Chapter 11
The Mausoleum of Theodoric: Archaeoastronomy, Numbers, Geometry and Communication

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Abstract The following paper focuses on the Mausoleum of Theodoric (520 ca.), one of Ravenna's Byzantine monuments and a UNESCO heritage site, presenting the results of different phases of research that begun in 2015. Starting from the instrumental survey carried out with laser-scanner and digital photogrammetry technology, the unit of measurement and the geometric properties of the decagonal shape of the design of this singular two-level building were analysed. The archaeoastronomical study has highlighted possible meanings of the orientation of the building and the positioning and sizing of small wall openings. Finally, a 3D model was developed from the survey data to verify the astronomical phenomena and to aid in the multimedia communication of the scientific content. It is increasingly clear how virtual models, both interactive and non-interactive, constitute an important edutainment tool. This element is indispensable to the development of contemporary methods of dissemination for the fruition of cultural sites and artifacts.

Introduction: The Foundation and the Main Topics

The historian known as *Valesiano* documents that the Mausoleum of Theodoric was commissioned by Theodoric himself before his death on AD 30 August 526 (Muratori 1738). Theodoric (Teodorico) was born around 454. At the young age of 12 he was sent to Constantinople as a hostage, and remained at the court of Leo I the Thracian until 472. Scholars do not agree on the terms and type of education he received in the East; however, it is undeniable that during his kingdom he showed great attention to architecture. This is testified by the restoration of ancient buildings in Rome and the construction of new buildings in Verona, in Pavia and, above all, in Ravenna.

The Mausoleum was developed on two levels: the ground floor has a decagonal plan in external profile and a Greek cross interior, while the upper floor has a

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G. Magli et al. (eds.), *Archaeoastronomy in the Roman World*, Historical & Cultural Astronomy, https://doi.org/10.1007/978-3-319-97007-3_11

decagonal exterior and a circular interior space. Like all monuments in Ravenna, the building has been the object of specialized studies and surveys (Bovini 1977; Gotsmich 1958; Guberti 1952; Haupt 1913; Heidenreich and Heinz 1971; Johnson 1988). In its long history, the small, central plan Mausoleum has been the object of multiple transformations and restorations, such as those of the eighteenth, nineteenth and twentieth centuries (Conti and Berti 1997; Guberti 1952: 8–19). The last interventions date back to 1977 (Bovini 1977: I–XV; Piazza 2013: 84–86; from the same volume see Novara 2013: 111–116) and 1998, the year in which the restoration of the stone of Aurisina took place (Bevilacqua et al. 2003; Piazza et al. 1998).

In the present study deeper discussion will relate to elements of the architecture and topics concerning the form and orientation of the building. It is thus particularly important to verify the authenticity and the dating of the elements involved in the analysis to avoid erroneous interpretation of the data.

A Description of the Mausoleum

The Question of Its 'Unfinished' Nature

Some small arches appear on the external face of the second floor, which may hint at the past presence of a loggia, perhaps lost or never finished. In this regard, the question of the 'unfinished' and the possible different dating of the two levels introduced by some authors does not appear to interfere with our observations. All reconstructions hypothesised for the second floor, amongst which one must remember the extremely accurate and sophisticated one by De Angelis d'Ossat (1962, with very accurate graphics), never involve the openings but only address the presence and shape of the portico, which is lower compared to the system of windows.

The Flooring

The current flooring of both rooms is certainly not original: in 1557 Leandro Alberti mentioned traces of a mosaic floor, evidently on the upper level of the building, as the bottom was buried underground (Fagiolo 1972: 148–149). Regarding the progress of the flooring element, historians have reported a major failure of the ground on the eastern side, which led to a drop of 14 cm in the ground floor and a 6 cm drop of the upper floor. The difference in height between the two levels has led scholars to believe that an initial failure occurred during the construction of the ground floor. For this reason, the upper floor was probably put in place 'levelling' the already installed plan, which however, later experienced another slight lowering.

The existing pavements were put in place during the works of the biennium, in 1975–1977 (Novara 2013: 116). The current floors of the two levels are more or less horizontal (with an incline of a few centimetres). One can still see the signs of the collapse by looking at the slight inclination of the band present in the tambour of the dome (the quotes and sources of the surveys can be found in Guberti (1952: 37, 56–58).

The Small Apse

On the eastern side of the top space there is a small apse, whose function many historians have questioned: its height cannot accommodate an altar or an officiant or even the great porphyry sarcophagus (today placed at the center of the space). On the keystone of the arch is a large Latin cross, the only sculptural element of the interior, highlighting its relevance in the project. The small space, whose floor was slightly lower than that of the rest of the room is, according to scholars, contemporary with the building (De Angelis d'Ossat 1962; Messina 1980: 128–129).

The Sarcophagus

According to tradition, the remains of King Theodoric were conserved in the great sarcophagus of red porphyry measuring 305 $\times$ 190 $\times$ 101 cm. The tub is characterized by four rings on the top edge and two lion's heads at the bottom center of the side faces. The sarcophagus' troubled history has been well documented, its movements traced by Ambrogi (1995: 109–111) recalling its relocation to the site in 1913.

There is no certainty regarding the original orientation of this object, which is, however, considered by scholars to be consistent with the building, and originally arranged in an east-west direction (the current one).

The Small Windows

The wall of the ground floor has a thickness of about 140 cm and is pierced by six splayed narrow slits arranged on three sides (two on the north wall, three on the east wall and two on the south wall) with approximately horizontal intrados. Their sizes vary in width from 11 to 25 cm, and in height between approximately 40 and 70 cm. The decagonal part of the upper level presents a central receding band, about 77 cm thick and perforated by 11 windows. Arranged approximately in the directions north-south, east-west with the two diagonals at 45° (directions of the compass rose), the small openings have dimensions that vary from 40 cm in height for the windows on the north-south axis, to 62 cm on the diagonal axes. These windows are almost unanimously considered contemporary with the founding of the building, excluding the rectangular south-western one which was clearly enlarged at a later date (Guberti 1952: 94; De Angelis d'Ossat 1962: 59).

Keeping the axes of the openings described above in mind, the internal lighting system of the two rooms, formed by 17 openings (11 + 6) can be traced back to 12 different directions: 5 in the lower deck and 8 in the upper one. Of these, only one—the eastern one—follows the trend of and lower system. Below the windows is a protruding band (of about 8 cm) on which inscriptions laid out on three different levels have recently been found (Novara 2013: 116, see also 85; Piazza 2009). These were investigated and restored in 2012 (but the results have yet to be published).

The Dome

The great monolith that covers the building has also been subject to a great number of specialized studies, which have investigated physical, technological, figurative, historical and design aspects (e.g. see Bianco Fiorin 1993; Dyggve 1957; Fagiolo 1972; Tabarroni 1973).

The inner diameter is about 925 cm and the height on the springing is about 190 cm. A large crack, which popular tradition blames on a bolt of lightning, marks the southern side where a lighthouse was built adhering to the building.

Twelve protruding elements with triangular perforations are present on the outer edge of the roofing, conveying the image of a 'royal crown'. Historians have often questioned the real function of these elements and their figurative origin (Fagiolo 1972). The assumption is that they were used for the passage of cables and ropes necessary for the positioning of the roof, as hypothesised by Antonio da Sangallo in a previously published drawing (see Heidenreich and Heinz 1971: 63, Fig. 65), may be considered unfounded because of the enormous weight of the monolith and the common technical operations of the time (Tabarroni 1973). What all scholars emphasize is the lack of regularity in the arrangement of the dodecagon traced by the protruding elements, for it is not aligned with any of the geometries of the building. The monolith is in fact slightly rotated in relation to the main axis of the building, which has led to the unanimous conclusion of a faulty, unfixable installation due to the creation of the dangerous lesions on the southern side.

The names of the apostles and evangelists are inscribed on the vertical faces of the elements in a sequence (from the door, clockwise): Lucas, Marcus, Mathias (?), Matteus, Felippus, Johannes, Jacobus, Andreas, Paulus, Petrus, Simeon, Thomas. The reasons for this particular sequence have been widely investigated (Fagiolo 1972; Heidenreich and Heinz 1971; Tabarroni 1973). All elements are finished with a gable roof, almost simulating a small sarcophagus, except for one: that of Petrus has a flat roof. This has led researchers to believe in the existence of a terminal element made of a different—and perhaps more valuable—material (which then went missing), highlighting the figure of Petrus, the founder of the Church (Tabarroni 1973: 141).

The Architectural Survey

The architectural survey was carried out by M. Incerti and P. Lusuard with a Faro focus3d scanner. Thirty different survey stations were established covering the interior and exterior of the building. Individual clouds were registered with the aid of spherical targets (software for data management *Scene 5.3*, data elaborated by M. Incerti).

At a later date, two different photographic campaigns were carried out for the reconstruction of the three-dimensional textured model (M. Incerti): the first relating to the exterior, the second to the interior. The exterior shots were taken with a compact Lumix DMC-TZ7. The interior shots, due to matters of critical illumination, were produced with a digital SLR camera on a tripod. The upstairs photography was particularly problematic, as the view was obstructed by a railing which inevitably projected into the wall surface. It was also difficult to address the problem of backlighting generated by the perforated doors with cross motifs, as was the issue of artificial lighting, which created disruptive shadows.

Survey Drawings: Methods and Procedure

The thirty clouds available produced a dense pointcloud with rather limited bands of occlusion (the absence of this data is only found in small portions of the building where the height of the scanner failed to balance the overhanging parts of the structures).

For the creation of the two-dimensional canonical drawings (plans, elevations and sections), used to effectively describe dimensions and geometries, the point cloud model was divided by horizontal and vertical planes. A thin slice (thickness of 1 cm) was extracted from the cloud for each cut-plane as well as high definition screenshots. By importing the slice with vectorial software by interpolation of the points on a 1:1 scale, and exported for the realization of definitive raster images 1:50 scale. The choice of using a ‘slice’ of such reduced points yet still obtain a sufficiently detailed section was possible thanks to the particular density of the pointcloud, which provided a high degree of detail even on particularly elaborate portions such as the shell decorations on the interior brackets. The screenshots, mosaicized in order to achieve a high definition end result, allowed accurate control over the size and even deformations of elevation orthophotos produced by the digital photomodelling software, enabling the correct adjustments of projection elements.

The final elaborates are therefore the result of the overlapping of parts in section and projection obtained through the procedures described above. This work format, now well established in the scientific world, ensures greater metric control of the architecture (through comparison and contamination of drawings obtained through different processes, distinct survey campaigns and different instruments). It also allows for detailed graphics containing material and chromatic information that a traditional survey would not have been able to capture.

Archaeoastronomical Analysis

The Orientation

The Mausoleum has also been subject of archaeoastronomical research conducted by Giuliano Romano, who measured its orientation (Azimuth 84.5°; Romano 1995). The building is rotated by 5.5° compared to the equinoctial direction, which should not be overlooked during the alignment operations. Despite this apparent irregularity and approximation of the directions of the axes, an in-depth study of the consequences of these data seemed of interest.

Following the correction of the slight rotation, the survey methodology involved specially processed survey drawings. By overlaying graphics to the four main astronomical directions (solstices and equinoxes), the small windows placed in the 45° directions were not found to be perfectly aligned in relation to the center. Despite this, it is clear that these windows allow the entry of light during the two solstitial dates.

The Windows

Only three of the seventeen windows, those on the north side (two downstairs and one on the top floor) do not receive significant sunlight. All of the others are involved in important moments of the astronomical year. The behaviour of sunlight on horizontal and vertical surfaces was analyzed through plans and sections. Height and azimuth angles were traced to the ephemeris through specific software. Among the phenomena we noted (Fig. 11.1) that:

1. The rising Sun entered the cross-shaped window (second floor) on the days of the equinoxes, illuminating the previously mentioned thin band with painted writing on the axis of the cell. On the day of the summer solstice, about an hour after sunrise, the spot of sunlight passed over the stone sarcophagus.
2. The Sun entered the four narrow windows on the door (second floor) at sunset on the days of the equinoxes, illuminating the same scripted band. For other examples, see Incerti et al. (2016).

Phenomena of this kind may have been used for ritual purposes (see Fagiolo 1972, and the chapter by Hannah in this book), but also to mark the advent of a particular date in the year, or for the computation of time: in other words, to indicate a precise moment of the day (sunset, in this case).

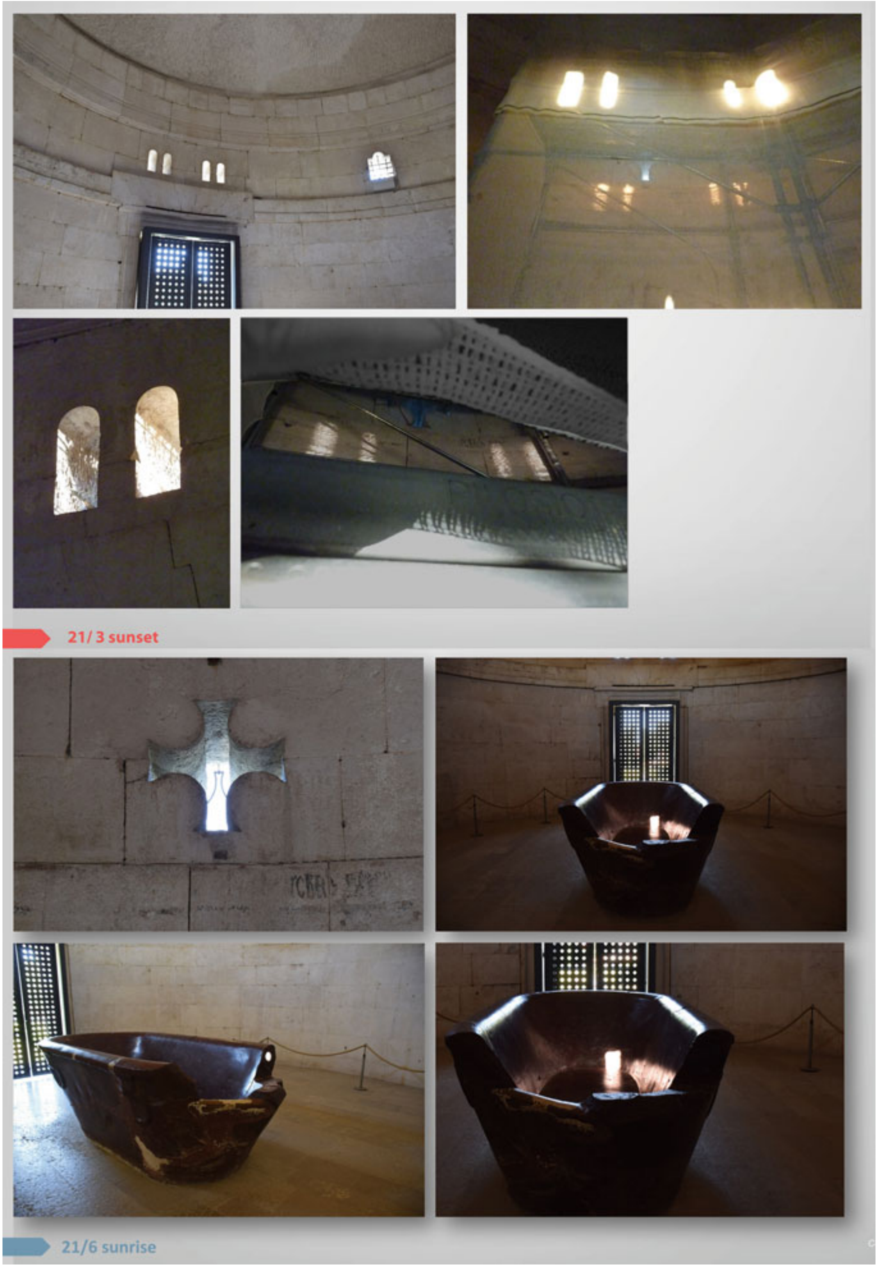

Fig. 11.1 Photographs of the effects of light (21/3 sunset, 21/6 sunrise)

The Dome

The results of our survey allowed us to verify that the arrangement of the protruding elements does not follow the directions of the decagonal geometry, but the cardinal directions with rather accurate approximation. The item marked with the name of Petrus (the only one with a flat roof), is aligned south. Aligned to the east is Jacobus, to the west is Lucas, and to the north is Matteus. This azimuth value is a possible explanation for what scholars consider an 'executional mistake' since the upper elements appear inconsistent with the main axes of the plant.

The Interactive Models for the Dissemination of the Research Project

The above study of Theodoric's Mausoleum and the instrumental survey that supports it, have translated into a multitude of results and materials of a different nature. From the massive amount of data collected, new information has emerged regarding the geometrical and archaeological characteristics of the building. The issue of disseminating and communicating the results of the research is a theme that our group has faced for some years. We have concentrated on the production of explorable and electronically searchable digital models as complementary and heterogeneous containers of information.

The 3D digital model made for the Ravenna Mausoleum can be explored in dynamic perspective on screen. This constitutes a visual support that provides the user with multiple information about the object's morphology: its colours, the materials, its state of conservation and much more. It can also be used as a visual database, useful in systematizing and making use of data beyond the range of the naked eye (dimensional data, geometrical relationships between elements, archaeoastronomical analyses, wall stratigraphy, external metadata such as video and Multimedia, etc. . . .). The interrogation of the model and reasoned structuring of information according to different levels of depth, facilitates the understanding of complex phenomena for the recipient of the information.

Starting from the pointcloud from the digital survey, a 3d model of the entire building was created, both external and internal, in order to allow a direct visualization of the light phenomena affecting the spaces on particular dates of the year. The model, designed to be optimized for real-time applications, is a textured quadrangular mesh (*quad-modelling*), texturized with *UV mapping* starting from the orthophotos extracted from the SFM survey. This model, oriented and placed in a Cartesian space for reference, has been linked to a directional light simulating the parallel rays of a source similar to the Sun, and is therefore best suited to reproduce the Sun's movement within the Mausoleum. The light has been assigned an animated path that reproduces the Sun's movement on the ecliptic, where each key movement on the animation (*keyframe*) was created by parameterizing the values derived from the calculation of

Fig. 11.2 Model and rendering of the building

the ephemeris at significant times. In particular, the exact time of sunrise has been entered as the starting point, and sunset as the end of the path. This time span was further subdivided into half hour intervals. Intermediate times result automatically from the data provided: the construction phase of the model thus becomes a test and comparison of the calculations previously made. The procedure was repeated for four remarkable dates (solstices and equinoxes). This model has been used as a kind of virtual laboratory for observing the effects of light within the burial cells in an ideal condition, since the light has no obstacles and external elements which, at present, obscure the sunrays (Fig. 11.2).

Numbers and Geometry

Research on the units of measurement used in both the project phase and during execution, can yield interesting results on the author of the project, identified by some as Aloisio—o Aloiosus—(Messina 1980: 33), an architect of debated Syrian origins (V. Aloisio and A. Iacobini, *Enciclopedia dell'Arte Medievale*, 1991). The initial problem of authorship, and secondly that of the possible sources of the geometrical and measurement knowledge used, is certainly an important topic to investigate. The two possible units of measurement verified are the Roman foot (rf = 0.2956 m) and the Byzantine foot (bf = 0.315 m, also called *Parmac*). The theme of the measurement of the Byzantine foot has been tackled in various papers (Ousterhout 2008: 75–76; Schilbach 1970, 1991; Underwood 1948) from which we extrapolate the values 0.312 m and 0.315 m (Martini 1883: 178). Throughout the research, both of these measurements were tested, with the result that the second value gave more 'whole' figures. The question of measurements, however, cannot be treated separately from the geometrical knowledge of the time.

The graphics elaborated by the instrumental survey made it possible to detect the presence of a geometrical design that led the metric control of the investigation. Beginning our analysis from the ground floor, the plan is based on a series of circumferences with a 'whole' radius measurement in which concentric decagons are inscribed (Figs. 11.3 and 11.4). The diameter of the circle in which the decagon is inscribed measures (Figs. 11.3 and 11.4) 45 Byzantine feet (bf), but also 47.92 Roman feet (rf), so almost 48 rf, two interesting measurements from a metrological analysis. Continuing with the measurements of the other decagons, we find that the internal line of the niches on the external side corresponds to the decagon inscribed in the circle with a diameter of 35 bf, and the diameter of the inscribable circle in the inner space of the ground floor (which can be traced back to the decagonal figure itself) measuring 25 bf. Finally, the thickness of the walls in the direction of the apothem is almost 9bf (the exact measurement is 8.9 bf).

It should be remembered that the relationship that binds the radius of the circle and the side of the inscribed regular decagon within is the irrational number 0.618, the result of the division of a unitary segment 'in extreme and mean ratio'. This numerical relationship between the parts of a segment, already present in *Elements* by Euclid (Book VI, Theorem VI, 30; Herz-Fischler 1998: 14), makes it clear that if the side of a decagon has a whole measurement (integer), the radius of the circumscribed circumference cannot have the same characteristic, and vice versa. With this binding condition comes the difficulty of calculating its area. Given the presence of an irrational number, the measurement of its surface has been subject to approximations such as those developed by Heron (Metric I, 23¸ Herz-Fischler 1998), whose formula $L^2 \times 15/2$ tries to be as rigorous as possible: $L^2 \times$ *fixed number of decagon* (the relationship between the apothem and the side), $L^2 \times 7.694$. Another numerical relationship used for the fixed number of the decagon is 38/5 (7,6) which comes closer to the exact value of 7.694 (Herz-Fischler 1998: 110).

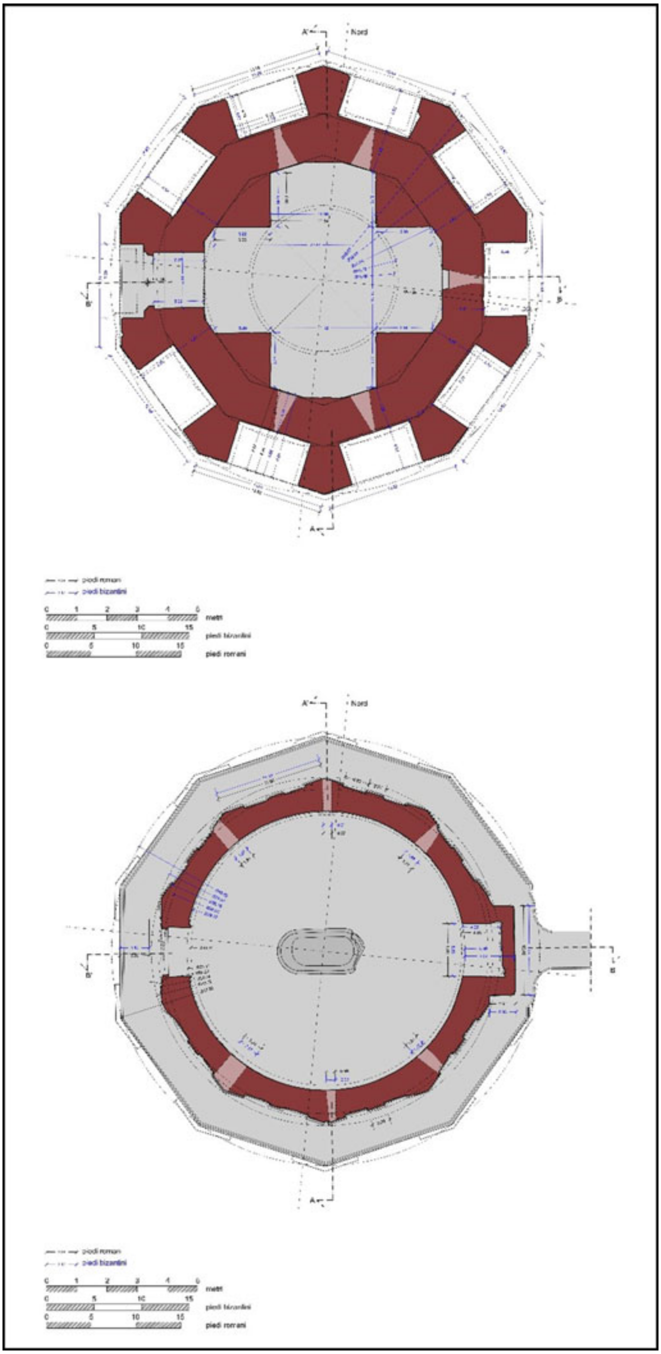

Fig. 11.3 Plan of the first and second floor

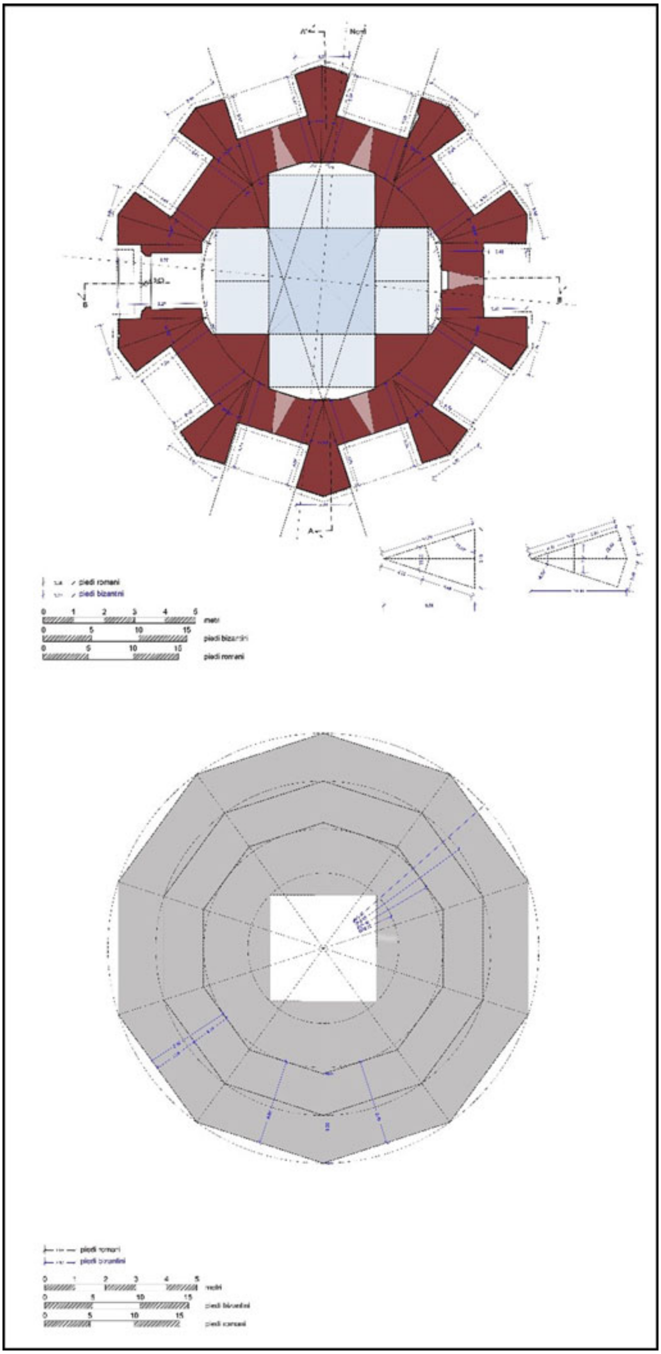

Fig. 11.4 Plan of the first floor: geometry and measurements in Byzantine feet

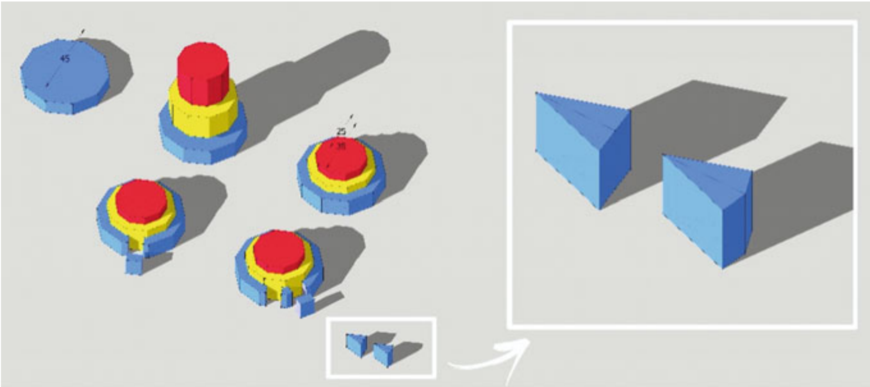

Fig. 11.5 Schematic drawing of the mausoleum volumes

An interesting geometrical quality of the decagon is that it can be divided into 10 isosceles triangles whose base angles measure 72°, and the other half of the opposite, i.e. 36°. The 10 powerful external pillars (Fig. 11.5), that are constructed on a quadrilateral made of two triangles with 10 bf hypotenuse and 9.5 bf side (angles 18°, 72°, and 90°), can be traced back to these triangles, the sum of which results in an isosceles triangle 36°, 72°, 72°, with equal sides of 10 bf and height 9.5 bf. The minimum dimension of the section of the pillar bordering the outer niches is of 3 bf (Fig. 11.4). Finally, the interior space can be easily approximated by a Greek cross, whose central square measures 11.1 bf, while the four lateral arms are rectangles with a 1/2 ratio to the square.

Regarding the upper floor of the building, it is necessary to state that the conditions of the external stone blocks do not allow, in our opinion, an accurate reading of the measurements of the existing profile. It can be hypothesised that the circumscribed circle at the base of the pilasters measured 36.65 bf, corresponding to 39 rf. The side of the inscribed dodecagon could thus be 11.33 bf, a dimension that is relatable to 12.06 rf. The upper cylinder on which the slot openings are found has an external diameter of 34 bf and an average thickness of about 2.45 bf.

The interior elevations (Fig. 11.6) are characterized by decimal measurements attributable to the unit division into 1/3, 2/3 bf. The main architecture lines of the lower floor appear to rely on a 2 × 3 square grid, while the higher one on a 5 × 8 grid (amount very close to the golden ratio). Even the arrow of the vault is attributable to the Byzantine foot and measures 6 bf. The 2 × 3 ratio is also present in the exterior elevation on the side of the decagon of the first level. In this case, the rectangle is displayed vertically and its measure depends on the side of the decagon of the plan. Its value is thus an irrational number derived from the measurement of the circumscribed circle of 45 bf.

Finally, it should be mentioned that other architectural elements are related to the Byzantine foot: for example, the maximum thickness of the cylinder on which the cupola rests is 4 bf. One must also highlight that certain measurements yield whole

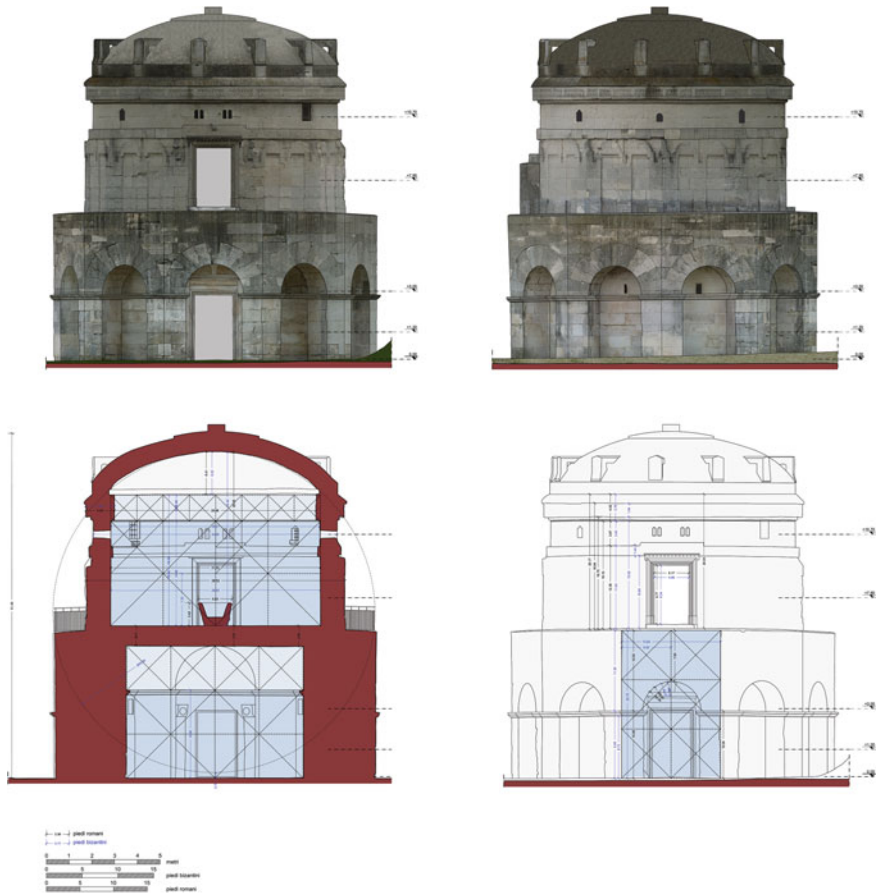

Fig. 11.6 Orthophotos; section AA' with indication of the proportions 2 × 3 and 5 × 8. 9; external elevation with indicated proportion 2 × 3

numbers in Roman feet. This is the case of the outer band decorated with a 'pincer' pattern (2 rf), the outer extent of the apse equal to 10 rf (whole number), and the pilasters of the smaller width of the gallery, which amounted to approximately 2 rf. On the ground floor the total height of the frame is 13 rf, the door height is 10 rf.

The Decagon and Boethius

In AD 526 (or according to tradition, in 524) Anicius Manlius Severinus Boethius, questor, patrician, consul and *magister officiorum* at the Theodosian court, died in Pavia, imprisoned and killed by Theodoric. The philosopher, as we know, is credited with the term *quadrivium*, a word that was used to describe the art of late-ancient scientific knowledge. The four disciplines—arithmetic, music, geometry and astronomy—have their roots in Greek tradition and constituted the 'preparatory paths of philosophy'. Architecture students had to follow such structured science, and were of course also trained in practical themes: the balance between the theoretical and the operational skills in late antiquity certainly had different outcomes in Roman society and Byzantine society (Briggs 1927; Frothingham 1909; Kostof 2000; Meek 1952; Schibille 2009; Vagnetti 1980). Within the present study, some reflections on the possible practical application (in the design phase) of the theoretical knowledge possessed by Boethius at that time certainly appear necessary.

The writings on the scientific subject attributed to Boethius have only partly reached us, unfortunately fragmented and incomplete, as attested by the relative philological studies. While the *De Institutione Arithmetica* reached us intact, the same cannot be said for other sections: *De Institutione Musica*, *De Geometria* and the Astronomy. The first work contains the knowledge of Nicomaco di Gerasa (already translated by Apuleio). The sources of the third have to be found in the documents of *Euclid's Elements*, while the astronomical works of Tolomeo were used for the fourth (see the letter between Theodoric and Boethius reported by Cassiodoro, *Variae*, I, 45, 4).

Scholars have long debated the authenticity of the two geometry books attributed to Boethius (Folkerts 1970), highlighting the incongruous traits and elements that move the dating of the earliest manuscripts to the eleventh century. However, some fragments are contained in the third and fourth book of the *Ars Geometriae et Arithmeticae* in five books (Boezio 1867). In this work, which will remain a point of reference for Cassiodorus and the measurements of the Middle Ages, a brief description of the decagon appears (book II, XXX). The short passage describes the properties of the decagon, not so much from the geometrical point of view as from the arithmetic point of view across the figurate numbers. In the book on geometry, the author associates the decagonal number 370 with the figure of the decagon (Fig. 11.7), which, although not appearing in *De Institutione Arithmetica*, can be traced back to the same arithmetic principles of the polygonal numbers (Incerti et al. 2017: 76).

It is clear that the geometric rules followed by the anonymous designer of the Mausoleum belonged not so much to the field of arithmetical calculation and the properties of particular numbers such as the decagonal ones cited in the *De Geometria,* attributed to Boethius, but to the geometric knowledge already present in the Euclid's *Elements*.

Conclusions

To conclude, an archaeoastronomical investigation has certainly yielded significant results which have extended our knowledge of this extraordinary building into topics that were previously unexplored. The critical reading of the survey measurements also allowed us to highlight the presence of a geometrical project that controlled the general

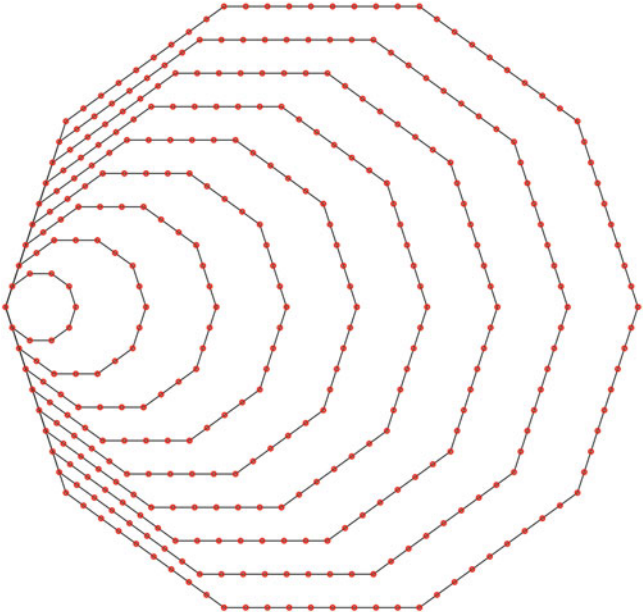

Fig. 11.7 The figure corresponding to the decagonal number 370

measures of the buildings based on Byzantine foot measurements. In addition to the encircled and circumscribed decagons, whose diameters were integer figures, other numerical relationships were found in the plans and elevations, such as: 1:2, 2:3 and 5:8. The comparison of some Roman integer measures, however, makes it clear that this second unit of measurement has also been used not so much during the project phase as during the execution of the work. Finally, we have tested the important contribution of digital models both in the phase of analysis and in the communication of complex and stratified contents such as the historical-astronomical ones.

Acknowledgements We thank the Polo Museale Regionale dell'Emilia Romagna and the Compagnia delle Misure for the use of their Faro focus3d scanner during our architectural survey of the Mausoleum. Sections "Introduction: The Foundation and the Main Topics", "A Description of the Mausoleum", "The Architectural Survey", "Archaeoastronomical Analysis", "Numbers and Geometry", "The Decagon and Boethius", "Conclusions" are by M. Incerti; Section "Survey Drawings: Methods and Procedure" by G. Lavoratti, Section "The Interactive Models for the Dissemination of the Research Project" by S. Iurilli.

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