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Sunlight simulation of the church of Saint Nectaire in virtual reality: a digital time machine.

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Abstract

*The roman church of Saint Nectaire, like many churches in Auvergne, France, is richly decorated with carved capitals. Most of them represent figures or symbols of Christianity and are periodically illuminated by the sunlight that comes to strike them at different times of the day throughout the year. The periodicity of these occurrences, which seem to correspond to a "targeted" temporality around religious feasts, appeals to historians who foresee the possibility of a perpetual religious calendar marking the times of the Christian liturgy with regularity and precision. The observations made since 2009 by Daniel Tardy [Dan13] have made it possible to highlight the high number of luminous phenomena, particularly concerning the remarkable lighting of the choir capitals: this has made it possible to hypothesize peculiar coincidences between the day of the luminous event and the date of the Julian calendar (used from 46 B.C. to 1582 AD) corresponding to the Christian celebration of the illuminated figures. The presence of hills, however, recurrently masks the sun at the beginning and end of the day and prevents the illumination on a certain number of sculpted figures that one would expect, given the number of calendar occurrences already observed elsewhere. Considering its experience in the field of digital survey 3D modeling and real-time simulation in the field of heritage [ASL15], [MDSB14], [NMRS13], [SCN*13], [Sal18], the MAP laboratory created a complete numerical model of the church and to submit it to a virtual heliodon in order to predict the illumination of the interior decorative elements at "critical" moments throughout the year if the surrounding hills did not exist: the question of the primary location of the church is currently the subject of many conjectures. This experiment consists in a methodological approach whose purpose is to validate a solar simulation method on an existing building and to verify its validity by direct confrontation between the simulation produced and the observable effects in reality. This not only allows us to make hypotheses about the constructive history of the the church of Saint Nectaire, but also - in the near future- to apply this method to several nearby churches, similar in their history, their architecture and their religious iconography.*

CCS Concepts

• ***Applied computing*** → ***Architecture (buildings);*** • ***Computing methodologies*** → ***Modeling and simulation; Virtual reality;*** • ***Human-centered computing*** → ***Visualization systems and tools;***

1. Introduction

The church of Saint-Nectaire has 103 capitals, 25 of which are decorated. Of these, 80 faces are carved with figurative elements and only 53 faces (66%) are lit, in situ, on one day or another of the year but 27 of the 80 faces (33%) sculpted never light up. Finally, out of these 27 faces that do not light up, 14 (17%) could only light up at sunrise, and 13 (16%) could only light up at sunset, when the sun is hidden by the surrounding hills. Since June 2010, D. Tardy has counted the remarkable occurrences over more than 80 days and has observed that:

- at sunrise on the winter solstice, the hills to the east of the church block out the sun's rays up to 5° elevation, up to 7° elevation on the summer solstice and up to 10° elevation around the equinox.
- at sunset, to the west of the church, other hills obscure the sun's rays between 0° and 4° (winter solstice) and up to 7.5° (summer solstice) elevation before the theoretical disappearance, on the astronomical horizon, of the sun.

In order to remove this uncertainty, the MAP-aria laboratory proceeded to the complete modeling of the church of Saint Nectaire through numerous lasergrammetric and photogrammetric survey campaigns, both terrestrial and aerial [Bar17]. The model produced was positioned in a digital heliodon that simulated the course of the sun in 1067 and 2012. The year 1067 was chosen because it is located at the heart of the period assumed for the construction of the church, and valid for the whole roman period of its existence. The 2012 model made it possible to compare the accuracy of the digital simulation with the iconographic corpus constituted by Daniel Tardy, rich in several hundred photos. A more detailed analysis of all the historiated capitals has made it possible to identify 150 figurative items, including 127 representations of faces, including 9

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Figure 1: *The illuminated capitals of the church of Saint Nectaire.*

representations of the Christ and 34 figures with a nimbus which certainly represents the saints whose feast date must have appeared in the martyrologes of Bede the Venerable and/or Usuard, in use in the Roman period [Dan13].

On the basis of these findings, Daniel Tardy puts forward two hypotheses:

- all the faces (80) of the 25 historiated capitals should light up at least once a year, in accordance with the notable events of the Christian liturgy, which would make this church a true "solar calendar" giving meaning to the whole iconographic programme of the building. Indeed, it seems unlikely that the builders of the time, out of aesthetic concerns and with even very elaborate calculation methods, would have designed and positioned the windows and capitals that could light up if the hills were not there.
- the most likely hypothesis for the design of such a complex iconographic programme would be that this church could be an identical reproduction of another church where a solar calendar of this type has already been implemented. However, many of the capitals of Saint-Nectaire are unique in France and no other church is known to have had such a solar calendar. It could be deduced that, if this church is a copy, its original model has disappeared. However, it is perfectly attested that the mother house of Saint-Nectaire, the Roman church of the abbey of La Chaise-Dieu on which the priory of Saint-Nectaire depended (where Abbot Aymon de La Queuille was buried in 1306) disappeared precisely in 1344 by order of Pope Clement VI. According to tradition, the Roman church of La Chaise-Dieu is "quite similar" to that of Saint-Nectaire. This abbey is built on a hill, and is therefore illuminated from the first rays of the sun but also by its last rays, which is extremely rare.
  The outcome of this reasoning could put forward the hypothesis, albeit tenuous, of an initial construction of this church in La Chaise-Dieu, a town 89 kilometres away from Saint-Nectaire [Dan13].

2. Related works

" It is well-known that many prehistorical and historical building structures (e.g. the Pyramids of Giza and several temples in Egypt, Stonehenge, Newgrange, India, or Mesoamerica) have been erected following astronomical orientation patterns. Some buildings have been erected following the cardinal directions with surprising accuracy, while in other cases definite links to the brightest of all celestial bodies can be seen by following directions where the sun could have been seen to rise or set on solstice days " [Zot16a]. Many research projects use digital simulators to show natural [MYKI06], [Bar18] or anthropogenic [Hof17] light phenomena in order to validate or reproduce ancient ritual practices of a religious or societal nature [Ave03] [FF12] and [SCM04].

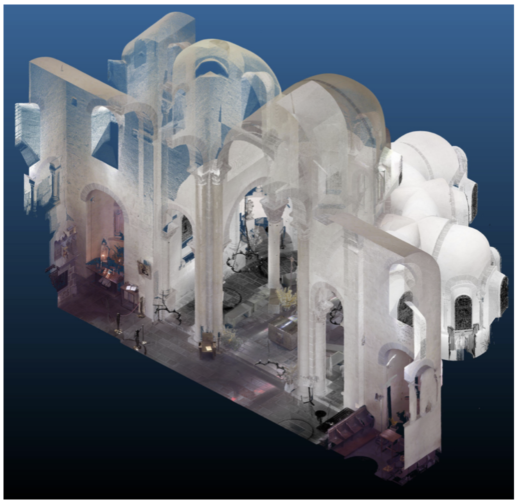

Figure 2: *Detail of the laser scanner point cloud.*

Remarkable works such as those of [Zot16b], [PHKA15] and [Les15] demonstrate the usefulness of numerical simulations in order to reproduce as accurately as possible either solar illumination conditions or remarkable alignments of celestial bodies (sun, planets and/or stars) from which the apparent movement may have shifted significantly over the ages and highlight the possibilities offered by digital tools in the field of astronomical simulation in general [GSGC07], [HMD*10]. In this paper, the solar illumination of the church of Saint Nectaire has been considered in its main architectural aspects, questioning the spiritual significance of its lapidary inner decorations and through the transformations that may have affected its architecture along 800 years of history.

3. The experiment

The luminous phenomena produced by the sun inside the church of Saint Nectaire are the result of an extremely precise alignment of the masonry elements. The accuracy of the digital model as well as the precision of the illumination model were determining factors in order to ensure the precision and therefore the predictive validity of the digital heliodon. To this end, it has been essential to:

- ensure the geometrical accuracy of the building in all its parts, both in terms of the position and thickness of the masonry and the positioning of all its bays.
- ensure the accuracy of the sunlight model at the dates relevant to the scientific hypotheses put forward.
- calculate with an extreme accuracy the orientation of the building itself.

3.1. The geometrical accuracy of the building

The church of Saint Nectaire was the subject of an interior and exterior accurate survey by photogrammetry and laser scanner. The photogrammetry campaign was carried out with both aerial and ground shots. The laser survey, carried out with a FARO X130 laser scanner focus, allowed to capture - at the discretion of 51 stations, (28 indoor and 23 outdoor) a cloud of 165,404,000 3D points.

Most of the stations were captured in grayscale for time saving. This point cloud model guided the whole modeling process and was permanently used throughout the study as a geometrical reference for all the fine dimensioning or positioning of particular elements (windows, capitals...). The dimension of the site did not require the use of ground control points (GCP) as most of the 51 stations consolidation have been achieved by automatic correlation of geometric entities easily discriminable within the actual environment (walls, floors, masonry details...).
The photogrammetric surveys were used in addition to the laser survey, capturing not only the external geometry of the building using 3 UAV flight sessions (one with a 3DR SOLO equipped with a GoPRO 4 and two sessions with a DJI MAVIC 1 drone), but also thanks to several terrestrial pictures, in particular for the precise survey of each of the decorated capitals. The photogrammetric post-processing was performed using both MicMac and Photoscan software. This pipeline brought to life the detailed 3D models of the 25 major capitals of the church and to a complete and textured exterior model of the building which was superimposed and adjusted to the global point cloud produced by the laser scanner. Although a minimum 3D resolution of 1cm can be counted on most of the external building's constituent elements, the precision was refined at the bays - close to 0,15 mm for the geometrical accuracy of the solar projections on the interior surfaces - and at the level of the ornamented capitals, in order to make the sculpted figures perfectly recognizable and also to spatially discriminate the iconographic elements as accurately as possible.

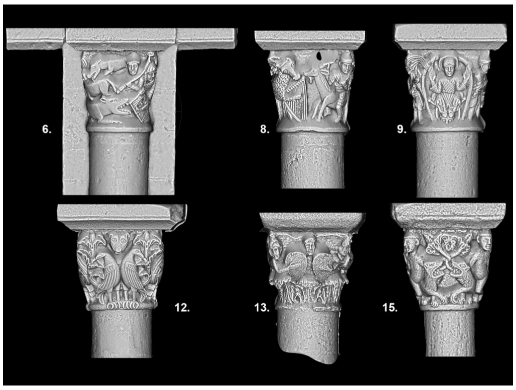

Figure 3: *Photogrammetric survey of the decorated capitals.*

NB: for clarity of reading, the elements of the 3D interior model have not been textured. The lapidary decorations are detailed enough in our opinion to be readable without adding color and the whole building has been modeled as a "white shaded model" in order not to overload the final rendering unnecessarily as it was intended to be used later in real-time desktop and VR applications.

3.2. Accuracy of the illumination model

To ensure the accuracy of the illumination model, the laboratory used open access information provided by CalTech's Jet Propulsion Laboratory, using databases provided by NASA [Cha]. It must be said that many solar models exist and are available online as detailed spreadsheets, standalone applications or as plug-ins for commercial 3D applications. However, most of them only roughly approximate the solar path and do not offer the accuracy expected and necessary for a simulation of this type. The data available on the NASA portal often serves as a reference for the work carried out by the Institut de Mécanique Céleste et de Calcul des Ephémérides (IMCCE) of Paris, whose valuable advices have accompanied our approach. It is thus possible to download the ephemeris of all the celestial bodies of the solar system (the sun and the planets, main asteroids, comets, planetary satellites and many space probes). The temporal validity of the solar model HORIZONS goes from March 20 -9998 00h00 to December 31 9999, 23h59. Targeted data extraction was discrimined within a single minute step from January 1st 00h00 to December 31st 23h59 over the totality of two distinct years, 1067 and 2012. The lines below illustrate some successive one step per minute database inputs for the positioning of the virtual sun on June 21:

2012-Jun-21 19:35 304.6268 0.0004
2012-Jun-21 19:36 304.8054 -0.1434
2012-Jun-21 19:37 304.9844 -0.2868
2012-Jun-21 19:38 305.1635 -0.4300
2012-Jun-21 19:39 305.3430 -0.5728

The data provided is a function of the subject's position in latitude, longitude and altitude relative to mean sea level (AMSL). Initial time-steps of 10 or 5 minutes were not enough to detect most of the transient light phenomena occurring in the church. So, a time-step of 1 minute (525,602 entries/bisextile year in the database) was finally implemented in the simulator to ensure the visibility of the most fleeting sunlight occurrences.

The phenomenon of horizon diffraction has also been taken into account: we thus consider that the hour of effective sunlight begins and ends at -4° elevation, which will make it possible to highlight a number of remarkable phenomena that would occur in reality during the first or last minutes of solar illumination. A further development could involve the implementation of a function able to interpolate the sun's position between two "minute-steps" in order to make the model even more accurate in terms of temporal predictability by reducing the granularity of the data provided by the NASA database to finally have a virtually continuous model of the sun's position.

3.3. Calculation of the orientation by topographic survey

In order to establish a perfectly predictable model, it has been necessary to orient the virtual model as precisely as possible. At the scale of the building, a deviation of 0.5° would correspond - at a distance of 38m (approximately the length of the church) - to an error of almost 33cm, which corresponds to more than a third of the dimension of one of the choir capitals: this could make invisible many phenomena that appear on site thanks to a solar virtual angular precision smaller than 0.1°, or on the contrary to produce false positives that would disturb the interpretation of the results. A topographical survey was carried out all around the site on the basis of 5 fiducial points taken close to the church. This made it possible to calculate the orientation of most of the walls around the perimeter of the building from which we oriented the virtual model. The median axis of the church - arbitrarily stopped between the center of the main portal and the center of the median window of the central absidiola of the choir - is thus equal to 98.6548765°, which corresponds to a deviation of 0.88802877° from the measured angle of the north wall, equivalent to 99.54290527°. This angular deviation between the north wall and the centerline of the church is not surprising, as most of the perimeter walls are not parallel to the direction chosen for the overall orientation of the model. The accuracy of the positioning was further refined by a systematic comparison between major solar conjunctions observed and documented on site and the corresponding effects produced on the virtual model.

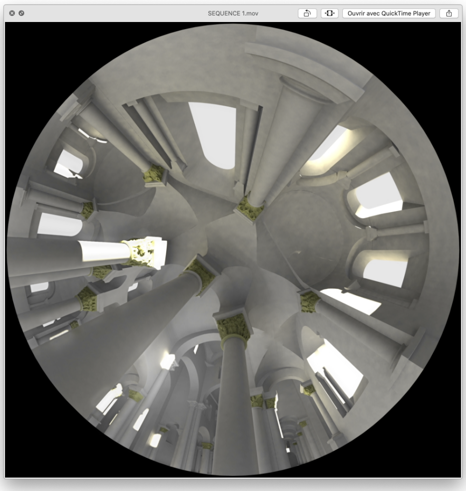

Figure 4: *The spherical display for the Vaulx en Velin planetarium dome.*

4. The digital simulation

In view of the large number of possible solar conjunctions, the solution of an immersive virtual scene has been chosen; it will thus be easy to experiment with all possible lighting configurations by freely interacting and walking through the model. With the help of a graphical interface accessible via keyboard keys or buttons permanently displayed on a 3D interface, the user can walk through the church and appreciate the effects of lighting on all or part of the church at any time of the year. To this end, the complete 3D model of the building - modeled under Autodesk Maya - and the ephemeris of the sun in 1067 and 2012 have been implemented in a standalone application developed in Unity, a multimedia programming interface usually used for interactive entertainment contents, such as video games, real-time simulations, scientific demonstrators... and possibly exported to MacOS or Windows platforms through desktop or Virtual Reality environments.

A custom C# script has been developed to provide a fast access to the database inputs and for an instant switching of the date events. The user interface allows to choose the month, day, hour and minute to visualize the effect produced by solar lighting on the elements of the decor: it is so possible to loop the loading of the sun ephemerides and thus display the scene autonomously all year long. As mentioned, it is also possible to switch the current year between 1067 and 2012 and finally to change "on the fly" the point of view between several pre-defined cameras set up around the model. On an exploratory basis, the laboratory has also experimented with a virtual reality interface (SteamVR/HTC Vive) in order to place the user in a virtual point of view (POV) experience. The interface accessible from the desktop version of the simulator can be manipulated in the virtual world with the control handles, thus making an autonomous and intuitive immersive experience possible. Other research of the laboratory are currently developing wide immersive scenes that can be visited "solo" or guided by a technical mediator present nearby. It is worth noting to what extent the exploitation of virtual reality tools can produce unexpected cognitive results or simply in terms of appropriation of space. Intuitively one might think that an immersive virtual visit does not presuppose any prior learning as we are only transposing the haptic modalities we use into reality.

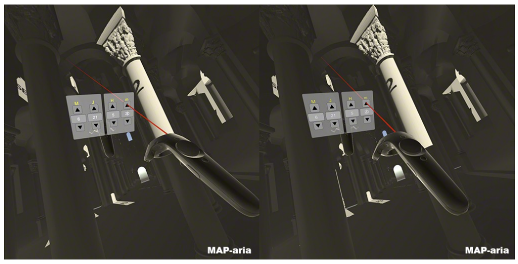

Figure 6: *The VR environment put to test.*

Some of our recent full-scale experiments conducted with audiences of all ages generally show a well-established predisposition towards younger audiences, which is not the case with older people for whom we have often had to set up "assistance" devices for dembulation by taking, for example, remote control of game controllers or even directing the entire walk-through experience. For "informed" users, however, it seems that the immersive experience almost transparently replaces reality and the experiences lived in immersion naturally enrich the user's existing cognitive background. Latest research scientifically demonstrates the advantages of an immersive simulation (compared to observing a computer screen, for example) in terms of quality of the cognitive experience and the impact on explicit memory in particular [KPV19] and [BWA*20].

An interesting proofing of the immersive modality took place under the dome of the Vaulx en Velin planetarium, where - on the occasion of the "Arta Sacra" festival in September 2019 - an open discussion took place in a collaborative context in the presence of architects, art and architecture historians and members of the scientific community related to the MAP laboratory. On this occasion, with a spherical projection of the virtual heliodon under the dome in the presence of 150 spectators - which would have been today

Figure 5: *Developed view of the choir.*

technically impossible in VR - the discussion gathered in an immersive, shared, on-demand and "close-up" modality, all the arguments put forward by the session presenters. Furthermore, the planetarium's projection tools made an unexpected contribution to the demonstration in that it was necessary to reroute the particle computing resources traditionally devoted to displaying galaxies and stellar clusters in order to project the point clouds resulting from the lasergrammetry campaigns under the dome. This was made possible thanks to a specific conversion tool developed for the occasion. On the other hand, all the textured immersive spherical representations were handled by the planetarium "raster" display pipelines, capable of cutting out and projecting a pre-calculated equirectangular image through the 6 video projectors distributed all around the dome.

We took for geographical reference of the church its current coordinates (WGS84 projection in decimal degrees), in the heart of the village of Saint Nectaire: Lat: 45.588223 - Lon: 02.9926595. Despite the use of highly accurate datasets, a further validation of the conformity of the model was carried out by comparing views from the simulator to 50+ real events documentated in 2012. It should be noted that the virtual model features openings without glass surfaces, which in reality produce a light diffraction effect on the targeted objects. The illuminated areas in the virtual model thus present a very sharp cutout of the light spot, contrasting significantly with the effect produced in reality but for almost all tested samples, the modeling and simulation of the light impact is consistent with the observations made in situ.

As an example, below are two side by side comparisons showing the correspondence of the simulated phenomena with reality. As mentioned, the model does not take into account the effect of light diffusion by the glass panes, nor the colors of 19th century stained glass, nor even the indirect reflection of ambient light. The "rendering" can therefore not be as subtle as the real views but the direction and impact of light on the digital model are fully consistent with the observations made in situ and seem to be a good indicator to appreciate the reliability of the simulation.

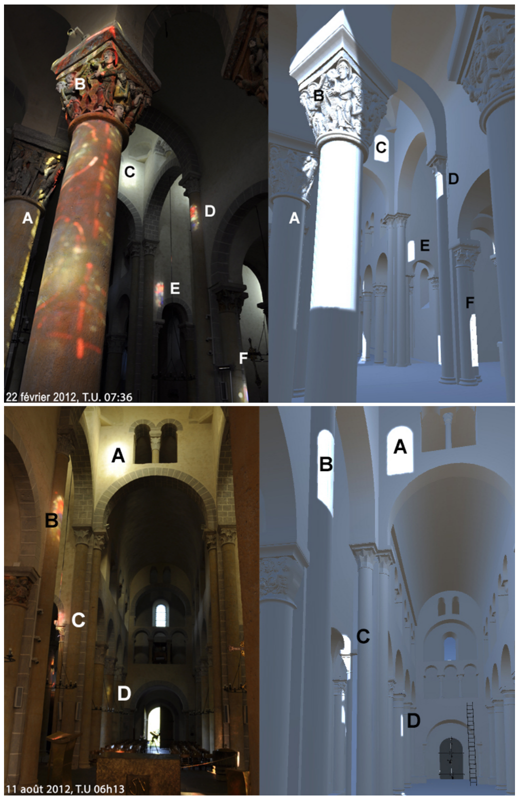

Figure 7: *Comparing reality with the 3D model.*

5. Exploitation of simulations

The average duration of illumination of a capital face mentioned here is quite short, of the order of 10 to 30 minutes and as seen, this duration is very directly proportional to the distance between the window and the subject. Given the significant increase in the num-

ber of capital faces illuminated in the absence of hills, it seemed important to question the part of chance in these illuminations and their presumed possible concordance between iconography and the calendar. If we consider only the 8 capitals of the sanctuary, we count 30 faces. In situ, 6 of these faces never light up. The simulation shows that 29 faces out of 30 would light up in the absence of the hills. Considering that the quality and precision of the sculpture of these eight capitals of the choir being in all points identical on each of their faces, the fact that the face representing the Passion does not light up might be an anomaly due to the missing windows on the western facade.
Because of the orientation of the last 11 faces that still do not light up, the hypothesis that needs to be worked on is to question the modifications that were made to the western façade, which was profoundly reworked in the 19th century. We thus found that 100% of the faces that could only be illuminated in the rising sun would be well lit in the absence of the surrounding hills, and that 86% of the historiated capitals (69 of the 80 faces) would be illuminated one day or another in the year 1067, taking into account the original state of the building as recorded by Bruyere in 1868: a lithograph by Baron Taylor dating from 1829 attests to this, but does not yet allow us to precisely reposition the original windows. A stone-by-stone survey of the building dated 1868 by the architect Louis-Clémentin Bruyère (responsible for the second restoration of the church of Saint-Nectaire as part of its protection as a Historic Monument) shows indeed a very large number of walled windows: it is thus possible that the two restoration campaigns carried out in 1854 (Mallay) and 1875-1877 (Bruyère) may have significantly modified the "solar behavior" of the building.

Figure 8: *Desktop implementation of the digital heliodon.*

6. Conclusion

The resulting model allows to simulate the occurrence of luminous phenomena produced by solar illumination on the interior and partly exterior architectural elements of the church of Saint Nectaire throughout the year. The tools and methods involved during this work make it possible to predict the luminous occurrences that would happen in the absence of "obliterating" phenomena, whether they are due to environmental imponderables (sunlight masking) or to the successive transformations of the building over its history. The heliodon 3D demonstrator also brings a lot of "unforeseen" information that could be used, by reciprocal effect (considering the day they light up) to identify characters or symbols not identified so far. In the same way, some capitals that are not illuminated because of the redesign of the building's façade could, in return, allow us to define the potential locations of former bays, leading to future possible physico-chemical surveys on precise parts of the current walls in order to verify the presence or not of anomalies in the composition of the substructure at these very locations. The fact remains that the observed or foreseen phenomena seem indeed to accompany with regularity the cycles of the liturgical calendar and opens up scientific horizons as yet unexplored.

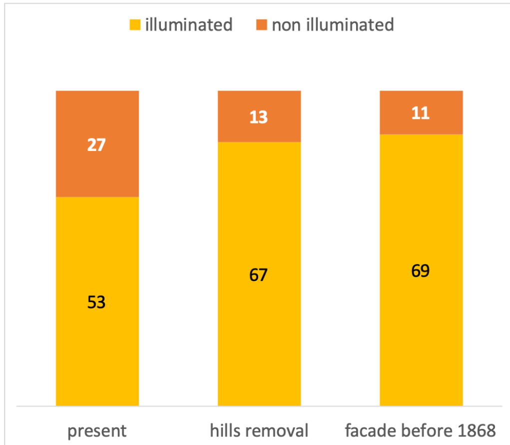

Figure 9: *Number of enlighted capitals faces throughout the research.*

7. Acknowledgements

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- The observations as well as the historical hypotheses cited in this article were written and recorded by Daniel Tardy in the book "Toute la lumière sur l'église romane de Saint Nectaire - Tome 1" published by BZT et Cie, cited in the bibliography.

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