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The Mausoleum of Galla Placidia in Ravenna: Archaeoastronomy, Numbers, Geometry and Communication

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Abstract. The Mausoleum of Galla Placidia is one of Ravenna's UNESCO protected monuments, globally renowned for the extraordinary mosaic decorations that cover the internal surfaces. The famous starry vault profoundly engages and inspires the observer. It has been studied for its accuracy in the representation of the real sky, but also because of its mystical and symbolic meaning in relation to the iconographic tradition of the time. The building has also been subject of archeoastronomical research (Romano in Orientamenti ad sidera. Astronomia, riti e calendari per la fondazione di templi e città. Un esempio a Ravenna. Edizioni Essegi, Ravenna, 1995), which is here presented in depth. The present contribution also examines other architectural elements beyond orientation: particular attention is payed to the small slit windows of the building to investigate their possible archaeoastronomical significance. In the study of these elements, particular attention should be payed to the elaboration of architectural survey data, which has to be produced following established procedures and techniques. A functional 3D model will be developed from the data of the archaeoastronomical analysis to display the original morphology of the building (the floor was about 1.4 m lower because of subsidence movements), astronomical phenomena, and allow for multimedia communication of the scientific content produced. Finally, the related issues will be investigated: the geometric and projective transformations of the starry dome, the geometric shape of space also in relation to the unit of measurement used.

Keywords: Galla Placidia · Survey, archaeoastronomy · 3D model Multimedia communication

1 Introduction

The small and precious Ravenna monument is attributed to the Roman empress Galla Placidia (about 390 AD—Rome 450 AD), daughter of Teodosio I, of whose life we remember the central role of his Christian confession, which was also highlighted through the commission of several important sacred buildings. The church of St. John the Evangelist in Ravenna (ca. 426 AD) was founded as an ex-vote for surviving a shipwreck. The building of Santa Croce (ca. 417–425 AD), whose remains attest to the

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existence of several phases of construction (David 2013), celebrates the devotion of the Augusta Empress to the relic of the True Cross. The mausoleum, named after her was, most probably one of the two sepulchral chapels on the North and South extremities of the narthex of this basilica. Among other works we should also mention the chapel of Saint Aquilino, of St. Lorenzo's Basilica in Milan, in which archaeoastronomical elements and important astral iconography have been studied (roman portal, on the left, are depicted: Sun, Jupiter, Mars, Victory or Nemesis, Venus, Moon).

Today, the mausoleum presents itself as a small, latin-cross plan building, whose arms are topped by barrel vaults and a dome at the crossroads. In the present study, some elements of the building have been considered starting from the survey data executed for this study.

2 The Survey

The architectural survey was carried out with a Faro focus3d scanner; 23 stations were performed covering the interior and exterior. The individual clouds have been registered with the aid of spherical targets. At a later date, two different photographic campaigns, needed for the reconstruction of the three-dimensional, textured model, were made: the first relating to the exterior, the second to the interior. The shots were performed by digital SLR camera on a tripod. In this stage, 459 photographs were elaborated and 119 targets used as follows (Fig. 1). The small size of the interior of the building, the exterior elements positioned very close to the wall (vegetation and the wall of the road on the south side) and shiny marble surfaces have created several difficulties for the digital photogrammetry process.

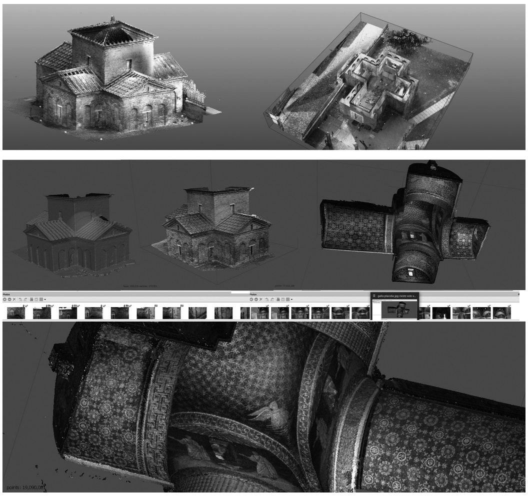

Fig. 1. Up: the screenshot of the pointcloud, scanner Faro Focus 330, software Scene 6.2, survey (dated 6/03/2017) and elaboration of data M. Incerti. Down: the textures were extracted using digital photomodelling software (exterior: 247 photos, 29 targets; interior: 212 photos, 90 targets; survey and elaboration of data M. Incerti)

3 Survey Drawings: Methods and Procedure

The registration of the 23 scans has produced a pointcloud with a density of 300,000,000 points, describing the interior and exterior of the mausoleum to a good degree of accuracy. The limited shadow areas are due to the presence of fixed or not-movable furniture that can not be removed or reduced, and thus did not allow for complete survey coverage.

To obtain the canonical elaborations of the survey and proceed to a more thorough analysis of the metric and geometrical relationships of the artefact, vertical and horizontal slices of the thickness of 10 mm were extracted from the cloud. The good density of the pointcloud has guaranteed the necessary detail for the slice even at such a reduced thickness, thus allowing for accurate CAD rendering of the horizontal and vertical sections.

With reference to the same cutting planes used for the extraction of the slices, the corresponding high-definition screenshots were produced from the cloud, which were also imported to the same CAD format, allowing the re-drawing of the projected parts of the architecture. Similarly, ortophotos have been extracted from the photogrammetric model corresponding to the cloud, which, when overlapped with the CAD drawings, allowed postproduction to add important details regarding colour and material to the two-dimensional elaborations (Fig. 2).

This procedure, consolidated over the years, has allowed the creation of three plants (one of each of the three different levels of the openings), four elevations and four sections (two transversal and two longitudinal), on which a series of readings and insights can be based. Two-dimensional elaborations are also used for morphological and dimensional control in the phase of 3D modelling.

4 The Issue of «Form»

The irregularities of the shape of this structure, especially evident in the plant, cannot be attributed to a lack of care in its realization, but must be traced back to a precise compositional design of the axes, which are not orthogonal to each other.

4.1 Orientation

The building has been the subject of archaeoastronomical research carried out by Romano (1995): the Azimuth value of 180.2° highlights a north-south, trend which is decidedly singular in comparison to other Byzantine buildings of Ravenna. The transept is not orthogonal to the nave, and has an orientation of 94.3° (Fig. 2). The reason for the rotation between these two elements cannot be casual. The azimuth of the transept is aligned with the sunset of the sun on the 26–27 March and the 13–14th of September at the time of construction (pre 450). The first date is very close to 25th of March, celebration of the Annunciation of Mary, a celebration which was already documented in the Martirologio Gerominiano dating back to the IV/V century. The 14th of September also celebrates the Feast of the Cross, and the main church of the

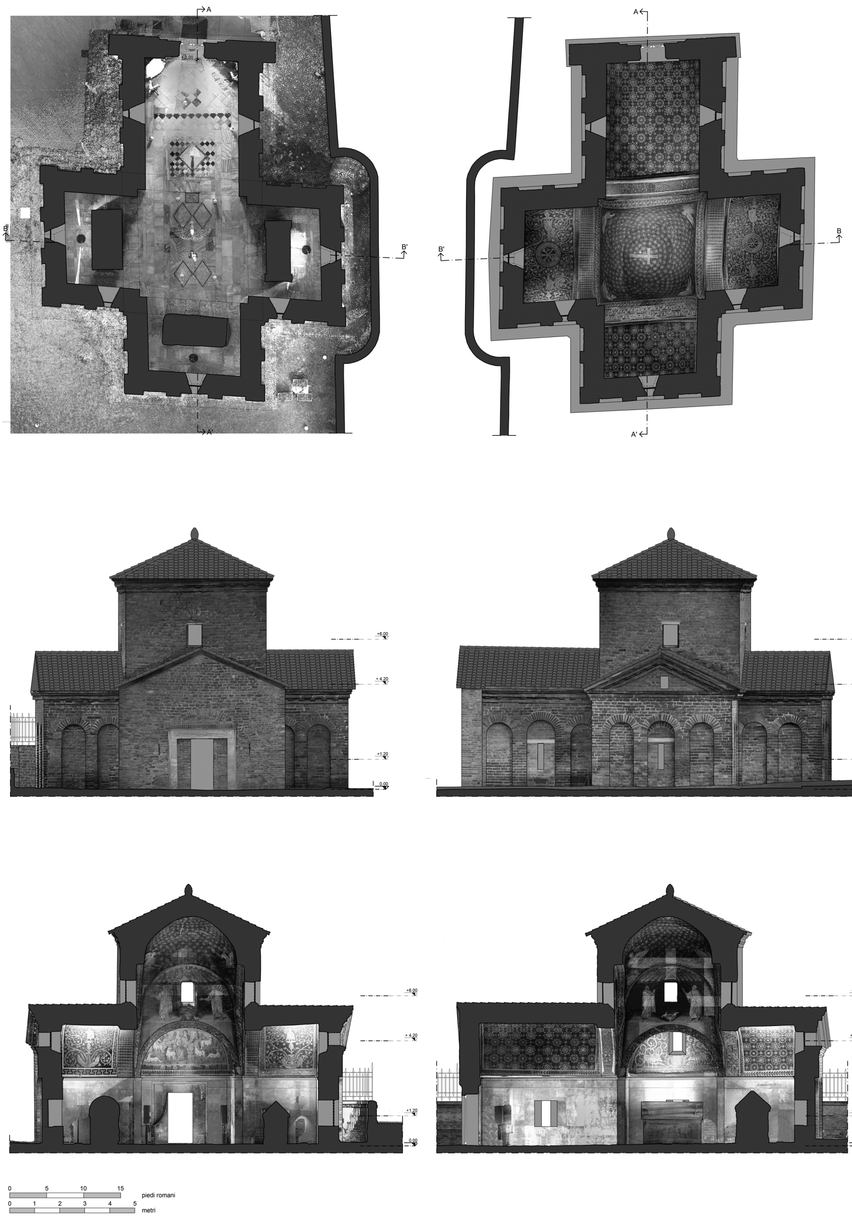

Fig. 2. Plan of the ground floor, +1.20 m; plan of the dome; material restitution of North and West elevations (by photomodelling software); material restitution of sections AA′ and BB′ (from the pointcloud) (drawings by G. Lavoratti)

complex is dedicated to this very festivity. The difference between the direction of the transept of the mausoleum and the nave of the Church of the Cross, (measured on the survey with laser scanner) is of about 2°.

4.2 The Levels of the Floors

During the restorations (Iannucci 1995; Ricci 1914), the level of the ancient flooring was brought back to the surface, at a height of −1.40 m. Because of the significant phenomenon of subsidence (which caused the level of the phreatic zone to rise) it has not been possible to restore the original conditions. For this reason, the proportions of the current space are very different from those planned by the original architect (Figs. 3 and 4).

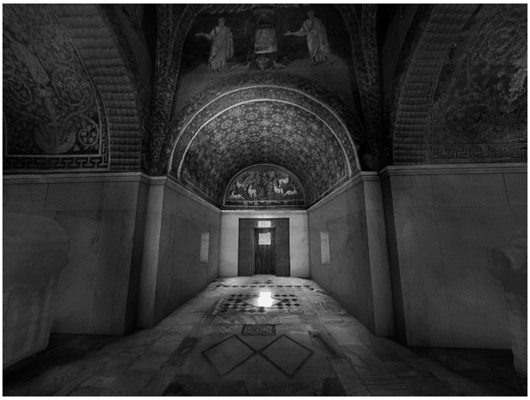

Fig. 3. Rendering of interiors, current state (S. Giannetti)

Fig. 4. Rendering of interiors, the level of the ancient flooring (−1.40 m). At midday of the Winter Solstice, a ray of light illuminates the door (render by S. Giannetti)

4.3 The Windows and the Light

Particular attention is payed to the slit windows of the building, which were reopened following the restorations carried out in the last century (Iannucci 1995) to investigate their possible archaeoastronomical significance. In the study of these elements, specific care should be payed to the elaboration of architectural survey data, which has to be produced following established procedures and techniques.

The Mausoleum of Galla Placidia today has several windows, organized into three levels:

– 7 on the lowest floor (2 east, 3 south, 2 west);
– 3 on the lunettes (1 east, 1 south, 1 west);
– 4 on the vault (1 east, 1 south, 1 west, 1 north).

The openings are now closed with alabaster slabs donated by King Vittorio Emanuele III in 1911. Due to the bright nature of the material, it has a very fascinating effect, which has completely changed the reading of the colours and the internal brightness: the sun's rays are heavily filtered and it is no longer possible to observe their course on the surfaces.

From an initial analysis of the graphic drawings, only looking at the windows facing the south, we can see that:

– At midday of the Winter Solstice, a ray of light illuminates the door of the ancient *sacellum* at a height of −1.4 m (windows of the lunettes and vault, Fig. 4).
– At midday of Equinoxes, the sun begins to enter.
– At midday of the Summer Solstice, the sun does not enter.

A functional 3D model will be developed from the data of the archaeoastronomical analysis to display the original morphology of the building (the floor was about 1.4 m lower because of subsidence movements), astronomical phenomena, and allow for multimedia communication of the scientific content produced. This aspect of the work, still in its study phase, will allow to verify the presence of other light effects related to the other windows.

5 Geometry and Measurements

Several measures of the plant of the building are consistent with the Roman foot, 29.56 cm (Docci and Maestri 2009) (Fig. 5).

The fact that the two arms, when traced, are not orthogonal to each other cannot be due to a trivial construction error: the plant is composed of a combination of much more complex parallelograms, which would be much more difficult to execute than a rectangle, especially in the construction of vaults and the dome. It is evident that the inclination between the two arms is intentional when it is overlapped to the exterior profile of the building using a 1-foot pitch 43 × 50 grid (Fig. 5). The vertices of the cross fall on the grid crosses (A, G, H, I, L) with very good approximation, and in some cases on the 1/2 foot sub-grid (vertices with circle B, C, D, E, F, M). The approximation between the theoretical figure and the observed figure is 3.5 cm on average. The rectangular triangle used to track the inclination of the walls CB, DE, HI and ML has a ratio of 11:1, while for the apse it is 19:1.5. This geometric and metrological data, along with the archaeoastronomical data, can support the hypothesis that the rotation of the east-west axis to the north-south axis is a precise condition sought by the ancient Roman builders.

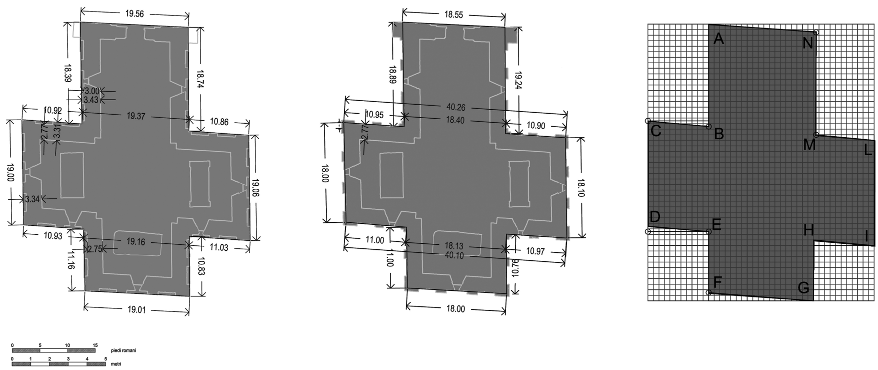

Fig. 5. The scheme of the plant and of the arches on pilaster strips, the size of the three smaller arms being 19 × 11 ft. Given that the depth of the stairs equal to 1/2 ft, the second alignment in the interior results in 18 × 11 ft (the margin is at most about 1/10 of foot, i.e. 3 cm). The north arm is 1/2 foot greater in width than the other three and narrows towards the apse. This element, as evidenced by some studies, aims to amplify the perception of the space of the small *sacellum* (M. Incerti)

6 The Starry Vault: Iconography

The famous starry vault profoundly engages and inspires the observer. It has been analyzed and described for its accuracy in the representation of the real sky, but also because of its mystical and symbolic meaning in relation to the iconographic tradition of the time (Ranaldi 2011; Rizzardi 2005; Swift and Alwis 2010). It has been noticed that the 567 eight point golden stars decrease in size from the springer to the keystone of the vault, a figurative device to perceptually broaden the natural prospective effect.

The geometric structure of the starry sky is formed by 5 concentric circumferences from which spherical curves begin. Inside the first circle are 7 stars distributed around the cross (3 to the lower right, 3 lower left and 1 in the top left). The large central Latin cross is placed individually, with a 90° rotation in relation to the axis of the mausoleum: this cross, (symbol of Christ) has the longer axis oriented in the east-west direction. The observer has to face east, with his back to the west, to have a correct view. Its orientation supports and greatly strengthens its solar significance, evident in the representations of Christ-Sun of the Chapel of Sant'Aquilino and the Mausoleo dei Giulii (Rome). Furthermore, each star lies on a deep blue background made of tesserae layed out according inscribed circles. Although these are not visible to the naked eye, they are still able to evoke the expansive movement of light.

The iconographic comparisons suggested by historians look at vaults decorated with mosaics.

In the Baptistery of San Giovanni in Fonte (Naples, V century, before Galla Placidia) the monogram cross (*chrismon*) is at the center of the starry vault, whose asters have different colours and 8 petal shaped rays that end with a small shiny point.

In the Church of Santa Maria di Casaranello (Lecce, V–VI century) the sky has three bands of blue-light blue sloping towards the cross, which is surrounded by a rigorous geometric composition of stars. The asters, of alternating colours, have six petal shaped rays that once again end with a small shiny point.

In the Baptistery of Albenga (Savona, around 450) the stars (8 rays) are here arranged according to a linear layout that follows the direction of the barrel vault. At the center is a christogram—Chi (X) and Rho (P)—repeated concentrically three times and surrounded by 12 doves.

In the church of Sant'Apollinare in Classe (Ravenna, 549, therefore later) at the center of the starry sky, in the apsidal vault, is the precious cross adorned with "pictures of precious stones" with the face of Christ in its middle; the stars with 6 rays are of alternating colours.

Finally, from the iconography present in the mausoleum, one must recall two Christograms inside two wreaths is present in the barrel vault of the transept. It is significant, as the iconography of the ancient coins of Galla Placidia includes the Christogram inside a wreath and a cross with a star above (Gerke 1966).

7 The Starry Dome: Geometry

The geometry of the dome of the Mausoleum of Galla Placidia is complex and difficult to interpret. Its lack of structural elements and its characteristic rounded corners make identifying the generatrices and directrices of its surface even more difficult.

One can get a better idea of its geometry and carry out more detailed analysis with the help of a laser scanner, by building a mesh model by triangulating the point cloud. This reveals that:

1. The dome comprises a slightly raised spherical cap;
2. The impost, which, as mentioned above, is difficult to identify, seems to be located at the height of the keystones of the four arches that frame the tholobate;
3. The course followed by the parallel sections of the dome, perpendicular to the axis, is unclear. Those at the height of the impost seem to be quadrilaterals (parallelograms) with rounded vertices, while those near the top are perfectly circular.

As described above, the dome seems to have been built by finding an average between the parallelogram of the tholobate and the circumference of the dome, creating a single continual surface, which differs from the classic hemisphere resting on four pendentives. At first sight, however, this architectural feature, without any other references, clearly appears hemispherical when seen from below.

Having said that, it is clear that projection is the only technique that can have been used to create the layout of the stars on the surface so that they appear to the observer to be evenly distributed on a hemisphere. This is proven by the physical distribution of the stars on the surface. The orthogonal projections were extracted from the textured mesh model produced during the photomodelling process. If one analyses any section along a plane that passes through the axis of the dome, it is clear that the stars do not lie on parallel planes, but instead on courses that can be defined as "festooned" (Fig. 6). These curves are obtained from the intersection of the cones (with vertices at the centre of projection and directrices corresponding to the circumferences lying on the impost plane) and the overall surface of the dome (Fig. 7). The intersection is the same used to

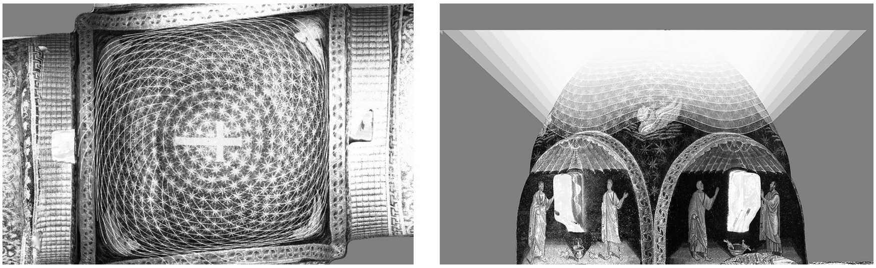

Fig. 6. The orthogonal projection extracted from the textured mesh model produced during the photo modelling process. The stars do not lie on parallel planes, but instead on courses that can be defined as "festooned". These curves are obtained from the intersection of the cones and the overall surface of the dome (S. Giannetti)

describe the *corde blande*, or curved beds, used by Brunelleschi in his dome in Florence.

In the orthogonal projection from below, although towards the top of the spherical cap the stars are distributed in a perfectly circular manner, as one draws closer to the impost they are laid out along the sides of a parallelogram (apparently at random). The only other projection that could have been used to position the stars on the surface is a central projection (Fig. 8).

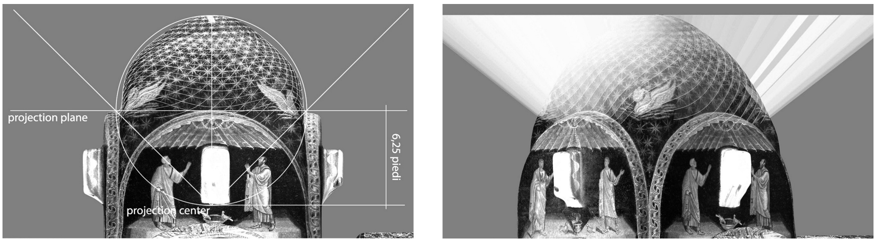

Fig. 7. The diameter of the theoretical hemisphere is equal to 12.5 Roman feet. The centre of projection (the antipodal point of the polar stereographic projection) is located at 6.25 ft from the projection plane. As the parallel ones, in the theoretical sphere the spiral curves should coincide with the loxodromic curves.In the actual dome they do not have any clearly defined geometry (S. Giannetti)

Identifying the centre of the projection was not straightforward. Firstly, the height of this point had to be hypothesised: earlier observations regarding the ring of stars near the impost and further analysis carried out on the textured model made it clear that the height of the centre must be higher than the current observation point (and therefore higher than the historic observation point). Indeed, the further the centre of projection is from the sphere, the squarer the ring of stars appears.

Various studies, in particular Bartoli's research into the dome of the Pantheon (Bartoli 1994), have investigated the coffers in Roman domes, noting that they were

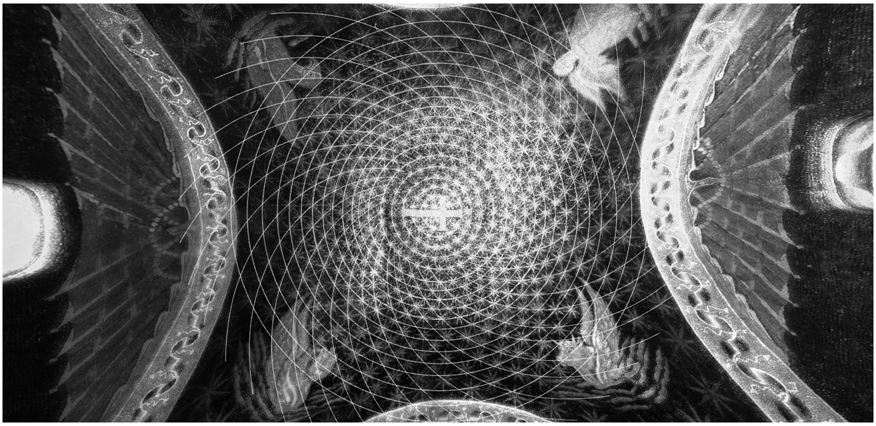

Fig. 8. The viewpoint placed in the centre of projection. At this point all the rings of stars, which on the surface are irregular, appear perfectly circular (S. Giannetti)

created using a polar stereographic projection. To check whether the starry dome in Ravenna was also created using this form of central projection, the diameter of the theoretical hemisphere had to be hypothesised: in this case this equalled the diameter of the real dome at its impost, 12.5 Roman feet. As a result, the centre of projection could be located at approximately 6.25 ft from the "equator" of the sphere, or from the impost plane described above (Fig. 7). When the viewpoint is placed in the centre, all the rings of stars, which in reality are irregular, appear perfectly circular. In addition, in the polar stereographic projection the loxodromic curves of the sphere have the appearance of logarithmic spirals on the plane. Analysing the spirals formed by the stars, it is clear that they can be described in this way with a high level of reliability until the fifth ring of stars from the cross. From here on it seems that the stars, although laid out in concentric circles, are no longer aligned along spirals. While in the theoretical sphere these curves should coincide with the loxodromic curves, it is obvious that in the actual dome they do not have any clearly defined geometry, as a result of the dome's irregularity.

8 The Digital Models for Research Verification and Dissemination

This last part of the contribution is part of the trials conducted by the research group, (Incerti and Iurilli 2016; Incerti et al. 2016) regarding the modes of multimedia communications, interactive and not, based on virtual models as an edutainment tool for the fruition of cultural sites and artefacts.

The objective of the three dimensional reconstruction of the Galla Placidia Mausoleum in Ravenna was to verify and communicate, by means of simulations, the archaeoastronomical data previously gathered from the same artefact. Having found the Rhinoceros software application, the creation of a sufficiently representative model of the architectural structure was the major contribution to the research. The model was made without losing any information concerning shape or dimension strictly connected to the evaluations of the research itself. In other words, geometric characteristics and characteristics of measurements had to be remodelled in a discretized form, offering a more efficient instrument of investigation (Fig. 9).

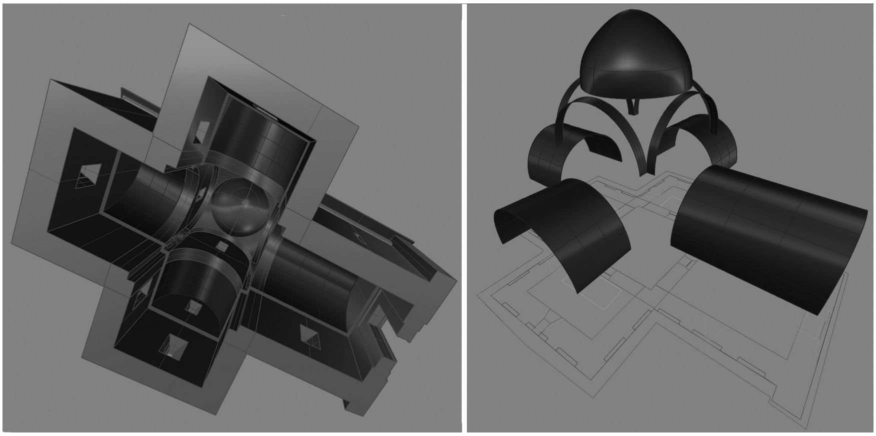

Fig. 9. The model in Rhinoceros: to the left, prospective view from the bottom. To the right, the inner surfaces of the vaults (S. D'Amico)

This intention has undoubtedly determined the result, that is the descriptive capacity of the digital model, which is also efficient in the study of more unusual architectural lines of the mausoleum. Without going into a detailed examination, it is worth underlining once again however, how assisted three dimensional modelling covers a role that is not simply instrumental but, nevertheless, investigative. Simply as an example, we can recall the emblematic characteristic of the Galla Placidia monument, visible in its layout and corresponding to the clear displacement which, along the longitudinal axis, shows the two respective eastern and western halves of the building. This anomaly in the design generates consequent adaptations in the geometric definitions of the inside surfaces of the ceiling: during the restitution of volume, the formal conditioning of the barrelled vaults of the four arms of the Latin cross has always had to be considered, so the central dome is a particularly interesting object. Its relief shows not only a more or less rhomboid base but also a rather variable vertical profile of the curves, so use of the model maker, in the study phase, has verified this variability. It is clear how, for the volume of the dome, generative geometric shapes which make it particular can be hypothesized by means of systematic and continuous comparison between two dimensional representations of certain metric data (different suitable sections) and their three dimensional construction: this is one of the objectives of the proposed virtual simulation.

The digital modelling of another architectural feature which provoked further consideration, coincides with the conformation of the joints between two different levels of wall, the one under the arms and the one above the central part which contains the dome: again deriving from conditions of the described design, the relative rotation, even if minimum, between these two levels of wall requires solutions of connection with the ceiling above which are not simple. The respective simulative definition tends to make clear the relationship of the planes which presumably are installed between the pitched roof over the four arms of the cross.

The experience I have described verifies, on a large scale spectrum, that digital model creation gives access to a whole range of opportunities.

If being able to compare the analytical sequences of an investigation, and managing to deal with the complexity in a global vision, seems to be something which has already been achieved thanks to the contribution of information technology, this work has, nevertheless, aimed to provide such use.

The choice of various application software for relief and restitution has been determined, in effect, also to constitute a data bank to gather and sort out data which comes from research; all this information, after necessary verification, as mentioned before, has to be visualized, in virtue of the final but substantial necessity which is to communicate the outcomes of research.

So that is why the digital model has become a truly representative form, because it is both a combination of material data and illustration of different meanings, not always clearly recognisable and because it is a narration of an architectural, technical, cultural and symbolic patrimony.

9 Communicating the Cultural Heritage

The widely debated theme regarding the management and maximisation of cultural goods necessarily requires a profound knowledge of individual historical artefacts, fundamental to their proper preservation and safeguarding. As we know, the digital instrumentation currently used in architecture surveys and the know-how of the operators working on capturing and processing the data enable the creation of more and more virtual models that are loyal to the original structures, allowing the appreciation of morphologic and geometric features as well as chromatic colors. It also allows to perform any studies and readings deemed necessary on the structure at a later date.

In the scientific community, it is widely believed that digital modelling is not only a convenient tool for analysis of architectural artefacts at a distance, but represents an important means of communication and promotion of the good, making it accessible and useful to a wider audience. Increased accessibility to architectural artefacts over the years, albeit in virtual form, has opened the way to more advanced forms of communication of cultural goods for both experts and an ever-growing audience. In different forms, both can approach and explore the object, extrapolating information or just enjoying its viewing.

10 Conclusions

The first results of the research conducted in this famous paleo-Christian building support the hypotheses that the apparently irregular geometric shape of its plant was rigorously constructed with a square knit of 1 Roman foot, and that the orientation of the transept was also designed for archaeoastronomical reasons. More complex geometric knowledge was also needed to trace the starry sky onto the central dome. Though not being traceable to a regular geometry, it can be read as a semisphere thanks to the 567 stars and their arrangement.

Finally, this work demonstrates how digital tools (IT) can really innovate both the methods of investigation and the representation of architecture, as well as the communication and dissemination of stratified and complex archaeoastronomical content (for this reason of difficult appropriation). The two models we built, the mesh from the point cloud and the discretized reconstruction with 3d software, have been functional in the various fields of research. This allows for the integration, synthesis and communication of the material for architectural, historical and cultural research. The model, its quality and its material yield and the modes of execution now cover a central role as suggested by the London and Seville Charts.

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