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DIPLOMA THESIS

COMPARATIVE INVESTIGATION OF THE 3D REPRESENTATIONS OF THE HOLY AEDICULE OF THE TOMB OF CHRIST

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LIST OF ACRONYMS

2D: Two-dimensional
3D: Three-dimensional
A.D.: Anno Domini
CSS: Cascading Style Sheet
C2C : Cloud-to-Cloud comparison
C2M : Cloud-to-Mesh distance or Cloud-to-Model distance
DoD : DEM of Difference
Dpi: dots per inch
EXIF: EXchangeable Image File format
FTP: File Transfer Protocol
GCP : Ground Control Points
GECO: Geomatics & Communication for Cultural Heritage Laboratory
GIS: Geographic Information System
GPS: Global Positioning System
ICP: Iterative Closest Point
IPTC: Information Interchange Model
M3C2: multiscale Model to Model Cloud Comparison
NaN : Not a Number
NTUA: National Technical University of Athens
QGIS: Quantum Geographic Information System
RMSE: Root Mean Square Error
TLS: Terrestrial Laser Scanning
uDig: User–Friendly Desktop Internet GIS
UNESCO: United Nations Educational Scientific and Cultural Organization
UNIFI: University of Florence (Università degli Studi di Firenze)
URL: Uniform Resource Locator
WCS: World Coordinate System

ABSTRACT

The present diploma thesis is aiming to investigate and compare the various three-dimensional representations of the Holy Aedicule of the Tomb of Christ, which exist both in physical and in digital form. More specifically, in the context of this research, the three-dimensional representations of the Aedicule are divided into two major categories: the replicas constructed worldwide and the geometric documentations of the monument's condition through the years. Regarding the replicas, a list of the detected representations is created and this database is visualized and depicted in an online web map. The data acquired during the surveys of the National Technical University of Athens and the University of Florence for the geometric documentation of the Aedicule, are further processed in order to construct a new 3D model and to compare the already existed 3D models. The major purpose of this thesis is to present the evolution of the form of the Aedicule, from the time of its erection until today, through its replicas and its geometric documentations. Additionally, this research's goal is to emphasize the global influence of the Tomb of Christ.

Initially, the main structural phases of the Aedicule are presented, including its destructions and restorations. Moreover, the different categories of the three-dimensional representations of the monument are defined. With reference to the replicas, both the reasons of their construction and their list in the form of a dataset table are presented. The specific database is visualized with the use of an open source Geographic Information System (GIS) and based on this visualization an online web map is created through the personal website provided by the National Technical University of Athens. Furthermore, the previous geometric documentations and surveys of the Aedicule of the Tomb of Christ are presented. An attempt is made for the construction of a new 3D model with the implementation of photogrammetry and the use of analogue data from the survey which was undertaken by the National Technical University of Athens in 1993-1995. A comparison is carried out between the 3D models of the Aedicule, which were created by the University of Florence in 2007 and the National Technical University of Athens in 2015. Following the decimation and the rigid body transformation of the 3D models, several cross sections are created for the calculation of deviation errors and the detection of deformations. Another way to detect deformations and differences between the two 3D models is through the M3C2 algorithm, which computes the local distances of the points of the 3D models. The impact of the Holy Aedicule across the world is examined through statistics based on the type, date of construction and location of the replicas. The possible deformations of the monument's structure are detected from the assessment of the results from both the processing and the comparison of the 3D models. In conclusion, future works are suggested focusing on the discovery of the total number of replicas worldwide and the monitoring of the condition of the Aedicule.

The software used during this research is Zoner Photo Studio X for editing the photographs, Geomagic for the transformation of the 3D models and the extraction of the sections, AutoCad for designing the sections, FileZilla for the online web map, CloudCompare for the M3C2 algorithm computation and the photogrammetric software Agisoft Metashape.

ΠΕΡΙΛΗΨΗ

Αντικείμενο της παρούσας διπλωματικής εργασίας είναι η μελέτη και η σύγκριση των τρισδιάστατων αναπαραστάσεων του Κουβουκλίου του Πανάγιου Τάφου, τα οποία υπάρχουν τόσο σε φυσική υπόσταση όσο και σε ψηφιακή μορφή. Ειδικότερα, στο πλαίσιο της συγκεκριμένης έρευνας, οι τρισδιάστατες αναπαραστάσεις του Κουβουκλίου κατατάσσονται σε δύο κατηγορίες: στα αντίγραφα του Κουβουκλίου που έχουν κατασκευαστεί παγκοσμίως και στις γεωμετρικές τεκμηριώσεις της κατάστασης του μνημείου στο πέρασμα των χρόνων. Σχετικά με τα αντίγραφα, δημιουργείται μια λίστα με τις αναπαραστάσεις που εντοπίστηκαν και στη συνέχεια η συγκεκριμένη βάση δεδομένων ψηφιοποιείται και απεικονίζεται με τη δημιουργία ενός διαδικτυακού χάρτη. Τα δεδομένα που συλλέχθηκαν κατά τη διάρκεια των μελετών του Εθνικού Μετσόβιου Πολυτεχνείου και του Πανεπιστημίου της Φλωρεντίας για την γεωμετρική τεκμηρίωση του Κουβουκλίου, δέχονται επεξεργασία προκειμένου να δημιουργηθεί ένα καινούργιο τρισδιάστατο μοντέλο του μνημείου και να συγκριθούν μεταξύ τους τα τρισδιάστατα μοντέλα που είχαν προκύψει από τις αντίστοιχες μετρήσεις. Κύριος σκοπός της συγκεκριμένης διπλωματικής εργασίας είναι η ανάδειξη των διαφορετικών μορφών και της κατάστασης του Κουβουκλίου , από τη στιγμή της ανοικοδόμησής του μέχρι σήμερα, μέσα από τα αντίγραφά του και τις γεωμετρικές του τεκμηριώσεις. Στόχος αυτής της έρευνας είναι επίσης να τονίσει το παγκόσμιο αντίκτυπο του Πανάγιου Τάφου.

Αρχικά, παρουσιάζονται οι κύριες κατασκευαστικές φάσεις του Κουβουκλίου, συμπεριλαμβανομένων των καταστροφών και των αποκαταστάσεων του μνημείου. Επίσης, ορίζονται οι διαφορετικές κατηγορίες των τρισδιάστατων αναπαραστάσεων του Κουβουκλίου. Σχετικά με τα αντίγραφα, αναφέρονται οι λόγοι κατασκευής τους και παρουσιάζεται η λίστα των αντιγράφων σε μορφή πινάκων. Η συγκεκριμένη βάση δεδομένων ψηφιοποιήθηκε με τη χρήση ενός Συστήματος Γεωγραφικών Πληροφοριών (ΓΣΠ) ανοιχτού κώδικα και δημιουργήθηκε ένας διαδικτυακός χάρτης που απεικονίζει αυτά τα δεδομένα. Στη συνέχεια, γίνεται αναφορά στις έρευνες και γεωμετρικές τεκμηριώσεις που έχουν πραγματοποιηθεί για την καταγραφή της κατάστασης του Κουβουκλίου. Παρουσιάζεται η προσπάθεια δημιουργίας ενός νέου τρισδιάστατου μοντέλου του μνημείου από αναλογικές φωτογραφίες που συλλέχτηκαν κατά τη διάρκεια της έρευνας του Εθνικού Μετσόβιου Πολυτεχνείου την περίοδο 1993-1995. Έπειτα, πραγματοποιείται σύγκριση μεταξύ των τρισδιάστατων μοντέλων του Κουβουκλίου που δημιουργήθηκαν από τις γεωμετρικές τεκμηριώσεις του Πανεπιστημίου της Φλωρεντίας το 2007 και του Εθνικού Μετσόβιου Πολυτεχνείου το 2015. Μετά από την μείωση των σημείων των μοντέλων και την εφαρμογή μετασχηματισμού που διατηρεί την κλίμακα στα συστήματα αναφοράς τους, σχεδιάζονται τομές των τρισδιάστατων μοντέλων του μνημείου για τον υπολογισμό σφαλμάτων απόκλισης και τον εντοπισμό παραμορφώσεων. Παραμορφώσεις εντοπίζονται και με την εφαρμογή του αλγορίθμου M3C2 που υπολογίζει τις τοπικές αποστάσεις μεταξύ των σημείων των μοντέλων. Η επίδραση του Πανάγιου Τάφου σε παγκόσμιο επίπεδο εξετάζεται μέσω στατιστικών αναλύσεων του είδους, της ημερομηνίας κατασκευής και της τοποθεσίας των αντιγράφων. Στο τέλος, παρουσιάζονται προτάσεις σχετικά με τον εντοπισμό του συνόλου των αντιγράφων και μεθόδους παρακολούθησης της κατάστασης του Κουβουκλίου στο μέλλον.

Τα λογισμικά που χρησιμοποιήθηκαν στο πλαίσιο της παρούσας διπλωματικής εργασίας αποτελούνται από το Zoner Photo Studio X, το Geomagic, το AutoCad, το FileZilla, το CloudCompare καθώς και το Agisoft Metashape.

1. INTRODUCTION

The present thesis is divided into six (6) different chapters and the content of each one of them is present below:

In Chapter 1 is the introduction, where the topic and the purpose of the specific research are defined as well as the significance of the Aedicule of the Tomb of Christ as a sacred site of cultural heritage.

In Chapter 2 the major structural phases of the Holy Aedicule are presented, from the original rock-cut tomb that the body of Christ was laid until the present day, including all the destructions and restorations it has undergone.

In Chapter 3 the reasons for the construction of three-dimensional representations of the Aedicule, especially of its replicas, are specified. The database, which was created with the aim to detect the replicas of the Aedicule and the Holy Sepulchre worldwide, is also presented. It includes information regarding the replicas such as their type (miniature model, true-to-scale replica, edifice, calvary or building inspired by the Holy Sepulchre), the place and date of construction and an image if existed. The procedure for the visualization of these data and the creation of an online interactive web map depicting them is also described.

In Chapter 4 the previous geometric documentations of the Aedicule of the Tomb of Christ are presented. Moreover, an attempt was carried out for the construction of a new 3D model of the monument. Analogue data were provided from a previous survey of the National Technical University of Athens in 1995. The two sets of data consisted of colored and grayscale photographs and were processed through an automated photogrammetric software.

In Chapter 5 a comparison is performed between the 3D models constructed during the surveys of the University of Florence in 2007 and the National Technical University of Athens in 2015. The Greek point cloud was decimated in order to achieve the same density with the Italian point cloud. A rigid body transformation was also required, because of the different reference systems of the 3D models. Initially, several sections were created at the aligned point clouds, a horizontal section (+1.60 m elevation), a transverse section and two longitudinal sections. Distance deviations were defined based on these sections. Finally, the differences of the 3D models and consequently the possible deformations of the structure were also detected through the computations of the M3C2 algorithm.

In Chapter 6, the final chapter, the results of all the previous investigations of this thesis are presented and evaluated and some potential future works are suggested focusing on the Aedicule of the Tomb of Christ.

Cultural Heritage is a living evidence of history, tradition, art, music, religion, customs and knowledge of the previous generations, which define the development of today's society worldwide. Based on the definition given by UNESCO in its Draft Medium Term Plan 1990-1995: *The cultural heritage may be defined as the entire corpus of material signs - either artistic or symbolic - handed on by the past to each culture and, therefore, to the whole of humankind. As a constituent part of the affirmation and enrichment of cultural identities , as a legacy belonging to all humankind, the cultural heritage gives each particular place its recognizable features and is the storehouse of human experience* (UNESCO, 1989). Cultural Heritage can be divided to tangible and intangible. Tangible cultural heritage consists of: movable cultural heritage (paintings, sculptures, coins, manuscripts etc.), immovable cultural heritage (monuments, archaeological sites etc.), underwater cultural heritage (shipwrecks, underwater ruins and cities). On the other hand, some examples of the intangible cultural heritage are the oral traditions, performing arts, rituals etc. (UNESCO, 2017).

The sacred sites constitute a special category of cultural heritage and represent the various traditions and cultures of the world. Their significance is undeniable, due to their combination of historical, spiritual and religious value to people and communities. Moreover, such monuments are considered to be blessed, because they are the places where either an incident of a saint's life happened or a personal item of a saint is located. The miraculous power of a saint is believed to be existent at these places and consequently they are respected by the faithful. Moreover, many sacred sites are often gathered in one area, depending on the history of each religion. As a result, numerous historic cities are recognized as holy cities by different communities, since they include various important sacred sites. There is one city, which has been acknowledged as the Holy Land for three different important religions from the very past until today. Jerusalem is the Holy City of Christianity, Judaism and Islam and faithful from all over the world undertake pilgrimages to this important religious destination. With a total of 220 historic monuments, it comes as no surprise that Jerusalem was included in 1982 in UNESCO's List of World Heritage (UNESCO, 2020). Among the sacred sites situated in Jerusalem there is one which proves the authenticity of the Christian belief. This is the Tomb of Christ, which is probably the most important monument of Christianity, because it verifies both the entombment and resurrection of Christ in the eyes of the Christians. The tomb is enclosed in a small edifice, which is called the Aedicule and its purpose of construction was to protect the most sacred monument of Christianity.

The Aedicule of the Tomb of Christ, like most cultural heritage monuments, is an important shrine which should be preserved through time for the next generations. The significance of preservation can be seen in the efforts of the national and international organizations which document cultural heritage objects and sites, with the implementation of both traditional and innovative methods. *The research area of Cultural Heritage is currently being influenced by computer technology and utilizing the advantages of digital documentation* (Georgopoulos, 2009). Regarding the conservation projects, a method which is identified by the scientific community as the most accurate for representing the morphology, texture and color is 3D modeling. The major contribution of 3D modeling in cultural heritage is at the restoration, monitoring, research, documentation, visualization and analysis of their condition (Chacon, 2016). In recent years, laser scanning and digital photogrammetry offered new perspectives for 3D cultural heritage recording, with precise and representative outcomes.

Consequently, when the integrity of the structure of the Aedicule was at risk, the experts who undertook several metric surveys for the geometric documentation of this edifice applied the specific techniques. The condition of the Aedicule was recorded in different time periods from various scientific groups, such as the University of Florence and the National Technical University of Athens. Thus, two 3D models of the Aedicule were constructed, one from each survey, which represent its state in 2007 and in 2015.

A different way of 3D representation and therefore of documentation of the Aedicule is by its replicas, whether they are buildings or relics. Many pilgrims took measurements of the dimensions of the monument when they visited Jerusalem, with the aim of reconstructing a replica at their homeland. The significance of this sacred site is highlighted through these structures which exist worldwide. Each replica corresponds also to a structural phase of the original, thus the study of these representations result in perceiving the evolution of the form of the Aedicule.

This present thesis will focus on the investigation of the three-dimensional representations of the Aedicule of the Tomb of Christ which exist either in physical or in digital form. Initially, regarding the replicas, a research will be held for the detection and archiving of as many of their locations as possible, with the aim of creating a list with their name, type, date of construction and image. Afterwards, this database will be visualized and digitalized with the use of an open source Geographic Information System (GIS). The final goal is the creation of an online interactive web map, which will depict all the spatial and attribute data related to the replicas. As a result, all the users of the internet will have access to the map and it will be possible to extract information about the place where the most replicas are located, which is the replica closest to them etc.

In the context of this thesis, the 3D models created by the University of Florence in 2007 and the National Technical University of Athens in 2015 were provided for further process. A comparison will be carried out between the two representations of the Aedicule of the Tomb of Christ. In this way, both the alterations and the deformations of the shape of the edifice through time will be detected, with the creation of 2D drawings and the application of the M3C2 algorithm. Furthermore, from the analogue data, which were acquired by the National Technical University of Athens during another metric survey on the monument in 1995, an attempt will be made so at to construct a new 3D model through digital photogrammetry and eventually compare the new reconstruction with the previous ones. Finally, based on the assessment of the results, the reasons of the probable deviations between the 3D models will be determined.

2. MAJOR HISTORICAL PHASES OF THE HOLY AEDICULE

There are many cities that have a great impact on the global developments and are landmarks of world history. Jerusalem is a prominent example, since it represents the place where numerous significant historical events occurred, from the day of its foundation until today. It s a multicultural city and *has a central role in the spiritual and emotional perspective of the three major monotheistic religions*: Christianity, Judaism and Islam (Gordon et al, 2019). Jerusalem is one of the most famous pilgrimage sites, especially for the Christian community. In view of the fact that, Jerusalem is the Holy City where the scenes of Christ's crucifixion, burial and resurrection took place. The Holy Rock of Golgotha (Calvary), the Tomb of Christ and the spot that parts of the Holy Cross were discovered are enclosed within the Church of the Anastassis (Resurrection) or the Church of the Holy Sepulchre, which is located inside the walls of the Old City of Jerusalem (Image 1). Adjacent to these main religious sites, there are also various chapels and monk cells from all the Christian Communities. The Greek Orthodox, the Roman Catholic Franciscans, the Armenian Apostolics, the Copts, the Ethiopians and the Syrians represent the Christian Communities that are all active and each one "owns" different sections of the monument. The peaceful coexisting and the respectful sharing of common areas for religious ceremonies are achievable due to the Status Quo of the Holy Sepulchre, which defines the ownership, the rights and the privileges of each community. The most vital religious shrine that all Christian Communities are devoted to and attracts thousands of pilgrims from around the world is the Tomb of Christ.

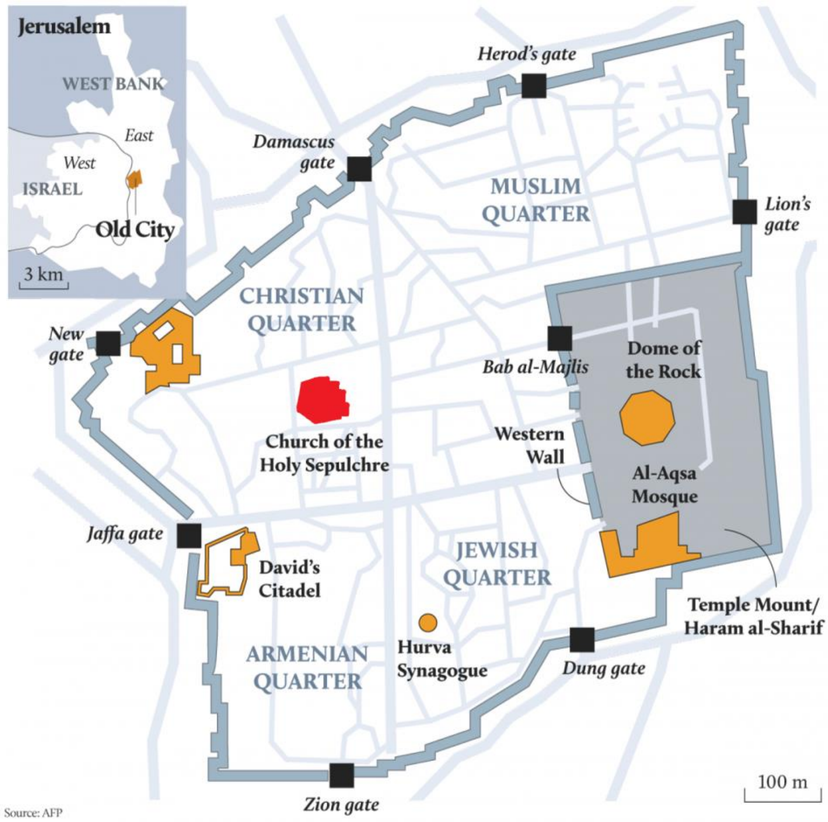


Image 1: The Church of the Hoy Sepulchre in the Old City of Jerusalem

©Middle East Eye

The Tomb of Christ, the place that Christ was temporarily entombed after his crucifixion and was found empty after the Resurrection, is situated in the Church of the Holy Sepulchre, in the center of the Rotunda which is a tall cylindrical building. The original Holy Rock is covered by the Aedicule or Kouvouklion (Κουβούκλιον) in Greek, a little structure that is aiming to protect and frame the holiest monument of Christianity. This significant small edifice has undergone various alterations from the time it was firstly erected until today, as a consequence of several destructions, damages, earthquakes, fires and attempts of reconstructions. The structural sequence of the tomb is divided into seven distinct periods:

1. From the original rock-cut tomb that the body of Christ was laid until the construction of the Hadrian's temple in 135 A.D.
2. From the buildings of Hadrian in 135 A.D. until the discovery of the tomb by Empress Helena in 325 A.D.
3. From the erection of the first Aedicule around the tomb by Constantine in 325 A.D. until the severe destruction by Khalif al-Hakim in 1009 A.D.
4. From the reconstruction of the Aedicule in the early 11th century by the Christians and the Crusaders until the restoration by Bonifacio of Ragusa in 1555 A.D.
5. From the Aedicule as rebuilt by Bonifacio in 1555 until it was damaged by fire in 1808
6. From the Aedicule reconstructed by the Greek architect Komnenos in 1810 until the rehabilitation project of the National Technical University of Athens in 2017
7. The Aedicule from the restoration of 2017 until the present day.

- <u>30-135 AD: Crucifixion and Resurrection of Christ</u>

There is no visual evidence of the form of original tomb where the body of Christ was placed after his crucifixion in 30 A.D. The only descriptions could be found at the events described by the Apostles in the Gospels. Even though there are many similar references of the crucifixion and the burial of the Christ at the majority of the Gospels, like in Mathew's, Mark's and Luke's, the one which is more detailed in the presentation of the form of the tomb is that of John's. The essential facts that should be taken into account seem to be that the tomb was outside the city in a cultivated area not far away from the place of the crucifixion, it belonged to a wealthy man and it was rock-cut, previously unused, with a large stone which could be rolled against the entrance. What is more, in order to go inside the tomb, there was a low passage. Within there was only one room which could fit at least five persons and on the right-hand was the burial bench where the body of Jesus had laid (Image 2). The kind of tomb suggested by the Gospels is alike the type of tombs which were constructed that period in the area of Jerusalem. Their characteristics are that they were hewn out of the rock, they had a low entrance which was closed by a moveable stone and they consisted of raised burial benches at their inner part (Biddle, 1999).

Image 2: The Tomb of Christ in 30 AD © *National Geographic*

Apart from the Gospels, there is also a different approach of the form of the tomb. Through the research of Martin Biddle (1999) based on the records of pilgrims and depictions from later periods, the new evidence suggests some alterations at the descriptions of the Gospels. First of all, the tomb consisted of two parts, a partly covered rock-cut porch and the enclosed rock-cut Tomb Chamber which were connected with a low passage. The entrance to the Tomb Chamber was closed by a large stone which was not necessarily round. At the interior of the Tomb Chamber there would be probably two or even three burial benches on the sides of the room. The shape of the chamber would be square or rectangular with a flat roof and its floor could have been lower than the porch. As far as the dimensions are concerned, *the porch could have been 3-4 meters wide and 3-4 meters deep from east to west.* Furthermore, *the Tomb Chamber was perhaps 2.8 meters square and 2 meters high, the benches were probably each 2 meters long and 0.8 meters wide* and 0.5 meters above the floor (Biddle, 1999).

The Gospels also specify that Jesus was buried outside of Jerusalem, near the place of his crucifixion on Golgotha ("the place of skulls"). In other words, according to the New Testament both the Tomb of Christ and Golgotha were located outside the walls of the city of Jerusalem in an area of abandoned stone quarries (Church of the Holy Sepulchre, 2020). Moreover, the presence of other tombs of the same period near the area where the Tomb of Christ was discovered indicates that it was a Jewish cemetery. In those times it was prohibited by law for cemeteries to be situated within the city (Romey, 2016). Thus, there is evidence which proves that the location of the crucifixion and burial of Christ in 30/33 A.D. was undoubtedly outside the city walls of Jerusalem (Image 3). On the other hand, the Church of the Holy Sepulchre in the present day is at the centre of the Old City of Jerusalem within its walls. This contrast between the recorded location and the reality was the main argument of the controversy for the authenticity of the traditional site. There were some people who suggested different rock-cut tombs as the original site of Christ's burial, such as the Garden Tomb (also known as Gordon's Tomb) (Bible Study, 2020). The excavations of Kathleen Kenyon in the 1960s, and later those of Ute Lux, not only revealed the course of the Second Wall of Jerusalem in Christ's time, but undeniably proved that the site of the tomb of Christ had indeed been outside the walls until the construction of the Third Wall by Herod Agrippa in AD 41-4. The traditional sites of the crucifixion and burial have remained within the city walls ever since. Unfortunately, nothing is known for the history of the Tomb of Christ for the era from the resurrection until 135 A.D.

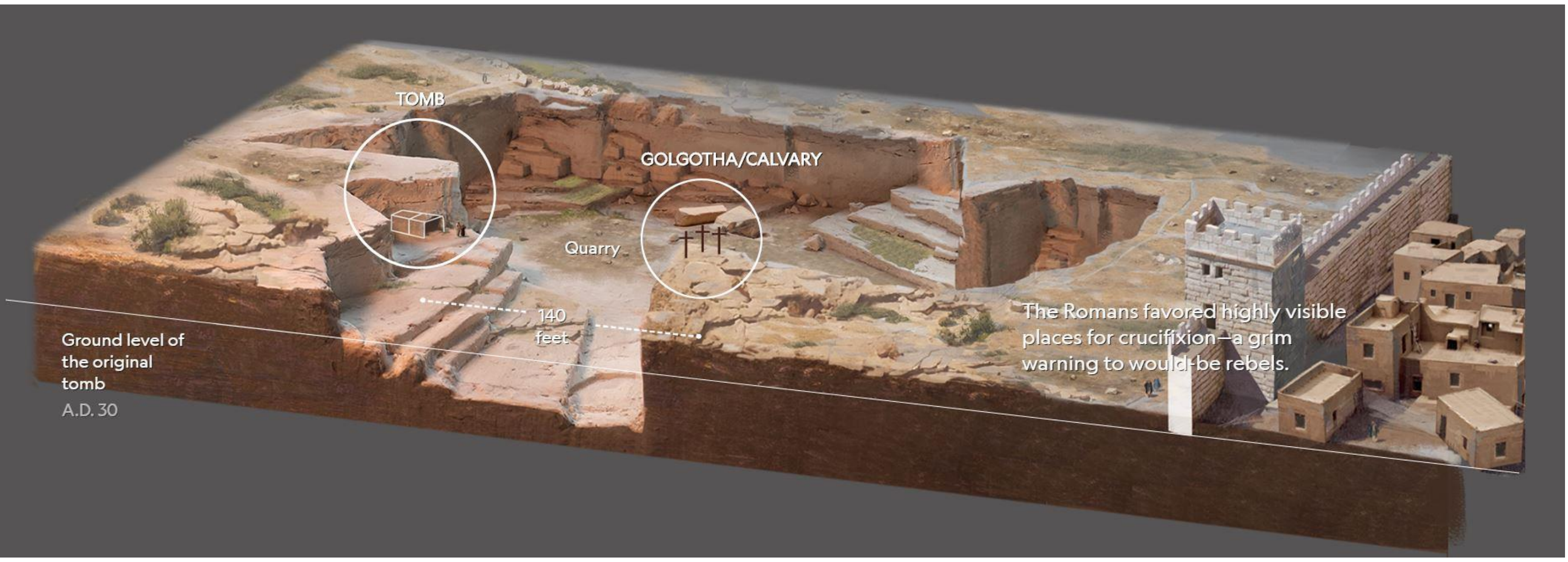


Image 3:The tomb and the Calvary in 30 AD © *National Geographic 2017*

➢ <u>135 AD: Hadrian</u>

The foundation of Colonia Aelia Capitolina by Hadrian in 130/1, on the ruins of the city destroyed in 70 from the first Jewish–Roman War, brought major alterations to the area. *Eusebius, Bishop of Caesarea, was an observer of Hadrian's buildings as they still existed in 320 A.D. and not only of their removal but also of what was revealed beneath them* (Biddle, 1999). Thus, he is an important witness of the constructions and the works that were made by Hadrian. According to Eusebius, the whole site had been covered with a great quantity of soil and paved with stone. On top of the leveled ground a temple to Aphrodite had been erected over the sacred cave. The fact that the temple was dedicated to Aphrodite is in contrast to the information provided by Jerome ("Epistola LVIII 3=PL XXII 581") who claimed that it was a temple of Jupiter with a statue of Venus standing on the rock of the Cross (Image 4). Nowadays it has been proven by Dan Bahat, an Israeli archaeologist, that the temple was dedicated to Jupiter (G. Lavvas, 2009). Since these structures were later demolished and new buildings were erected upon them, it is very difficult for modern archaeologists to identify the form of Hadrian's temple. Excavations at the interior of the Church of the Holy Sepulchre during the 20th century revealed remains of Roman buildings which are believed to be Hadrian's temple, but it is doubtful if they can be precisely dated (Romey, 2016).

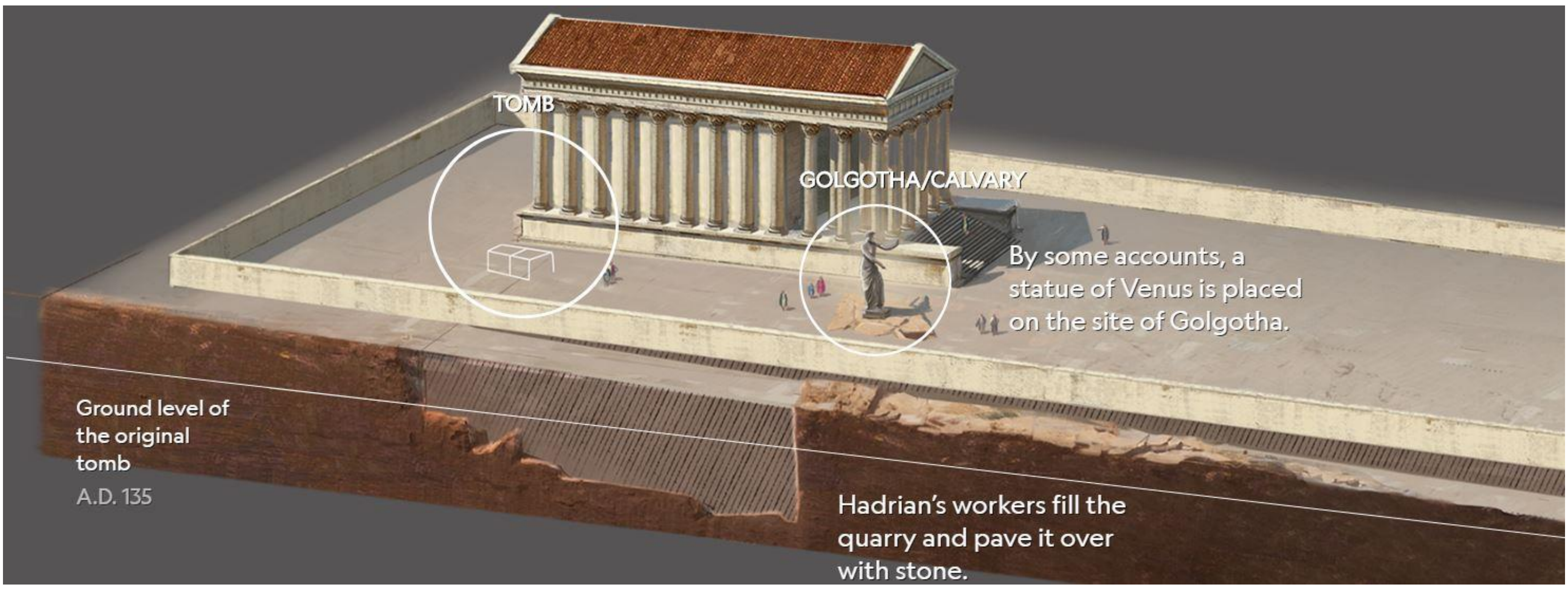


Image 4: The temple which was built by Hadrian in 135 AD © *National Geographic 2017*

➢ <u>326 AD: Emperor Constantine</u>

The rise of the Roman Emperor Constantine the Great, who converted to Christianity, marked the recovery and restoration of the Christian holy places in Jerusalem. His mother, the Empress Helena, on her famous pilgrimage to Palestine, caused the temple of Hadrian to be demolished, the soil to be removed and the sacred spot was found in its old condition. It is said that she had discovered Christ's Tomb there as well as the remains of the original Holy Cross. On this discovery, the emperor ordered the erection of a church which would house these holy sites and it would be *'on a scale of rich and imperial costliness' according to Eusebius* (Macpherson, 1892). Eusebius was the first one to visit the tomb immediately after its discovery. He describes the form of the tomb, indicating that in the inner space of the burial chamber there was only a carved out burial bench, which means that there was room only for one body. The burial chamber was small and its dimensions were approximately 2.10 meters in length, 1.30 in width and 1.90 in height. The bishop reports that Constantine's architects, led by Zenobius Eustathios of Constantinople, isolated the area of the tomb of Jesus and carved away the surrounding rock. This was the first recorded alteration in the tomb's appearance (Skarlakidis, 2015).

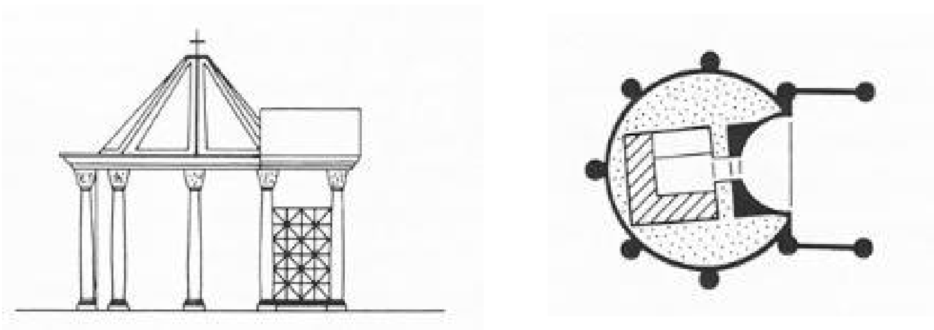


Image 5: (Left) South View of the Aedicule in 325 AD, (Right) Plan of the Aedicule in 325 AD

©Martin Biddle 1999

After the uncovering of the tomb and the removal of a part of the rock that was around it, Emperor Constantine erected also the first Aedicule which would enclose the sacred site and protect it. In essence, the Aedicule consisted of two parts. At the east side there was a porch which consisted of four columns and a gable roof. Passing the porch to the west was the entrance for the Tomb Chamber. The rock that remained around the burial chamber had a rounded or polygonal shape at the outside and it was decorated by five columns with semi-detached bases and capitals. Over the burial chamber a conical roof or tapering panels were placed, which were topped with a cross (Image 5). The stone that had closed the tomb was still lying before the entrance (Biddle, 1999). In addition, a new cylindrical building with a dome was erected, which was surrounding the Aedicule and was called the Rotunda.

- <u>614 AD: Persian Emperor Chosroes II</u>

During the Dark Ages that succeeded the fall of the Roman Empire and the era of barbarian invasions from the East, the monuments on the Holy Sites at Jerusalem were in great danger (Jeffery, 1919). In the year 614 the Persians under their emperor Chosroes II invaded Palestine. They destroyed a large part of Constantine's church by setting it on fire. The Tomb of Christ was also damaged. *What is more, the Holy Cross, which was thought to have been the original that was discovered by Constantine's mother Helena in 326 and was kept with other relics of the passion in a treasury room, was stolen by the Persians (Wright, 1995).*

- <u>629 AD: Abbot Modestos</u>

Fifteen years after the first destruction of the church an attempt was made to restore it. The person who was responsible for the reconstruction of Constantine's church was Modestos, Abbot of St Theodosius. The completion of the works was achieved in 629, the same year of the triumphal return of Emperor Heraclius who celebrated his victory over Chosroes and brought back to Jerusalem the Holy Cross, which he had recovered from the invader on the 14th of September. Although Modestos was aiming to rebuild the whole complex identically to its initial form, the restored church was not as beautiful and magnificent as it was before the destruction. Detailed information of the outcome of the restoration is provided by Arculf, a French bishop, who visited Jerusalem in 670 A.D. The church preserved its round shape and in the center of it was the Tomb of Christ. The bishop describes the tomb as 'a round cabin cut out of the rock'. He refers to the elevation of the burial chamber, which was 'a foot and a half' above a standing man of ordinary height. Furthermore, the exterior of the tomb was covered with marble and a golden cross was placed at the summit of the roof. On the other hand, the interior was unadorned, so that the marks of the hewer's tool could be distinguishable on the rock surface. The burial bench was located at the north side of the chamber 'three palms from the floor and about seven feet in length'. Arculf also records that there were twelve oil-lamps in the Tomb Chamber that were burning night and day. Regarding the stone which used to cover the entrance to the burial chamber, it was broken in two parts. The smaller part was used as an altar at the entrance, while the larger part was similarly used at the eastern side of the Rotunda (Macpherson, 1892).

- <u>637 AD: Arab invasion</u>

Jerusalem was occupied by the Arab Mohammedans for the first time. The Christian leader decided to surrender to the khalif when he was ensured that his people would be safe and secure, the Christian churches would be preserved and they would still have the right to worship within them (Macpherson, 1892). The Arabs did not cause any damage to the restored church or the Tomb of Christ and they were peacefully coexisting with the Christians at the holy site. *The friendly terms on which Moslem and Christian at first lived together in the Holy City seem to have been continued during the ninth century, taking under consideration the legendary history of Charlemagne and his friend Haroun-er-Raschid* (Jeffery, 1919).

- <u>1009 AD: Khalif Al-Hakim Bi-Amr-Allah</u>

Even though Muslims and Christians were initially living in harmony, the situation changed rapidly when al-Hakim bi-Amr-Allah, the ' mad khalif of Egypt' was the ruler of the area. In 1009 he ordered Yaruk, governor of Ramla, to completely destroy the church of the Resurrection and 'knock the church down to its foundations'. Apart from parts of the Church or things that were impossible to be destroyed of difficult to be taken away, the destruction of the building was massive (Biddle, 1999). The damage which was caused to the whole structure was incomparable to any previous vandalism and the command was so faithfully carried out that there was also an attempt to destroy the Tomb of Christ. It is possible that the tomb was injured but eventually it was not destroyed (Macpherson, 1892).

- <u>1012-1023 AD</u>

Three years after the complete destruction of the church of the Holy Sepulchre, in 1012, the Christians were permitted to start repairing and reconstructing what had remained of the previous building. In 1014 an attempt to rebuild the Tomb of Christ was made by al-Hakim's mother Maria, who was Christian herself. These years constitute *the first phase of the post-Hakim reconstruction* (Biddle, 1999).

- <u>1037-1040 AD</u>

The second phase of the reconstruction was taken over by the Byzantines and it started around 1037/1038 and finished either by the time of Michael IV the Paphlagonian (1034–1041) before 1041 or of Emperor Constantine IX Monomachos (1042–1059) in 1048 (Jeffery, 1919). The Byzantines at first focused on the reconstruction of both the Rotunda and the Tomb of Christ but the entire complex became much smaller. Concerning the Aedicule, taking into consideration that during the restorations, at least the lower part and thus the plan of the tomb was preserved, there can be no surprise that the form and the functional elements of the Constantinian monument were reflected in the Byzantine Aedicule. *The eleventh-century Aedicule consisted of two principal elements: a rounded western structure enclosing the burial chamber and a narrower rectangular eastern room providing the entry to the tomb* (Biddle, 1999).

➢ 1099-1187 AD: Crusaders

The Crusaders' mission was to secure the control of the Holy Land, which was considered sacred from both Christians and Muslims, through a series of religious wars. Their goal was accomplished already at the First Crusade in 1099, when they entered in the Church of the Holy Sepulchre as victors. Jerusalem was again under the control of Christians until 1187. During this period a slow progress of reconstruction had began**.** When it comes to the Aedicule, the main part of the form of the edifice was altered with the adjustment of four additional elements, which were never significantly modified and they still exist in the form of the Aedicule as it is the present day. These elements are:

1. An eastern room (now the Chapel of the Angel), which was fully integrated with the rounded western structure, thus leading to the characteristic horse-shoe shape of the Aedicule (Moropoulou et al,2019)
2. A cupola supported on pillars, which was covered with silver plates and set on top of the western structure, over the burial chamber
3. A chapel attached to the west end of the Aedicule, an altar surrounded by iron walls and a roof of the same material (now the Coptic Chapel). The altar is believed to be situated against the place where Christ's head rested at the time of his burial (Wright, 1995).
4. Two benches, which were placed at the entrance on the sides of the door of the Aedicule.

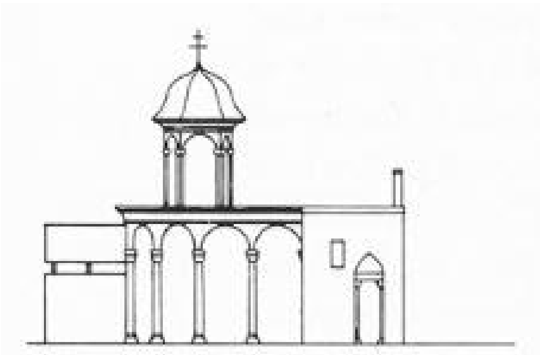
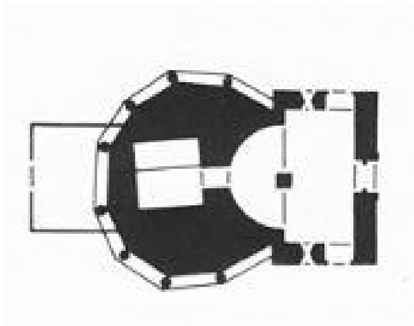



Image 6: (Left) South View of the Aedicule in 1099, (Right) Plan of the Aedicule in 1099 ©*Martin Biddle 1999*

The cupola and the western chapel were first recorded in the twelfth century.

The eastern room corresponds to the porch with the gable roof supported on four columns, which was forming the entrance of Constantine's Aedicule. *The spaces between the columns to north and south were closed by low railings and the space to the east by a double gate.* From pilgrims who visited the site, it has been recorded that the porch had three gates and each one was three feet wide and seven feet high: one at the northern wall, one at the eastern wall and one at the southern wall. Moreover there were guards in the porch, controlling the people coming in through the north gate, visiting the tomb and leaving through the south gate. The west wall of the porch was apsidal. The two side doors were walled up by the Muslims after the surrender of the city in 1187 and as a result the porch was turned into a fully enclosed room with a single entrance from east.

It is not yet known when exactly the benches were installed in front of the entrance of the Aedicule. It is possible that they were placed after the walling-up of the north and south doors of the porch. That is why, the guardians controlling the entry to the tomb would have been standing outside the single eastern entrance at that time, so the purpose of the benches would probably have been to accommodate the guardians of the Aedicule.
The Tomb Chamber was rebuilt and enclosed in a rounded structure, which was decorated externally with eight columns carrying an arcade of rounded arches. A domed roof was constructed over the tomb in order to leave an opening for the practical purpose of allowing the smoke of the oil-lamps to escape. However, since the dome of the Rotunda was open at the top, allowing the rain to pour in, the new opening was covered by a cupola supported on six columns (or six pairs of columns) (Image 6).

The form of the burial bench was also modified by the Crusaders. Both the upper surface and the vertical face were covered with marble slabs and the original rock, that the body of Christ was said to have been laid upon it, was no longer visible. This coverage was placed around the Holy Rock so as to protect it and prevent the pilgrims who visited the tomb from cutting away parts of it as relics. However, pilgrims were able to touch the rock through three circular holes that were pierced at the marble slab of the vertical face of the tomb.
Between 1099 and 1106/8 the Crusaders made some more alterations at the Aedicule of the Tomb of Christ. They had erected a gilded silver figure of Christ on top of the cupola, which was later removed, possibly because it was tarnishing under the open dome. It had been replaced by a cross topped by a bird, a dove in particular, and both of them were presumably made of a material that was not affected by the weather. The cupola was likewise covered with plates of gilded silver and the flat roof of the Aedicule with sheets of gilded copper.

Sometime before 1170 the Crusaders covered the interior with mosaics and it was perhaps at this time that the eastern compartment became more solidly enclosed. At least fourteen Latin inscriptions were placed around the exterior, in the Chapel of the Angel, in the Tomb Chamber and at the ironwork enclosing the altar built against the west end of the Aedicule. In the middle of the century the Byzantine emperor Manuel I Comnenos (1143-80) covered the burial couch with gold.

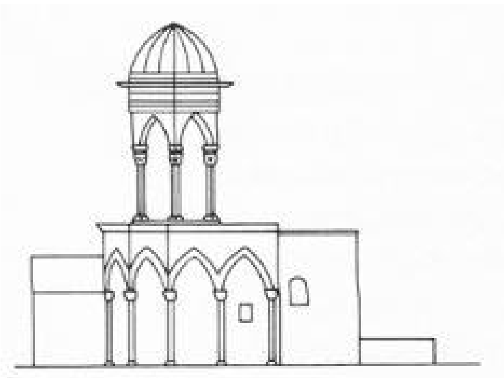
By 1187 the decoration of the Aedicule had reached a peak of magnificence it has never since regained. Nevertheless, this state of the Aedicule would not be preserved for a long time, because the autumn of that year the silver that covered the exterior was stripped off. It was minted into coins in order to pay the knights who would defend the city from its invaders. Eventually, Jerusalem surrendered to Saladin on the 2nd of October 1187. After the negotiations over the future of the Church of the Resurrection, the Christians were permitted to keep the possession of the church and it was not therefore demolished (Biddle, 1999).

- 1244 AD

In June 1244 Jerusalem was under the Khwarazmian dynasty. According to the testimonies of that period, the Muslims were furious and disrespectful towards both the Christians and their holy sites. The events that occurred between the two different religion groups, as described by the witnesses of that time, were aiming to disgrace the Christians. Thus, not only Christian families were harmed, but also the most important monument of Christianity, the Tomb of Christ. The damages of the Aedicule were focused mainly at the exterior, with the removal of the marble slabs covering the surface of the tomb and of the carved columns that were placed in front of the tomb for decoration. From the records of the Christians for the specific era, their despair is detected and that is why it is possible that they had been exaggerated at some points. But the details of the damage provoked to the Aedicule are precise. For the next three centuries until 1555 the Aedicule seems to have been in continuous decay. There is no record of repairs, probably because these were forbidden (Biddle, 1999).

- 1555 AD: Bonifacio of Ragusa

The state of the Aedicule as time passed was deteriorated and decayed. After the damages that were caused by two strong earthquakes in 1453 AD and in 1545 AD, the restoration of the edifice was then crucial. In 1555, restoration was carried out by the Franciscan custodian, Bonifacio of Ragusa. It has also been recorded that on 27 of August 1555 the Tomb of Christ was opened and the original form of the rock-cut tomb was visible during the restorations of this period. Although, as Bonifacio had claimed, the reconstruction was from the foundation, there is a possibility that only the cupola was restored and some parts of the structure were repositioned (Moropoulou et al, 2019) (Image 7). In the course of the centuries following the specific restoration, the Aedicule began again steadily to decay. Through the years, some blocks of the marble were removed and new ones were placed, but apart from that no more repairs were possible to be applied to the Aedicule (Biddle, 1999).



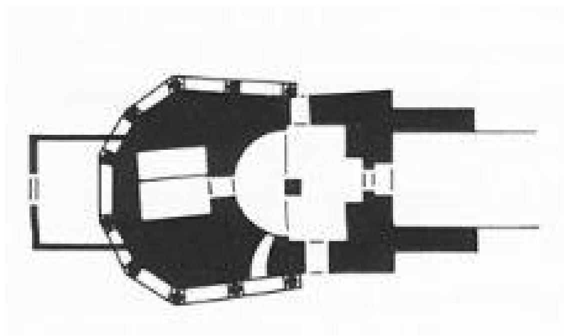


Image 7: (Left) South View of the Aedicule in 1555, (Right) Plan of the Aedicule in 1555

©Martin Biddle 1999

➢ <u>1728 AD</u>

Some years after Bonifacio's adjustments, further restoration was carried out by the Franciscans in May of 1728. In this case the work was completed in a very short time and was aiming on reconstructing the marble slabs of the interior of the Tomb Chamber of the Aedicule. The restoration was observed by Father Elzear Horn, who had the opportunity to examine the material behind the marble slabs of the chamber. According to Horn, the Tomb Chamber was not completely built in the living rock as he expected, but there were walls made of stonework in some parts. *Despite the fact that it hasn't been recorded to which marble slabs Horn was referring, it is still visible until nowadays that the west and east walls are constructed at least partly of cut stone and not out of rock.*

➢ <u>1808 AD: Fire destruction</u>

The Church of the Holy Sepulchre was once again extensively damaged by a fire that broke out in 1808. The roof of the Rotunda collapsed on to the Aedicule and as a result the outer parts and the cupola of the edifice were mainly damaged. The door of the Aedicule survived the fire and is preserved today in the Museum of the Greek Orthodox Patriarchate. The signs of the fire are still visible on the surface of the door, with its lower part on the outside blackened and slightly burned. It seems that the door had protected the interior of the Aedicule from the worst effects of the heat and smoke, although some of the decorations located in the Chapel of the Angel were eventually destroyed (Biddle, 1999).

➢ <u>1809-1810 AD: Kalfa Komnenos</u>

Since the last destruction caused by the fire of 1808, the whole complex of the Church of the Resurrection and especially the Tomb of Christ were in urgent need of a reconstruction. Therefore, in March 1809 the Greek Orthodox community obtained from Sultan Mahmud II a firman authorizing them to restore the church, but the work should have been completed within a period of thirteen months (Lavvas, 2009). The person who was responsible for the accomplishment of this goal was a Greek architect called Nikolaos Ch. Komnenos. He was also known as Kalfa Komnenos, a characterization in Turkish which means 'master builder'. The restoration of the buildings of the Church of the Holy Sepulchre began on the 3rd of May 1809 and were completed on the 13th of September 1810, which is a remarkable short period of time taking under consideration the extend of the assignment Komnenos had undertaken. Regarding the Aedicule of the Tomb of the Christ, it was rebuilt from its foundations in March 1810. The only parts that remained in their position were the marble slabs of the Tomb Chamber, the base of the structure's exterior and the Coptic chapel which preserved its shape and form. The Chapel of the Angel, the dome over the Tomb Chamber, the exterior walls and the cupola were rebuilt in the new style (Image 8).

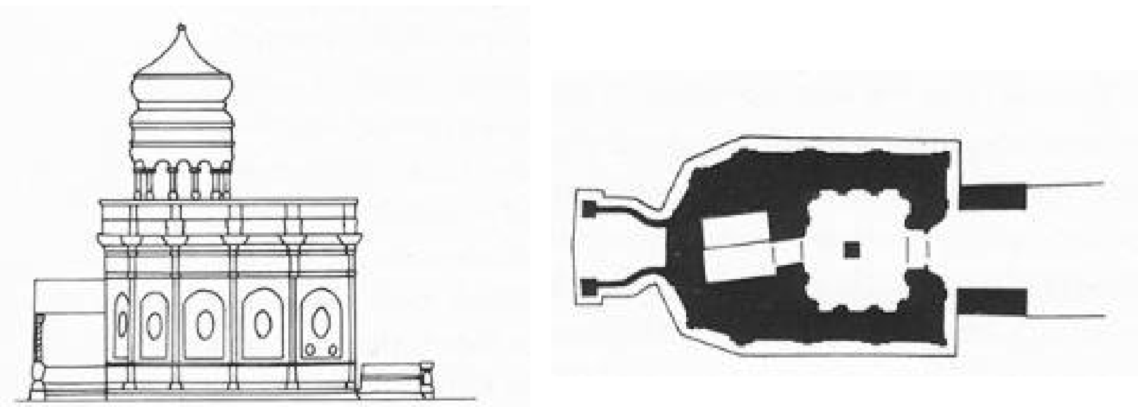


Image 8: (Left) South View of the Aedicule in 1810, (Right) Plan of the Aedicule in 1810

©Martin Biddle 1999

The Aedicule was dismantled down and all the external material surrounding the edifice was removed. Maximos Simaios was present during the restoration in October and November 1809 and recorded what was revealed concerning the structure of the Aedicule. The Tomb Chamber was partially formed in the rock, the north and south walls in particular, but the east and west walls as well as the roof were built up with stonework. Moreover, the Chapel of the Angel was artificial in total. The floor both in the Tomb Chamber and in the Chapel of the Angel was the natural rock. *As Maximos' description suggests, Komnenos opened only the west end of the tomb-structure, the marble slabs were left in their position and the east end was observable from outside, without being dismantled.* At the upper surface and the vertical face of the burial bench there were two layers of marble slabs. If the outer layer comprised the marble slabs still visible today, the inner layer could have been the medieval slabs, which could possibly had been left in position and covered by Bonifacio of Ragusa in 1555 and they were removed by Komnenos. It is believed that the marble slabs covering the burial bench were not removed, since the inner part of the Tomb Chamber was not damaged by the most recent fire. However, there was an alteration over the marble slabs of the burial bench with the addition of shelves made of red marble on the west, north and east sides of the room. *A marble icon of the Anastasis above the tomb replaced a painting of the same subject of the sixteenth century or even from medieval date* (Biddle, 1999).

- 1927 AD: Earthquake destruction

The Aedicule was damaged once more by an earthquake in 1927. Furthermore, several structural defects existed that had a great impact on the structure of the edifice. For example, until the central opening of the dome over the Tomb of Christ was provided with a cover rain poured down to the Aedicule. The water rotted the connective materials that were keeping the edifice in one piece. As a result the weight of Komnenos upper works, such as the cupola over the Tomb Chamber and the domes in both chambers, was causing major problems to the stability of the structure. Consequently the external marble panels were forced to bulge outwards and presented many deformations.

- 1947 AD: Iron frame installation

An external iron frame was installed by the Public Works Department of the British Mandatory Government of Palestine in March 1947 (Image 9), as a temporary solution, in order to prevent the collapse of the Aedicule (Moropoulou et al, 2019). The religious communities of the Church of the Holy Sepulchre cooperatively decided that the restoration of the church was a vital parameter for its survival. Thus, in 1960 a Common Technical Bureau started working on the reconstruction of the building and a recovering of the ancient infrastructures (Constantinian, Byzantine and Crusader) was achieved. Although a new dome was constructed for the Rotunda by two British engineers, the Aedicule did not undergo any modifications and was still in a hazardous state (Biddle, 1999).

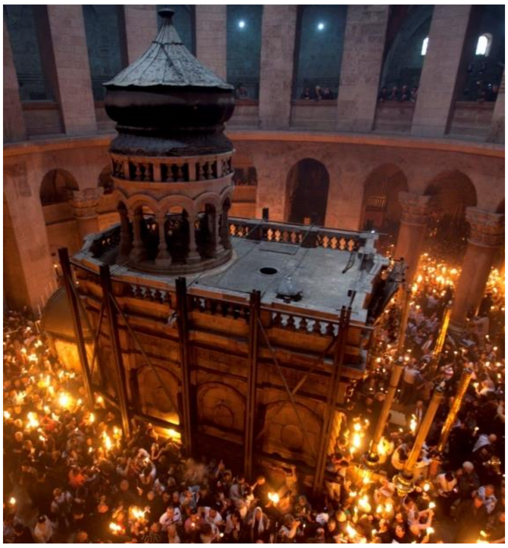


Image 9: The Aedicule with the iron frame installation © *The Daily Beast*

- <u>2016-2017 AD: Rehabilitation Project by NTUA</u>

After many years of decaying, a rehabilitation project was carried out focusing on the Aedicule by the National Technical University of Athens, which would intend to restore the monument. The research on the condition of the Aedicule's structure was initiated on the 22nd of March 2016. Based on the results of the study and the proposals for the modifications, the rehabilitation project was successfully completed in March 2017. The main goal of the specific restoration was the assurance of the sustainability of the Aedicule, which was finally achieved. Throughout the rehabilitation project the Aedicule was accessible both to the pilgrims and to the Christian Communities for the performance of their ceremonies within the monument. The major adjustments and alterations that were carried out during the restoration of the Aedicule consist of:

- The dismantling and removal of the stone panels from the exterior facade. This process was applied to specific areas and not across the entire edifice, because *deformations had been observed only at the middle to lower parts of the overall structure.* Each stone slab was fully documented with the use of 3-D laser scanning and was later transferred to the conservation laboratory, where it would undergo cleaning and protection interventions.
- After the stone panels were removed the filling mortar and the inner masonry were revealed. Subsequent step was the cleaning of the joints, the replacement of the damaged mortars with a compatible one and the application of grouts as well as various new reinforcements systems.
- *Following the strengthening of the main masonry, the external stone panels were reassembled*. Moreover, a restoration concrete was added between the masonry and the stone slabs for further support.
- The columns not only at the interior of the Aedicule but also on the external facade were reset in order to be vertically realigned.
- The opening of the Tomb of Christ was necessary during the grouting of the structure, in order to protect the burial surface. Consequently, after the permission of the Christian Communities, the top marble slab was shifted and the original rock was revealed. In addition, parts of another tombstone with a cross engraved upon it were discovered, which had probably been used as a previous cover for the Holy Rock during the Crusaders period.
- Also, a window-like opening was created in the interior wall opposite the tomb to control the grouting at the south interior area. As a result, a glass window was installed later so as to provide views of the Holy Rock.
- Finally, the iron frame that was installed in 1947 and supported the Aedicule since then was removed after the rehabilitation project (Moropoulou et al, 2017).

The Aedicule at the present day has obtained again its magnificence, which reflects both its historic and religious value. Its style and form are identical to the architectural style that Komnenos had created in 1810 (Image 10). The monument has approximately a length of 8.3 meters, a width of 5.5 meters and a height of 6.7 meters plus the 6 meters cupola on its roof (Georgopoulos et al, 2017). When entering the Aedicule there is the Chapel of the Angel in memory of the angel who appeared to the Holy Women, sitting upon the great stone that had closed the tomb entrance, and announced the Resurrection to them. Part of that stone is preserved in the middle of the chapel. There are also two staircases inside this chapel, the one on the right is used by the Latins and the one on the left by Orthodox and Armenians and two small circular windows on the north and south sides of the room. Beyond there is the Tomb Chamber, which is connected with the previous chamber with a narrow short passage. The burial bench is located at the north side of the chamber and above it there are three depictions of the Resurrection: the middle one is Greek, the left one Latin and the right one Armenian (J.R. Wright). Last but not least, not only at the inner part, but also at the outer part there are many oil-lamps, candle-holders and inscriptions in Greek which invite all the people to praise the risen Christ (Gil et al, 2019).

Image 10:The Aedicule at the present day © *National Geographic*

3. REPLICAS OF THE AEDICULE OF THE TOMB OF CHRIST

3.1. THREE-DIMENSIONAL REPRESENTATIONS OF THE AEDICULE

It is beyond doubt that the Holy Sepulchre and more specifically the Tomb of Christ, is a unique monument with great significance not only for Christianity but also for the whole world. It indicates the place where it is believed that Jesus was temporarily buried for the three days before his resurrection. Both death and resurrection constitute the most important events and are the foundations of the Christian faith. This is the reason why the Holy Land is one of the most famous pilgrimage sites from the very past until today.

The places where saints had lived or their relics were located constitute exceptional and essential destinations for the pilgrims, even from the beginning of Christian pilgrimage in the 4th century. It was believed that *the benevolent power of holy persons was present both in their mortal remains after death and at their burial sites.* Consequently, those places were considered to be divine and pilgrims would visit them so as to pay tribute to the memory of saints or to profit from their power to cause miracles. The showplaces of the life and Passion of Christ in the Holy Land could not be excluded from this category of sacred sites. Moreover, the measuring of sacred objects or places by the pilgrims was an alternative way to retain a part of their spiritual energy. It should be emphasized that *the degree of the sacredness of a site was proportional to the care with which pilgrims recorded its measurements.* Therefore, it comes as no surprise that the Tomb of Christ was documented with particularly numerous measurements by most pilgrims, in compare to all the other sacred sites (Naujokat, 2014). Finally, some of the pilgrims, when they returned to their homelands, they would take advantage of these measurements by constructing replicas of the holy monuments.

As a result, there are many examples of various attempts of reconstructions regarding the Aedicule across the globe. It is even conceivable that this monument, in particular, was represented in three-dimensional reconstructions from the early days of Christianity until today. Even if there might be multiple differences according to the purpose of formation, the accuracy of the measurements or the equipment that was used for each case, their importance is equivalent. Bringing the three-dimensional documentations of the Aedicule into focus, they could be divided into three categories:

- the true-to-scale replicas (1:1)
- the replicas produced at a different scale, usually smaller, in contrast to the original (1:N)
- the Point Clouds which were created with the implementation of either laser scanning or photogrammetry and are stored in digital form.

The history of the evolution of the Aedicule of the Holy Sepulchre of Jerusalem could be highlighted from the research on these representations of this small edifice. The several structural phases of the Aedicule in Jerusalem could be identified through their reconstructions, even those forms that no longer exist. Thus, each kind of the three-dimensional documentations provides information for both the edifice itself and the expansion of Christianity through the Tomb (Guilbert-Roed, 2017).

3.2. STRUCTURES AND EDIFICES

In various parts of the world, there have been numerous edifices erected and small objects constructed, which represent the Aedicule of the Tomb of Christ and the Holy Sepulchre. Churches, tombs, burial sites, calvaries, monasteries, relics and religious items comprise the main examples of this category. It is not a coincidence that there is an abundance of this kind of copies worldwide. Apart from the fact that the prototype is such a significant monument, there are more reasons that account for these reproductions' creation.

Initially, a primary factor is that the majority of the faithful could not travel to the Holly Land due to the remote location of Jerusalem in comparison to their homeland and to the lack of means of transport. For this reason, they would visit a replica of the holy sites located closer to them instead of the original, either to pray or to honor the saints. In this way, they would feel as if they were standing in front of the original Aedicule in Jerusalem. The closer the resemblance of the replica, the more powerful the spiritual experience of the pilgrims was. Thus, both the accuracy of the dimensions and the form of the reconstructions of the Tomb of Christ had a significant impact on its value to the pilgrims (Yoseph, 2011).

Moreover, many people feel the urge to experience and learn further information about the Passion of Christ, through the Church. One approach, so that the pilgrims would succeed in fulfilling these expectations, was the recreation of the Stations of the Cross. This is how calvaries were constructed since they consist of many different chapels and each one of them represents an incident of the life of Christ. Such places, from the time they were created until today, provide also a setting in which the events of Christ's death and resurrection could be celebrated each year during the Easter liturgy. For this reason, even more significance and respect from the faithful was attributed to the replicas.

Finally, someone cannot set aside the purpose for which the Aedicule was originally constructed: as a burial monument. Hence, it is common that many of the copies were built as tombs in cemeteries. On one hand, the person to whom this burial place was dedicated could have been of great position and importance in the society and on account of this, it should be honored by creating a tomb similar to Christ's. On the other hand, *the model of the Aedicule was reproduced to receive deceased persons, perhaps with the idea of obtaining by this tomb the assurance of the resurrection.*

The date of the construction of each replica indicates the structural phase of the Aedicule that it represents. Most of these reconstructions were built during the Counter-Reformation which began in 1545 and ended in 1648, so they are similar to the form of the Tomb of Christ as restored by Bonifacio of Ragusa in 1555. These replicas were located in the ancient kingdoms of Bohemia, Austria and the possessions of the Habsburg family. Nowadays, the specific areas correspond to the countries of Czech Republic, Germany, Austria, Poland, Slovakia and Slovenia. Various representations of the Aedicule can also be found in France, Belgium, Italy, Russia, Canada, United States of America, Georgia and even in Jerusalem itself.

Many of these replicas were built due to the work of various religious groups. The Franciscans had a key role to their construction, taking under consideration that a certain number of Franciscan monasteries own a replica of the Aedicule. Furthermore, the Capuchin friars or Jesuits, branches of the Franciscans after the Council of Trent, had constructed also numerous replicas between the end of the 17th century and during the 18th century. In addition to these religious communities, even former pilgrims, bishops and private individuals have contributed to the creation of representation of the Tomb of Christ (Guilbert-Roed, 2017)

Apart from the Aedicule, some distinctive architectural details of the Church of the Holy Sepulchre, such as the Rotunda, had also influenced the architecture of many medieval churches and monasteries in Western Europe (Kroesen, 2018). The Crusades and the pilgrimages to the Holy Land resulted in the building of round churches in different European countries, which was an unusual architectural phenomenon for the specific period.

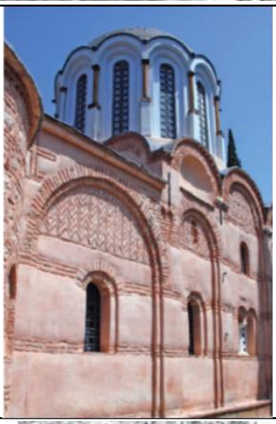
3.2.1. LIST OF THE REPLICAS

As a result, a survey with the aim of detecting both the three-dimensional reconstructions of the Aedicule of the Tomb of Christ and the churches that were inspired by the Holy Sepulchre worldwide, which would record the place and the time they were constructed, was considered an interesting idea. The creation of a list of these buildings and objects was one of the main goals of this research. Eventually, the amount of the discovered replicas was 109 in total and they consist of different types, which were divided into various categories:

- True-to-scale replicas of the Aedicule (23 of them)
- Edifices of the Aedicule (9 of them)
- Miniature Models of the Aedicule (15 of them)
- Calvaries (45 of them)
- Buildings inspired by the Holy Sepulchre (17 of them)

More precisely, the edifices of the Aedicule are composed of structures that represent the Aedicule, but they are not identical replicas of the original. Moreover, concerning the Calvaries, although plenty of them were detected, only these which had a chapel dedicated to the Tomb of Christ were finally selected.

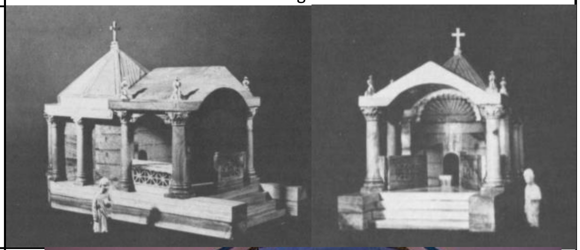
The list created is presented below in the form of database tables:

Name	Type	Location	Time of Construction	Image
Artophorio (container for the Holy Bread)	Miniature of the Aedicule	Athens (Benaki Museum)	end of the 18th century-beginning of 19th century	
Model of the Aedicule	Miniature Model of the Aedicule	Athens	2017	
Mount Filerimos - The Acropolis of Ancient Ialyssos	Calvary	Filerimos Mountain, Rhodes	14th century	
Mother of God, Hosios Loukas	Dome of church inspired by the Aedicule	near Steiris, Phokis,	10th century	
Nea Moni	Dome of church inspired by the Aedicule	Chios	1050	
Panagia Krina	Dome of church inspired by the Aedicule	Chios	1200	
Hagioi Apostoloi	Dome of church inspired by the Aedicule	Pyrgi, Chios	13th century	

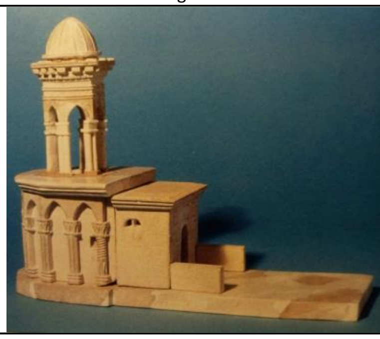
ITALY

Name	Type	Location	Time of Construction	Image
Sanctuario di San Vivaldo, La Gerusaleme Toscana	Calvary	Montaione	16th century	
The Sacro Monte of Nuova Gerusalemme (New Jerusalem)	Calvary	Varallo Sesia (province of Vercelli)	1486	
The Sacro Monte of Santa Maria Assunta	Calvary	Serralunga di Crea (province of Alessandria)	1589	
The Sacro Monte of San Francesco	Calvary	Orta San Giulio (province of Novara)	1590	
The Sacro Monte of the Rosary	Calvary	Varese	1598	
The Sacro Monte of the Blessed Virgin	Calvary	Oropa (province of Biella)	1617	
The Sacro Monte of the Blessed Virgin of Succour	Calvary	Ossuccio (province of Como)	1635	
The Sacro Monte of the Holy Trinity	Calvary	Ghiffa (province of Verbano-Cusio-Ossola)	1591	
The Sacro Monte and Calvary	Calvary	Domodossola (province of Verbano-Cusio-Ossola)	1657	
The Sacro Monte of Belmonte	Calvary	Valperga (Metropolitan City of Turin)	1712	
Rucellai Sepulchre	true-to-scale Edifice of the Aedicule	Florence (church of San Pancrazio)	began in about 1458 and was completed in 1467	 
Church of the Holy Sepulchre	Church inspired by the Holy Sepulchre	Bologna (Basilica di Santo Stefano)	5th century	
Santo Stefano Rotondo	Church inspired by the Rotunda	Rome	468-83	
Aquileia	Edifice of the Aedicule and the Rotunda	Aquileia	1050	

ISRAEL

Name	Type	Location	Time of Construction	Image
John Wilkinson model	Miniature Model of the Aedicule	Jerusalem (representation of the Constantine's Aedicule)	1972	
Kidane Mehret Church	true-to-scale Edifice of the Aedicule	Jerusalem	1901	

NETHERLANDS

Name	Type	Location	Time of Construction	Image
Stone Model of the Aedicule	Miniature Model of the Aedicule	found in Amsterdam (Egelantiersstraat), now in the Museum Catharijneconvent in Utrecht	late 16th to early 17th century	

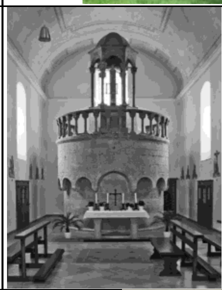
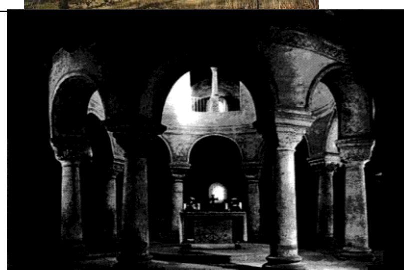
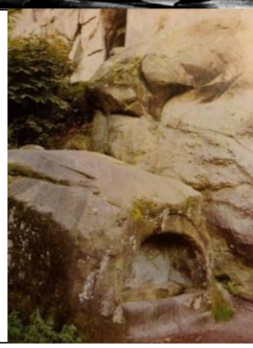
SLOVAKIA

Name	Type	Location	Time of Construction	Image
Calvary Mount of Banská Štiavnica	Calvary	Scharffenberg, Banská Štiavnica	between 1744 and 1751	
Calvary Mount	Calvary	Prešov		

RUSSIA

Name	Type	Location	Time of Construction	Image
New Jerusalem Monastery	Church inspired by the Rotunda and true-to-scale Edifice of the Aedicule	Moscow Oblast	1685	

GERMANY

Name	Type	Location	Time of Construction	Image
The Chapel of the Holy Sepulchre	true-to-scale Edifice of the Aedicule	Augsburg (St Anne's church)	1508	
The Heiliges Grab	true-to-scale Edifice of the Aedicule	Görlitz	1500	
Eichstätt monastery	true-to-scale Edifice of the Aedicule	Eichstätt	1194	 
Heiliggrabkapelle	true-to-scale Edifice of the Aedicule	Bühl am Alpsee	1667/68	
Kalvarienberg Reicholzried	Calvary	Reicholzried	1900	
Carolingian Church of St. Michael	Church inspred by the Holy Sepulchre	Fulda, Hesse	822	
Externsteine	Edifice of the Aedicule	Teutoburg Forest, near the town of Horn-Bad Meinberg in the Lippe district of the German state of North Rhine-Westphalia.	12th century	

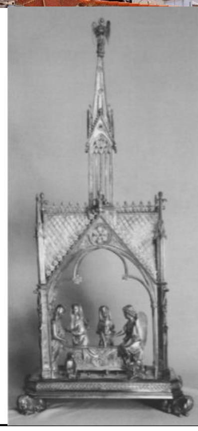
SLOVENIA

Name	Type	Location	Time of Construction	Image
The Holy Stairs with the Holy Sepulchre	Calvary	Šmarje pri Jelšah (Church of St. Rok)		

FRANCE

Name	Type	Location	Time of Construction	Image
Saint-Sépulcre d'Angers memorial	true-to-scale Edifice of the Aedicule	city of Angers (department of Maine-et-Loire)	from 1931 to 1935	
Neuvy-Saint-Sépulchre	Church inspired by the Rotunda and Edifice of the Aedicule (destroyed in the 19th century)	Indre (department in central France)	1049	
Aubeterre-sur-Dronne	Edifice of the Aedicule	Aubeterre (Église St Jean church)	end of the 11th century	
Cambrai	Rotunda and a Tomb Edicule (destroyed at the French Revolution)	Cambrai	11th century	
The Narbonne model	Miniature Model of the Aedicule	Narbonne	5th century	

SPAIN

Name	Type	Location	Time of Construction	Image
Vera Cruz	Church inspired by the Holy Sepulchre	Segovia	1208	
Cathedral of Granada	Church inspired by the Holy Sepulchre	Granada	1561	
The Three Maries at the Holy Sepulchre, Reliquary	Miniature Model of the Aedicule	Pamplona Cathedral Treasury	1285-1305	

CANADA

Name	Type	Location	Time of Construction	Image
Sanctuaire Notre-Dame-du-Cap/The Sanctuary of Our Lady of the Cape	true-to-scale Edifice of the Aedicule and Calvary	Trois-Rivières, Quebec	end of the 19th century	
Oka Calvary	Calvary	Lac des Deux Montagnes, Quebec	1740-1742	

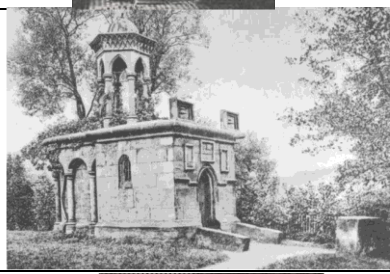
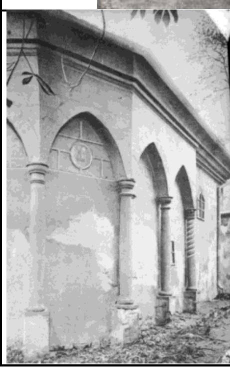
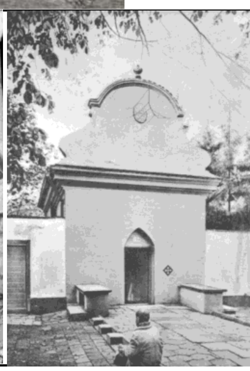
BELGIUM

Name	Type	Location	Time of Construction	Image
Bruges	Church inspired by the Holy Sepulchre and	Bruges	first half of the 15th century	
Moresnet chapelle	Calvary	Plombières	1903	

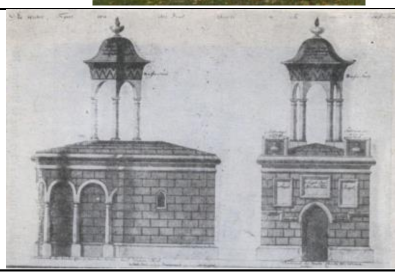
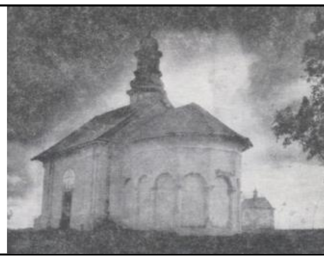
GEORGIA

Name	Type	Location	Time of Construction	Image
Svetiskhoveli Cathedral	Edifice of the Edicule	Mtskheta (northwest of the capital Tbilisi)	end of the 13th - beginning the 14th century	

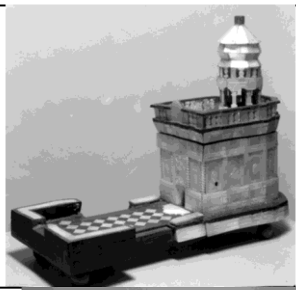
POLAND

Name	Type	Location	Time of Construction	Image
St. Mary's Church	Edifice of the Aedicule	Krakow	1750-53	 
Miechowski's Tomb of Christ	Edifice of the Aedicule	Miechów	1506	
Tomb of Christ in Zgorzelec	True-to-scale Edifice of the Aedicule	Zgorzelec	around 1500	
chapel of the Tomb of Christ	Edifice of the Aedicule	Przeworsk	18th century	
Piotr and Paweł	Edifice of the Aedicule	Nysa	1720-1727	
Kaplica Grobu Chrystusa w Żaganiu	True-to-scale Edifice of the Aedicule	Żagań	16-th century	
The tomb of Christ in Głogówek	Edifice of the Aedicule	Głogówek	around 1634	 

POLAND

Name	Type	Location	Time of Construction	Image
chapel of the Tomb of Christ	True-to-scale Edifice of the Aedicule	Potępie	1672	
The Sanctuary of Kalwaria Zebrzydowska	Calvary	40 km. southwest of Krakow and 15 km. east of Wadowice	1609	
Kalwaria Wejherowska	Calvary	Wejherowo	1651-1666	
Góra Kalwaria	Calvary	Dróżki	1670	
Kalwaria Wambierzyce	Calvary	Silesia	1686-1701	
Góra Kalwaria	Calvary	św. Anna in Silesia	1700-1709	
Kalwaria Pakoska	Calvary	town of Pakość near Inowrocław	1628-1629	
Kalwaria Ujazdowska	Calvary	near Warsaw	1724-1731	
Christ's grave at the Cistercian abbey church	Calvary	Krzeszów in Silesia	1738	
Kalwaria Pacławska	Calvary	Przemyśl poviat	1865	
Panewnicka Calvary	Calvary	Katowice	1911	

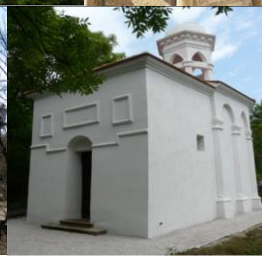
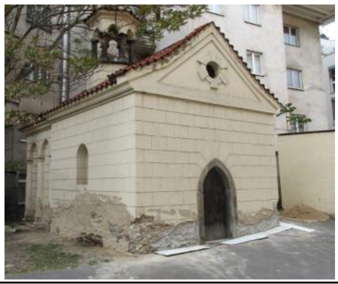
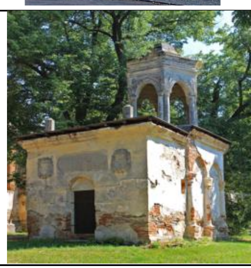
POLAND

Name	Type	Location	Time of Construction	Image
Model of the Tomb of Christ	Miniature Model of the Aedicule	Jagiellonian University Museum, Krakow		
Model of the Tomb of Christ	Miniature Model of the Aedicule	National Museum, Krakow	18th century	
Model of the Tomb of Christ	Miniature Model of the Aedicule	University Museum, Krakow	1555	
Reliquary in the shape of the Tomb of Christ	Miniature Model of the Aedicule	Miechów	1584	
Reliquary in the shape of the Tomb of Christ	Miniature Model of the Aedicule	Wrocieryż in the Jędrzejów poviat	1806	

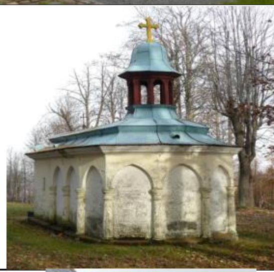
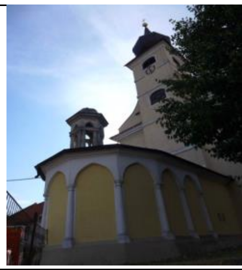
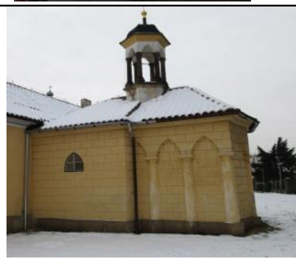
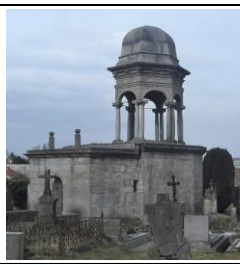
LITHUANIA

Name	Type	Location	Time of Construction	Image
Verkiai Calvary (Church of the Finding of the Holy Cross)	Calvary	near Vilnius	eighteenth century	
Žemaičių Kalvarija	Calvary	Žemaičių Kalvarija	1639	
Kalvarija	Calvary	Kalvarija	17th century	

CHECH REPUPLIC

Name	Type	Location	Time of Construction	Image
The Holy Sepulchre Chapel	True-to-scale Edifice of the Aedicule	Slaný	1665	
Mimoň Holy Sepulcher	True-to-scale Edifice of the Aedicule	Mimoň	1667	 
Stations of the Cross	Calvary	Mikulov	1630	 
The Chapel of the Holy Sepulcher	True-to-scale Edifice of the Aedicule	Prague, New Town, Zderaz (church of St. Peter and Paul of the cruisers - guardians of the Holy Sepulcher)	1721	
The Chapel of the Holy Sepulcher	True-to-scale Edifice of the Aedicule	Zderaz, Prague 2 , New Town (Church of St. Wenceslas) (extinct)	1643	
The Chapel of the Holy Sepulcher	True-to-scale Edifice of the Aedicule	Brno (Dominican Church of St. Michael the Archangel)	1707	
The Chapel of the Holy Sepulcher	True-to-scale Edifice of the Aedicule	Drahoraz (Church of St. Peter and Paul)	1698	
The Chapel of the Holy Sepulcher	True-to-scale Edifice of the Aedicule	Havlíčkův Brod (Augustinian monastery church of the Holy Family)	1725	
Stations of the Cross	Calvary	Horšovský Týn (St. Anne's Na Vršíčku)	1700	
Chapel of the Holy Sepulcher(extinct)	True-to-scale Edifice of the Aedicule	Chrudim (Capuchin Church of St. Joseph)	1665	

CHECH REPUPLIC

Name	Type	Location	Time of Construction	Image
Chapel of the Holy Sepulcher	Calvary	Jaroměřice near Jevíček	1713	
Chapel of the Holy Sepulcher	Calvary	Jiřetín pod Jedlovou	1764	
Chapel of the Holy Sepulcher	True-to-scale Edifice of the Aedicule	Olomouc (Church of the Immaculate Conception of the Virgin Mary)	1653	
Chapel of the Holy Sepulcher	Calvary	Ostrá	1707	
Chapel of the Holy Sepulcher	True-to-scale Edifice of the Aedicule	Pavlice (church of St. Philip and Jacob)	1677	
Chapel of the Holy Sepulcher	True-to-scale Edifice of the Aedicule	Prague (Church of Our Lady Victorious)	1750 - 1785	
Chapel of the Holy Sepulcher	Calvary	Prague on Petrin Hill	1738	
Chapel of the Holy Sepulcher	True-to-scale Edifice of the Aedicule	Votice	1689	
Chapel of the Holy Sepulcher	Calvary	Vratěnín	1668	

AUSTRIA

Name	Type	Location	Time of Construction	Image
Hernals Kalvarienberg (copy extinct)	Calvary	Hernals, Vienna	17th century	
Grazer Kalvarienberg	Calvary	Austein near the Mur in today's Graz district of Lend	1654	
Kalvarienberg Leoben-Göß	Calvary	Göss, Leoben	between 1843 and 1845	

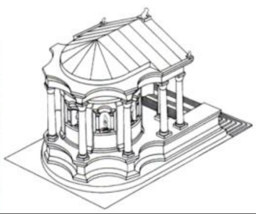
ROMANIA

Name	Type	Location	Time of Construction	Image
Way of the Cross	Calvary	village of Billed, county of Timiș		

ETHIOPIA

Name	Type	Location	Time of Construction	Image
Jerusalem of Ethiopia	Calvary	Lalibela	1205-1225	

LEBANON

Name	Type	Location	Time of Construction	Image
The Circular Temple (Temple of Venus)	Temple inspired by the Aedicule	Baalbek or Heliopolis (Ἡλιούπολις, "sun city"): town in the northern Bekaa valley	4th century	 

BOLIVIA

Name	Type	Location	Time of Construction	Image
Cerro Calvario	Calvary	Copacabana		

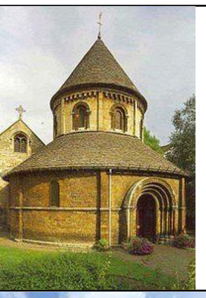
HUNGARY

Name	Type	Location	Time of Construction	Image
Calvary Hill	Calvary	Pécs		

ENGLAND

Name	Type	Location	Time of Construction	Image
Model of the Aedicule	Miniature Model of the Aedicule	Ashmolean Museum, Oxford	17th century	 
Model church of Holy Sepulchre in Jerusalem	Miniature Model of the Aedicule	British Museum, London	1753	
Model church of Holy Sepulchre in Jerusalem	Miniature Model of the Aedicule	British Museum, London	before 1753	
Model church of Holy Sepulchre in Jerusalem	Miniature Model of the Aedicule	British Museum, London	end of 17th century	
Model church of Holy Sepulchre in Jerusalem	Miniature Model of the Aedicule	Museum of the Order of St John and University of Birmingham 2016, Birmingham	end of 17th century	
Model church of Holy Sepulchre in Jerusalem	Miniature Model of the Edicule	Museum of the Order of St John and University of Birmingham 2016, Birmingham	end of 17th century	

ENGLAND

Name	Type	Location	Time of Construction	Image
Church of the Holy Sepulchre	Church inspired by the Holy Sepulchre	Northampton	1100	
The Round Church	Church inspired by the Rotunda	Cambridge	1130	
Temple Church	Church inspired by the Rotunda	London	1185	
The Church of St. John the Baptist	Church inspired by the Rotunda	Little Maplestead, Essex	1186	

3.3. CREATION OF AN INTERACTIVE MAP

The catalogue which consists of the replicas of both the Aedicule and the Holy Sepulchre provides information about the influence of the Holy Land to the Christian communities around the world. However, it is widely accepted that the human brain tends to process visual information far more easily than written information. Thus, a suitable depiction of this kind of information about the replicas would be more useful. On those grounds comes as no surprise that data visualization, which is the graphical representation of information, has seen massive growth in popularity. One of the major tools that is used for analyzing and displaying geographically related data is map visualization and more particularly geographic information systems.

A geographic information system (GIS) is a framework for gathering, managing, and analyzing data. GIS integrates many types of data, it analyzes spatial location and organizes layers of information into visualizations using maps and 3D scenes. (https://www.esri.com/en-us/what-is-gis/overview). The characteristic advantage of GIS software is the combination of spatial data that are geographically corresponding to the real world and of attribute data that provide additional information about each of the spatial features. In this way, the user is available to both have access to a wide range of information and display them in any such away in order to create a desired visual outcome. Moreover, it is possible to analyze the relationships between different features, the density of features in a given space, where the most or least of some feature exists, what is happening inside an area of interest, how this area has changed over time and also to calculate statistics. This is the reason why GIS constitutes a significant key not only for spatial analysis but also for problem-solving and decision-making procedures (https://researchguides.library.wisc.edu/GIS).

The ability of GIS for mapping the spatial location of real-world features and visualizing the spatial relationships among them was the primary cause of its selection as an implement for this research. There are numerous GIS systems available which cover all sectors of geospatial data processing, either commercial or open source. The most significant and defining examples are ArcMap, Quantum GIS (QGIS), User–Friendly Desktop Internet GIS (uDig) and Grass. The QGIS software was eventually chosen for the depiction and the visualization of the places where replicas of the Aedicule and the Holy Sepulchre were detected worldwide.

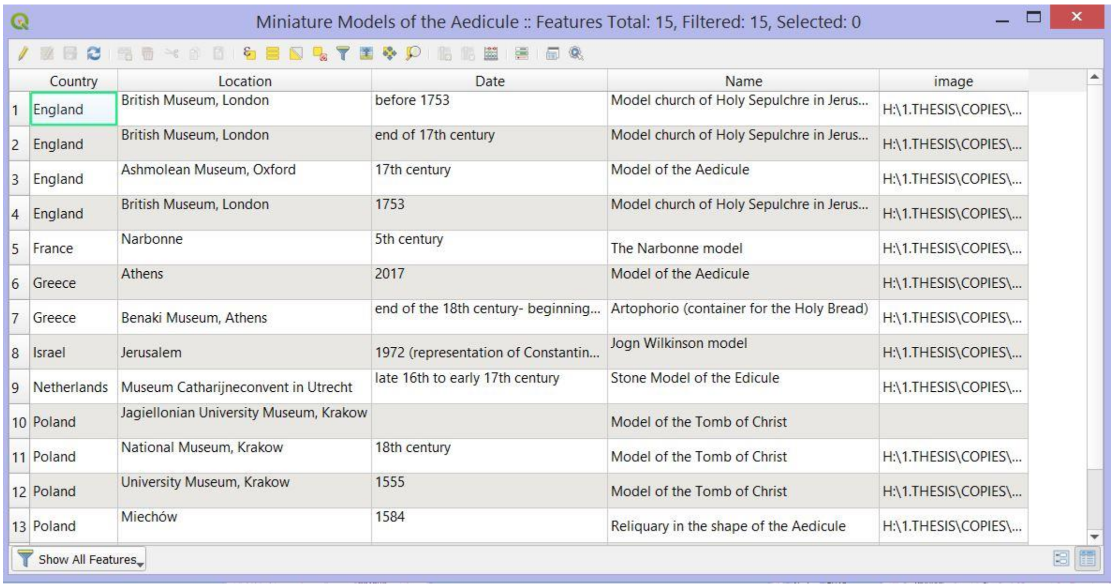
QGIS is a user friendly Open Source Geographic Information System (GIS) licensed under the GNU General Public License and it constitutes an official project of the Open Source Geospatial Foundation (OSGeo). It is compatible with Linux, Unix, Mac OSX, Windows and Android and supports numerous vector, raster, and database formats and functionalities. Apart from its operation as desktop software, it is capable also of providing to the user a spatial file browser, a server application and web applications. Written in C++, QGIS makes extensive use of the Qt library. There are also various plug-ins that extend the functionality of QGIS written in Python or C++ (https://www.qgis.org/en/site/about/features.html).

3.3.1. VISUALIZATION OF THE DATA IN QGIS

Eventually, based on the list presented previously and taking advantage of the tools provided by QGIS, a map was produced where the locations of the replicas were digitized and visualized. The structures were classified in five different categories (layers) depending on the type of the replica:

1. True-to-scale replicas of the Aedicule
2. Edifices of the Aedicule
3. Miniature Models of the Aedicule
4. Calvaries
5. Buildings inspired by the Holy Sepulchre

The Open Street Map was used as a basemap and the vector data, which describe geographic data in terms of points for this project, were placed at the location of each copy. To the Attribute Table of each group, new fields were added regarding the information provided by the list, for example, the date of construction, the name of the copy, the city and country where it is located and an image if a depiction of the replica existed (Image 11).



	Country	Location	Date	Name	image
1	England	British Museum, London	before 1753	Model church of Holy Sepulchre in Jerus...	H:\1.THESIS\COPIES\...
2	England	British Museum, London	end of 17th century	Model church of Holy Sepulchre in Jerus...	H:\1.THESIS\COPIES\...
3	England	Ashmolean Museum, Oxford	17th century	Model of the Aedicule	H:\1.THESIS\COPIES\...
4	England	British Museum, London	1753	Model church of Holy Sepulchre in Jerus...	H:\1.THESIS\COPIES\...
5	France	Narbonne	5th century	The Narbonne model	H:\1.THESIS\COPIES\...
6	Greece	Athens	2017	Model of the Aedicule	H:\1.THESIS\COPIES\...
7	Greece	Benaki Museum, Athens	end of the 18th century- beginning...	Artophorio (container for the Holy Bread)	H:\1.THESIS\COPIES\...
8	Israel	Jerusalem	1972 (representation of Constantin...	Jogn Wilkinson model	H:\1.THESIS\COPIES\...
9	Netherlands	Museum Catharijneconvent in Utrecht	late 16th to early 17th century	Stone Model of the Edicule	H:\1.THESIS\COPIES\...
10	Poland	Jagiellonian University Museum, Krakow		Model of the Tomb of Christ	
11	Poland	National Museum, Krakow	18th century	Model of the Tomb of Christ	H:\1.THESIS\COPIES\...
12	Poland	University Museum, Krakow	1555	Model of the Tomb of Christ	H:\1.THESIS\COPIES\...
13	Poland	Miechów	1584	Reliquary in the shape of the Aedicule	H:\1.THESIS\COPIES\...

Image 11: Example of the Attribute Table of the layer ' Miniature Models of the Aedicule' *© Author 2020*

The images were added initially as an attribute field and each replica was associated with its image by indicating the path of its folder in the computer. After the procedure was completed for every image, unfortunately, none of the depictions of the replicas was visible on the map, even though they existed in the Attribute Table. The solution to this was the creation of an 'action' in QGIS. Actions happen when the user clicks on a feature, allowing the retrieval of additional information. At the specific map, it would be possible to view an image by picking the replica that it represented. The first step would be to 'add a new action' from the Actions panel at the Layer Properties. At the Action Properties, the Type of the action was indicated as 'Open', the description of the action was 'Show Image', the option 'Capture output' was selected, the field 'image' was selected from the list and through the 'Insert' option, QGIS added the phrase [% "image" %] in the Action Text. Furthermore, in the Action Scopes the fields 'Canvas' and 'Feature Scope' were selected. When all the necessary features were applied the new action was completed (Image 12). The same process would be repeated for every layer separately.

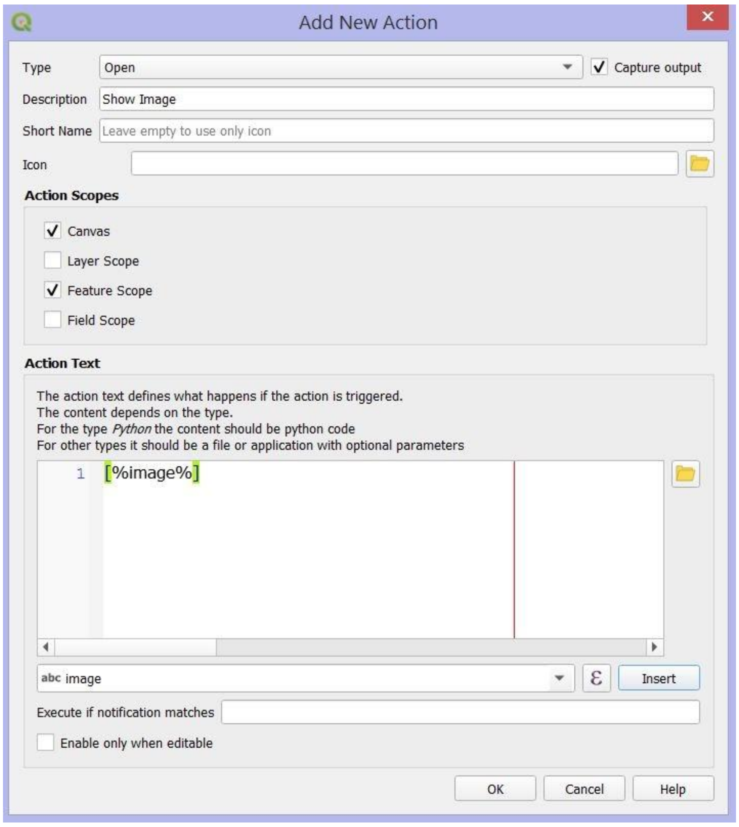


Image 12: The parameters of the action 'Show Image' in QGIS *© Author 2020*

In order to enable the new action, from the 'Run Feature Action' button at the Toolbar the 'Show Image' option should be selected. Thus, when a specific layer would be chosen, every time the user would click on a replica with an existing depiction, a new window would open with the specific image. Therefore, the final map that displayed all the information provided from the list of the replicas was created.

3.3.2. CREATION OF ONLINE WEB MAP

The subsequent step was the development of an online database that would be accessible by all the users of the internet. This could be achieved with the production of a web map. A web map is the presentation of a map online, which was initially created with a Geographic Information System (GIS), and the user is able to interact through different tools, such as pop-up windows with additional information for the visualized data, continuous pan and zoom, measurements of distances on the map etc. Each web map is mainly composed of a reference basemap in combination with data layers. (https://www.esri.com/arcgis-blog/products/product/uncategorized/web-mapping-101/).

Consequently, for the creation of the web map it is necessary to begin with the visualization of the spatial information that will be depicted, just like the project created in QGIS for the replicas of the Aedicule and the Holy Sepulchre. Afterwards, this project should be converted to a form which is compatible to a browser. For this reason, the Qgis2web plugin of the QGIS software was installed. The specific plugin generates a web map from the current QGIS project, either as OpenLayers or Leaflet.

More specifically, OpenLayers enables the depiction of dynamic maps in any web page. Various kinds of geospatial data are supported, for example tiled layers, vector data or markers from any source. OpenLayers has been developed to extend the use of geographic information and it is completely free (https://openlayers.org/). On the other hand, the Leaflet is an open-source JavaScript library for mobile-friendly interactive maps. Furthermore, it is designed with simplicity, performance and usability in mind. It works efficiently across all major desktop and mobile platforms and can be extended with lots of plugins. Leaflet provides a presentable, convenient and well documented API (Application programming interface) and a simple, user-friendly source code (https://leafletjs.com/).

Qgis2web creates the final web map by replicating as many aspects of the project as possible, including layers and styles, and converting them into HTML, Javascript, and CSS files, that can be viewed from the browser. When the desired map form and the data that will be depicted are selected, the final web map is exported and both an 'index.html' file and folders with associated Javascript/CSS files are generated. Server-side software is not required for this procedure. (https://plugins.qgis.org/plugins/qgis2web/). For the creation of the online web map, a web hosting account is necessary. Not only the ' index.html' file, but also the associated folders should be uploaded to the main public '.html' directory. Eventually, every time someone visits the URL of the website, the web map will be depicted in the browser (https://www.igismap.com/qgis2web-create-web-maps/).

With the aim of creating a web map for the project of the replicas of the Aedicule and the Holy Sepulchre, through the Qgis2web plugin the option 'Create web map' was selected. Then, the parameters of the web map were defined, which consist of the data layers, the overall appearance and the way that the web map will be exported. First of all, the Leaflet form was thought to be the best choice, due to its simplicity and the user-friendly environment. Moreover, all the layers of the project and their fields would be depicted at the web map. Regarding the appearance, the different layers would be presented at the upper right corner of the web map, pop-up windows with the additional information of the attribute table of each layer were enabled and the highlighting of every aspect that will be picked by the user was also selected. Some tools were added, such as the geolocation of the user, the metric measure tool for distances and areas (units: meters) and the research tool. The web map would be depicted in full-screen, with an extent which would fit to the layers and with maximum zoom level 28 and minimum zoom level 1 (Image 13). Finally, the folder where all the files would be exported was selected. The title of the web map was not available through the Qgis2web plugin, but it was added through the tab 'Project' > 'Properties' > 'Project Title'.

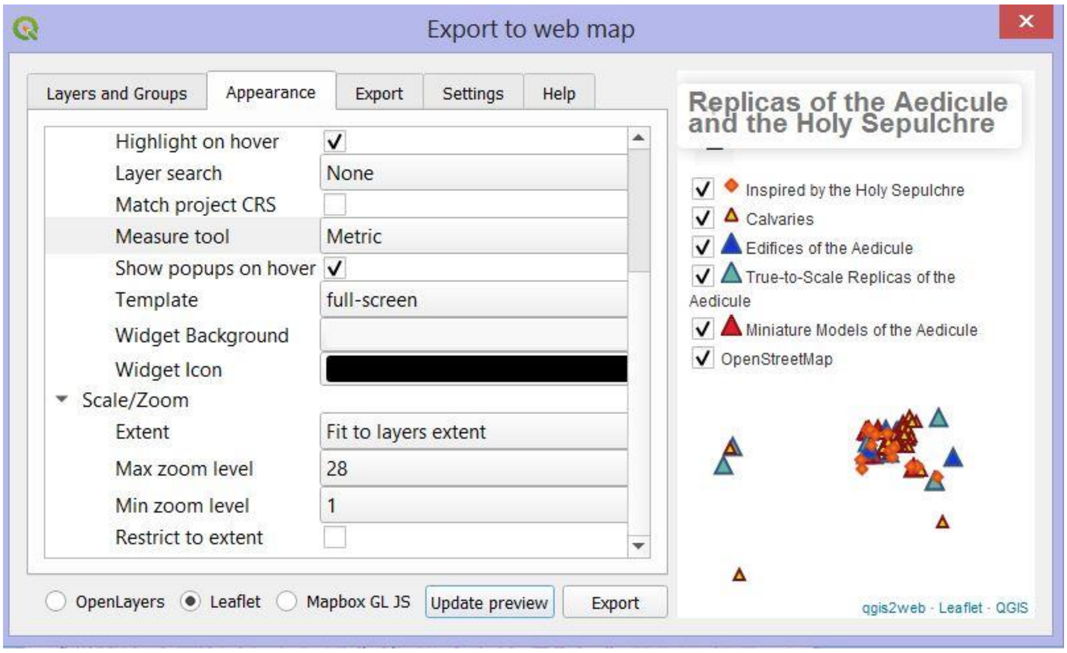


Image 13: Parameters of the Qgis2web plugin *©Author 2020*

As a result, the web map of the replicas of the Aedicule and the Holy Sepulchre was produced. In order to upload the specific web map to the internet, a web hosting account was required. For the presentation of the web map the web server of the National Technical University of Athens was used, which provides to the members of the university the ability to create a personal website. When the personal website has been activated, access to the personal website for modifications is available through the link: **ftp://username@users.ntua.gr/** and the use of FTP software, such as FileZilla. The user must enter the link of the web directory and the passwords in order to log in through the FileZilla software. When the access is permitted, there are two separate windows depicting the files of the desktop computer and the files in the web directory. The user decides which files will be transferred to the web directory. All the files should be in '.html' or '.htm' form, apart from the main directory files which should be in 'index.html' or 'index.htm' form. The existence of at least one main directory file at the web directory is obligatory to be compatible with the personal website. Otherwise, a message will appear at the website indicating that the user is not permitted to have access on the specific server. Moreover, the user can add some helpful tools in order to customize the personal website based on his intentions, like page counters, guestbook, search engine and web statistics.

Thus, the 'index.html' file and the folders with associated Javascript and CSS files which were exported from the Qgis2web plugin were uploaded to the web directory (Image 14). The website was private at first and required the username and the password, but through alterations at the web directory (.htaccess file) it was converted to public.

	Όνομα	Μέγεθος	Ημερομηνία τροποποίησης
	css/		29/2/20, 1:56:00 π.μ.
	data/		29/2/20, 1:55:00 π.μ.
	images/		29/2/20, 1:56:00 π.μ.
	index.html	24.7 kB	29/2/20, 1:55:00 π.μ.
	js/		29/2/20, 1:56:00 π.μ.
	legend/		29/2/20, 1:56:00 π.μ.
	markers/		29/2/20, 1:56:00 π.μ.
	old_htaccess	213 B	26/2/20, 3:30:00 μ.μ.
	webfonts/		29/2/20, 1:56:00 π.μ.

Image 14: The Web Directory presenting the files and their name, size and date of modification *©Author 2020*

The web map of the replicas of the Aedicule and the Holy Sepulchre was finally online and accessible through the internet (Image 15). The URL of each personal website consist of the username of each member, so for the specific case the link is http://users.ntua.gr/rs13022

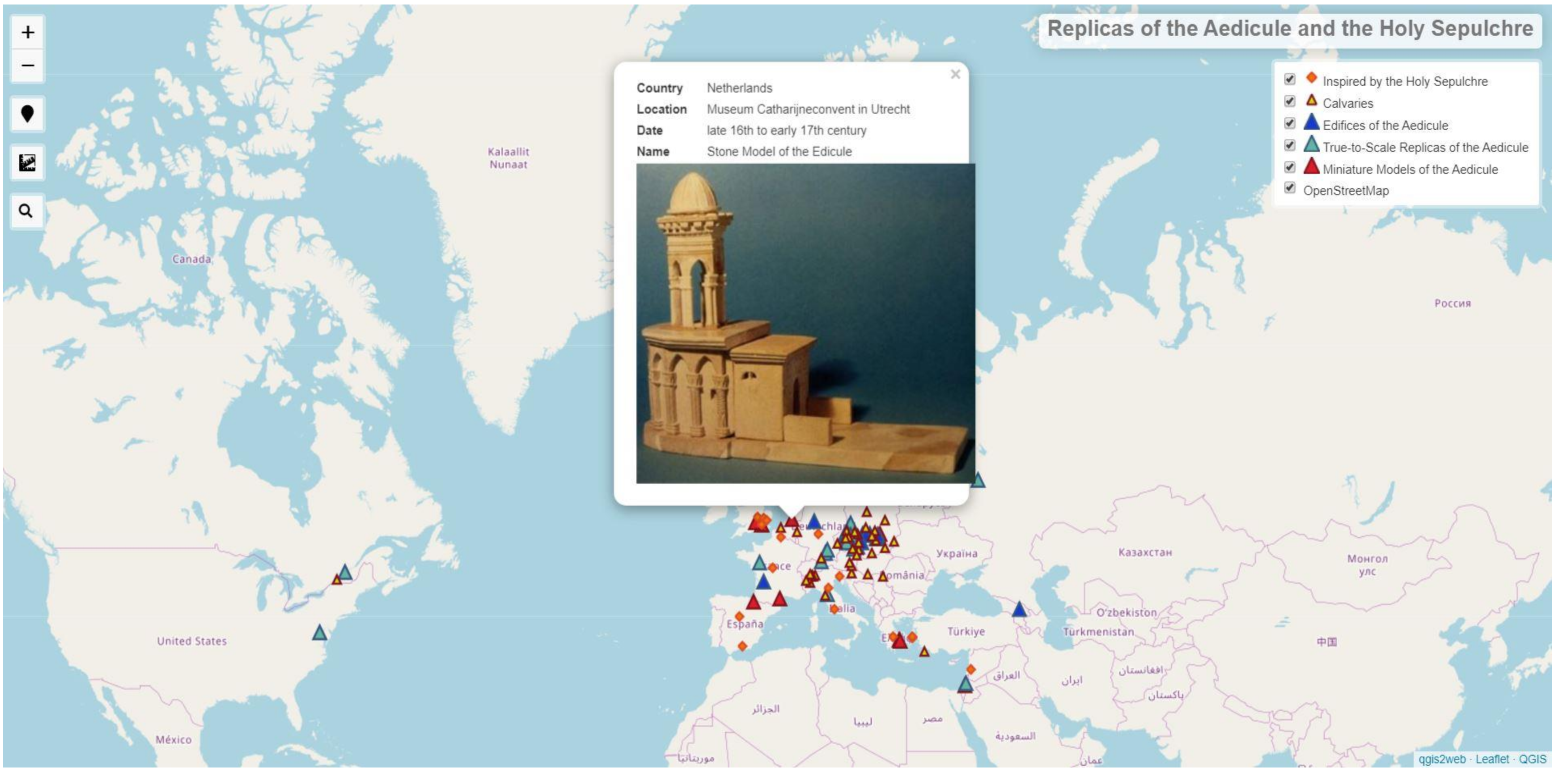


Image 15: The online web map of the replicas of the Aedicule and the Holy Sepulchre *©Author 2020*

4. GEOMETRIC DOCUMENTATIONS

4.1. PREVIOUS DOCUMENTATIONS OF THE HOLY AEDICULE

Through the years many sketches and artistic drawings have been created depicting the Aedicule of the Tomb of Christ in different structural phases. The majority of them were designed with the intention of keeping in memory the form of the holiest site in Christianity (Image 16). This is why there were no references for the exact dimensions of the edifice and only the basic architectural features were recorded. Although this kind of drawings cannot be characterized as accurate, they constitute important visual evidence of the shape of the Aedicule as it existed the time they were created.

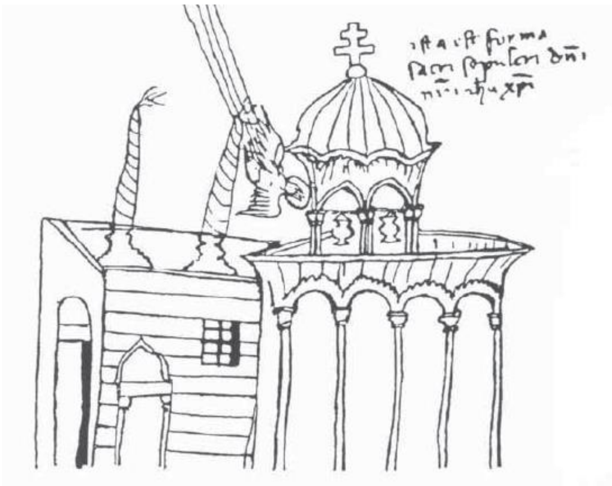


Image 16: Anonymous ink drawing of the Aedicule seen from north-east, 14th century *©Martin Biddle 1999*

On the contrary, the main purpose of some pilgrims' visit to Jerusalem was to take precise measurements of the dimensions of the Aedicule. These measurements were considered as valuable as the edifice itself and sometimes even replicas of the Tomb of Christ were constructed based on them. Therefore, there are also examples of drawings of the monument, which were more carefully designed and correspond to its actual shape. However, deviations between the recorded measurements have been noticed in the pilgrims' drawings. Obviously, the precision from the measurements in the late Middle Ages could not be compared to the accuracy of a modern metric survey. Moreover, this lack of resemblance could be justified due to the various measuring systems that existed in Europe, since every pilgrim would represent the dimensions in the units of his own region (for example cubits, feet or hands). Another important factor is the use of several measuring implements, like yardsticks or easy-to-transport straps, which pilgrims had tied knots at measured intervals (Naujokat, 2017). Despite their differences, these drawings constitute an initial type of geometric documentation of the Aedicule of the Tomb of Christ.

In recent years, the necessity of the Aedicule's restoration was urgent and metric surveys have been carried out by experts to geometrically document the condition of the structure. The results of the surveys were depicted again by technical drawings at first. With the evolution of technology new techniques of documentation and measurement acquisition were discovered. The utilization of both innovative equipment and various software that provide the depiction of the outcome in digital form, such as digital drawings and three-dimensional models, contributed to the precise and accurate recording of the Aedicule. In addition, the ability to further process the generated representations and obtain even more information about the structure through subsequent analysis resulted in the production of reliable materials regarding the state of the monument.

Consequently, even if the almost symbolic representations produced by pilgrims are excluded, many surveys have been carried out aiming to document, as precisely as possible for the time, the condition and the form of the Aedicule of the Tomb of Christ.

- Bernardino Amico (1593-1597)

Bernardino Amico da Gallipoli was a Franciscan monk who visited the Holy Places during his time in Palestine in 1593-1597 and created plans and drawings of the Aedicule based on his own measurements. Two editions of his work were published: (i) in Rome in 1609 with the original drawings engraved by A. Tempesti or Tempesta and (ii) in Florence in 1620 with new engravings in a smaller format by J. Callot (Image 17). Unfortunately, the units used for the measurements or the scales shown on some of the drawings, were converted from the ancient Roman palm (equivalent to 0.2234 m) to the ordinary palm which was in use in the Kingdom of Naples (equivalent to 0.2637 m). It is not yet known if this transformation was applied by the editor or Amico himself, but it has definitely caused a confusion concerning the dimensions depicted in the drawings. Consequently, a vital problem was that the scales on Callot's reduced engravings in the 1620 edition no longer correspond to Amico's creations, because these engravings had not been changed in order to match the change in scale of the original drawings. Moreover, the monk himself admitted that in some cases he had changed the actual form of the structure in order to beautify the design. For example in the elevations of the Aedicule, he made the external columns and their bases equal (Biddle, 1999). Apparently, there is a doubt whether the accuracy and the correspondence of Amico's drawings in contrast to the dimensions of the Aedicule of that period could be characterized as authoritative or reliable.

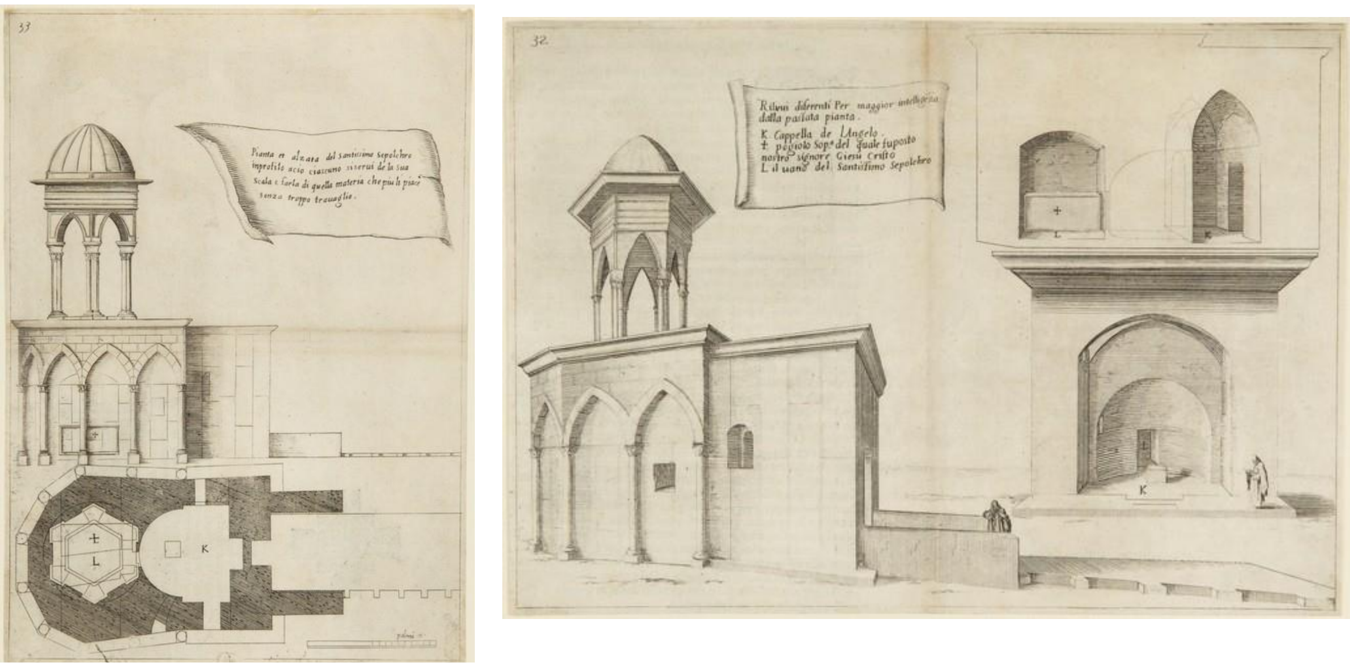


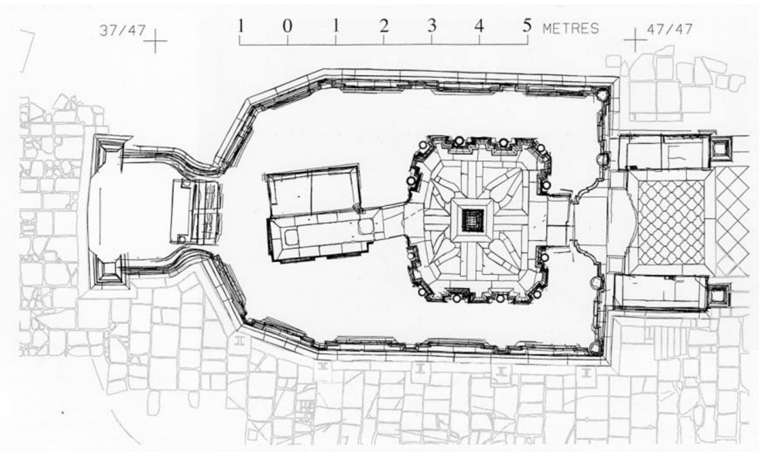
Image 17: Etchings and engravings by Jacques Callot (French, 1592–1635) after designs by Bernardino Amico (Italian, 1576–1620) *©Princeton University Art Museum*

- Virgilio Corbo (1960-1973)

After the severe earthquake in 1927, which caused serious damages to the structure of the whole complex of the Church of the Holy Sepulchre, the demand for a detailed metric survey on the condition of the building was unquestionable. The main goal was the creation of a restoration proposal for the protection of the holy sites, based on the results of the survey. Consequenlty, the Catholic, the Greek and the Armenian religious communities commonly agreed that a restoration project should be performed. The archaeological excavations in the Church of the Holy Sepulchre, which lasted 13 years, were carried out by a Franciscan monk named Father Virgilio Corbo, who was an experienced archaeologist. During his investigation Corbo documented most of the buildings of the church, including the Aedicule of the Tomb of Christ. The plans that were constructed consist not only of the new archaeological information, but also of architectural details. As a result, the specific drawings constitute the basis for all of the later studies analyzing the Church of the Holy Sepulchre. The outcome of Corbo's research was published in 1982 in Italian with the title: 'The church of the Holy Sepulchre in Jerusalem: archaeological aspects from its origins to the Crusader period'. His work was divided into three volumes: the first containing descriptions and textual information, the second tables of the designs and reconstructions, and the third photographic documentation. A significant feature of this publication is that the presented drawings were constructed by talented engineers, architects and designers who were involved in the survey alongside Corbo (Custodia Terrae Sanctae, 2020).

➢ Martin Biddle (1989-1992)

After the restoration of the Rotunda in 1960 by the Common Technical Bureau, the restoration of the Tomb of Christ could not remain neglected. Before any modification in the structure of the Tomb of Christ an accurate documentation of its state should be performed. For this reason, Martin Biddle, a British archaeologist and academic, and his wife Birthe Kjølbye-Biddle were invited to take part at both the archaeological investigations and the surveys concerning the Aedicule. The documentation project began in 1989 and was completed in 1992, without causing any disturbance of the edifice. The Aedicule was recorded with the implementation of both the traditional methods of architectural archaeology and the most recent (at that time) techniques of photogrammetry and 3D modelling. During the 1990 and 1992 seasons the photogrammetric record was carried out with colored photographs of the interior and exterior of the Aedicule. The photographs were later scanned and incorporated to the database. The photogrammetric survey of the tomb was undertaken by Professor Mike Cooper, Dr Stuart Robson and Roger Littleworth of City University in London. Regarding the methods of architectural archaeology, they consisted of descriptions by drawing, photographs and texts. Moreover, the surfaces were all described and drawn to scale stone by stone. The purpose of the drawings was to supplement the photogrammetric survey with details that might not have been detected, such as stone joints in angles, stone type, thickness, decoration and surface treatment. It is noted that, the method of photogrammetry had never before been used for documentation procedures for the Church of the Holy Sepulchre. The results of the specific survey were accurate and could precisely record the deformations and the condition of the Aedicule (Image 18). Indeed, the published floor-plans and elevations were the most reliable of all those constructed until that time. The survey also included the pavement of the Rotunda, on 1:20 scale using the same coordinate system as in the photogrammetric procedure (Biddle, 1999).



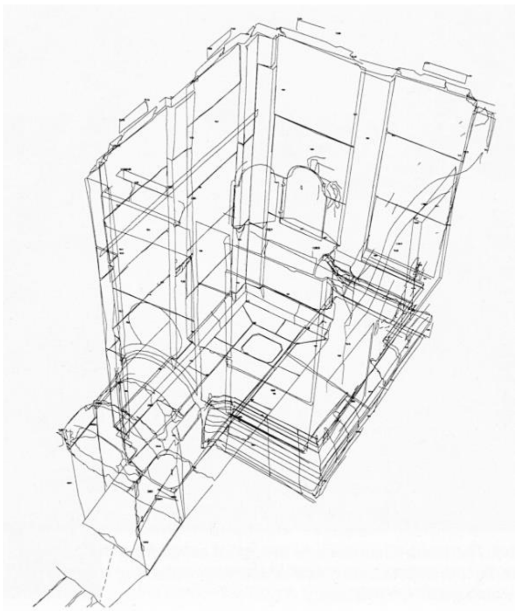
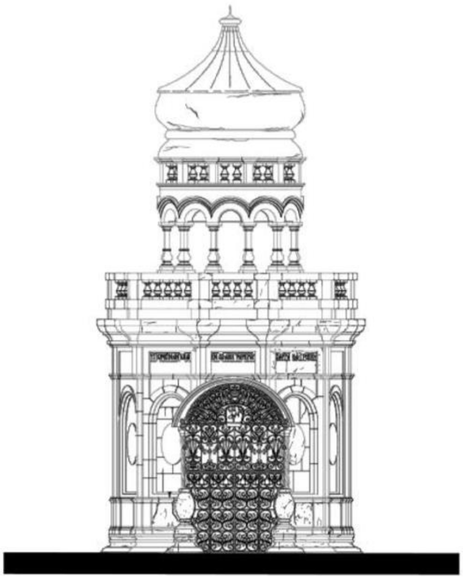


Image 18: (Left) Plan of the Aedicule depicting part of the floor of the Rotunda, (Right) Photogrammetric wire-frame 3D computer graphics model of the Tomb Chamber *©Martin Biddle 1999*

- Dionysios D. Balodimos, Andreas Georgopoulos, Georgios P. Lavvas (1995-1999)

In the years 1993-1999, the Laboratories of General Geodesy (Director Prof. D.-D.Balodimos) and Photogrammetry (Director Prof. A. Georgopoulos) of the NTUA in collaboration with the University of Athens (Prof. G. Lavvas) undertook the task of documenting the whole complex of the Church of the Holy Sepulchre at a scale of 1:50 for the Greek Orthodox Patriarchate (Balodimos et al. 2003, Georgopoulos & Modatsos 2002, Lavvas 2009). Such an extensive survey had never been carried out in the past until then. For the accomplishment of this assignment the collaboration of many different experts was essential. As a result, a scientific team of four surveying engineers, two photogrammetrists, two architects, one archaeologist and two photographers was formed. The combination of geodetic measurements and photogrammetry proved to be efficient. The data acquired consisted of more than 20000 points, 1500 metric and 500 non-metric analogue photographs for photogrammetric processing (mostly black and white negatives but also color slides) and 3000 photographs for documentation purposes. The survey measurements were used for the establishment of a rigid network, the photogrammetric control points and the section lines, while the details of the structures where recorded through photogrammetric procedures. Finally, 36 main drawings were produced (Image 19). They consisted of a horizontal plan of the whole complex, the four main exterior facades, horizontal and vertical sections through the main parts of the monument and the roof top plan (Balodimos, Georgopoulos, 2019)



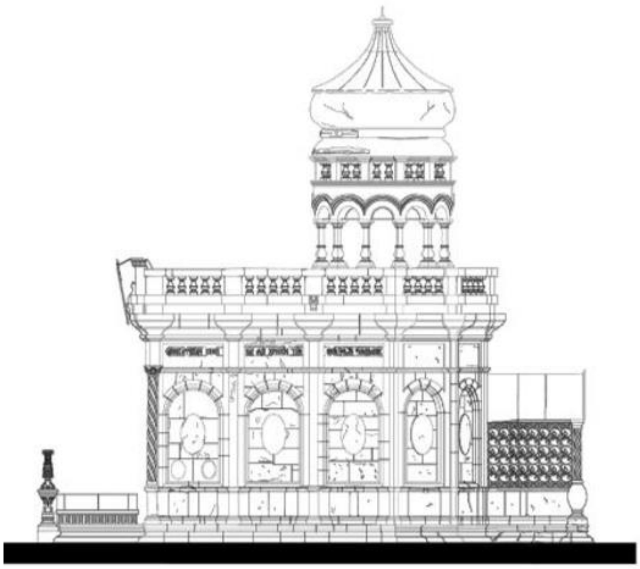


Image 19: The West (left) and North elevation (right) detailed vector drawings of the Holy Aedicule created by NTUA (1999)

©D.-D. Balodimos, A. Georgopoulos

- Grazia Tucci, Valentina Bonora (2007-2011)

The Church of the Holy Sepulchre had been damaged several times due to earthquakes and since they constitute a usual natural phenomenon in Jerusalem, a survey on the seismic risk of its structures was necessary. Particularly the study of the condition of the Aedicule was essential. Although its state was deteriorating and an iron frame had been installed by the British Mandate in 1947 as a temporary solution to prevent a potential collapse, the edifice had not been restored yet. Eventually, the three religious communities in charge of the Tomb of Christ, requested a research for the assessment of the effects caused by further seismic action to the Church of the Holy Sepulchre. The results of the specific survey would provide information for both the protection and conservation of the holy sites. This project was carried out by the University of Florence (G. Tucci, V. Bonora) in the years 2007-2011. The three-dimensional survey of the entire architectural complex, including the Aedicule, aimed at defining the seismic vulnerability of the buildings. For the accomplishment of the accurate geometric documentation of the holy sites, the methodologies and instruments used during the survey included GPS receivers, total stations, photogrammetric equipment and three-dimensional scans. The technique of the terrestrial laser scanning (TLS) was implemented for the first time regarding the three-dimensional representation of the Church of the Holy Sepulchre. The combination of topographic, photogrammetric and scanning techniques enabled both geometric and photographic information to be integrated: the geometric information was obtained from the detailed topographic survey and the 3D scans and the photographic information was obtained by projecting high resolution photographic images onto the 3D model. The final products of the research consisted of three dimensional coordinates of topographic vertices and control points, digital stereo-models from both analogue and digital photographs and a 3D model of the whole complex, including the Aedicule (Image 20), which constitutes the metric reference for the subsequent analysis of the present thesis. These data were reliable to be further processed for the seismic risk evaluation, due to the precision of the methods that were used throughout the survey (Tucci et al, 2011).

Image 20: View of the inside and outside of the 3D model of the Aedicule constructed by the University of Florence (2011) *©Grazia Tucci 2019*

- Antonia Moropoulou, Emmanuel Korres, Andreas Georgopoulos, Constantine Spyrakos, Charalampos Mouzakis (2015-2017)

The decayed and unstable Aedicule of the Tomb of Christ was in great danger of collapse for many years. The demand for immediate measures, in order to protect the most significant site of Christianity, was of high-priority. This is the reason why the Christian Communities decided to find a common solution for this crucial issue. Eventually, the Patriarch of Jerusalem Theophilos III requested from the National Technical University of Athens (NTUA) to undertake a project, which would aim to the inspection and restoration of the Aedicule (Moropoulou et al, 2019). In May 2015 the works for the diagnostic study of the Aedicule of the Tomb of Christ was initiated. For this demanding survey an Interdisciplinary Research Group was formed, consisting of Chemical Engineers, Geomatics and Surveying Engineers, Architects and Civil Engineers of NTUA (Antonia Moropoulou, Emmanuel Korres, Andreas Georgopoulos, Constantine Spyrakos, and Charalampos Mouzakis). The main goals of the specific research were to study and record the existing situation of the Aedicule and eventually propose the appropriate actions for its restoration. For this reason, a 3D model was created for the non-destructive measurements to be applied with the scope to base the rehabilitation proposal. After March 2016, when the three main religious communities accepted NTUA's proposal a work site was setup. The rehabilitation was to finish within eight months while the flow of the pilgrims should not be hindered. During this period several geometric documentations were carried out during all rehabilitation phases of the Aedicule. Data acquisition included geodetic measurements, digital image acquisition and terrestrial laser scanning (TLS) around and inside the monument. Specifically, the geometric documentation produced precise 3D models with the implementation of laser scanning, photogrammetric and geodetic methods (Image 21). For example, for the construction of the 3D model before the restoration 3.757 images in total were captured and 58 scans were needed, of which 13 around the Aedicule, 8 on top of its roof, 8 in the two staircases in the masonry, 10 from the Rotunda Gallery and 19 in the inside. In addition, laser scanning was also employed, in order to cover the areas where image acquisition was impossible, like e.g. the dark and smoked interiors of the two domes of the Aedicule and the two staircases leading to the roof. From each 3D model the

Image 21: 3D Model of the Aedicule berore (left) and after (right) the rehabilitation project by NTUA (2017)

production of sections at specific positions was also possible, supported by geodetic measurements, to assess the deformations and deviations of the structural elements (Georgopoulos et al., 2017). These data were georeferenced to an already existing local plane projection reference system from the previous work of NTUA (Balodimos et al., 2003). The ongoing documentation and monitoring throughout the restoration works was significant, since it was possible to thoroughly comprehend the structural problems of the Aedicule and make the correct decisions for the restoration interventions required (Moropoulou et al, 2017).

The three-dimensional models of the Aedicule constitute an accurate geometric documentation of its form and condition. In consequence of their analysis it is possible to perceive and detect the alterations of the structural features of the monument through the years. On these grounds, a new attempt was made for the construction of a three-dimensional model using part of the analogue data acquired during the NTUA survey in 1995. The specific photographs were captured with classical stereoscopic processing in mind. Moreover, all images concerned the Rotunda and not the Aedicule itself.

4.2. 3D MODEL FROM 1995 ANALOGUE DATA

From the survey of the Laboratories of General Geodesy (Director Prof. D.-D.Balodimos) and Photogrammetry (Prof. A. Georgopoulos) of the National Technical University of Athens in collaboration with the University of Athens (Prof. G. Lavvas) performed in 1995 at the Holy Sepulchre, analogue data, such as printed photographs, films and slides, were provided for the purpose of this specific research. Most of them were aiming to capture the Rotunda, although some parts of the Aedicule were also imaged. Some of these photographs were selected focusing on the Aedicule, in order to be processed through an automated photogrammetric software and to create a new point cloud.

The data that depicted parts of the Aedicule of the Holy Sepulchre was acquired with various analogue cameras. This is the reason why they were categorized depending on both their type and camera. In the end, four sets of data were formed:

1. <u>Hasselblad 6x6 slides</u> with 50mm focal length (29 of them)
2. <u>Canon AE-1 35mm films</u> with 50mm focal length (15 of them)
3. <u>WILD P31 metric camera slides</u> with 45,21mm focal length (7 of them)
4. <u>Printed Colored photographs</u> from an unknown camera (14 of them)

Analogue images from a camera must be digitized in order to be used in a modern digital photogrammetric system. Digitization is done either with specialized photogrammetric scanners or with normal desktop scanners with high resolution. Digitization is preferably performed directly to the negative or slide of the photograph, as printing on the photographic paper may result in image distortions and possible measurement errors.

Therefore, all of them were initially scanned with EPSON Scan software with a resolution of 1200 dpi (21 μm pixel size). Every scanned photograph had distinct dimensions and size, so they were cropped according to the group that they were classified.

- <u>Hasselblad 6x6 slides</u> with 2570x2543 pixels dimension
- <u>Canon AE-1 35mm films</u> with 1688x1122 pixels dimension
- <u>WILD P31 metric camera slides</u> with 4342x5604 pixels dimension
- <u>Printed Colored photographs</u> with 8446x5642 pixels dimension

Afterwards, the parameters of the interior orientation were necessary to be attached to every image. Interior orientation defines the internal geometry of a camera or sensor as it existed at the time of data capture. This kind of information could be added to the EXIF file. Every image includes two different types of data: EXchangeable Image File format (EXIF) and Information Interchange Model (IPTC). Both EXIF and IPTC data are referred to as *metadata* and provide information about the digital image. Some metadata is generated automatically by the device capturing the image. Additional metadata may be added manually and edited through an image editing software. Typical Exif information is mostly automatically generated by the camera and includes camera details and settings such as aperture, shutter speed, ISO number, focal depth, dots per inch (dpi).

Other automatically generated metadata include the camera brand and model, the date and time when the image was created and the GPS location where it was created. The IPTC data is added manually through imaging software by the photographer or someone managing the image. It consists of descriptive and administrative metadata, for example, the name of the image creator, keywords related to the image, captions, titles and comments, licensing rights, restrictions on reuse, among many other possibilities. Effective descriptive metadata is what makes images more easily searchable (Rouse, 2015).

The software that was eventually selected, for editing the EXIF file of the scanned photographs and slides, was Zoner Photo Studio X. The files were imported to the software and through the image information, it was possible to edit the EXIF file of each one (Image 22). In this way, information such as the focal length, the maker and the model of the camera were added.

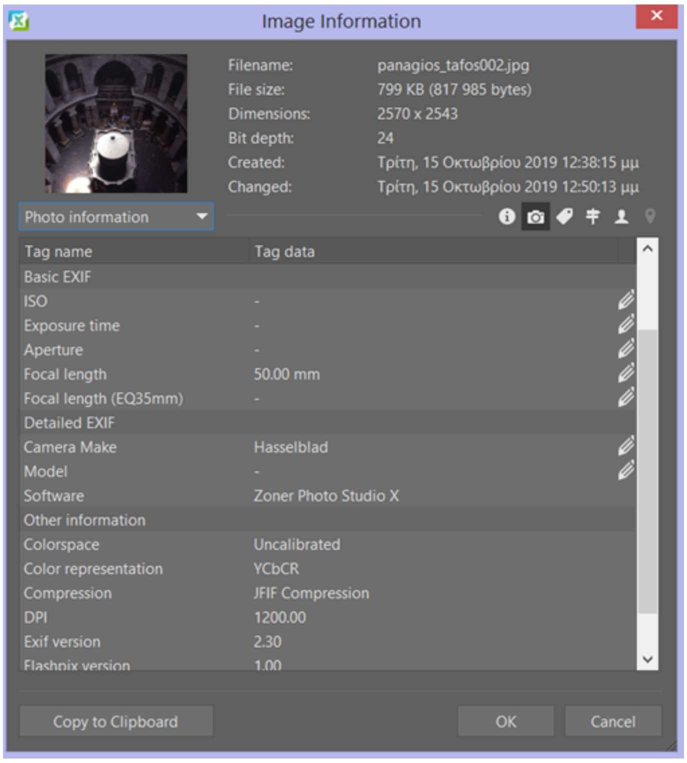


Image 22: EXIF file of a photograph in Zoner Photo Studio X © *Author 2020*

Eventually, when the photographs with the edited EXIF files were imported into the photogrammetric software Metashape, they were divided into separate camera groups. In this way, the software would be able to process the images correctly.

As mentioned, the purpose of the utilization of the specific photographs was neither for photogrammetric procedures nor for capturing the Aedicule and as a result, various difficulties occurred. For instance, the images that would be used were created from either slides, films or printed photographs, so there was a combination of different ways of depiction. Moreover, four different cameras were used and for one of them, there was no information about the model or the focal length. Problems may also stem from the fact that some of the images were in grey-scale (black and white) and they couldn't be matched with the color images, because the software detects common points depending also on their color. Another major obstacle was the absence of sufficient overlap between the photographs, which is the main essential condition for photogrammetry. What is more, most of the photographs were not of high resolution, causing the lack of the details of the monument. The lack of Ground Control Points (GCP) with known three-dimensional coordinates or of a measured distance of the Aedicule affects both the geometry and the scale of the final constructed point cloud. It is also important that the camera-to-object relative positioning the moment that the photograph was taken, varied even if the same camera model or the same focal length was used. Good lighting conditions would greatly impact the result of the photogrammetric model: its final texture, geometry, and potential errors, but the lighting of the room (Rotunda) wasn't helpful since some parts were too bright and some others too dark. Also, there were only a few photographs that could be used and unfortunately, they were not taken from different viewpoints, even when they were depicting a specific part of the Aedicule. Finally, the continuous population of the area by pilgrims caused many problems, because some parts of the Tomb were hidden by them and consequently there was a loss of information.

4.2.1. FIRST ATTEMPT: PROCESSING OF THE COLOR PHOTOGRAPHS

Taking into consideration all the circumstances, the first construction of a three-dimensional model from the color photographs was attempted. Initially, the images were classified in various groups (chunks) according to which part of the Aedicule they were imaging. After the photos were added to each chunk, their alignment was carried out with the specific parameters: high accuracy, 0 key point limit and 0 tie point limit. This first step is the feature matching across the photos. At this stage, Metashape detects common points in the photos following a procedure which is similar to the SHIFT algorithm (Semyonov, 2011). In the end, it computes the camera position and orientation for each photo using a bundle-adjustment algorithm and builds a sparse point cloud (Image 23). The results of every alignment were inspected and incorrectly positioned photos were removed or realigned. In some cases, markers on points of different locations that were not detected by Metashape were added or removed depending on their effect to the total error of the alignment.

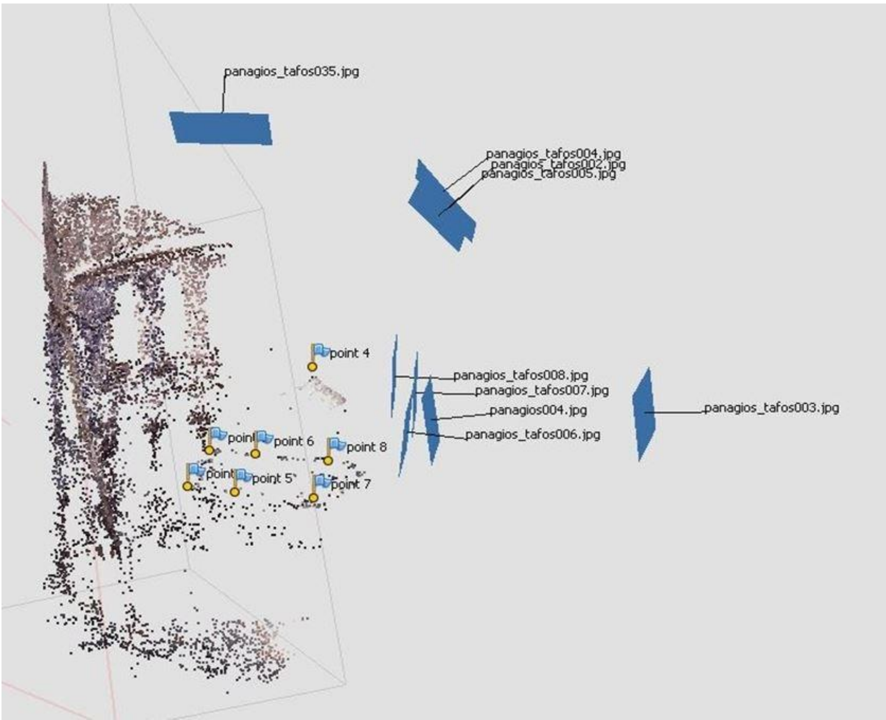


Image 23: The result of the alignment of a chunk depicting the top view of the Aedicule

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The next step is the creation of the dense point cloud. Based on the estimated camera positions, the program calculates depth information for each camera in order to be combined into a single dense point cloud. After adjusting the volume bounding box by resizing or rotating the region and removing from the sparse point cloud all the spots or areas out of real surfaces that appear as displayed imperfections in the image (noise) (IGI Global, 2020), the preferred reconstruction parameters for this procedure were selected: high quality and aggressive depth filtering mode. As a result, the dense point cloud of each chunk was generated and visualized. The results of the dense point clouds of each chunk are presented below:

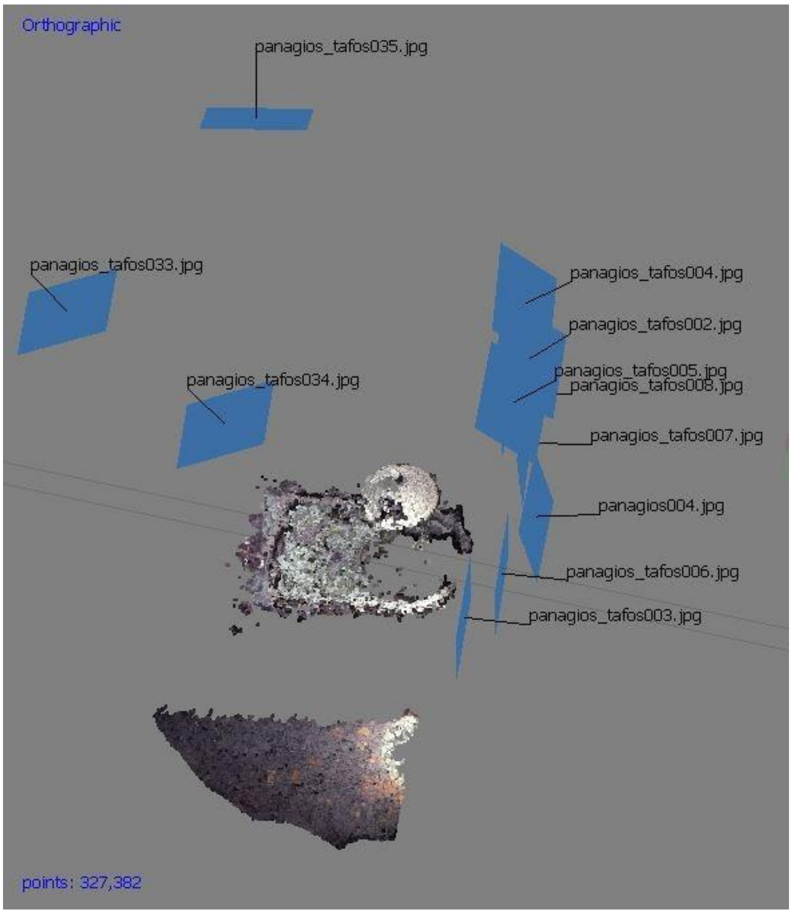

Image 24: The dense point cloud of the top view of the Aedicule from color photographs

© Author 2020

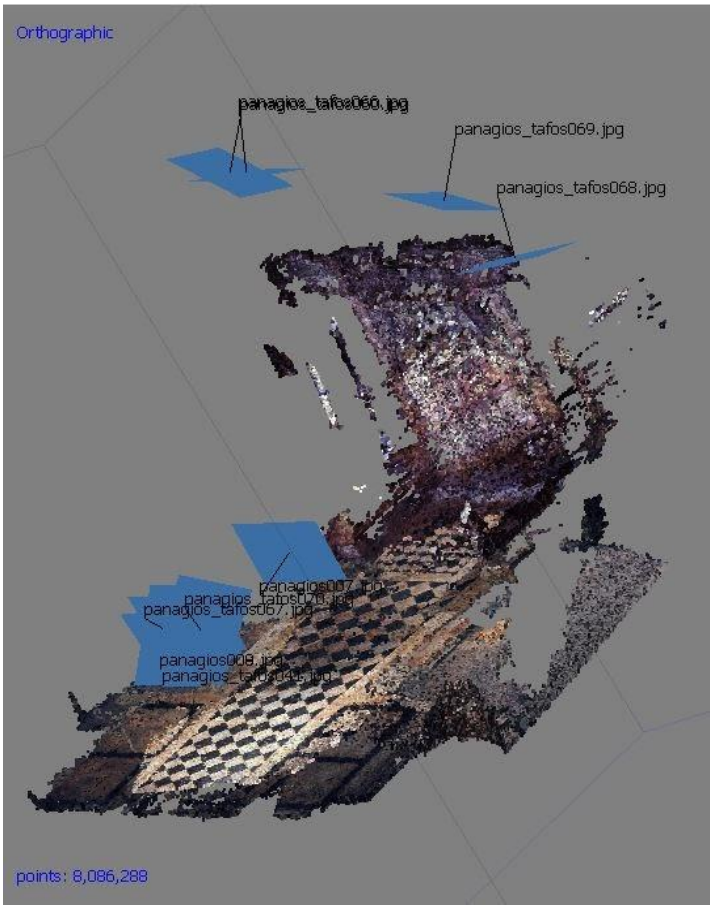

Image 25: The dense point cloud of the eastern entrance of the Aedicule from color photographs

© Author 2020

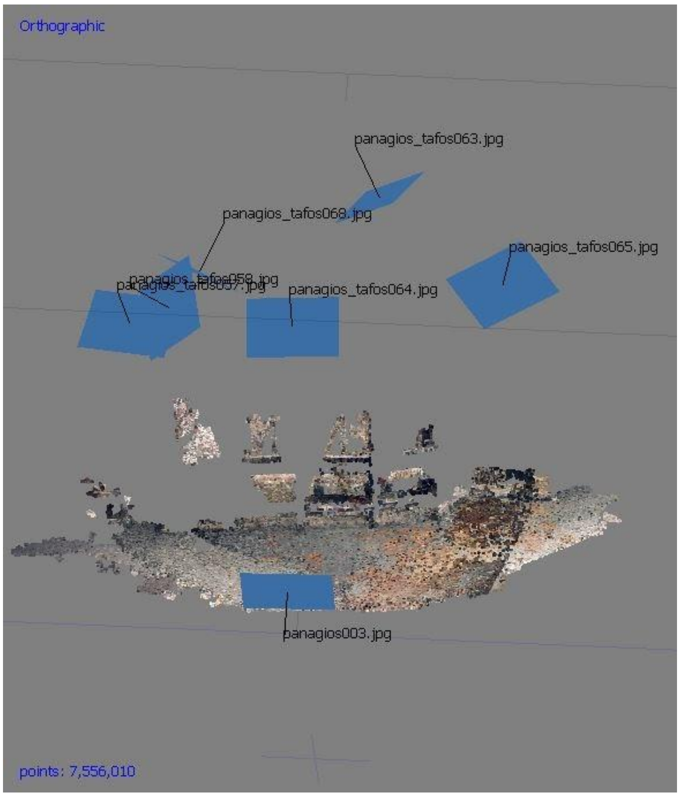

Image 26: The dense point cloud of the northern side of the Aedicule from color photographs

© Author 2020

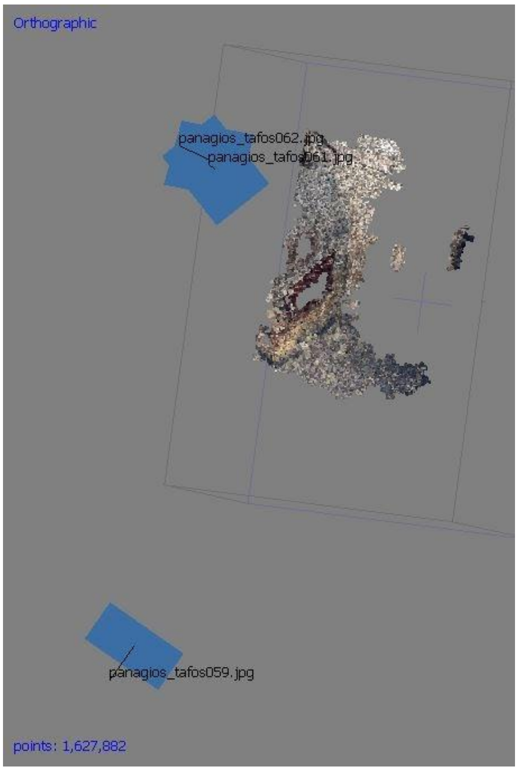

Image 27: The dense point cloud of the western side of the Aedicule from color photographs

© Author 2020

It is obvious that the results are not correct from a metric point of view. The geometry of the dense point clouds is not identical to the geometry of the Aedicule. There are also many deformations, many missing parts, a lot of noise and errors concerning the markers that were used to align the photographs.

4.2.2. SECOND ATTEMPT: PROCESSING OF THE GRAYSCALE PHOTOGRAPHS

A second attempt was carried out with the intention to take advantage of the grayscale photographs for a better outcome. Taking into consideration that this kind of photographs were very few, the color photographs were edited in Photoshop so that they could be combined all together. When the color images were imported into Metashape, the commands ‘Image’ > ’Mode’ > ’Grayscale’ would convert them to the desired form. Moreover, since the negative of the films was scanned in order to create digital images, some photographs that were in grayscale had to be edited as well. In that case, after selecting the full image the commands that were implemented consist of ‘Image’ > ’Adjustments’ > ’Invert’ to convert the area into photo positive.

Afterwards, the images were imported into Metashape again and separated into different chunks. Following exactly the same procedure as previously, the dense clouds that derived from the grayscale photographs are presented below:

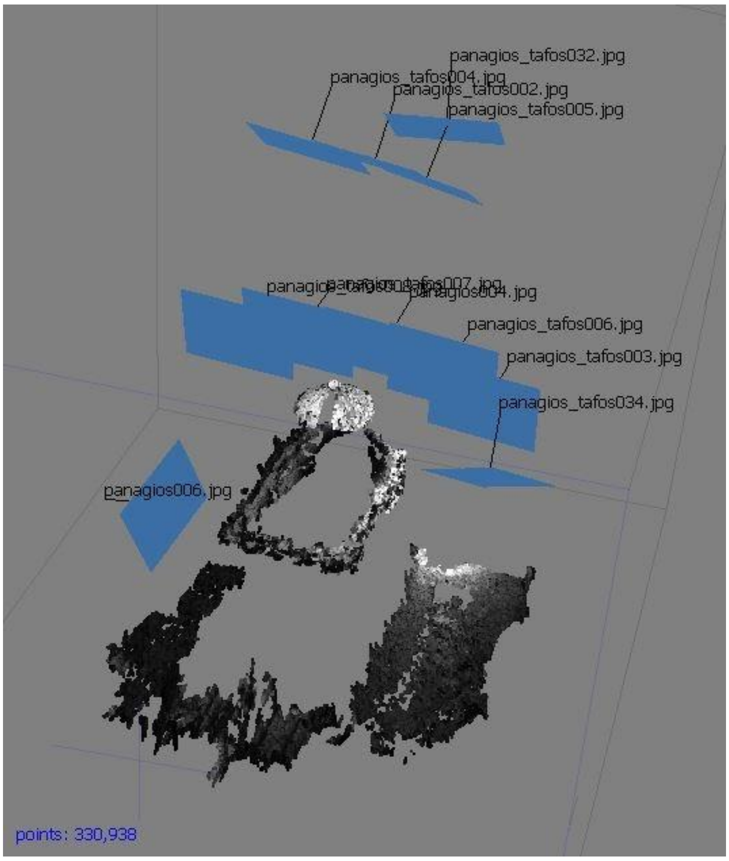

Image 28: The dense point cloud of the top view of the Aedicule from grayscale photographs

© Author 2020

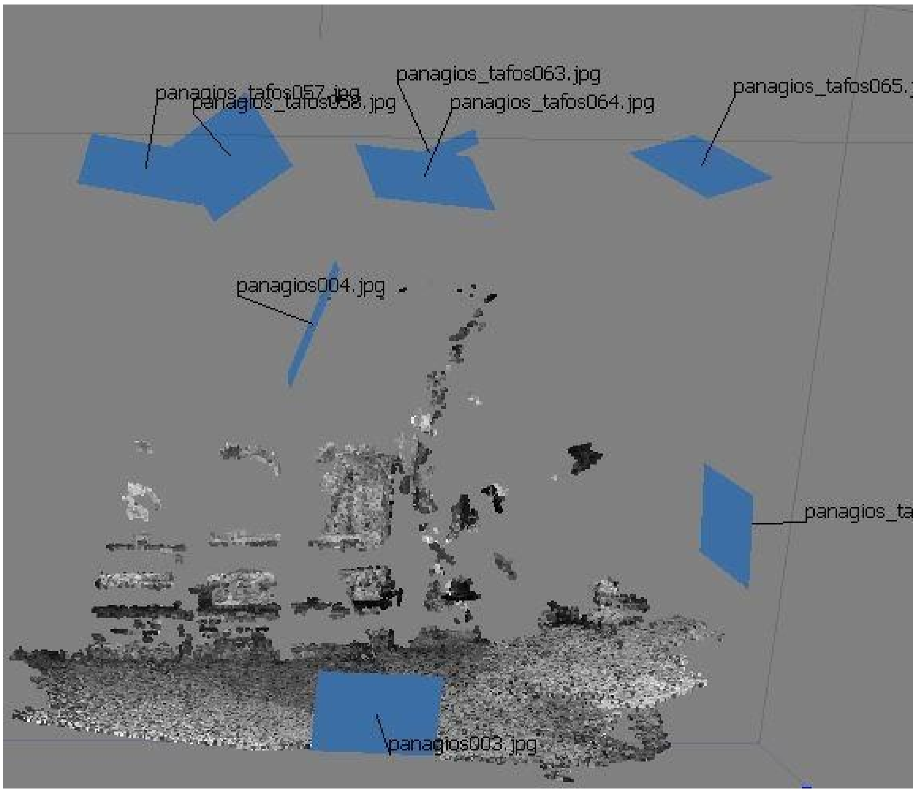

Image 29: The dense point cloud of the northern side of the Aedicule from grayscale photographs

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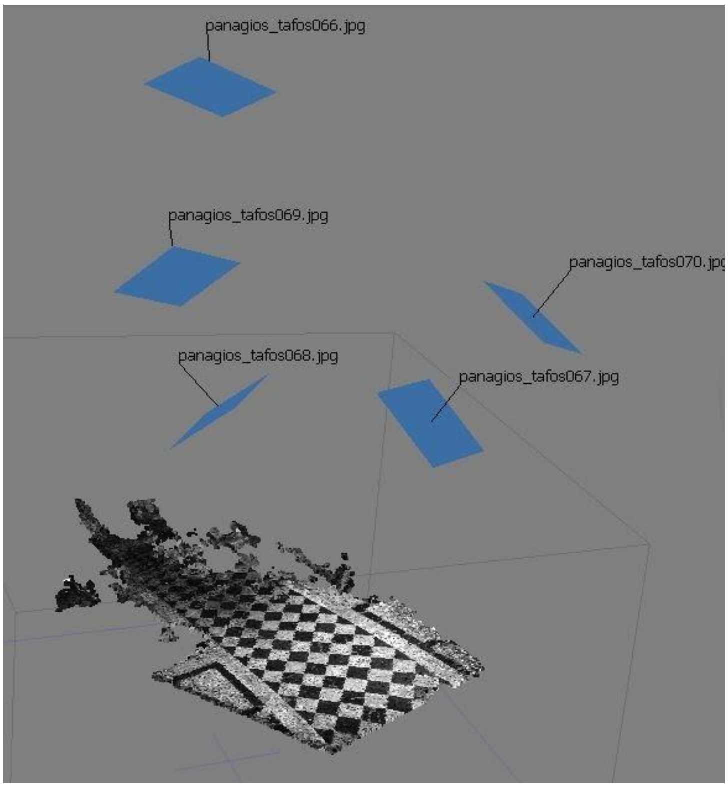

Image 30: The dense point cloud of the eastern entrance floor of the Aedicule from grayscale photographs

© Author 2020

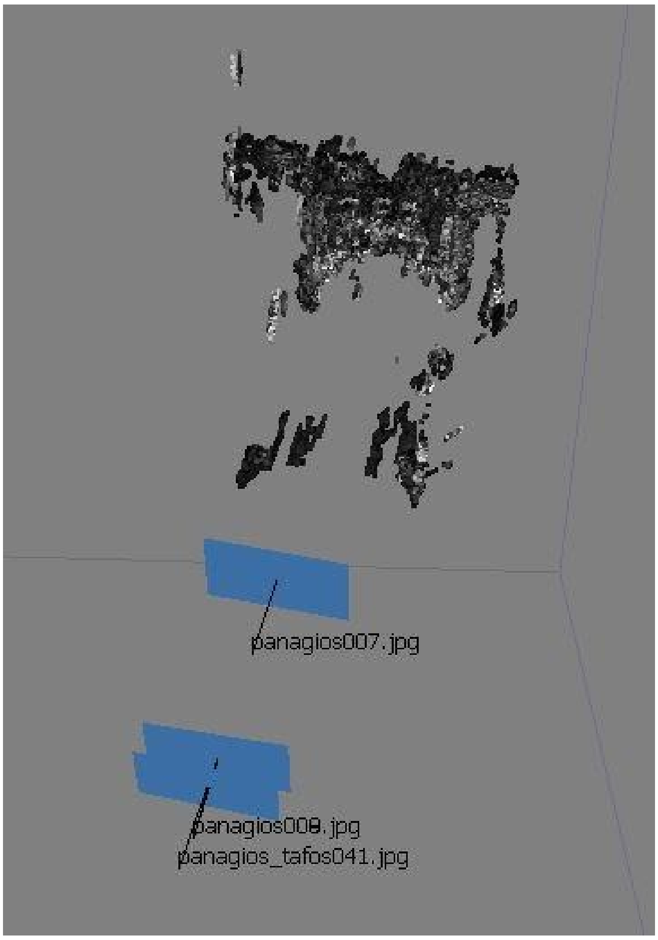

Image 31: The dense point cloud of the eastern entrance facade of the Aedicule from grayscale photographs

© Author 2020

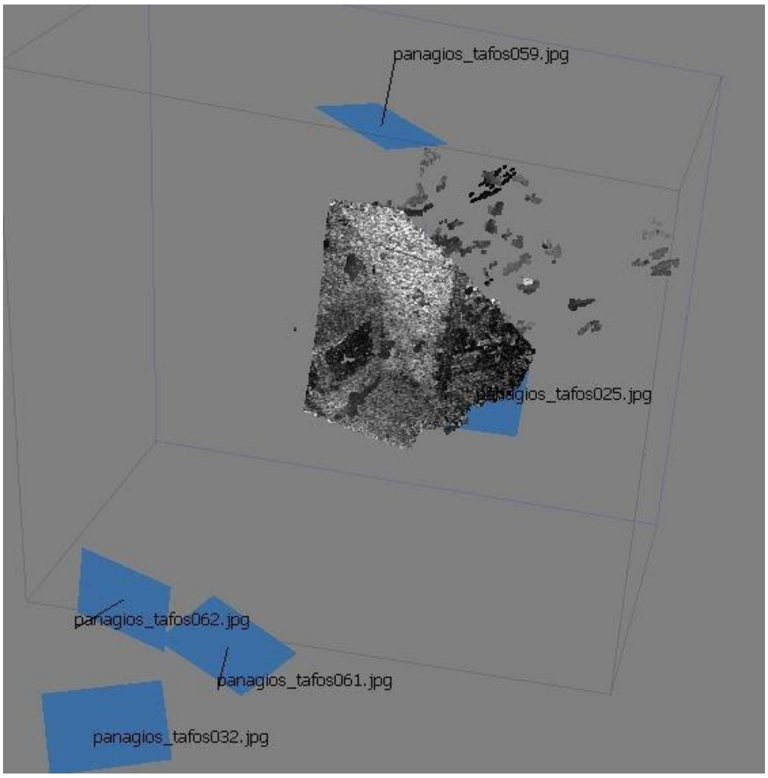

Image 32: The dense point cloud of the western side of the Aedicule from grayscale photographs

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Even though more photographs were aligned, 40 in this case, as opposed to 31 colour photographs, the result of the dense point cloud based on the grayscale photographs was not better or more precise than the dense point cloud from the color photographs. The images that were added didn't have point correspondences with the previous coloured photographs, although they were eventually aligned all together when converted to greyscale. Thus, the additional images which included more information about the monument didn't contribute to a visually improved outcome, because the parts that were depicted only on one photograph wouldn't be presented at the point cloud.

Furthermore, the lack of color affected the alignment because the software was unable to detect as many common points as in the first attempt. For example, for the top view of the Aedicule, only the top of the dome and the small columns on the roof are depicted, whereas at the color point cloud there was also the roof. Furthermore, the facade of the entrance was more detailed with the coloured photographs and could easily be aligned with the images depicting the floor in front of it in contrast to the grayscale photographs. On the other hand, the greyscale point cloud of the north facade displayed more information, including one of the stone panels of the structure. Also, in both point clouds, the part of the floor leading to the entrance of the Aedicule presented the most accurate three-dimensional reconstruction, due to its decorative pattern and therefore many common points could be identified by the software.

Taking everything into account, the specific point clouds cannot provide any information related to the dimensions, the scale or the structure concerning the Aedicule of the Tomb of Christ. One is only able to obtain an idea of the shape and the form of the edifice. Unfortunately, a better outcome could not be achieved by processing only these photographs which were apparently not suitable for reconstructing the Aedicule, as they were taken to restitute the surrounding Rotunda.

5. COMPARISON OF THE POINT CLOUDS

Different approaches and tools are required in Cultural Heritage Documentation to deal with the complexity of monuments and sites. The basic criteria that should be taken into account for a proper choice of methods and a successful workflow consist of site configuration, provided equipment, geometry, accuracy, resolution, georeferencing, texture and processing time (Grussenmeyer et al., 2012). While surveying a monument, it is necessary to adapt to the demand of nondestructive methods due to its historical value. This kind of structures usually endure through time. As a result, they have been through many phases of construction, damage and repair as well as various alterations due to naturale causes (erosion, earthquakes etc.) or vandalism. Moreover, cultural heritage sites should be measured with high accuracy, so that all the details are depicted precisely in the final products.

Terrestrial Laser Scanning (TLS) is a solution for the documentation, reconstruction and conservation of heritage buildings, monuments or archaeological sites. This method can provide better spatial information in complex 3D scenes in a brief period of time. A Laser Scanner records three-dimensional coordinates of thousands of points by sending a laser beam to the surface of the site of interest. The measurements of the angles and the distance to the reflecting point result to the estimation of its position through polar coordinates.

Consequently, at the two last projects which took place in Jerusalem and focused on the geometric documentation of the Aedicule of the Tomb of the Christ, three-dimensional models were constructed through terrestrial laser scanning (TLS). To begin with, the GECO Laboratory (Prof. G. Tucci) of the University of Florence visited the monument and performed the first survey with the application of a laser scanner. Some years later the National Technical University of Athens with the collaboration of the Laboratory of Photogrammetry (Prof. A. Georgopoulos) produced several 3D models of the Aedicule during the different stages of the restoration again with measurements that were acquired with the same method.

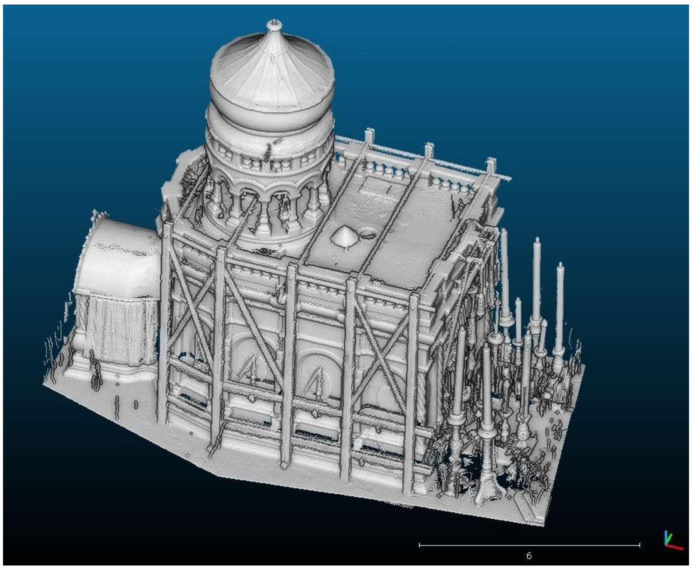


Image 33: 3D model constructed by the University of Florence in 2007 © UNIFI *GECO Laboratory 2007*

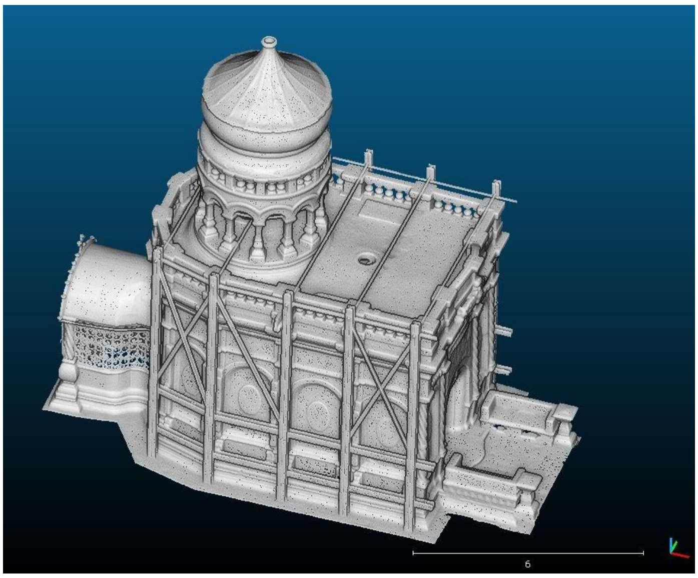


Image 34: 3D model constructed by the National Technical University of Athens in 2015 © NTUA *Laboratory of Photogrammetry 2015*

These 3D models are accurate representations of the Aedicule in different time periods. Therefore, their comparison and the assessment of its outcome will provide important information about the condition of the structure through these years. Hence, two models were selected to be compared, the one created in 2007 by the GECO Laboratory of the University of Florence (Image 33) and the model that was constructed in 2015 by the Photogrammetry Laboratory of NTUA before the restoration of the Aedicule (Image 34). With the aim of succeeding in the precise contrast of these three-dimensional models, attention should be drawn to both their density and reference system.

Point cloud density is an indicator of the resolution of the data: higher density results in more information (high resolution) while lower density results in less information (low resolution) (Maschak, 2018). For the objective comparison of the two point clouds, identical density should be ensured. Regarding the Italian point cloud, its resolution was approximately 5 mm. The Greek point cloud had higher resolution and as a consequence it was decimated. The final point clouds consisted of 14.522.720 points (Italian) and 21.102.657 points (Greek).

Since each survey established a new reference network and coordinate system, a transformation should be applied, so that it is possible to evaluate, from a metric point of view, relations between the point clouds. There are multiple types of transformations but in the specific case the shape and the size of the point clouds should be kept the same at the end of the procedure. Consequently, the rigid body transformation was applied, which typically consists of a translation and a rotation in 3D space (Image 35).

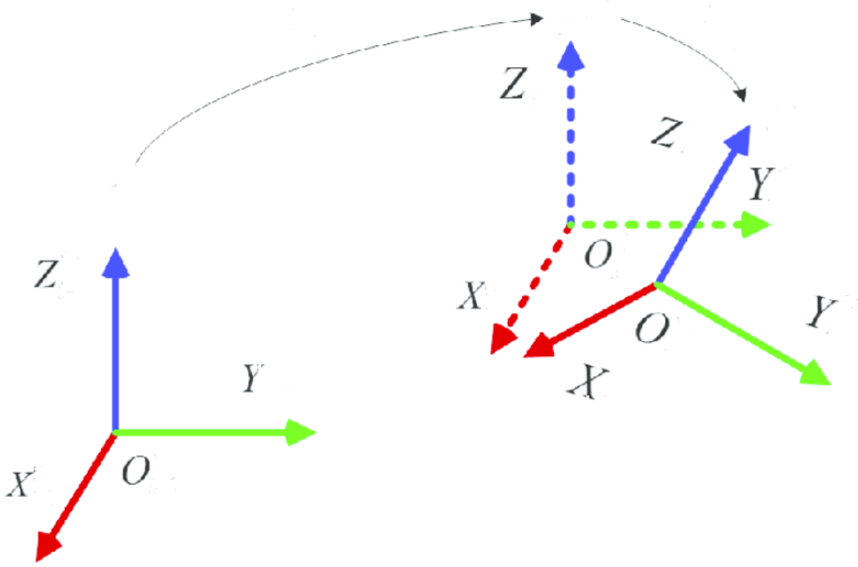


Image 35: The translation and the rotation of the rigid body transformation © *Author 2020*

The two reference systems differ in the three parallel translations of the origin of the axes and the three rotation angles of the axes of the first in relation to the second system.

The formula that describes the particular transformation is the following:

$$\begin{matrix} X_1 \\ Y_1 \\ Z_1 \end{matrix} = R \times \begin{matrix} X_2 \\ Y_2 \\ Z_2 \end{matrix} + \begin{matrix} \Delta X \\ \Delta Y \\ \Delta Z \end{matrix}$$

R is the orthogonal matrix of the rotation angles. In order to determine the transformation, at least three points known in both systems are necessary. When it comes to the reference systems of GECO Laboratory and NTUA, points which were common in both of them should be detected in order to succeed in the point set registration. More specifically, during the Italian survey in 2007, two vertices from the previous Greek survey in 1995 were discovered (Image 36). These points were also used as vertices for the traverses of the Italian survey. As a result, two common points existed between the Italian reference system and the Greek reference system of 1995. The latest Greek survey for the geometric documentation of the Aedicule, which was carried out in 2015, was performed with the reference system from the previous work of NTUA in 1995. Consequently, the coordinates of these two points (Grek1, Grek2) were known in the Italian reference system of 2007 and the Greek reference system of 2015.

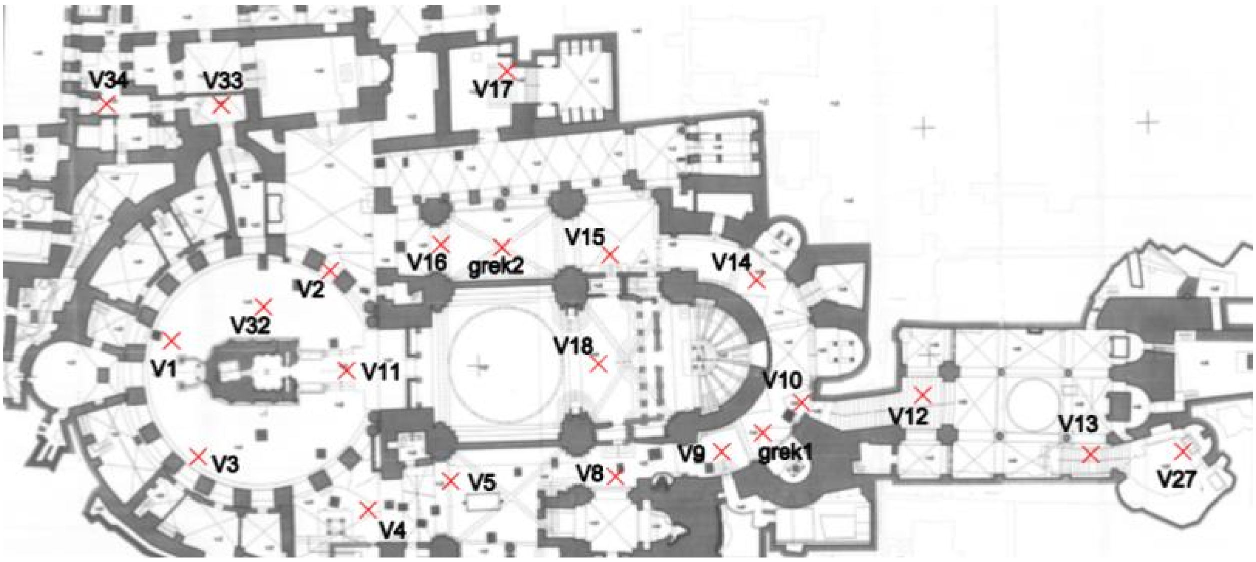


Image 36: The vertices of the Italian survey at the Holy Sepulchre in 2007 ***©UNIFI GECO Laboratory 2007***

The coordinates of the two vertices in the Greek reference system:

grek1 X=124.962m Y=92.527m Z=754.181m

grek2 X=102.670m Y=110.621m Z=754.194m

The coordinates of the two vertices in the Italian reference system:

grek1 X=1008.579m Y=994.131m Z=477.473m

grek2 X=983.864m Y=1008.804m Z=477.481m

There were no more common points required for the specific transformation, since at first it was assumed that the only rotation between the two reference systems was around the Z-axis. That is because in both surveys terrestrial laser scanner was applied for the data acquisition. *The coordinates of the points obtained by the scanner are defined in a reference system connected with the centre of the instrument. The transmission centre is the origin with coordinates (0,0,0). If the instrument is levelled, the Z-axis is vertical. The X-axis and Y-axis are perpendicular to each other and to the Z-axis and form the horizontal reference plane (Image 37). During the scanning process the x-, y-, z- coordinates are calculated from the measured distance between the scanner and the object and the corresponding measured angles θ and φ. φ angle is zero in the x-direction and is positive counting clockwise and θ is the zenith angle* (Deruyter, 2015).

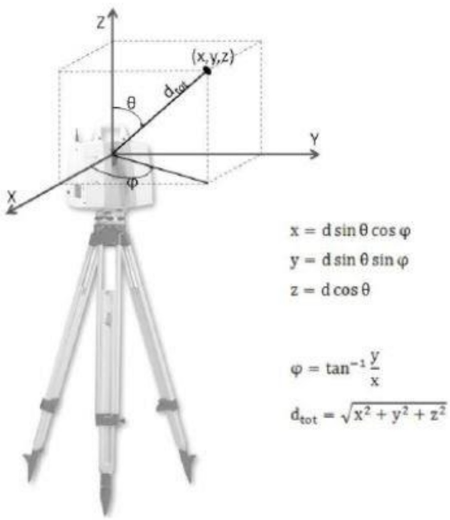


Image 37: Reference system of a terrestrial laser scanner © *Deruyter 2015*

Since in both surveys of the Aedicule, terrestrial laser scanners were implemented, the reference systems of the point clouds would be similar to the reference system of the instrument. In this way, the only rotation that would differ between them would be the one around the Z-axis.

The NTUA point cloud was selected to be the reference and the GECO point cloud would be the one which would be transformed. Therefore, the calculations were conducted, taking into consideration that X1, Y1, Z1 represented the Greek coordinates, X2, Y2, Z2 the Italian coordinates and the rotation matrix included only the rotation of the Z-axis.

The results of the transformation are presented below:

Translation:

ΔX -1017.697496 m

ΔY -744.047755 m

ΔZ 276.708 m

Rotation Angle:

$\omega(z)$ -8.377703^{0}

Afterwards, the two point clouds were imported into Geomagic software. For the computation of the rigid body transformation with the specific software, it is necessary the angles of the rotations of the axes to be in degrees. This is why the angle of the rotation of the Z-axis was calculated in the same units. The transformation would be applied to the Italian point cloud, so through the 'Tools' tab, the command 'Transform' was executed after the translation and rotation input. The alignment of the point clouds was improved, using the 'Global Registration' command, which uses the ICP (Iterative Closest Point) algorithm. In the Iterative Closest Point one point cloud, the *reference*, or *target*, is kept fixed, while the other one, the *source*, is transformed to best match the reference. *The algorithm iteratively revises the transformation (a combination of translation and rotation) needed to minimize an error metric, usually a distance from the source to the reference point cloud, such as the sum of squared differences between the coordinates of the matched pairs* (https://en.wikipedia.org/wiki/Iterative_closest_point). It should be stressed that the specific algorithm and Geomagic in general never cause any alterations to the scale or the shape of the point cloud, which are significant for the comparison.

The results of the transformation after the implementation of the ICP are presented below:

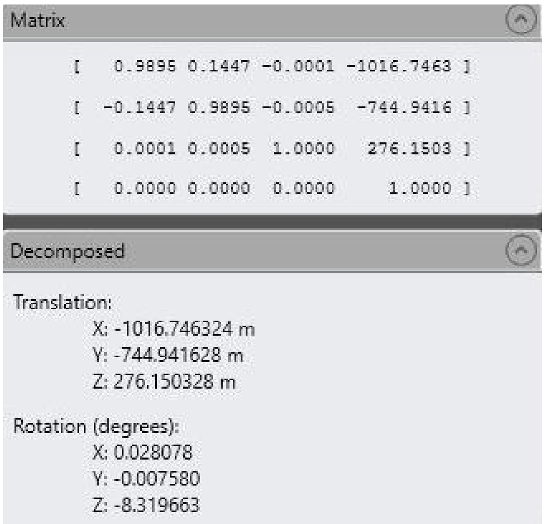


Image 38: Results of the Global Registration ***© Author 2020***

Both the translation and the rotation around the Z-axis were very similar to those that were initially calculated, although small rotations around the X-axis and the Y-axis also existed. Since only two common points with known coordinates existed, the assumption of a single rotation around the Z-axis was necessary for the rigid body transformation. Otherwise it would not be possible to calculate the parameters of the transformation. Moreover, the ICP algorithm does not change either the scale or the shape of the point clouds and thus it is presumed that the best possible registration result was achieved (Image 39). Considering that the point cloud registration was completed successfully, a comparison between them would be made by creating sections at the point clouds and using the tools of the CloudCompare software.

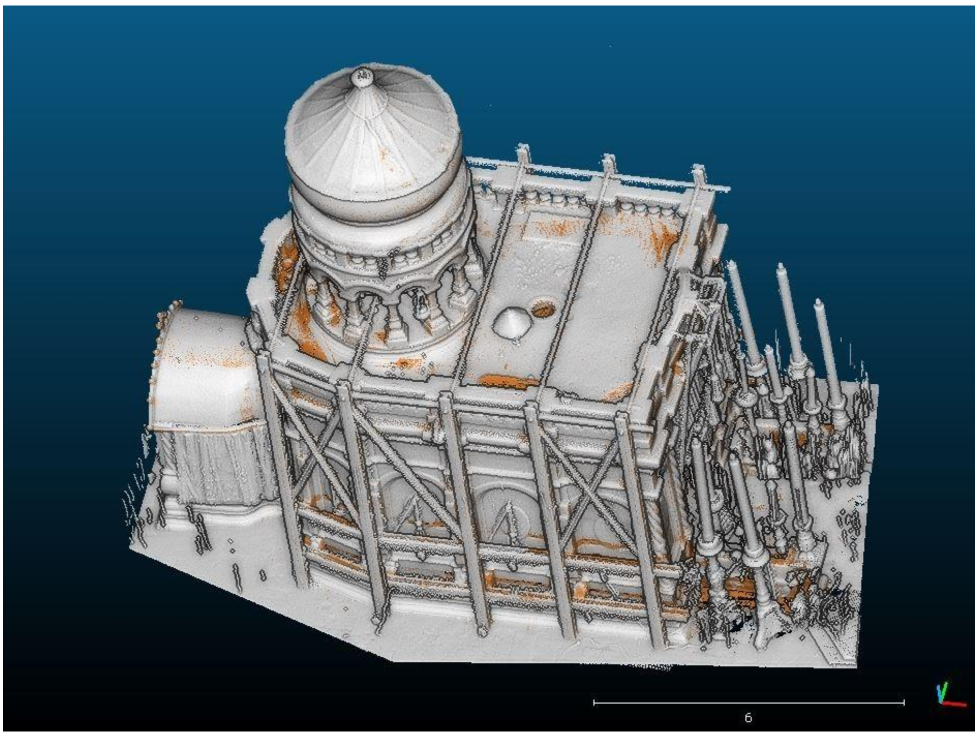


Image 39: The registered point clouds (gray=Italian point cloud, orange=Greek point cloud)
© UNIFI GECO Laboratory 2007, NTUA Laboratory of Photogrammetry 2015

Following the procedure of the point cloud registration, three different types of sections were created from each 3D model for comparison: a horizontal section (plan), a transverse section at the Chapel of the Angel and two longitudinal sections, one of them parallel to the axis of the burial chamber (Image 40).

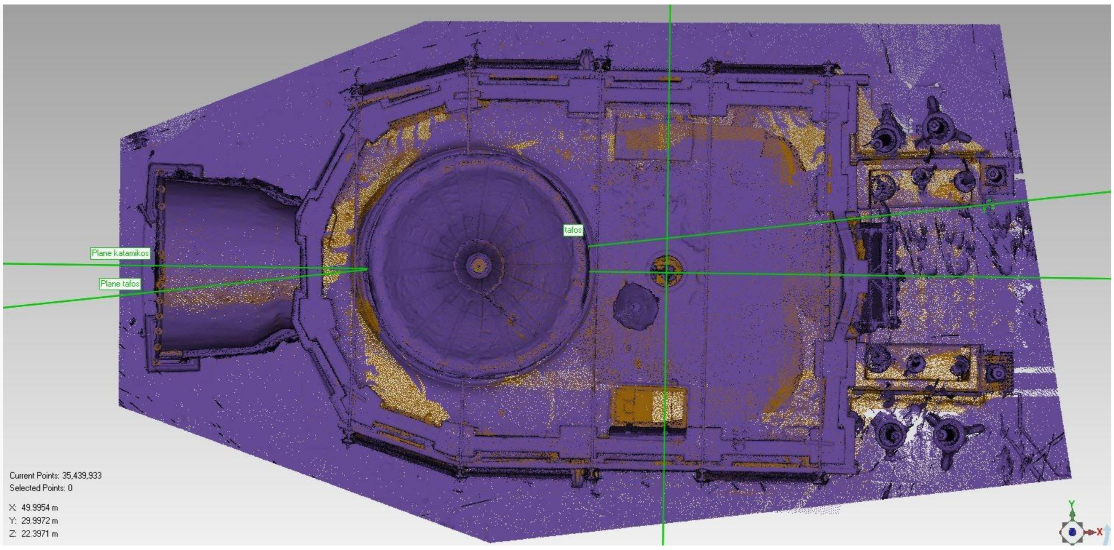


Image 40: Traces of the vertical sections (green lines) of the point clouds (purple=Italian point cloud, yellow=Greek point cloud) ***© UNIFI GECO Laboratory 2007, NTUA Laboratory of Photogrammetry 2015***

For producing the cross sections, the point cloud from the Laser Scanner was processed in the Geomagic software. The elevation of the plan section was set at +1.60m from the ground, relative to the exterior floor level, and then a "slice" of points was extracted at the specific height. Because there were a lot of points and thus too much information, a thin "slice" was chosen for easier creation of the plan section in AutoCAD software. Afterwards, the transverse and the longitudinal sections were constructed in the same way as the horizontal. The only difference was that in those cases, the reference system of the projection is not the same with the reference system of the drawing software, which is referred to as the world coordinate system or WCS. Every point in a two-dimensional drawing using the World Coordinate System can be identified by its X, Y coordinates while the Z-coordinate value is zero. This is the reason the points of these sections had to be transformed when imported into the AutoCAD with two rotations: firstly around the Z-axis and then around the X-axis (100g).

Finally, the new sections were designed depending on the points of the 3D models, four for each point cloud and therefore eight in total. It is important consider that the point cloud from the NTUA survey in 2015, as far as the specific research is concerned, consisted of fewer points than the original scans. As a result, not only the number of points depicted in the Greek sections was smaller than the number of points in the Italian sections, but also the sharp corners of the monument were depicted as curves in the sections of 2015. Moreover, there was much noise in both point clouds, due to the people visiting the Aedicule, the oil-lamps and the candles that were placed in the interior of the edifice. The complex decorations of the Chapel of the Angel and of the facade at the entrance could not be represented in detail based only on the points of the sections. Thus, photographs that depicted the specific parts of the Aedicule and provided information of their form were necessary for the completion of the sections. In addition, when it comes to creating sections of a monument without direct personal knowledge, more problems arise because of the difficulty in thoroughly comprehending the exact shape of the site of interest.

5.1.1. DISTANCE DEVIATIONS

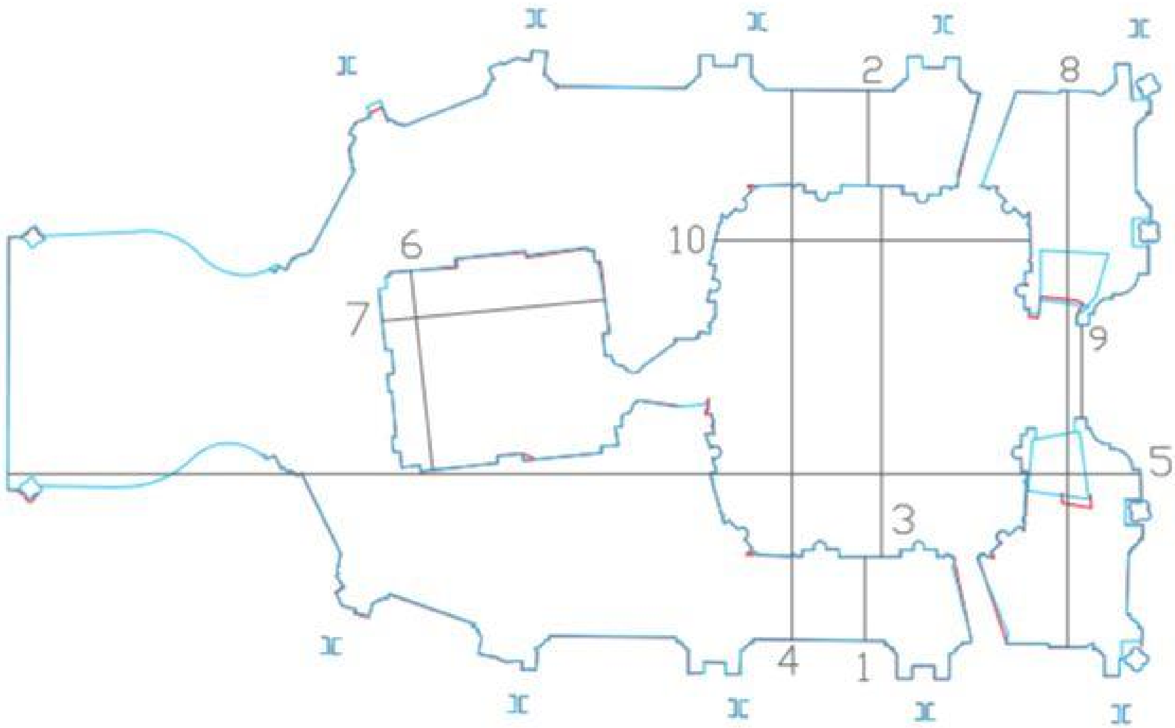
The primary purpose of the production of these sections was to enable a thorough comparison of the main dimensions of the structure, in particular the length, width and height both of the interior and the exterior. With the aim of accomplishing this, various measurements of common distances in different parts of the Aedicule were performed from every pair of sections (Italian-Greek). It comes to no surprise that the measurements between the same dimensions of the same type of section were not precisely equal. The differences detected range from small to large values. Through the examination of these fluctuations and their variability, a correct result of the comparison of the two 3D models could be accomplished. Consequently, an approximation of the deviation of the data between them was estimated.

The procedure was repeated for all the types of the sections created: the horizontal, the transverse, the longitudinal and the longitudinal with the orientation of the tomb chamber. Initially, the differences between the measurements of each distance were determined. These differences were signified as $(d_i - d_j)$, representing with d_i the Italian measurements and with d_j the Greek measurements. Subsequent step was to calculate the RMSE of the differences determined. For this purpose 10 distances that represent the main dimensions of the Aedicule, as depicted in every section, were selected. The formula that describes the RMSE is presented below:

$$RMSE = \sqrt{\frac{\sum_1^{10}(d_i - d_j)^2}{N-1}} = \sqrt{\frac{\sum_1^{10}(d_i - d_j)^2}{9}}$$

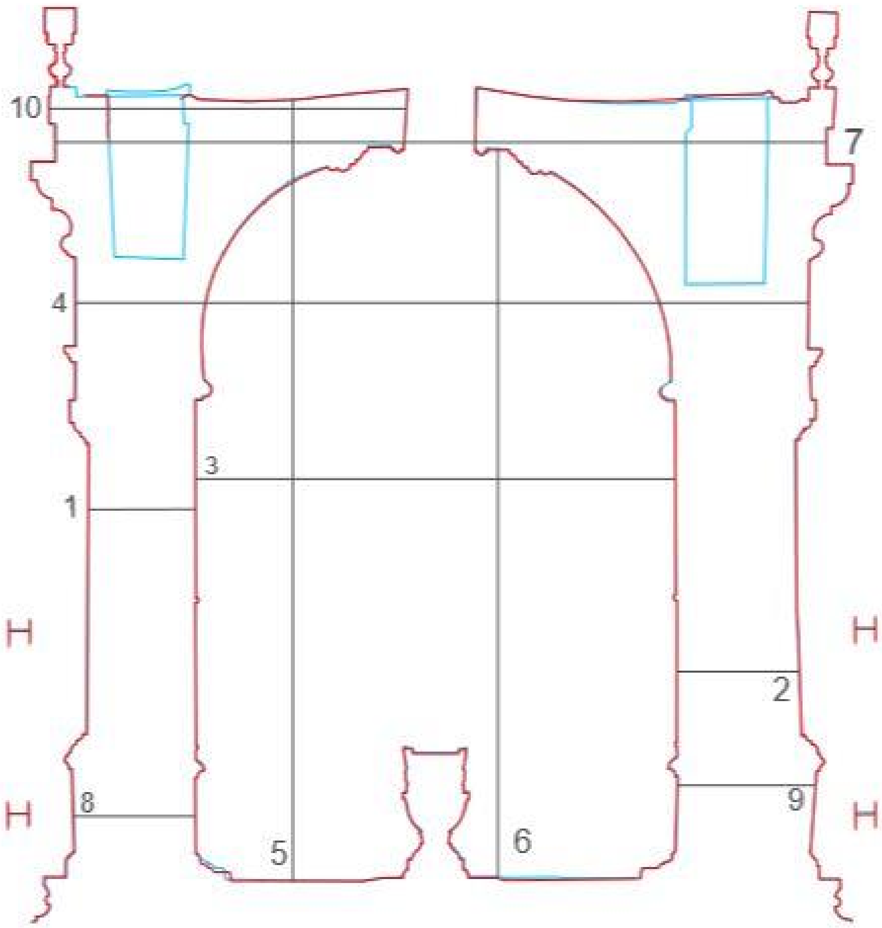
The tables below present the drawings of the four pairs of sections together with the calculations of the RMSE regarding to each type of section. Each drawing consists of the Italian section (red line), the Greek section (blue line) and the dimensions that were measured (black lines).

Horizontal Section (plan)



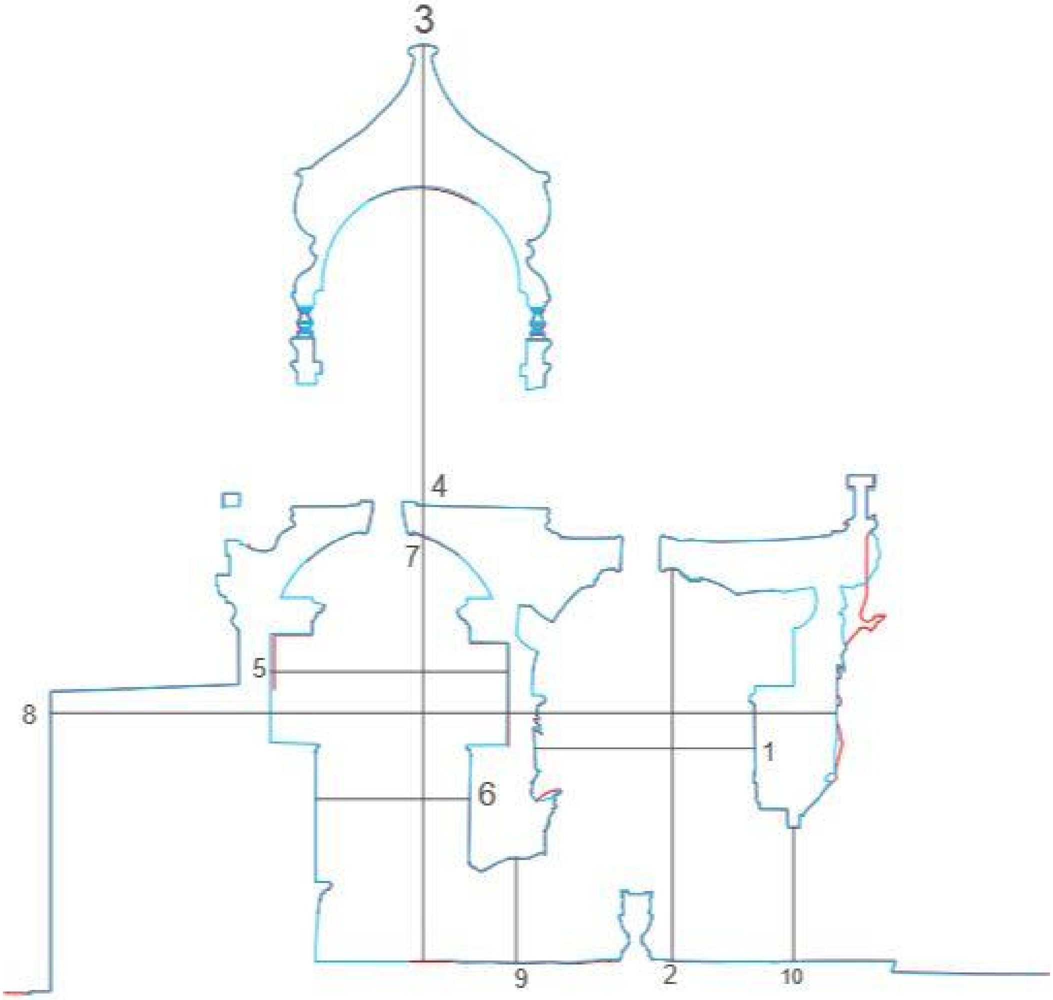
	Measurements on Italian section di (m)	Measurements on Greek section dj (m)	Δd=di-dj	(Δd)^2	Σ(Δd)^2	N-1	[Σ(Δd)^2]/[N-1]	RMSE (m)
1	0.7712	0.7708	0.0004	1.6E-07	0.000142	9	1.58322E-05	0.0040
2	0.8751	0.8794	-0.0043	1.849E-05				
3	3.4196	3.4134	0.0062	3.844E-05				
4	5.0662	5.0613	0.0049	2.401E-05				
5	10.3899	10.3936	-0.0037	1.369E-05				
6	1.8429	1.842	0.0009	8.1E-07				
7	2.0531	2.0513	0.0018	3.24E-06				
8	5.1234	5.1192	0.0042	1.764E-05				
9	0.855	0.8601	-0.0051	2.601E-05				
10	2.8948	2.8879	0.0069	4.761E-05				

Transverse Section



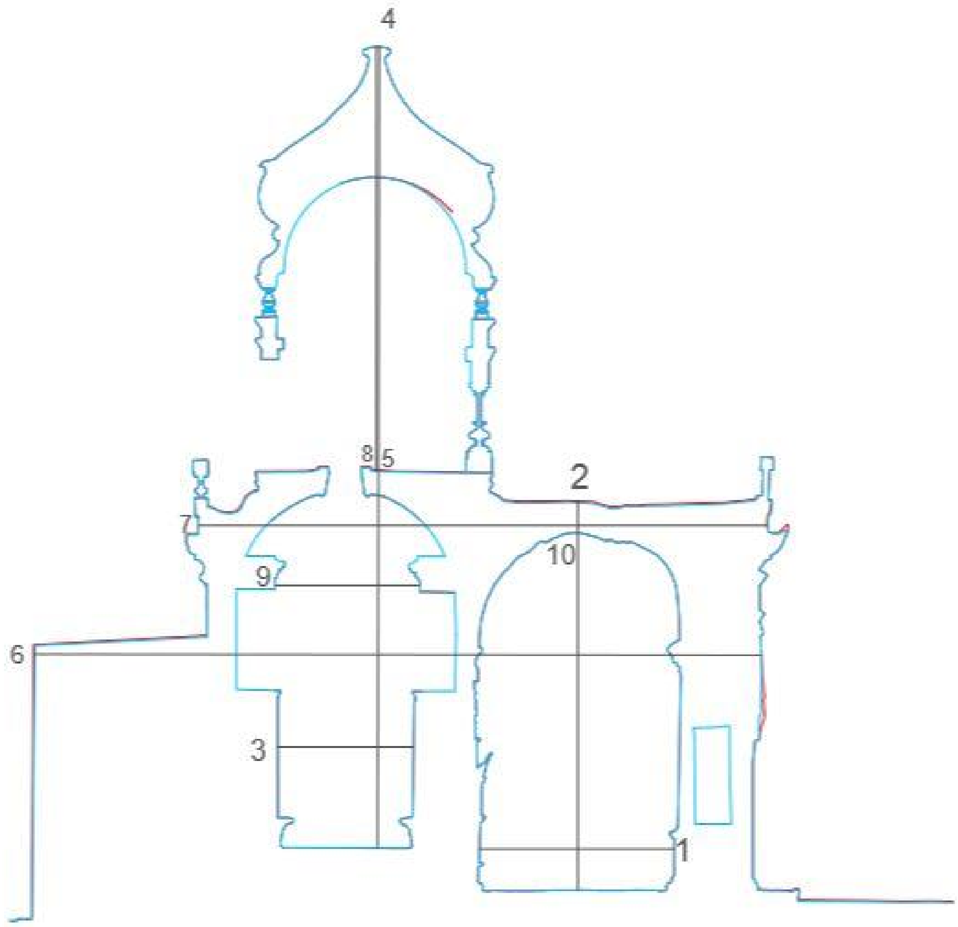
	Measurements on Italian sections di (m)	Measurements on Greek sections dj (m)	Δd= di-dj	(Δd)^2	Σ(Δd)^2	N-1	[Σ(Δd)^2]/[N-1]	RMSE (m)
1	0.7609	0.7609	0	0	0.000364	9	4.04833E-05	0.0064
2	0.8767	0.8682	0.0085	7.225E-05				
3	3.4127	3.4055	0.0072	5.184E-05				
4	5.2102	5.2031	0.0071	5.041E-05				
5	5.5508	5.5448	0.006	3.6E-05				
6	5.1739	5.1714	0.0025	6.25E-06				
7	5.4796	5.4746	0.005	2.5E-05				
8	0.8709	0.8645	0.0064	4.096E-05				
9	0.98	0.9758	0.0042	1.764E-05				
10	2.5398	2.5318	0.008	6.4E-05				

Longitudinal Section



	Measurements on Italian sections di (m)	Measurements on Greek sections dj (m)	Δd=di-dj	(Δd)^2	Σ(Δd)^2	N-1	[Σ(Δd)^2]/[N-1]	RMSE (m)
1	2.9287	2.9132	0.0155	0.0002403	0.002681	9	0.000297873	0.0173
2	5.1993	5.199	0.0003	9E-08				
3	12.1435	12.1483	-0.0048	2.304E-05				
4	6.0478	6.0405	0.0073	5.329E-05				
5	3.1045	3.1509	-0.0464	0.002153				
6	2.0457	2.0484	-0.0027	7.29E-06				
7	5.6349	5.6466	-0.0117	0.0001369				
8	10.423	10.418	0.005	2.5E-05				
9	1.3903	1.3881	0.0022	4.84E-06				
10	1.7752	1.7813	-0.0061	3.721E-05				

Longitudinal Section (Tomb Chamber Orientation)



	Measurements on Italian sections di (m)	Measurements on greek sections dj (m)	Δd=di-dj	(Δd)^2	Σ(Δd)^2	N-1	[Σ(Δd)^2]/[N-1]	RMSE (m)
1	2.8056	2.8056	0	0	0.002424	9	0.000269344	0.0164
2	5.5937	5.5717	0.022	0.000484				
3	1.9582	1.9582	0	0				
4	11.5277	11.5277	0	0				
5	5.4864	5.4538	0.0326	0.0010628				
6	10.4833	10.4607	0.0226	0.0005108				
7	8.1882	8.1955	-0.0073	5.329E-05				
8	6.0895	6.1072	-0.0177	0.0003133				
9	2.0881	2.0881	0	0				
10	5.1345	5.1345	0	0				

Eventually, four RMSE values were estimated (Diagram 1), one for each type of section, namely that of (i) the horizontal section error (0.0040 m), (ii) the transverse section error (0.0064 m), (iii) the longitudinal section error (0.0173 m) and (iv) the longitudinal section error with the tomb chamber orientation (0.0164 m).

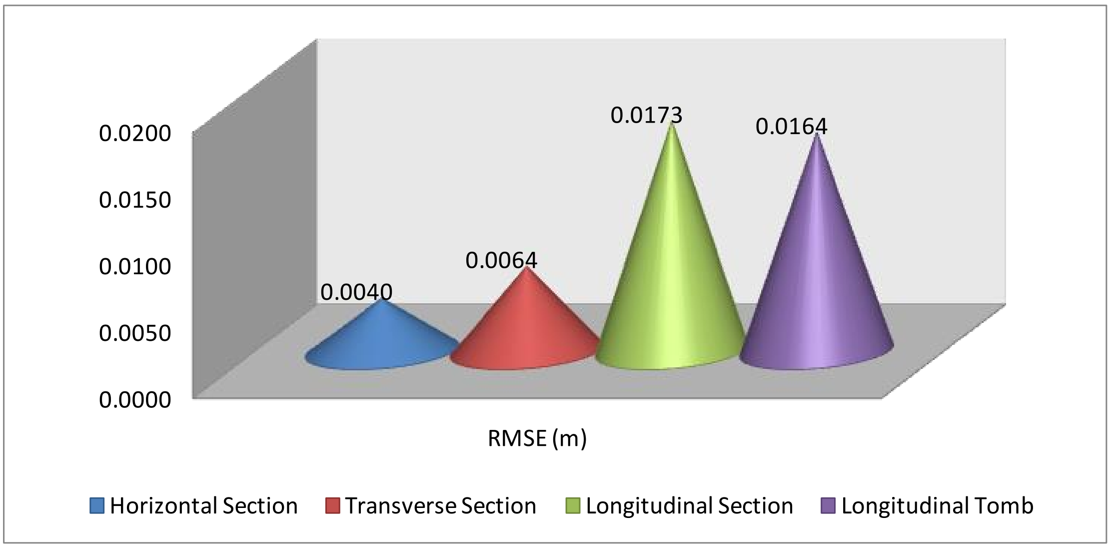


Diagram 1: Values of the RMSE in meters *©Author 2020*

It is noticed that the deviation of the measurements has larger values for the two longitudinal sections than for both the horizontal and the transverse section. A possible cause for this outcome could be the specific part of the Aedicule that these measurements refer to. Most of the dimensions in the longitudinal sections belong to the interior of the structure, while most of the dimensions in the horizontal and transverse section refer to the exterior. Moreover, a fact which is recognizable to the majority of the sections is that, the biggest deviations can be detected in the Tomb Chamber and at the Chamber of the Angel. Taking under consideration that the distances measured in the longitudinal sections were focusing to these two chambers and on the other hand the distances measured in the horizontal and the transverse sections concerning these areas were fewer, the difference between their errors is inevitable. What is more, even the measurements of similar dimensions, such as the height of the Chapel of the Angel, could not have been measured at the exact same point, because of the diverse depictions of the Aedicule in every section. Thus, errors should not be considered individually, since the existence of deformations at specific areas could be possible, due to the form of the monument.

It is even conceivable that multiple errors that occurred during the procedure of the production of the 3D models had contributed to the final deviations. First, a major parameter is the accuracy of the terrestrial laser scanner and of the total station for the acquisition of the data, which varies depending on the manufacturer. It is also important that the Aedicule is covered of marble slabs both inside and outside. This material is characterized by its reflectiveness which might have caused deviations to the measurements of the laser scanner. Furthermore, even if the alignment of the separate scans was precise and based on common points, errors always exist in this process and the final model could be affected by them. There is also the uncertainty of the registration of the two point clouds during the alignment together through the transformation. Finally, there might also be additional errors during the creation of drawings because of the difficulties of the designing procedure that were presented previously.

For all these reasons, two additional errors were estimated, which would define the deviations of the interior (average of the errors of the longitudinal sections) and the exterior (average of the errors of the horizontal and transverse section) of the structure.

$$RMSE_{interior} = \frac{(0.0173+0.0164)}{2} = 0.0168\ m \ > \ RMSE_{exterior} = \frac{(0.0040+0.0064)}{2} = 0.0052\ m$$

The total error derived from the average of the overall deviation errors and is equal to:

$$RMSE_{total} = \frac{(\ 0.004 + 0.0064 + 0.0173 + 0.0164)}{4} = 0.0110\ m$$

Through the analysis of the values of the deviation errors, it will be possible to compare the structure of the Aedicule as it was documented in 2007 and in 2015. At this point it should be highlighted that these errors do not imply that the point clouds are incorrect or inaccurate. Their estimation is aiming to indicate the metric differences and the probable alterations to the dimensions of the Aedicule through the years.

It is obvious that the deviations in the interior of the Aedicule are bigger than the deviations at the exterior. There is no doubt that the complexity of the structure of the monument, particularly in the interior, had definitely a negative impact on the measurements acquired by both surveys and in consequence on the deviations between them. When entering into the chambers of the Aedicule, someone is able to understand that the lack of space, the narrow passages, the complicated decorations on the surfaces of the walls, the oil-lamps and the candles would be a problem during the documentation, not only by laser scanning, but also by conventional survey.

In the final analysis, the total error of the deviation of the two point clouds indicates that there is generally a difference of $1.1\ cm$. Apart from the effect of the accuracy of the measurements, another determining factor is the decay of the edifice, which was in urgent need of a restoration because of the deformations and the damages it had undergone. Already since 1927 an iron frame was placed around the Aedicule to prevent its collapse. Through the years and as time passed the defects of the structure were increased and also the great number of pilgrims who visited the monument could have deteriorated its condition. All things considered, the result of the estimated total deviation error could be justified due to the combination of both the uncertainty of the previous processing stages of the point clouds and the state of the Aedicule through the eight years that had passed from the earliest to the latest survey (2007-2015).

5.1.2. DETECTION OF DEFORMATIONS AT THE SOUTHERN SIDE OF THE AEDICULE

During the survey for the geometric documentation of the condition of the Aedicule by the National Technical University of Athens in 2015, deformations were noticed at the external lower part of the southern side of the monument. In order to investigate if these deformations existed in 2007 or they were formed later as a result of decaying, new horizontal sections were created. The elevation of the two new sections was at +0.80 meters from the ground, relative to the exterior floor level and only the part of the Aedicule with the detected deformations was designed. Since both of the drawings had the same reference system, it was possible to compare them (Image 41). Even though the walls of the Aedicule generally did not have any differences, the columns at the lower southern side of the Aedicule seem to have been deformed through the years, since many differences were noticed.

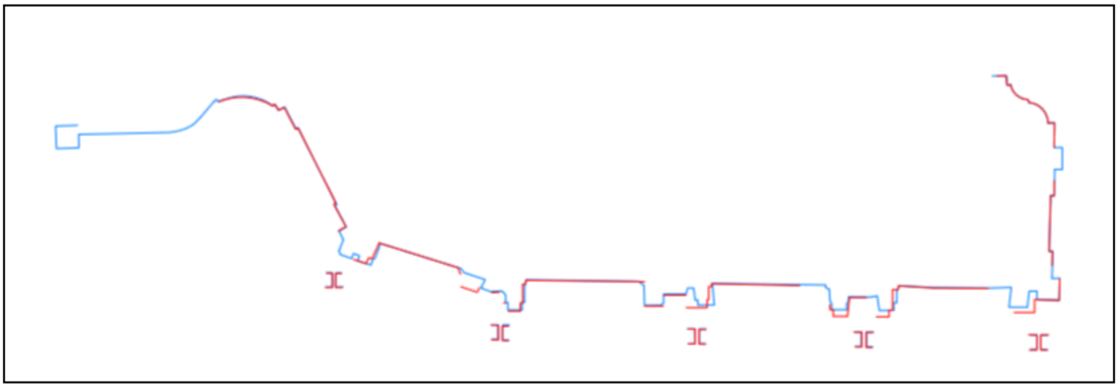


Image 41: Comparison of the horizontal sections at +0.80 meters (red line=Italian section, blue line=Greek section)

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5.2. CLOUDCOMPARE SOFTWARE- M3C2 ALGORITHM

5.2.1. THEORETICAL APPROACH

An alternative approach for the comparison of the two point clouds is through direct measurements between them. For this reason, many distance measurement methods are available including

- DEM of difference (DoD),
- direct Cloud-to-Cloud comparison with closest point technique (C2C),
- Cloud-to-Mesh distance or Cloud-to-Model distance (C2M) and
- multiscale Model to Model Cloud Comparison (M3C2)

As mentioned before, terrestrial laser scanning can document with high precision the complex geometry of a monument. To succeed in the production of an accurate three-dimensional model it compiles a large amount of points' coordinates. Consequently the 3D models that derive from laser scanning are characterized by high density.

When it comes to the comparison of point clouds that were constructed through laser scanning, the best method that is able to manage big data sets is the multiscale Model to Model Cloud Comparison (M3C2) (Barnhart et al, 2013). The specific algorithm combines three key characteristics:

- *it operates directly on point clouds without meshing or gridding.*
- *it computes the local distance between two point clouds along the normal surface direction which tracks 3D variations in surface orientation.*
- *it estimates for each distance measurement a confidence interval depending on point cloud roughness and registration error.*

More specifically, the way that M3C2 algorithm operates depends on two user-defined parameters: D (normal scale) and d (projection scale). At the initial phase of this method, the surface normals in three-dimensions are calculated (Image 42). For each point (i) of the point cloud (S_1) a normal vector $(\vec{N})$ is defined by fitting a plane to the vicinity within a radius of ${}^{D}/_{2}$. *The standard deviation of the distance of the neighbor points to the best fit plane is recorded and used as a measure of the cloud roughness* $\sigma_i(D)$ *at scale* D *in the vicinity of i.*

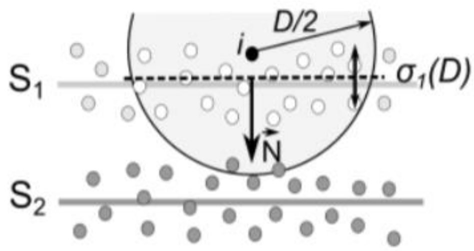

Image 42: Calculation of the surface normals (M3C2 algorithm) ***© Dimitri Lague***

Two normal vectors are calculated, one for each point cloud. The user can choose one of these normal vectors or the average of their directions. This choice will affect the distance measurements only if the point clouds are not locally co-planar. Since the procedure is based on the normal vector of the reference cloud, when there is change in surface orientation the average of the normal vectors is preferred.

The subsequent step is the calculation of the distance between the two point clouds (Image 43). The algorithm in order to accomplish these measurements, creates a cylinder of diameter d and axis $(i, \vec{N})$. In this way, two sub-clouds are defined by the intersection of the reference and compare cloud with the cylinder. These groups of points (n_1, n_2) of each cloud are projected on the cylinder axis, which has the orientation of the normal vector $\vec{N}$. From the average of the distances of their projections, the local median position of i for each sub-cloud is defined (i_1, i_2) and the two standard deviations are equal to the local estimation of the point cloud roughness $\sigma_1(d), \sigma_2(d)$ along the normal direction. As a result, the local distance $L_{M3C2}(i)$ between the point clouds is the distance between i_1, i_2.

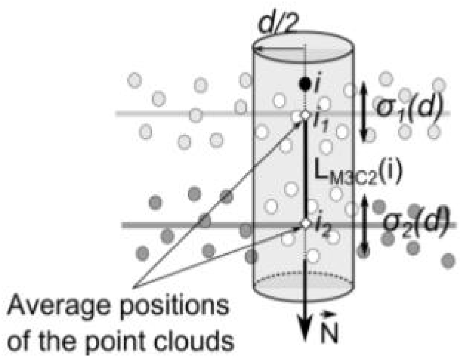

Image 43: Calculation of the local distance (M3C2 algorithm) ***© Dimitri Lague 2013***

As far as complex or rough surfaces are concerned, the normal scale D should be chosen carefully, because *if the normal vector $\vec{N}$ is measured at a scale too small with respect to the surface roughness characteristics its orientation will strongly vary.* This will cause the overestimation of the distance between the two clouds. It is even conceivable that, if there is missing data to the compare cloud and consequently no intersection with the created cylinder, no distance calculation occurs (Lague et al, 2013).

Aiming to apply the M3C2 method to the point clouds of the Aedicule, so that differences between them would be detected, both of them were imported into CloudCompare

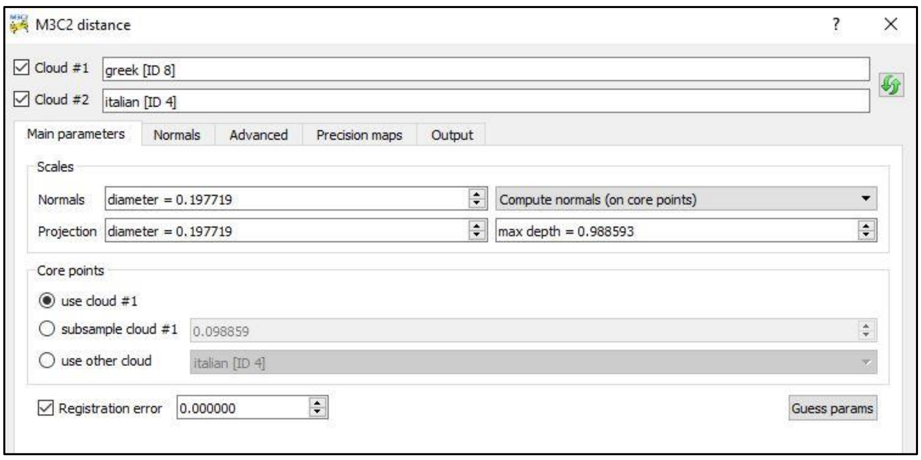

Image 44: Parameters of the M3C2 algorithm in CloudCompare software
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software. For the execution of the algorithm the two point clouds were initially selected from the 'DB Tree' window and then through the 'Plugins' tab the 'MEC2 distance'. Following step was the definition of the algorithm's parameters (Image 44).

First of all, the user has to choose which point cloud will be the reference cloud (Cloud #1) and which will be the compare cloud (Cloud #2). Afterwards, at the 'Main parameters' the scales should be determined. At the second tab more advanced options are specified regarding their computation:

- *Default: the normals are computed based on the normal scale parameters defined in the previous tab*
- *Multi-scale: for each core points, normals are computed at several scale and the most planar is used*
- *Vertical: no normal computation is done, only purely vertical normals are used (perfect for 2D problems)*
- *Horizontal: normals are constrained in the (XY) plane*

In order to speed up the computation the algorithm offers the possibility to use Core Points which are *a sub-sampled version of the reference cloud, but all calculations use the original raw data.* The user can choose either the whole cloud, or the sub-sampled version or custom a set of core points. Also, it is possible to generate additional scalar fields and decide where the results will be projected.

The result of the algorithm is a new colored point cloud, where a scale next to it explains which distance each color represents. Points without any corresponding points in the compare cloud are colored gray (they are associated to NaN - not a number - distances). This means that no points in the other cloud could be found inside the search cylinder. The user can customize the colors scale and choose the NaN points to be invisible. The units of the measured distances are equivalent with the units of the point clouds (https://www.cloudcompare.org/doc/wiki/index.php?title=M3C2_(plugin)).

5.2.2 APPLICATION OF THE M3C2 ALGORITHM

In the case of the Aedicule, the Greek 3D model was the reference cloud and the Italian 3D model was the compare cloud, the 'Default' option was selected for the normal scale, the whole reference cloud (Greek) was eventually used as core points and the result would be projected also on this point cloud. The color scale was chosen to present distances from -0.141 meters to 0.144 meters and the Nan points were invisible. The final outcome of the comparison together with some sections is presented below:

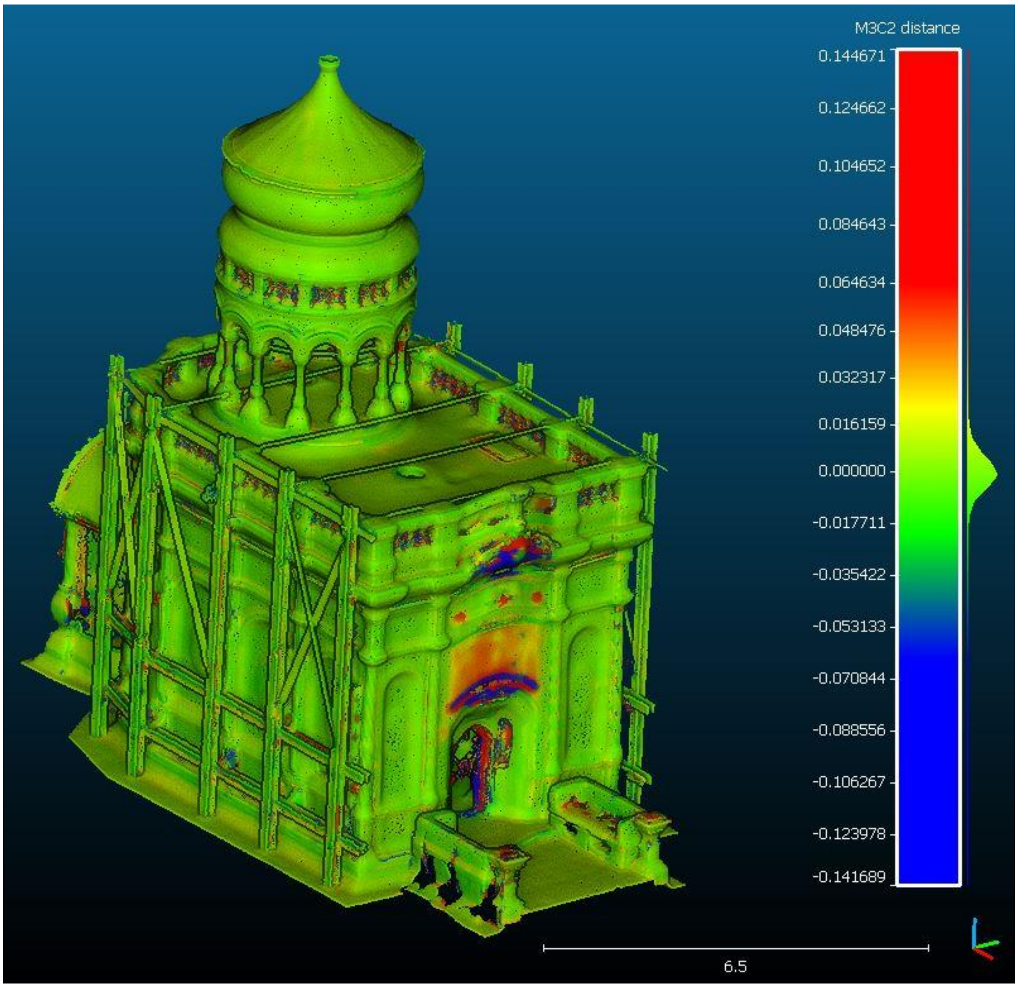

Image 45: Result of the M3C2 algorithm for the exterior of the Aedicule ***©Author 2020***

Concerning the exterior of the Aedicule (Image 45), the majority of the values of the distances between the point clouds are ranging from 0.000 meters to 0.018 meters, since most of the surface of edifice is colored green. The parts where different shades of red, yellow and blue color are noticed correspond to distance values from 0.032 meters to 0.14 meters. These areas consist of the part of the entrance above the door, the benches, the walls of the Coptic Chapel and the small columns around both the roof and the dome. The changes that were detected at the entrance could have been created due to the paintings and the oil-lamps that were placed in front of the facade. Moreover, the differences at the benches could be justified because of the pilgrims who were sitting on them and the candles that were decorating them. The Coptic Chapel is an unstable structure made of iron walls that is detached to the west side of the Aedicule, therefore it is reasonable that bigger distance values were calculated at the specific part. A vital difference is that of the small columns at the top of the structure placed around the roof and the dome, which might be proof of deformation of the structure.

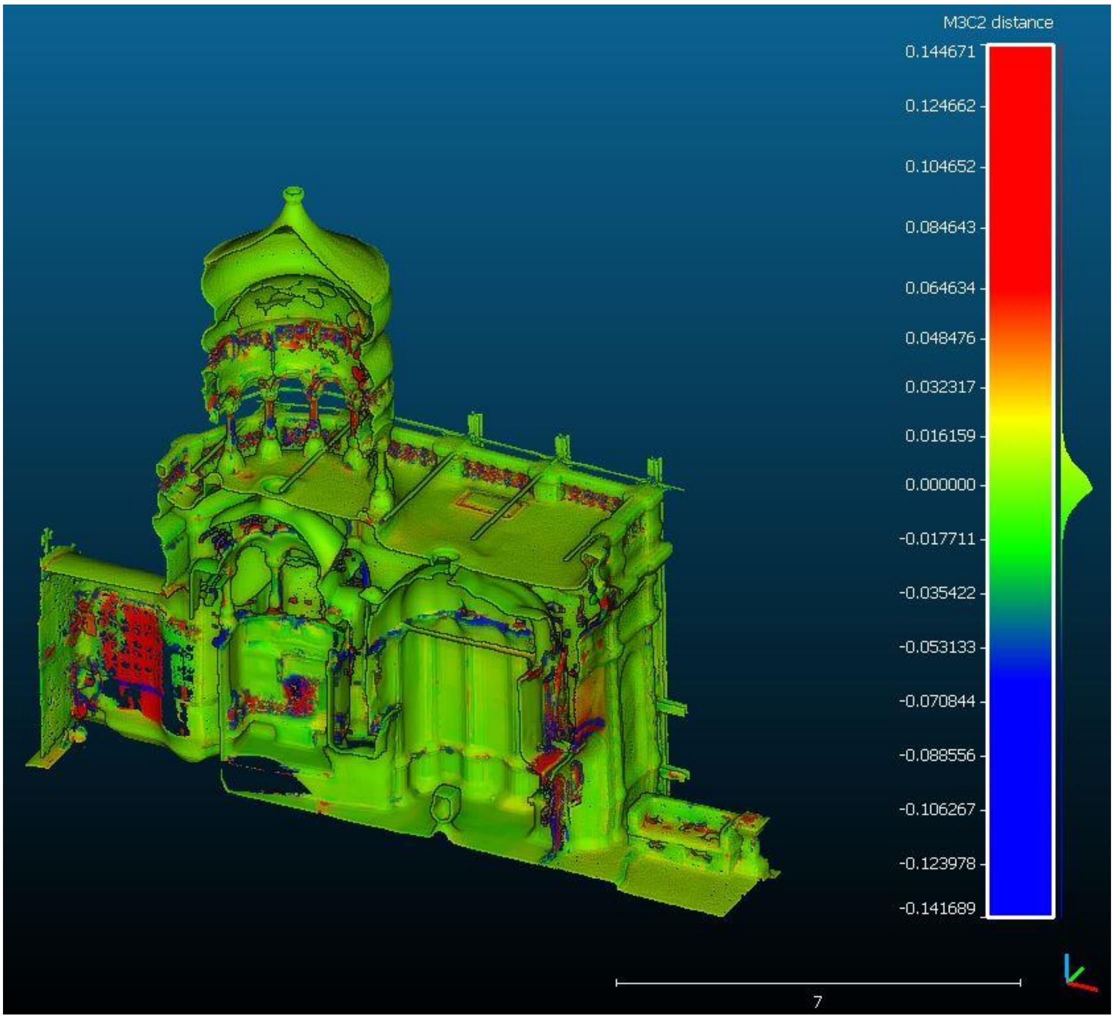

Image 46: Result of the M3C2 algorithm for the interior of the Aedicule *©Author 2020*

A longitudinal section of the original M3C2 distance point cloud was created in order to examine the results at the inner part of the Aedicule (Image 46). The same range of distance values, as at the exterior, was also used for the representation of the changes between the point clouds at the interior of the Aedicule. It is obvious that more differences were detected in this case, since a variety of colors is depicted at the surface of the edifice. The part with the bigger distance values is again the Coptic Chapel. Although in general the color that prevails is the green (0.000 m - 0.018 m), many red and blue points can be noticed (0.032 m - 0.14 m) particularly at the Tomb Chamber and the Chamber of the Angel. More precisely, at the Chamber of the Angel more differences are displayed around the dome of the chamber and at the wall above the passage to the inner room which has carved, detailed decorations. Considering the Tomb Chamber, apart from the area of the dome of the chamber, distances of significant value were detected also above the tomb's shelf, where it is typical to be decorated with candles, oil-lamps and paintings. Furthermore, a significant observation is that the west part of the tomb is not depicted, which indicates that the distance values of this area are even bigger than 0.14 m. Last but not least, differences among the two point clouds are visible as well at the inner part of not only the small cupola of the edifice, but also at the columns that support it.

6. CONCLUDING REMARKS

The significance of the Aedicule of the Tomb of Christ can be identified through the numerous three-dimensional representations of this small edifice. The research on the replicas of the Aedicule and the Holy Sepulchre, has revealed that many reconstructions exist globally. Whether they are churches, monasteries, chapels or relics, every one of them represents the form of the monument as existed at the time of their creation. It is noticed that certain types of replicas were preferred and were massively constructed (Diagram 2). More precisely, calvaries outnumber the rest of the replicas' types and at least one of them exists in most of the areas with detected replicas of the Aedicule. Moreover, they are common pilgrimage sites since they consist of several chapels which refer to incidents of Christ's life, including, of course, the entombment. Consequently, calvaries are significant worship places for Christians and therefore plenty of them have been created. Another type which was also widely constructed is the true-to-scale replicas of the Aedicule. The representations which can be detected in similar numbers are the miniature models of the Aedicule and the buildings inspired by the architectural features of the Holy Sepulchre. The edifices of the Aedicule are the type of replicas with the fewest reconstructions worldwide. Based on these results it is obvious that the number of replicas for each type depends on their similarity to the original. The better the correspondences, the more replicas of this type were constructed.

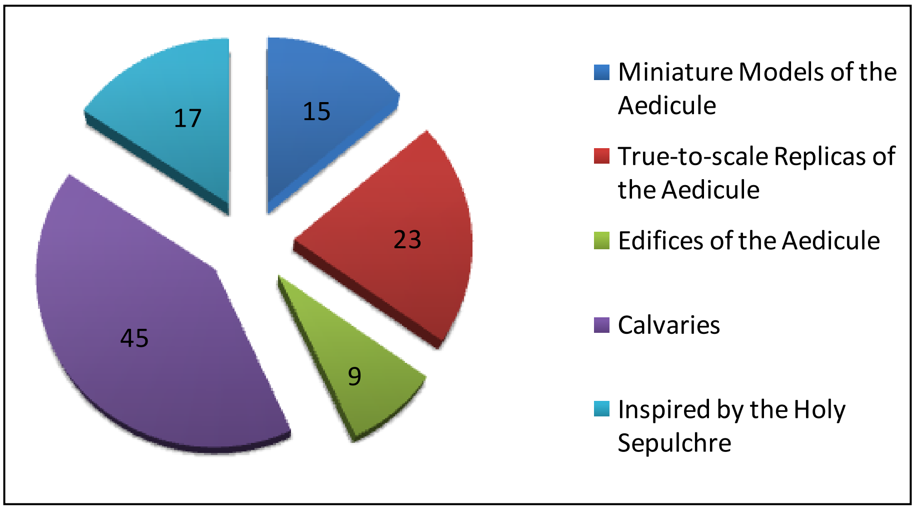

Diagram 2: Number of replicas for each type *©Author 2020*

Furthermore, there are various forms of the replicas because they represent different construction phases of the Aedicule. Part of them are associated either to the Constantinian phase, the Crusaders phase or the present state of the monument, but most of the replicas are similar to the Aedicule as it was restored by Bonifacio of Ragusa. This implies that the majority of them were constructed between the 16th and 17th century, which is actually valid depending on the recorded dates from the database presented in a previous chapter.

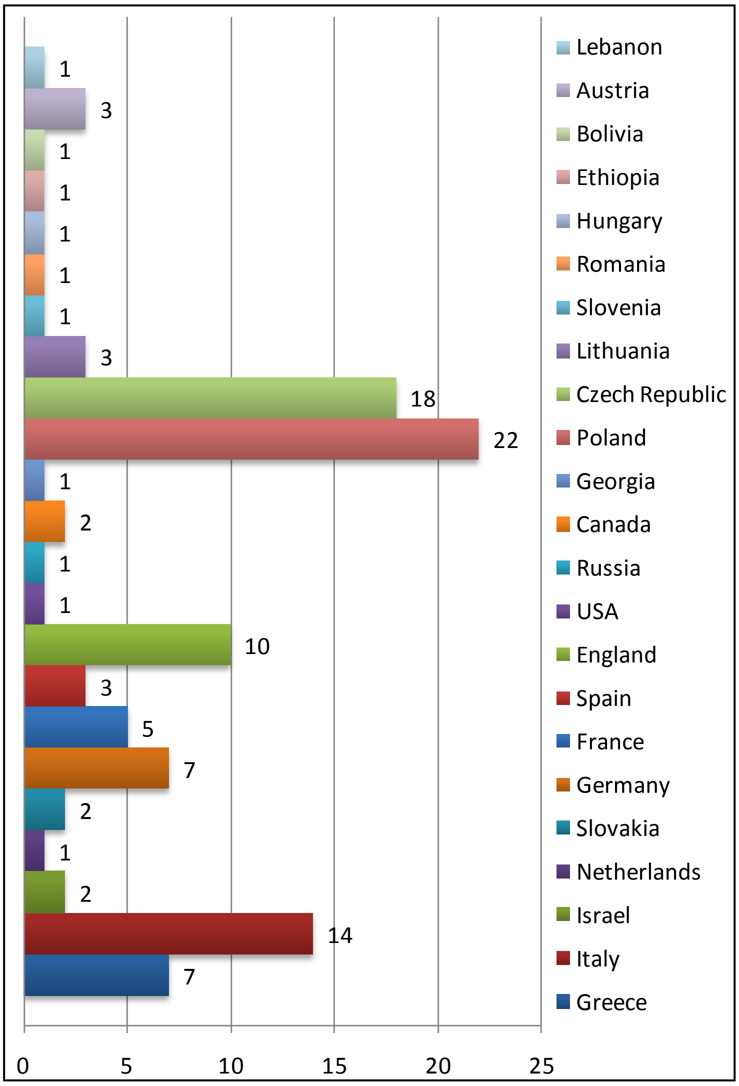

Diagram 3: Number of replicas per country *©Author 2020*

These replicas are located in many different parts of the world and they can be detected in places either far away or close to Jerusalem. It has been observed that in specific areas there is an abundance of representations of the Aedicule. On the other hand, in most cases just a few of them exist. The countries where several replicas have been constructed are 23 in total (Diagram 3) and they are situated in Europe, Asia, North and South America. Those with the biggest number of replicas are Poland (22), Czech Republic (18), Italy (14) and England (10). A significant number of representations of the Aedicule are also detected in Greece, Germany and France. The number of the replicas for the rest of the countries is ranging from 1 to 3. In other words, the majority of the reconstructions of the Aedicule are located in Central Europe. It is possible that the Christian communities in those areas wanted to prove their devotion by creating these replicas of the most important shrine in Christianity. Moreover, the existence of so many structures indicates the global influence of the Holy Sepulchre and the Tomb of Christ.

Even more information about the replicas derives from the online web map, which constitutes a visualization of the database from the previous research. This interactive web map was firstly created in QGIS software and through a server is consequently available to every user of the internet. All the replicas are depicted in this map and at the upper right corner there is a legend with the different symbolizations of their types. Every time the user selects a replica, its symbol is highlighted and a window appears including its country, location, date of construction and an image (if existed). Some additional tools are the measurement of distances and areas, the search tool, the zoom in and zoom out. Although there is also the geolocation tool, the web browser does not allow its function due to security reasons. Through the specific online web map it is possible to detect which type of replica was mainly constructed in each area. For example, most of the true-to-scale replicas are located in Czech Republic and in Germany and the majority of the calvaries are both in Poland and in Northern Italy. As a result, the user is able to discover the replicas located at his place of interest.

Apart from the replicas, there are digital three-dimensional representations of the Aedicule of the Tomb of Christ. These forms of representations were mainly created for the geometric documentation of the monument and are characterized by high accuracy. In the context of this thesis, an attempt was carried out for the construction of a new 3D model of the Aedicule, with the use of analogue data from the survey of the National Technical University of Athens in 1993-1995. Two sets of data, colored and grayscale photographs, were processed through an automated photogrammetric software. Unfortunately, both of the point clouds constructed do not have accurate geometry and consequently they cannot be considered as geometric documentations of the Aedicule. The main reason for this outcome is that the photographs were not taken to depict the Aedicule and the lack of GCP points. For the creation of a precise 3D model through photogrammetric procedures, the site of interest should be captured from different positions and angles and each point of it should be clearly visible in at least two images, therefore a sufficient overlap between the photographs is necessary. High resolution is very important as well as good lighting conditions. Finally, some points with known coordinates or a known distance are essential for the scale and the geometry of the 3D model.

During the surveys of the University of Florence in 2007 and the National Technical University of Athens in 2015 a 3D model of the Aedicule was constructed by each scientific team with the use of terrestrial laser scanning (TLS) and image-based modelling. These representations of the monument recorded its state in two different time periods. In the present thesis a comparison was performed between the two 3D models. Initially, several sections were created at specific parts of the structure. The deviation errors of these sections, which were calculated based on measurements of common distances, had larger values for the interior of the Aedicule than the exterior. This difference can be justified due to the complexity of the structure of the edifice at the two chambers of the interior. The total error of the deviation of the two point clouds was equal to 1.1 cm. As a result, for the particular sections, it appears that there are no significant differences at the selected areas of the Aedicule from 2007 until 2015.

Further analysis was carried out for the detection of additional deformations focusing on the exterior lower southern side of the edifice. New horizontal sections were created in both 3D models, with elevation at +0.80 m. Although the two sections were in general identical, considering that no deviations were detected at the walls of the Aedicule at this side of the structure, there seems to be some differences at the columns. Thus, it is assumed that through the years the columns have been deformed, but it could not be identified in which way exactly.

Furthermore, the multiscale Model to Model Cloud Comparison (M3C2) was applied to the point clouds. The values of the measured local distances of the 3D models were ranging from -0.141 meters to 0.144 meters. The bigger values were detected in parts with decorations or unstable structures, such as the Coptic Chapel, and in the lower part of some of the columns at the southern side of the Aedicule. A significant difference is that of the small decorative columns at the top of the structure in the balustrade, which might be proof of deformation of the structure.

Even more differences between the point clouds were noticed in both of the domes of the Chapel of the Angel and of the Tomb Chamber. A significant observation is also that the distance values of the west part of the burial bench were bigger than 0.14 m. Further investigation on the results proved that the Italian point cloud had some gaps at the specific areas and therefore the computation of the distances was not correct (Image 47). These gaps are justified due to the difficult circumstances during the data acquisition with the laser scanner, considering that none of the decorations, the oil-lamps and the candles of the interior were removed. However, during the Greek survey it was permitted to take away these obstacles before the documentation of the Aedicule. Therefore, these distances between the two 3D models should not be taken into account. Apart from these cases, most of the distance values of the edifice were ranging from 0.00 meters to 0.018 meters.

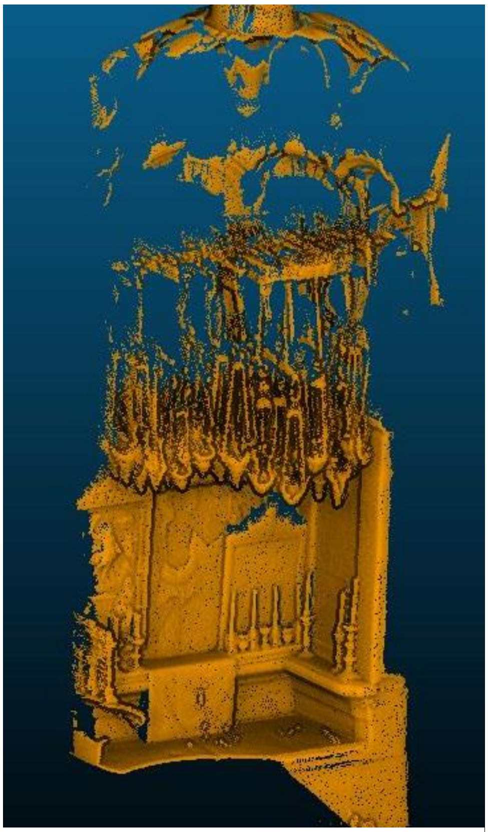

Image 47: The Tomb Chamber of the Italian 3D model *©UNIFI GECO Laboratory 2007*

Eventually, the outcome of the comparison computed by the algorithm is similar to the distance deviations which derived from the sections. The condition of the structure had remained in general the same from 2007 until 2015. The only major deformations which were detected are those of the columns at the southern side of the Aedicule and those of the small columns around the roof and the cupola.

6.1. FUTURE WORK

The investigation on the replicas of the Aedicule and the Holy Sepulchre and the creation of the online web map depicting them was aiming to provide as much information as possible for these reconstructions. Through these representations one is able to perceive the significance of the original monument and the need of the faithful to pay their respects even though they could not visit the Holy Land. The web map constitutes a useful tool for whoever is interested in the study of the Holy Sepulchre.

This database could be enriched in the future with either new discovered replicas or replicas which already exist and are not included in the present list. This goal could be accomplished through Crowdsourcing. The definition of this term based on Estelles-Arolas and Gonzalez Ladron de Guevara is that: *Crowdsourcing is a type of participative online activity in which an individual, an institution, a non-profit organization, or company proposes to a group of individuals of varying knowledge, heterogeneity, and number, via a flexible open call, the voluntary undertaking of a task* (Arolas, Ladron, 2012). For the purpose of the present thesis, the collaboration of various religious communities, researchers and scholars who are related to the Holy Aedicule and its replicas would be beneficial. For this reason, it would be convenient the online web map to be not only available to the users of the internet, but also easily modified by them. In this way, additional data could be depicted on the map and finally the total amount of the replicas around the world would be detected.

The results from the comparison of the 3D models represent the condition of the Aedicule's structure through the years. Possible deformations were detected with the processing of the 3D models. Therefore the geometric documentation of the Aedicule in the future, the comparison of the new outcome with the already existed 3D models and the assessment of the new results will aim to monitor the state of the shrine, especially the parts where deformations existed. These continuous surveys will be helpful for the maintenance and the potential future restorations of the monument.

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