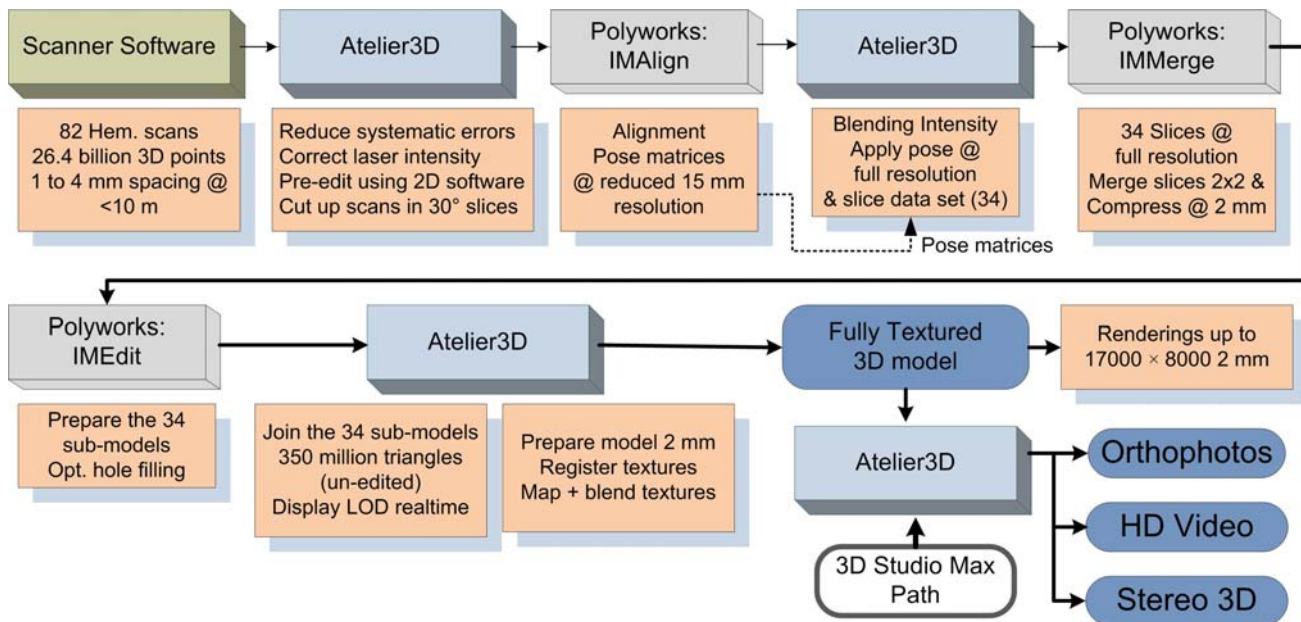


Figure 8. Block diagram of the data processing that combines custom made tools found in NRCC’s Atelier3D and Polyworks™.

4.3.1. Processing, modeling and texture mapping with large 2D/3D datasets:

The main challenge we tackled is the enormous size of the datasets that current laser scanners can produce: billions of 3D samples and hundred of gigabytes of digital photographs for single objects or scenes. To achieve this, we had to rethink existing algorithms so that they work at this new scale. One key aspect was to automate the different steps of the process as much as possible, because any form of human interaction becomes extremely costly and time-consuming for such large datasets. Specifically, we improved on 2D and 3D alignment, data integration, and correction of errors and deformation due to intrinsic scanner characteristics. One recent advance is our work on automatic high precision alignment of 2D and 3D data, where the pose, camera parameters, and residual deformation linking a 2D photograph and a 3D model are computed and optimized automatically whenever possible, and a very efficient user interface allows completing the work in minimal time. This is an important development as this is one of the most difficult and time consuming activities for a human operator to perform when processing sensor data for texture mapping purposes.

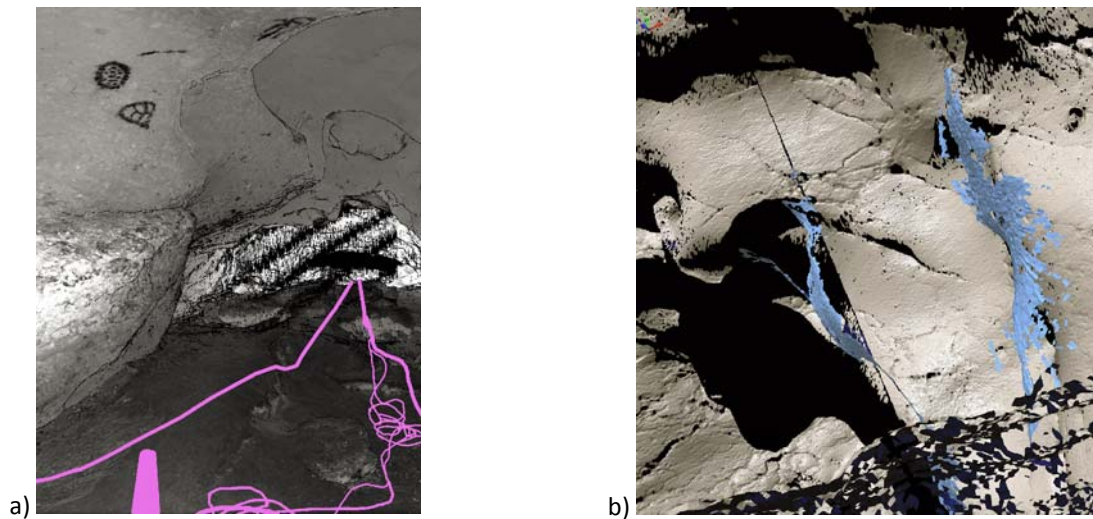


Figure 9. Some aspect of the processing of the raw 3D data: a) editing of unrelated equipment and objects data was performed with the help of 2D processing software in combination with a tool from Atelier3D, b) alignment error when the range was limited to less than 9 m, the problem was corrected by using all the 3D information.

Other features include the editing (see Figure 9a) of the raw 3D data using the laser intensity image generated by the scanner. The intensity images are edited with by a standard 2D processing software and the resulting image is batch processed by Atelier3D in order to clean the 3D image. One interesting result, from the alignment process, was noticed when data deemed too noisy (i.e., above 9 m) was removed. It was found that all the 3D data had to be included in the alignment of the global model (see Figure 9b). Furthermore, to help in the alignment process, a series of spheres were placed in strategic locations within the cave to facilitate the alignment of the 3D scans together. Once the global alignment was done at a 15-mm resolution, the transformation matrices were applied to the high resolution 3D data set and the resulting model was then sliced in 34 pieces so that they could be edited, if necessary.

4.3.2. Interactive visualization and display of large 2D/3D datasets:

The ability to interact with 3D models is a continuing problem due to the fact that the demand for detailed models is growing at a faster rate than computer hardware advances. The rendering algorithms have to be capable of delivering images at real-time frame rates of at least 20 frames-per-second even at the full resolution of both geometry and texture. The NRCC-developed Atelier 3D.ca system, a view-dependent real-time system for multi-resolution models is being applied the current project. For instance, when the 3D model is viewed at close range, the full resolution is shown (see **Figure 10**). As the model is moved away from the observer, the resolution is decreased smoothly so no artefacts are visible. This part of the software is based on the Geomorphing of Levels of Detail (GoLD) system⁴². The datasets can be interactively visualized at full resolution and high quality on inexpensive laptops or desktop computers.

4.3.3. Analysis of large 2D/3D datasets:

High resolution and accurate 3D scanning provides information, not only about overall shape and color, but also of fine surface details and variations that need to be assessed within a larger context and can be hidden within global surface features. We, therefore, seek to do more than only displaying it in a photorealistic manner, but also transforming it in order to enhance its understandability by the viewer and, as a result, maximize the value of the dataset. Atelier3D implements numerous real-time data transformation techniques on the graphics processing unit (GPU) that enabled real-time extraction of all the information available in the models.

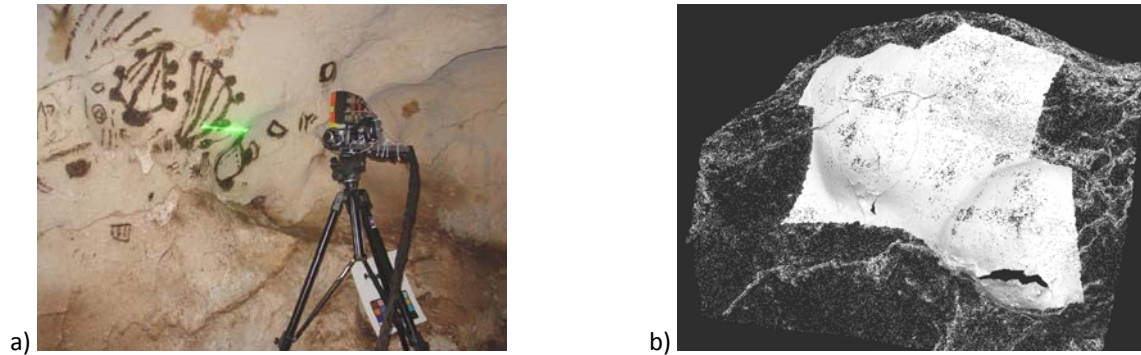


Figure 10. Multi-resolution 3D model of a section of the cave with a series of pictograms: a) photograph of close range scanner, b) point cloud of a section of the 3D model (1.75 m \times 2.35 m) created from data acquired by both scanners.

4.4. Data quality metrics & safety

In order to establish a direction for the model, a rod was scanned in several scenes. The rod was oriented using a liquid-filled precision compass and inclinometer ($1/3^\circ$ accuracy). The leveling of the 3D model was possible by aligning it with the normal of the surface of a small pond (the data from the water-soil interface was used). A more sophisticated leveling strategy was envisioned. Indeed, a number of TOF laser scanners are equipped with an inclination sensor which makes it possible to level the scanner during measurements. Tests on many types of commercial TOF scanners have shown that it is possible to level a scan to better than 1:20000 (i.e. $50 \mu\text{rad}$) using the inclination compensation within the laser scanner⁴³. This would have been well within our error budget. Unfortunately, because of time constraints and problems locating such a scanner on time, we could not apply this technique to our project. Safety concerns are divided into laser exposure, physical safety while working in a confined area, and Radon concentration. The last item was of concern because of the type of site. Radon-222 (Rn) levels were measured in three zones of the cave: entrance (A), middle (B) and at the end of corridor (C) as indicated on **Figure 7b**. According to Italian law defining maximum Radon exposure levels for work environments, the maximum permissible time while in the cave varies from very low in zone A to 1000 hours/year in zone B and finally to 250 hours/year in zone C. These values are well above the time spent by team members in the cave over a ten-day period in both visits⁴⁴.

4.5. Deliverables

High-resolution textured 3D models of museum objects and heritage sites contain a wealth of information that can be examined and analyzed for a variety of conservation, research, and display applications⁴⁵. For example, in the case of a site that must be closed or subjected to limited access for conservation reasons, an immersive 3D virtual reality theatre can be used to enable visitors to “virtually” visit the site. Researchers can magnify or zoom in on a 3D model to examine, measure, and compare fine surface details for signs of deterioration. Enhancement techniques can be used to improve the legibility of faded images. Furthermore, 3D models recorded before and after an actual conservation treatment, can serve as vital archival record for ongoing site monitoring and maintenance. Once a detailed 3D model draped with color is created then a number of derived multi-target products can be produced to satisfy different applications. Here are some of those products or deliverables:

- Creation of a 3D polygonal model with texture from the 3D and 2D raw data,
- Creation of transversal and longitudinal cross-sections of the cave with a resolution down to 1 mm (see **Figure 11a**), comparison between manual survey and 3D survey (see **Figure 11b**).

- Creation of high-resolution realistic renderings or images (e.g. 17.000 x 8.000) using color and shape using a given perspective or in ortho-view (orthophoto) with a 1-mm resolution,
- Creation of high-resolution unrealistic renderings (e.g. 17.000 x 8.000), points, shape enhancing shading,
- Creation of a database of critical areas for reliably monitoring the condition and stability of the site (surface deterioration, cracks/collapse),
- Extraction of information from model in order to assist restoration/preservation work (e.g. cracks),
- Creation of a 3D polygonal model for stereoscopic displays⁴⁶, low cost holograms,
- Creation of a Video (e.g. 720p or 1080p) animation from the 3D digital polygonal model
- Creation CD-ROMs, web sites, etc...

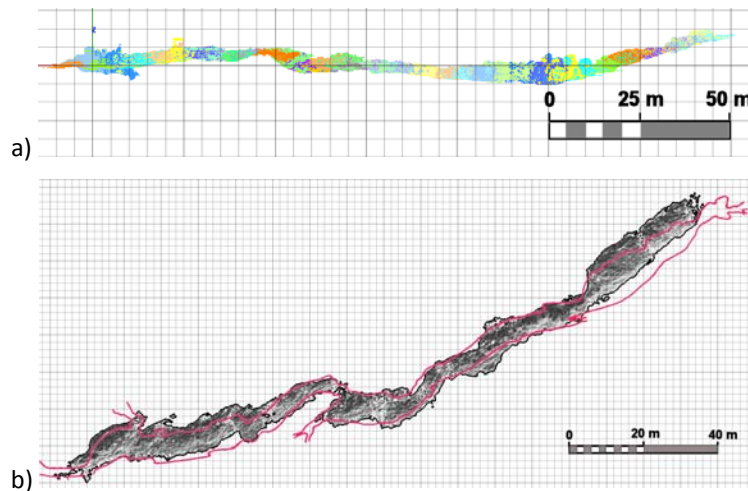


Figure 11. 3D model of part of the Grotta dei Cervi: a) vertical cross-section - colors show the different scans, b) horizontal cross section - superposition of floor plans extracted from the 3D model versus current knowledge about the cave (red outline).

5. CONCLUSION

This paper presented a summary of best practices resulting from a project aimed at documenting the Neolithic Grotta dei Cervi in Italy that was closed for conservation reasons soon after its discovery in 1970. This 3D documentation which includes two sets of high-resolution three-dimensional (3D) acquisitions that were captured in 2005 and 2009 respectively, along with two-dimensional images. The 3D textured model will allow for a virtual access to the site and pictographs without invading the fragile environment of the cave. We presented along with best practices some results obtained up to now and a description of the processing pipeline that deals with more than 27 billion 3D coordinates. Future work will include a return to the cave for a short duration with a long range TOF system and a strategy for positioning the cave in a global coordinate system.

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