# GEOMATIC TECHNIQUES AND 3D MODELING FOR THE SURVEY OF THE CHURCH OF THE HOLY SEPULCHRE IN JERUSALEM

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**Abstract**:
*The Basilica of the Holy Sepulchre in Jerusalem's Old City is an architectural complex consisting of several different structures mainly built between the first century and the Age of the Crusaders. In the past two centuries a fire and an earthquake have damaged the Church. These events and the restoration work consequently undertaken define the current state of the building. In the Basilica, visited by large numbers of pilgrims, various religious communities still coexist. For the CABeC (University Centre for Cultural Heritage, Director Prof. P.G. Malesani) of the University of Florence the need to assess the effects of further seismic action has been an opportunity to undertake a major project aimed at understanding and preserving the Basilica.*
*The main precondition for the effective progress of the investigations is the reliability and completeness of data related to the geometry of the monument. The most innovative methodologies and instruments have been used the to document the state of the building: the joint use of GPS, total stations, photogrammetry and three-dimensional scans reach a real "integrated metric survey".*
*This paper focuses only on the data acquisition, carried out in three main campaigns between 2007 and 2008. Forthcoming publications will illustrate further elaborations, 2D and 3D graphical products.*

## 1. INTRODUCTION AND PRESENTATION OF THE PROJECT

The study described in this paper was undertaken in response to a request from the religious communities entrusted with the Custody of the Basilica of the Holy Sepulchre, that the seismic risk to which the Basilica is exposed be assessed. The initiative attests to the willingness of the Greek Orthodox, the Franciscans and the Armenians to participate in a common project for the better understanding and preservation of this monument.

The three-dimensional survey of the entire architectural complex aimed first at supporting structural analysis in defining the seismic vulnerability of the Basilica. This also allowed documenting - through 2D and 3D representations - the complicated structure of the whole complex for the purposes of research and preservation. A morphometric description is an essential precondition for correctly interpreting structural behaviour when analysing the seismic vulnerability of monumental buildings; the reliability and completeness of the geometrical data pertaining to the monument are essential for effective research. This is one of the reasons why geomatic methodologies and tools were used to metrically document the spatial architectural complexity: GPS, total stations, photogrammetry and three-dimensional scans were combined in a truly “integrated metric survey”.

Over the last decade, the laser scanner has proved to be a powerful instrument of three-dimensional metric survey and its use has greatly enhanced our understanding of historic monuments.

Detailed documentation of the present state of conservation of the Basilica of the Holy Sepulchre was collected applying digital and three-dimensional survey systems. Fig. 1 shows an example of the acquired data.

Once the appropriate positioning of the laser scanner has been calculated and the instrument settings have been defined, data acquisition can start. The laser scanner automatically “scans” all the surrounding space, transmitting a very rapid series of pulses and measuring an average of 50,000 points per second. It detects all surfaces that are visible from the instrumental position. When the result of the scans is appropriately aligned in a single reference system it provides a digital model of all the areas surveyed, made up of points in a 3D space.

## 1.1 The Basilica

At the beginning of the 1st Century AD the site of the Basilica was a disused quarry outside the city walls; tombs had been cut into the vertical west wall left by the quarrymen. In 135 Hadrian filled in the quarry and built a Capitoline temple. Macarius, Bishop of Jerusalem (314-33), demolished the temple and brought to light what has been since then considered the tomb of Christ.

The construction of Constantine’s church started in 326: it was comprised of an atrium, which reused part of Hadrian’s temenos wall, a covered absidal basilica, an open courtyard and the tomb.

The building was set on fire by the Persians in 614 and subsequently reconstructed by the Patriarch Modestus. In 1009 the Caliph Hakim destroyed the building again. A new restoration began in 1012, but a large part of the original construction (the atrium and the basilica) had to be abandoned.

The Crusaders transformed the restored church. During the 12th Century the monastery of the canons was erected and the crypt of St. Helena excavated; a Romanesque church covered the Constantinian courtyard and a bell tower was added. [1]

In subsequent centuries the church suffered desecration and destruction more than once and a series of improper repairs worsened the situation. A fire in 1808 and an earthquake in 1927 caused extensive damage, but it took until 1959 for the three major communities (Greek, Latin and Armenian) to come to agreement on a major repair programme [2,3].

**Table 1:** Characteristics of the surveyed building

| | |
|---|---|
| Dimensions of the block | about 140m (from Christian Road to Khan az-Zelt) x 110m (from St. Helen Road to Via Dolorosa) |
| Dimensions of the main building | about 120m x 70m |
| Max difference in height in the church | about 51m (from the ground of the quarry under St. Helen chapel to the top of the cross on the Anastasis Dome) |
| Surveyed area at ground floor | about 4.500 $m^2$ |
| Surveyed area at roof level | about 6.800 $m^2$ |

## 1.2 Previous surveys and archaeological studies

The Basilica has always been the object of many studies, as it is considered the symbol of Christianity [4, 5, 6, 7, 8, 9, 10, 11]. Father Michele Piccirillo, a Franciscan archaeologist, has recently carried out in-depth researches on the models reproducing the Holy Sepulchre on a smaller scale [12]. This may explain why he grasped the potential of this new method of producing documentation and of this new type of “model” which, though it remains three-dimensional, is now virtual (because it is numerical) and objective (because it is not the result of an interpretation). The coordinates of the millions of points acquired all refer to a single reference system. This means that it is possible to use the very detailed geometric database to provide information relating to distances and elevations, to check alignments, and to analyze different spaces even when they are not directly connected.

Even if we exclude the “Compendiario”-style and almost symbolic representations produced by pilgrims starting from the 4th-5th Century, this is not the first survey carried out for the whole complex. Some examples are the survey of Bernardino D'Amico, complete with measurements and deemed iconographically effective [13]; the patient work of analysis and interpretation carried out by Father Corbo [14]; the careful photogrammetric survey of Martin Biddle for the Aedicule [15, 16], as well as the admirable restitution of the whole structure performed recently by a team of Greek colleagues [17]. Consequently, our group took up a tricky challenge. Thanks to digital technologies, the third dimension is now the best tool to represent and explore real buildings too.

Therefore, the application of these systems of digital and 3D survey enabled the production of a very complete documentation of the present conditions of the whole complex, of the foundations resting on the rocks, up to the covering structure, representing a privileged viewpoint to understand the relations between the spaces of the Basilica and the spaces of the buildings surrounding it and crossing each other.

## 2. INSTRUMENTS AND SURVEY METHODS

The integration of different methods and measurement techniques made it possible to produce the info-graphical representations required for the structural study. The database is the starting point from which it is possible to extract different kinds of information required for documenting the Basilica: raster (rectified images and orthophotos), vectorial representations and three-dimensional models.

The integration of topographical, photogrammetric and scanning techniques enables geometrical and photographic information to be also integrated: the geometrical information was obtained from the detailed topographical survey and 3D scans, the photographic information was obtained by projecting high resolution photographic images onto the 3D model.
The following factors were considered in the data acquisition plan for the Basilica of the Holy Sepulchre:
- the number of scan positions was kept to a minimum to reduce costs and save time;
- complete surface documentation was required to avoid the final digital model having areas without data (the so-called "holes")
- subsequent phases of data elaboration required a sufficient degree of overlap between adjacent scans
- the surfaces had to be acquired from an orthogonal viewpoint in order to obtain the most accurate measurements.

Each range map is initially reported to a reference system intrinsic to the scanner. It is therefore necessary to define further the parameters of the geometric transformations required so the coordinates of the different scans can be expressed within a single reference system.

In the case of the Basilica of the Holy Sepulchre the laser scanner survey was referenced within a pre-defined topographical reference system.

**Figure 1:** The 3D survey of the facade: on the left, the 3D scanner in front of the Basilica; on the right, the acquired data.

The different kinds of numerical information produced by each acquisition technique are: three dimensional coordinates of topographic vertices and control points, analogical and digital stereo-models, 3D model of the building (as depicted in Fig. 2) which constitutes the metrical reference for subsequent analysis. The accuracy and completeness of the acquisitions and the methodological approach followed throughout the survey make it possible to process the data for seismic risk evaluation, and to subsequently integrate the data and process them for other purposes.

## 2.1 Survey campaigns

The speed of acquisition of the instruments employed reduced the time in situ to a few weeks. As summarized in Tab. 2, three survey campaigns were organized between 2007 and the end of 2008: the first from 16th to 30th of April 2007, the second from 24th January to 8th February 2008, the third from 19th November to 12th December 2008.

For the survey of the Church it was decided to start from the Anastasis and to gradually progress towards the outside where the interaction of the building with the bedrock on which it is founded could be documented.

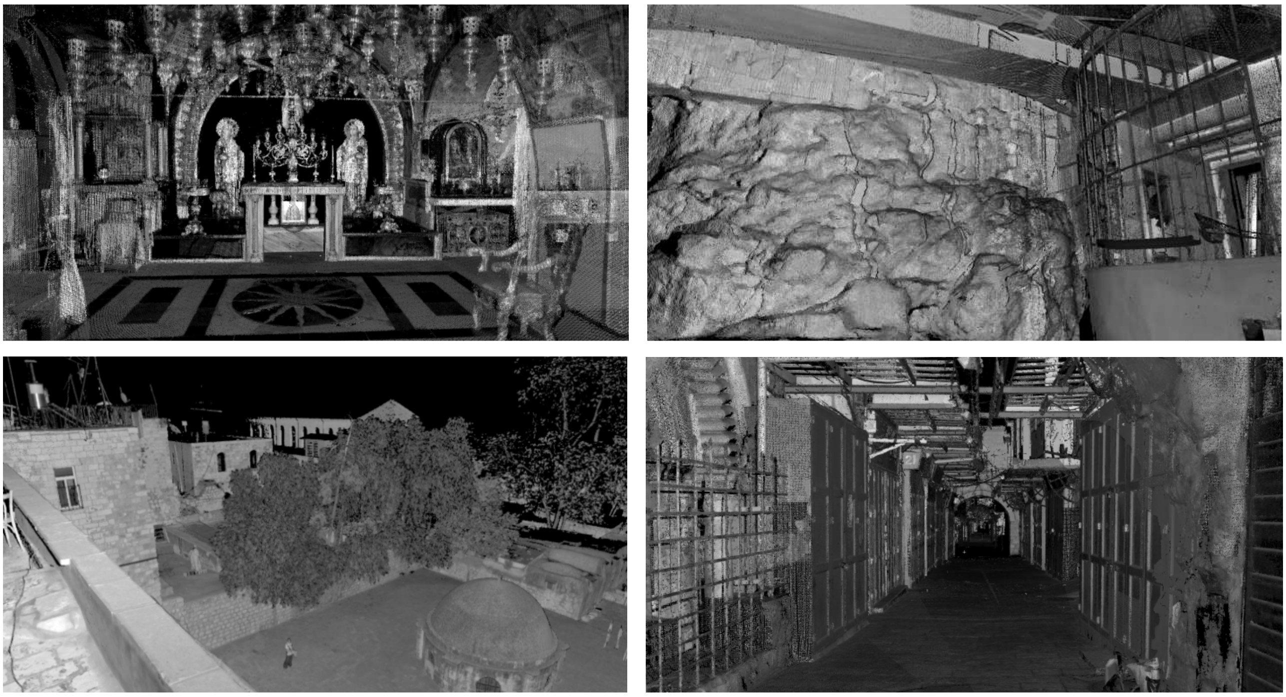


**Figure 2:** The relief has involved all involved all the internal ambient of the Basilica (on the left: the chapel on Golgotha; on the right, a view of the rocky configurations); the covering of the chapel of St. Elena, occupied in part by the Coptic monastery); the roads marking the boundary of the complex (on the lower right, Christian Road, from where there is access to the Basilica from the Crusades era).

Metric stereo photos were taken in order to complete the documentation of the surfaces.

To complete the metric acquisition phase photogrammetric images were taken and a thorough photographic documentation was obtained. These graphic representations were checked during the last campaign, which took place from 10th to 16th March 2009.

## 2.2 Quantification of the data acquired through 3D scanning

The number of 3D acquisitions required depends on the range of 3D scanners and on the complexity of the object being surveyed: in the Church of the Holy Sepulchre about 300 scans were carried out.

Common reference points were needed to link all the data acquired from different positions: for this purpose we used points of known coordinates in a single reference system, materialized by means of specific targets.

The scanning of internal environments has been carried out with a field of view of 360 degrees horizontally and 155 degrees vertically (excluding only the shadow cone projected by the tripod).

The scanning resolution was adapted to the average distance of the surfaces to survey.

By way of example, we consider here the technical characteristics of the laser scanner HDS6000, used in the last two measurement campaigns.

To acquire data for internal spaces we generally worked at a distance of 10-25 m from the surfaces to be measured; consequently, we set a “Medium” resolution corresponding to the points acquired at angular intervals of 1.26 mrad – i.e. 1 point/12 mm at 10 m, 1 point/3 cm at 25 m. The “Medium” resolution corresponds internally (externally a huge number of points is not acquired because it is oriented towards the sky or because it involves objects outside the measurement range) to an acquisition made of 5000 x 2150 points, i.e. 10.75 million points.

The internal scanning of the last mission, carried out with a “Medium” resolution, provides a complex database of over 1 billion points, while the external scanning of over 1.5 billion points.

**Table 2:** Summary of the activities during the three campaigns.

| | **1st campaign** | **2nd campaign** | **3rd campaign** |
|---|---|---|---|
| **Times** | April 2007 | January/February 2008 | November/December 2008 |
| **Instruments** | 1 scanner time of flight<br>1 total station<br>1 semi-metric photo-camera<br>1 calibrated digital camera | 1 scanner phase shift<br>2 total stations<br>1 calibrated digital camera | 1 scanner phase shift<br>1 total station<br>1 digital camera |
| **Team** | 4 people, in 2 working teams | 4 people, in 2 working teams | 5 people, in 2 working teams |
| **Scanning days** | 10 days | 10 days | 14 days |
| **Range maps acquired** | 37 scan positions | 93 scan positions | 120 scan positions inside the church<br>39 scan positions on the roofs |
| **Points** | About 235 million | About 1 billion | About 2.5 billion |
| **File sizes (.IMP databases)** | 5 GB | 22 GB | 31 GB data inside the church<br>21 GB data on the roofs |
| **Topographic vertices** | 6 vertices | 34 vertices | 40 vertices |
| **Target used to reference the scans** | 83 targets | 58 targets | 154 targets inside the church<br>57 targets on the roofs |

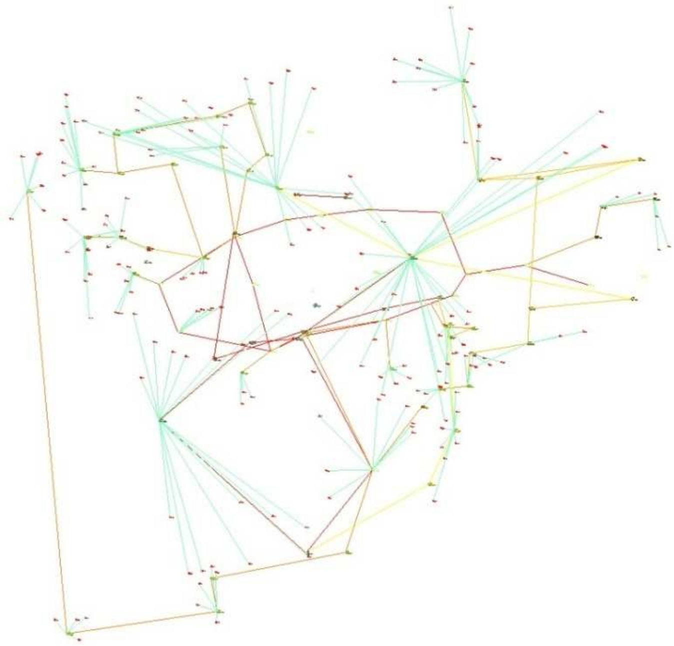
## 3. TOPOGRAPHICAL FRAMEWORK AND REFERENCE SYSTEM

In order to define a common framework for all the measurements acquired inside and outside the Basilica (as depicted in Fig. 5), a topographical network and a single reference system were established. This made it possible to merge all the data collected irrespective of the survey campaign, the area surveyed and the instruments used. It therefore becomes possible to gather all the data collected within a single model (even when the internal and external environments are not directly connected) and to evaluate, from a metric point of view, relations between different spaces. Let's consider, for example, the difference in height between Christian Road, which defines the western boundary of the structure, and the East front, on the *cardo maximo*. The adopted reference system has a false origin at the vertex V30 (1000m, 1000m, 500m) and the Y axis is north-oriented (WGS84).

The calculation and adjustment of the vertex coordinates of the main network were carried out with rigorous methods using the least square principle.

In order to extend the reference system to all the areas to be surveyed, the main network was integrated with secondary traverses; every vertex was materialized to simplify the retrieval process and to enable the following data update.

The detailed topographic survey was used to meet a twofold requirement: controlling points for range map registration, and controlling points for metric image orientation.



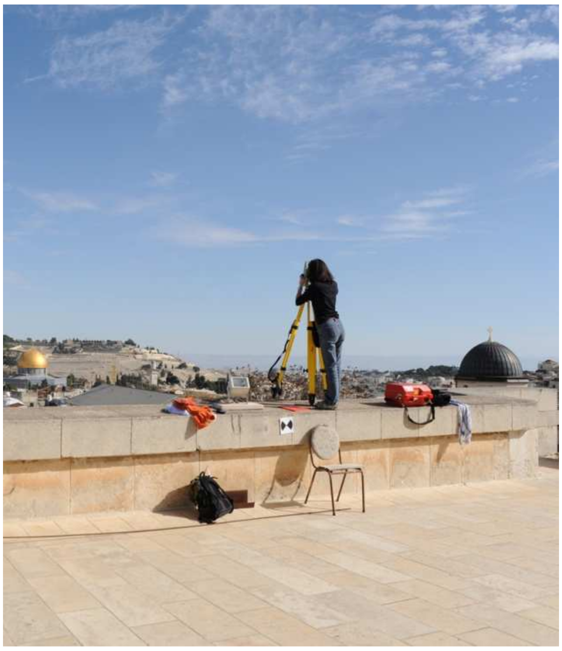


**Figure 5:** The topographical framework: on the left, the outline of the vertices; on the right, a view during the measurements.

## 4. DATA ORGANISATION

The large amount of data acquired by 3D scanning raises specific issues. For example, as far as geometrical information is concerned, 10 GB of data were acquired in the January/February 2008 campaign and 15 GB in the November/December 2008 campaign. The whole survey produced a total of more than 3 billion points: this enormous amount of data made it impossible for the entire model to be visualized or managed at the same time.

Hence, the database needed to be structured according to subprojects limited in size. This subdivision, established during the acquisition phase, was made taking into consideration the spatial articulation of the structures surveyed in order to base the following analyses on architecturally coherent portions.

The common referentiation of the different subprojects first enabled their partial reassembly into four macro projects and then the unit visualization of all the data acquired inside and outside the Basilica.

## 5. DATA ARCHIVING

During the acquisition phase, tool settings (scan resolution, acquisition area, file naming and so on) were controlled by a PC through a web browser. The data were stored on a hard disk inside the scanner and then imported into special software for their management (Cyclone, by Leica Geosystems).

The storage format is ZFS; once the data have been imported into Cyclone they are stored in the IMP database. Both formats are proprietary and undocumented and they allow using data only through specific software, by limiting the possibility of interchanging different formats.

The storage and archiving of the data acquired through scanning are part of a bigger issue concerning preservation and accessibility of digital information. The "Charter on the Preservation of Digital Heritage" adopted in 2003 by UNESCO states that "Continuity of the digital heritage is fundamental. To preserve digital heritage, measures will need to be taken throughout the digital information life cycle, from creation to access. Long-term preservation of digital heritage begins with the design of reliable systems and procedures which will produce authentic and stable digital objects." [18]

As regards data archiving, we chose the controlled duplication of information on hard disk. To ensure the possibility of accessing data, irrespective of the software currently available, they were exported to PTS format. It is an ASCII format that stores a list of coordinates and their corresponding intensity values, underneath a header with the number of rows (points) of the file.

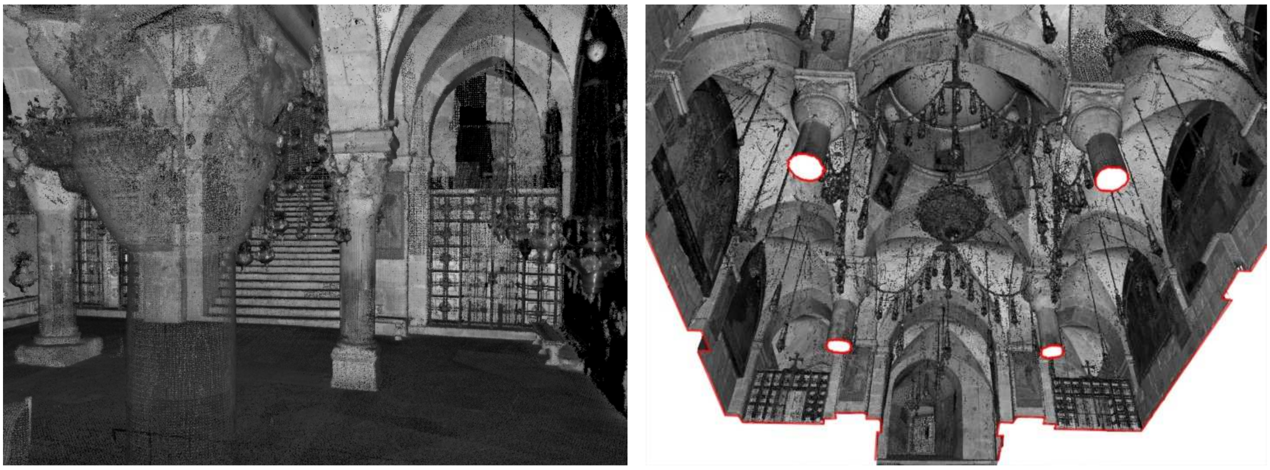


**Figure 6:** A relief of the chapel of St. Elena: on the left, as seen in the 3D model; on the right, the sectioned model to visualize the vaulted structures.

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The status quo and the large groups of pilgrims that visit the church make access difficult in certain areas. We were allowed access to all parts of the church and we were permitted to remain inside when it was closed to the public. The time spent inside the church together with the religious custodians living there every day helped us better understand the monument.
In particular, we would like to thank Father Michele Piccirillo, who both understood the potentiality of this new way of producing documents and grasped the significance of the “model”, and who enthusiastically followed this study up until it completion.