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Evaluation of the use of symbolic solar lighting in Inca sacred sites: Ingapirca archaeological complex

José Ramón Leyva Guzmán1[1*], Flavio Ernesto Mejía Villacís[2], Vivian Jadith Pavón Guevara[3]
[123] Faculty of Architecture, Design, and Arts (FADA), Indoamerica Technological University, Ecuador

*Corresponding author E-mail: joseleyva@uti.edu.ec

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Abstract
The use of solar lighting in Inca sacred sites has been the subject of growing interest. The Ingapirca Archaeological Complex, recognized as a World Heritage Site, still presents interpretive challenges regarding its lighting design. This research evaluated how symbolic solar lighting influenced its architecture and what the combined contributions of the Cañari and Inca cultures were. An architectural and astronomical analysis of the complex was carried out using 2D drawing tools, 3D modeling, and solar simulations, focusing on key dates. The results were compared with historical sources and ethnographic studies. It was identified that the main structures of Ingapirca are aligned with the sunrise and sunset during the solstices, rather than the equinoxes, as previous studies had indicated. The solar illumination highlighted ceremonial elements, reinforcing their symbolic and spiritual significance. This evidence points to intentional architectural planning linked to the Cañari-Inca worldview. In conclusion, solar illumination at Ingapirca not only served a practical function, but also a ritual and symbolic one, demonstrating the integration of astronomy, architecture, and spirituality at the sacred sites of both cultures.

Keywords: Solar illumination, Ingapirca, Cañaris, Incas, Sacred sites

1. Introduction

Sacred Inca architecture constitutes a complex system of integration between astronomy, landscape, and the Andean worldview [1]. Various studies have shown that sites such as Machu Picchu [2], Coricancha, and Ollantaytambo are precisely aligned with key solar events (solstices and equinoxes), revealing sophisticated astronomical knowledge. These phenomena of symbolic solar illumination not only marked agricultural and ceremonial cycles, but also reinforced the political and religious power of the Tahuantinsuyo [3]. Today, disciplines such as archaeoastronomy use advanced technologies (LIDAR, 3D modeling, and solar simulation software) to decipher these patterns with greater precision [4].

However, many peripheral sites of the empire, especially in the northern region of present-day Ecuador, remain poorly studied from this perspective, despite their potential for understanding the expansion and adaptation of Inca principles in diverse territories. The Ingapirca Archaeological Complex, whose name in Quechua means "wall of the Inca," is located in the province of Cañar and emerged as a key administrative and ceremonial center during the Inca occupation in the 15th century. Archaeological research led by Idrovo [5] confirmed that the site integrated Cañari and Inca architectural elements, with the Temple of the Sun standing out for its peculiar orientation. Preliminary studies identified possible solar alignments during the solstices, but without delving into their ritual significance. In 2018, a team from the University of Cuenca [6] took measurements on site that suggested correlations between the temple's lighting and ceremonial dates on the Inca calendar, although these were not verified using modern digital tools. On the other hand, ethnohistorical analyses of colonial documents revealed that Ingapirca functioned as an ushnu (ceremonial platform), without fully clarifying the interaction between its architecture and solar cycles [3].

Figure 1. Panoramic image of the Ingapirca archaeological complex [6]

The study of symbolic solar illumination has provided insight into essential aspects of the Andean worldview [7]. At Ingapirca (Fig. 1), this approach has revealed links between architecture, astronomy, and power, enriching the appreciation of cultural heritage. It has not been precisely determined which structures were designed to interact with sunlight, on what dates, or in relation to which specific astronomical events. Nor has it been systematically explored whether these lighting effects responded to a complex calendar system or to Cañari cultural influences [8]. The hypothesis was proposed that: the geometric configuration and orientation of the Ingapirca Archaeological Complex reflected an architectural intent linked to the symbolic-ritual use of sunlight on specific ceremonial dates, such that the lighting effects associated with these events can be identified, verified, and reproduced through two-dimensional analysis, three-dimensional modeling, and contemporary digital solar simulations. This research analyzed the solar lighting patterns at Ingapirca using 2D diagrams and 3D modeling, focusing on the solstices and equinoxes.

2. Methodology

2.1. Theoretical framework and methodological approach

This research adopts a mixed (qualitative-quantitative) approach with a non-experimental descriptive-analytical design, based on a systematic review of the literature and comparative analysis of archaeological and textual evidence. The methodological justification lies in the need to integrate diverse empirical data (architectural, astronomical, and historical) to reconstruct cultural patterns associated with solar observation in pre-Columbian societies, specifically in the Ingapirca Archaeological Complex. The study is classified as exploratory-descriptive, given that it seeks to:

1. Systematize material and written evidence on solar alignments in Cañari and Inca contexts. The choice of this approach is based on the interdisciplinary nature of the subject matter, which requires combining techniques from archaeoastronomy, historical archaeology, and symbolic analysis to achieve a holistic interpretation [9].

2.2. Specific procedures and techniques

2.2.1. Population and Sample

Unit of analysis: Ingapirca Archaeological Complex (Ecuador), with emphasis on the "Castle" and associated structures.

Selection criteria: structures with verified astronomical orientation (e.g., Solar Temple); stratigraphic records showing Cañari and Inca interventions, and primary sources (colonial chronicles, excavation reports) documenting ritual uses.

2.2.2. Instruments and Tools

Systematic review: Academic databases (Scopus, Web of Science) with key terms: Andean archaeoastronomy, Ingapirca, Cañari worldview.

Material analysis: High-resolution photography, AutoCAD software, and SketchUp software to reconstruct solar alignments; solar azimuth and elevation data (3D SUN-PATH software) compared with architectural orientations, and solar data (NOAA Solar Calculator from the Global Monitoring Laboratory) on declination, sunrise, and sunset times.

Primary sources: Chronicles by Cabello de Balboa (1586) and Murúa (1613) on solar rituals, and reports from the INPC (National Institute of Cultural Heritage) on excavations from 1970 to 2020.

2.2.3. Collection and Analysis Procedure

Qualitative phase: thematic coding of historical texts to identify narratives of symbolic domination. Quantitative phase: measurement of architectural orientations with the general topographic survey in AutoCAD 2026 (.dwg) format provided by the Cañar canton [10] and more specifically of the monument and its surrounding areas with the help of 2D digitization of the image downloaded from the Military Geographic Institute [11] using AutoCAD 2026 (.dwg) software; and calculation of angular deviations from solstices and equinoxes using the NOAA Solar Calculator from the Global Monitoring Laboratory [12] and sunpath2d software [13].

Data integration: comparative matrices to cross-reference architectural, astronomical, and textual evidence, methodological triangulation to validate hypotheses about cultural overlaps, and three-dimensional verification model. Aerial photographs captured with a DJI Phantom 4 drone were used, taken from: Ministry of Culture and Heritage of Ecuador: Ingapirca – Terrestrial and aerial photogrammetry. Open Heritage 3D [14].

These images were used to generate a 3D mesh using GlobalMapper [15] and Pix4Dmapper [16], prioritizing the detail of the temple and applying the software's own georeferencing. The accuracy of the model was verified in Google Earth [17] and QGIS [18]. The model was then analyzed in 3D Sun Path [20] for an initial simulation of the sun's path. Due to the accuracy limitations of this platform, it was reprocessed in Revit 2025 [20], which allowed for a more accurate quantification of the annual solar incidence.

Finally, the georeferenced model was incorporated into Twinmotion [21], where digital simulations and representative renderings corresponding to the most relevant solar moments of the year were developed.

3. Results and discussion

3.1. Key results

3.1.1. Cultural stratigraphy

The Ingapirca Archaeological Complex shows an evolutionary construction process where the Cañari base, characterized by circular structures and elliptical platforms (Fig. 2) linked to their worldview [22], was architecturally reinterpreted by the Incas using stone masonry techniques and orthogonal spaces [23] [24]. This stratigraphic superimposition suggests a possible commemorative character, where the conservation of Cañari elements—particularly in the "Castle"—along with Inca interventions, would reflect a strategy of political legitimization through the symbolic appropriation of the pre-existing sacred landscape [22]. The astronomical layout of the solar temple, which integrates both building traditions, would reinforce this memorial function as a material trace of Inca domination over the Cañari territory [25] [26].

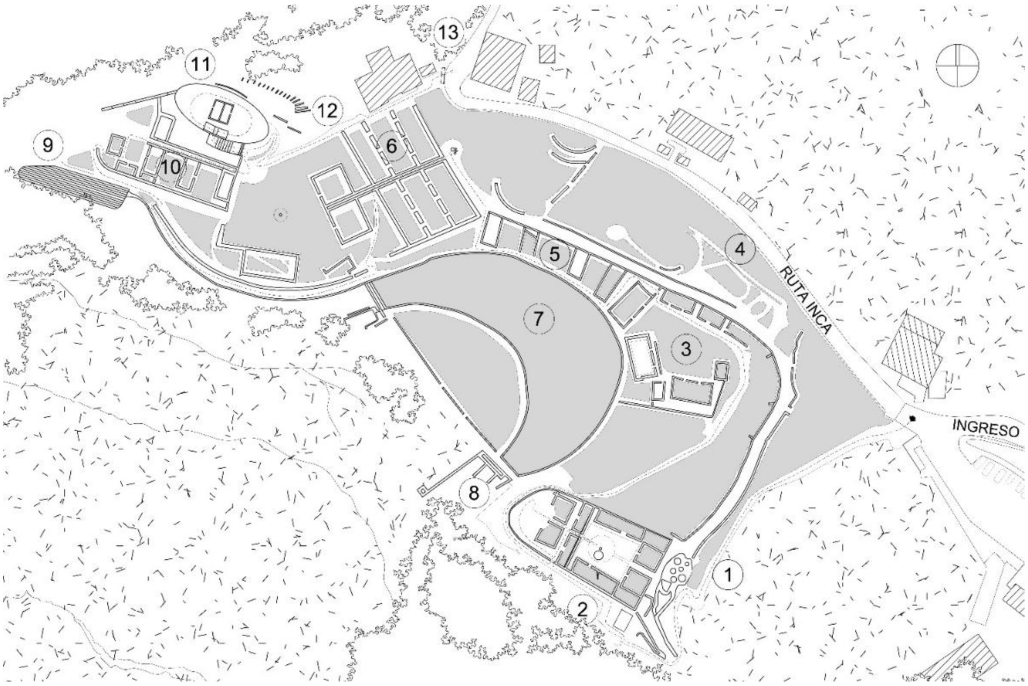

Figure 2. Current map of the Ingapirca archaeological complex

Legend: (1) Collcas; (2) Pilaloma - Collective Tomb; (3) Gran Cancha; (4) Cañari Archaeological Zone; (5) Warehouses; (6) La Condamine; (7) La Vaguada - Farm Terraces; (8) Ceremonial Baths; (9) Lintels and Ashlars; (10) Acllahuasi - Chambers; (11) Temple of the Sun; (12) Stairways and (13) End of the Tour. The "Castle or Temple of the Sun" (Fig. 3) features a Cañari foundation oriented toward the sunrise on the winter solstice, over which Inca architecture was later superimposed [9], [27], [28]. In contrast, La Condamine is oriented toward the sunrise on the summer solstice. This angular divergence of approximately 44° suggests a reinterpretation of the ceremonial axis in relation to solar cycles [29], [30].

3.1.2. Textual evidence

The chronicles describe Inti Raymi rituals in Ingapirca, linking the architecture to ceremonies of renewal of power [3]. The ceremonial nature of Ingapirca, related to the cult of the Sun, is described by many sources, evidenced by the orientation of its gates: one to the east (east) and one to the west (west). Based on the previous analysis, a comparative matrix was developed to examine the different areas that make up the Archaeological Complex. It identifies the cultures responsible for its construction, systematizes the architectural and astronomical evidence associated with each sector, and integrates references from documentary sources and historical chronicles. This approach allows for a comprehensive interpretation of the complex, considering both the material and symbolic contributions of the cultures involved (Table 1).

Table 1. Comparative matrix of architectural, astronomical, and textual evidence

Complex Area	Culture	Architectural Evidence	Texts or chronicles
(2) Pilaloma - Collective Tomb	Cañaris / Inca	The complex featured a type of dwelling known as a kancha, characterized by a trapezoidal floor plan with one of its short sides rounded and an approximate east-west orientation along its longitudinal axis. The	The complex had a dual function, both residential and ceremonial, as evidenced by a collective burial of a principal figure with ten companions and the presence of numerous nail heads, suggesting its sacred nature. It was hypothesized that it may have

Complex Area	Culture	Architectural Evidence	Texts or chronicles
		characteristics that Pilalom ly exhibits indicate that the current remains include adaptations made by Inca architects.	housed women dedicated to worship (acllas), and its cardinal orientation, together with the ritual findings, constituted strong indications that the ceremonial activities were associated with solar worship in the Inca state religion [9] [30].
(5) Bodegas and (7) La Vaguada - Cultivation Terraces		The sectors known as Las Bodegas and La Vaguada - Cultivation Terraces correspond to a functional architectural system located in the depression that connects La Condamine with Pilaloma, characterized by orthogonal enclosures defined mainly by stone foundations and simple masonry walls. The morphology and dimensions of Las Bodegas, together with its proximity to hydraulic infrastructures, allow it to be interpreted as a storage space linked to the logistical support of the complex [5], [27]. For its part, La Vaguada shows evidence of a systematic transformation of the land through agricultural terraces adapted to the natural slope, associated with canals and water control areas, revealing intensive production practices integrated into the general functioning of the settlement [31], [32].	Under the direction of resident archaeologist Antonio Fresco (1978-1982), a new set of walls ("La Vaguada y Bodegas") was discovered that architecturally connected the sectors of La Condamine and Pilaloma.
(6) La Condamine	More associated with the Cañaris	To the south of the archaeological site is a rectangular architectural complex, organized around a northeast-southwest axial corridor. The complex has a bipartite layout, consisting of four elongated rooms arranged in symmetrical pairs on either side of a central courtyard, a pattern that replicates the Inca kancha model, complemented by two quadrangular enclosures at the southwest end. Adjacent to this, in the depression known as "La Vaguada," a system of hydraulic and storage infrastructure (baths, canals, and warehouses) was identified, which was essential for the subsistence of the population settled in the complex [33].	Beneath the foundation levels of this building, 39 burials of both sexes were found, belonging to a Cañari cemetery prior to the Inca occupation of the site [33]. The function of this complex remains undetermined, with suggestions that it may have been a tambo [33] or, alternatively, an akllawasi [34]. The material evidence and typological parallels (e.g., Huánuco Pampa) suggest an administrative-residential function, possibly as an akllawasi (house of the chosen ones), a structure linked to the management of state labor and rituals.
(11) Temple of the Sun	Its base probably belongs to	The Castle is a stylistically very distinct complex, standing out as the area with the highest degree of	The site was described in the 16th century by chroniclers such as Pedro de Cieza de León, who recorded the

Complex Area	Culture	Architectural Evidence	Texts or chronicles
	the Cashaloma-Cañaris cultures. The upper part belongs to the Incas.	Inca influence in the architecture of the entire complex. It is recognized for its extraordinary Cuzco-style wall, which synthesizes this marked influence, and for its original architectural design. It is a pyramidal structure with an oblong oval floor plan. Its pyramidal appearance is particularly evident on the north side, where the difference in height is most noticeable and where there are up to three incomplete terraces below the general level of the platform on which the complex stands. Access to this platform is via the south side, where there is a double-jamb door that is currently accessed by a four-step staircase. Behind the door, there is a double staircase facing each other: one facing east and the other facing west, both with seven steps. This type of staircase embedded in the platform to which they give access is relatively common in Inca architecture. On the central platform, oriented east to west, stands the "Guard House," a square structure with two separate rooms. Each room has niches in its north and south walls and is accessed through doors in the east and west walls, flanked on the outside by niches similar in size to the openings. This architectural layout, together with the orientation of the complex, supports the interpretation of the complex as an *ushnu*, where the upper platform would have housed a temple to the Sun. This interpretation coincides with the early proposal by González Suárez, who identified these two unconnected rooms—one facing east and the other west—as a possible place of worship.	"great rooms" of Hatún Cañar, although without specifically mentioning the name Ingapirca. The first accurate documentation was made in 1736 by scientists from the French Geodesic Mission, Antonio de Ulloa and Jorge Juan. Despite a valuable technical description, their interpretation was erroneous, classifying the complex as a "fortress and palace." The academic Carlos María de La Condamine, a member of the same mission, published in Europe the most complete and detailed description of the time, accompanied by a very precise sketch. This plan included the "Castle" (tower) and its surrounding rooms. During the 19th and 20th centuries, the site was studied by prominent naturalists (Humboldt, Caldas) and researchers (González Suárez, Rivet, Jijón, and Caamaño), who documented its advanced state of deterioration. González Suárez noted the worshipful nature of the "Castle" building, due to the orientation of both chambers, one receiving the sun from the east and the other from the west [9]. According to studies by Dr. Mariusz Ziółkowski [35] of the University of Warsaw, conducted during the 1970s, which provided fundamental evidence, his conclusions determined that the constructions were directly linked to astronomical observation, identifying the complex as a center of solar worship, which reaffirmed its primary ceremonial function over any other hypothesis. According to recent research, the "El Templo" complex was not a military fortress, royal palace, or lodging, but rather a religious building, as determined by its shape, position, and structural details. Given the brief Inca occupation of a previous Cashaloma-Cañan settlement, it is likely that "El Castillo" is an Inca construction superimposed on a sacred indigenous site, the center of which would contain a pacarina or huaca. This, probably a prominent rock on the edge of the ravine that forms the core of El

Complex Area	Culture	Architectural Evidence	Texts or chronicles
			Castillo, remains hidden under the Inca structure, a hypothesis supported by the presence of a large rock field on the north side of the complex [9] [30].
(12) Stairways	Cañaris	A pre-Inca stone staircase (cañari) with 117 steps has been identified, which served as a utilitarian access route from the lower area to the ceremonial plaza, skirting the base of the Temple of the Sun. Due to its fragile state of preservation and the lack of systematic studies, it can only be observed from the top of the ravine.	There are no texts describing this area.

3.1.3. Analysis of solar alignments (two-dimensional)

A comprehensive and accurate survey of all the construction elements of the complex (Table 4) was carried out in order to corroborate the hypothesis put forward. This work was necessary because the existing literature agrees in attributing a ceremonial character to the site, although most of these sources maintain that the orientation of its walls corresponds to alignments associated with the equinoxes and solstices. Detailed analysis allowed these theoretical postulates to be contrasted with precise data obtained digitally, enabling rigorous verification of the orientations and the relationship between the architectural layout and possible astronomical phenomena linked to the original design of the complex. Using a high-precision aerial image, the perimeter of the Ingapirca Archaeological Complex was digitized in AutoCAD 2026 to perform a comprehensive survey of the azimuths of all its walls and main architectural elements, systematically measuring the orientation of each discernible wall and structure. Once processed, the data was tabulated to create a complete record of the absolute orientations, which was compared with a table of precalculated astronomical azimuths for the most relevant solar ephemerides—solstices and equinoxes—both at sunrise and sunset, in order to establish direct comparisons between the construction alignments and the main events of the solar trajectory (Table 3). The exact geographical location data of the Ingapirca Archaeological Complex was used, for which the specific solar diagram generated for its coordinates was used in order to accurately analyze the relationship of the structures with the solar trajectory at that particular location.

Table 2. Exact location of the Ingapirca archaeological complex

	Altitude (m.a.s.l.)	Latitude (° degrees)	Longitude (degrees)
Altitude and location	3,160 m above sea level	-2.5461° S	78.8758° W

Table 3. Azimuth of trajectories at sunrise and sunset for equinoxes and solstices.

Solar ephemeris	Date of the year	Time of day	Official time	Azimuth (° degrees)
Spring Equinox	March 21	Sunrise	06:19	90.0
		Sunset	5:55 p.m.	270.0
Summer solstice	June 21	Sunrise	06:18	66.56
		Sunset	6:17 p.m.	293.44
Autumnal equinox	September 22	Sunrise	05:34	90.0
		Sunset	5:41 p.m.	270.0
Winter Solstice	December 21	Sunrise	06:06	113.44
		Sunset	6:22 p.m.	246.56

Important: Azimuth is a unit of measurement in angles and is taken from north in a clockwise direction.

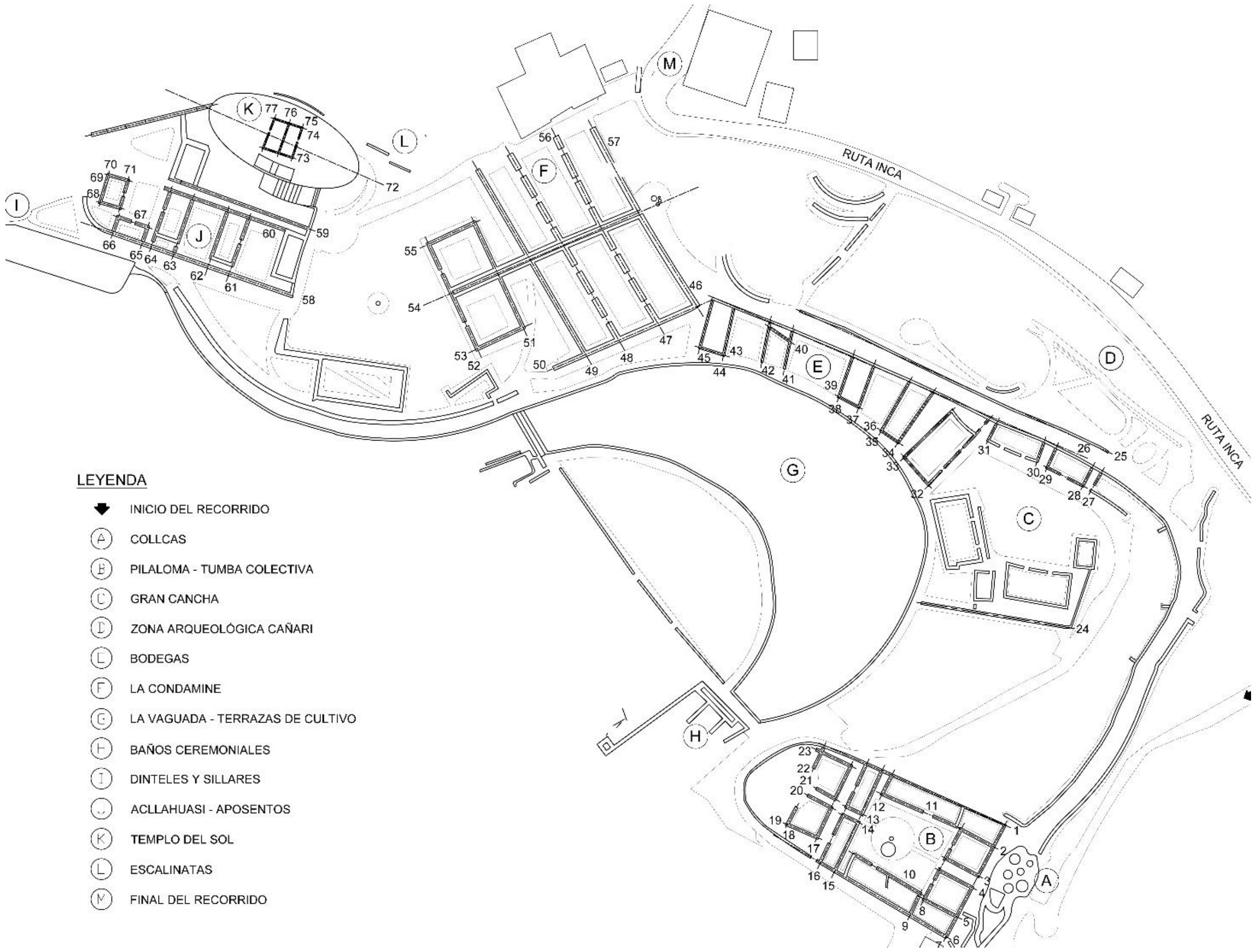

Figure 3. Map showing the survey of all azimuths of the walls or elements of the Ingapirca Archaeological Complex. Example (F) La Condamine (axis 54) and (K) Temple of the Sun (axis 72)

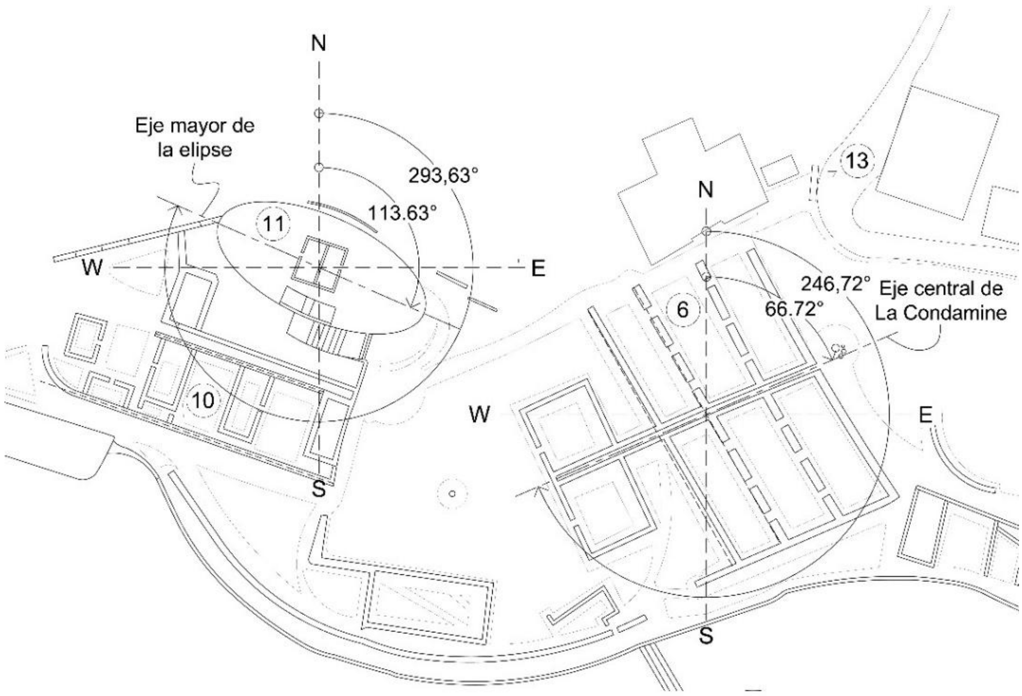

Figure 4. Map of the northwestern area of the Ingapirca Archaeological Complex with a description of how the azimuths of the walls or elements of the most representative buildings in the complex were surveyed.

To ensure that the orientation of the walls aligns with the sun's path on these significant dates, based on the location of the Archaeological Complex (Table 2), the geometry of the structure must be adjusted to several irregular angles according to solar astronomy (Table 3); for the summer solstice (June 21), the azimuth must be 66.56° for sunrise and 293.44° for sunset, while for the winter solstice (December 21), the azimuth for sunrise is 113.44° and 246.56° for sunset. For the equinoxes (march 21 and September 22), the azimuth angles would be 90° for sunrise and 270° for sunset on both dates.

Table 4. Selection of azimuths for representative structures and comparison with notable azimuth angles for solar astronomy according to time of year/day

Complex Area	Element	Azimuth of the structural element (° degrees)	Comparison with notable azimuths for solar astronomy
(B) Pilaloma - Collective Tomb	1	113.84	The azimuth is oriented toward the sunrise on the winter solstice and the sunset on the summer solstice.
	2	118.19	No matches.
	3	118.16°	No matches.
	4	117.60	No matches.
	5	118.07	No matches.
	6	120.52	No matches.
	7	27.77	There are no matches.
	8	27.88	No matches found.
	9	25.07	No matches.
	10	120.72	No matches.
	11	113.51	The azimuth is oriented toward the sunrise on the winter solstice and the sunset on the summer solstice.
	12	26.94	No matches.
	13	114.97	The azimuth is oriented approximately toward the sunrise on the winter solstice and the sunset on the summer solstice.
	14	115.26	No matches.
	15	25.22	No matches.
	16	25.18	No matches.
	17	25.18	No matches.
	18	28.19	No matches.
	19	113.34	The azimuth is oriented toward the sunrise on the winter solstice and the sunset on the summer solstice.
	20	117.77	No matches.
	21	119.36	No matches.
	22	25.49	No matches.
	23	115.53	No matches.
(C) Gran Cancha	24	99.45	No matches.
(E) Bodegas	25	114.59	The azimuth is oriented approximately toward the sunrise on the winter solstice and the sunset on the summer solstice.
	26	113.24	The azimuth is oriented toward the sunrise on the winter solstice and the sunset on the summer solstice.
	27	30.07	No matches.
	28	27.24	No matches.
	29	24.47	No matches.
	30	19.56	No matches.

Complex Area	Element	Azimuth of the structural element (° degrees)	Comparison with notable azimuths for solar astronomy
	31	26.62	No matches.
	32	42.50	No matches.
	33	45.64	No matches.
	34	34.87	No matches.
	35	29.75	No matches.
	36	124.32	No matches.
	37	19.92	No matches.
	38	19.02	No matches.
	39	117.47	No matches.
	40	124.80	No matches.
	41	11.92	No matches.
	42	11.47°	No matches found.
	43	107.55°	No matches.
	44	12.38	No matches.
	45	15.05	No matches.
(F) La Condamine	46	149.64	No matches.
	47	149.33	No matches.
	48	149.66	No matches.
	49	149.66	No matches.
	50	66.60	The azimuth is oriented toward the sunrise on the summer solstice and the sunset on the winter solstice.
	51	155.00	No matches.
	52	155.00	No matches.
	53	65.00	The azimuth is oriented approximately toward the sunrise on the summer solstice and the sunset on the winter solstice.
	54	66.72	The azimuth is oriented toward the sunrise on the summer solstice and the sunset on the winter solstice.
	55	65.00	The azimuth is oriented approximately toward the sunrise on the summer solstice and the sunset on the winter solstice.
	56	151.32	No matches.
	57	151.52	No matches.
(J) Acllahuasi - Chambers	58	109.21	No matches.
	59	109.98	No matches.
	60	109.11	No matches.
	61	19.85	No matches.
	62	19.29	No matches.
	63	19.21	No matches.
	64	19.21	No matches.
	65	19.19	No matches.
	66	19.21	No matches.
	67	109.19	No matches.
	68	105.76	No matches.
	69	105.76	No matches.
	70	16.36	No matches.
	71	16.36	No matches.

Complex Area	Element	Azimuth of the structural element (° degrees)	Comparison with notable azimuths for solar astronomy
(K) Temple of the Sun	72	113.63	The azimuth of the major axis of the ellipse is oriented toward the sunrise on the winter solstice and the sunset on the summer solstice.
	73	108.41	No matches.
	74	108.19	No matches.
	75	18.49	No matches.
	76	19.66	No matches found.
	77	20.99°	No matches.

The results obtained showed that a large number of the elements that make up the complex did not have significant orientations in relation to the solar cycle. However, it was confirmed that certain components did coincide with azimuths corresponding to the trajectories recorded in the solar ephemerides. This finding allowed us to refine previous interpretations of the astronomical nature of the site, indicating that, although there were solar references in the design, these were not a dominant criterion in the general orientation of the architecture, but rather selective and possibly associated with specific observation points or particular moments in the solar calendar.

3.1.4. Simulation of solar trajectories (three-dimensional)

To contrast and verify the results obtained above, three-dimensional modeling was used (Fig. 5). The process began with the collection of 1,260 aerial photographs, captured with a *DJI Phantom 4* drone. These images were extracted from the following source: Ministry of Culture and Heritage of Ecuador 2022: Ingapirca - Terrestrial photogrammetry, Aerial photogrammetry. Distributed by Open Heritage 3D [36].

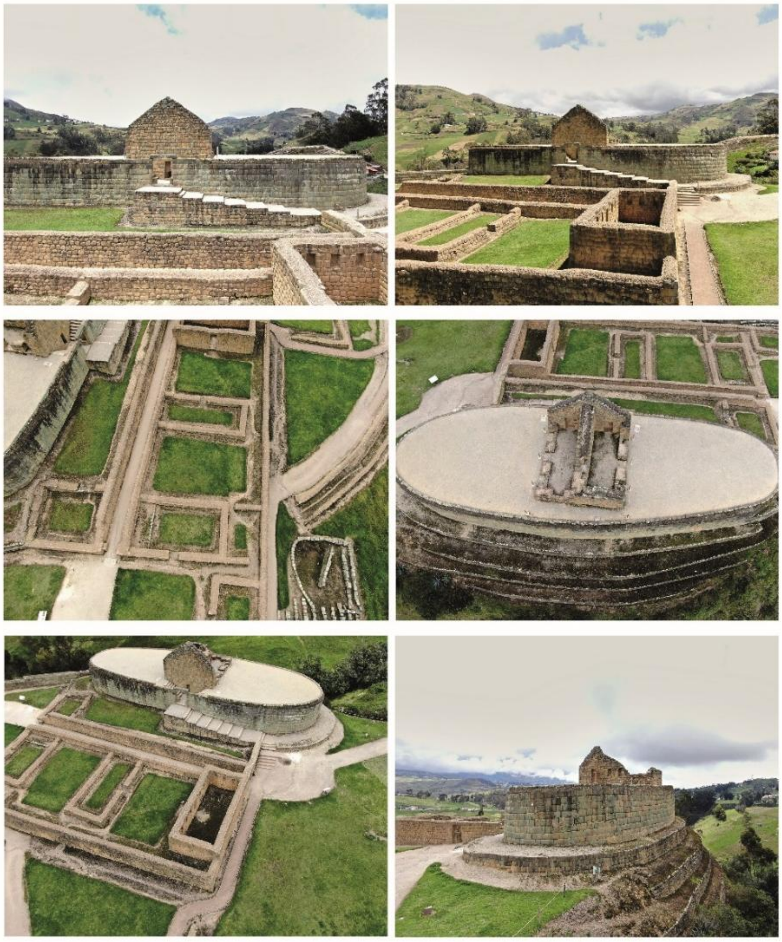

Figure 5. AGR_01_1234 Photograph of the main temple

Using this material, Pix4Dmapper software was used to perform the photogrammetry process with the aim of generating a three-dimensional *mesh* of the study site, with special emphasis on obtaining a higher level of detail in the area corresponding to the temple and the sites that show evidence of the use of solar trajectories (Fig. 6, 7 & 8).

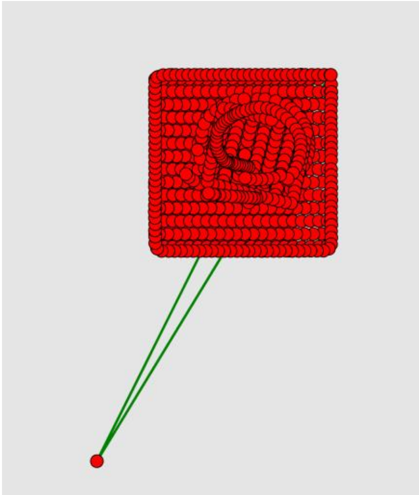

Figure 6. Drone route extracted from: Pix4D

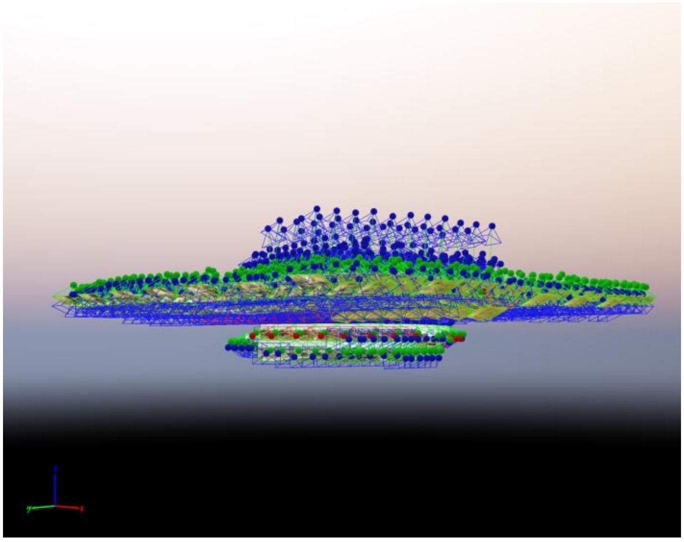

Figure 7. 3D mapping taken from: Pix4D

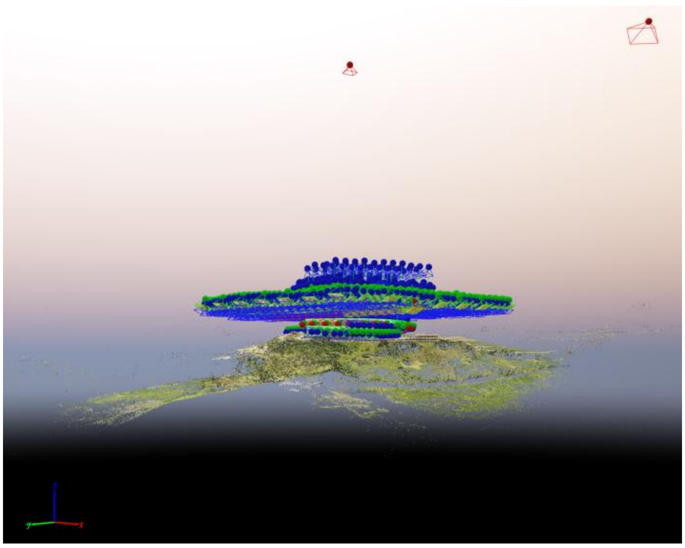

Figure 8. Tomas and point cloud generated. Taken from: Pix4d

Figure 9. Temple point cloud. Taken from: Pix4d

To ensure the correct spatial location of the model, the software's own georeferencing system was used, which allowed the 3D object to be accurately positioned within its actual territorial context. Subsequently, a verification phase was carried out using Google Earth and QGIS software, with the aim of checking both the geometric accuracy and geographical consistency of the generated model (Fig. 9).

Once the digital model was validated, it was incorporated into Andrew Marsh's sunpath3d platform [19]. In order to make an initial approximation of the solar path that directly affects the site. However, due to the quantitative and accuracy limitations of this platform, the model was then imported into Revit 2025, which allowed the effect of the sun's path at different times of the year to be established with metric accuracy.

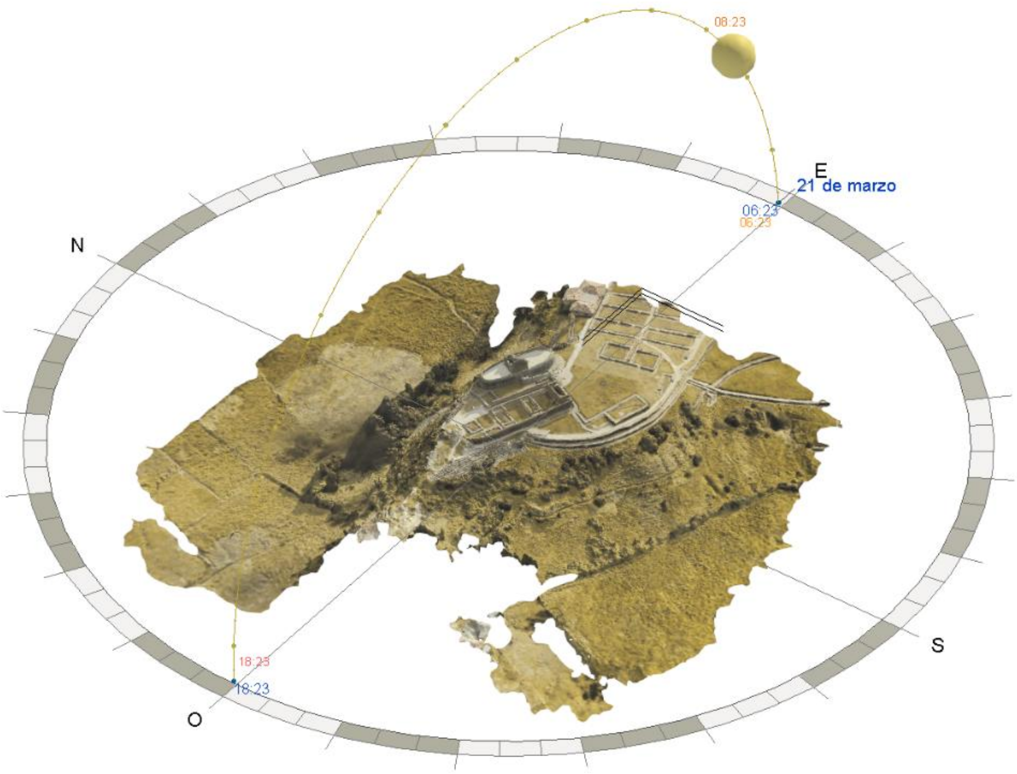

Figure 10. Ingapirca Dome. Taken from: Revit

Finally, the georeferenced model was imported into Twinmotion, where an advanced digital simulation of light and shadow behavior was performed (Fig. 10). This process made it possible to generate representative renderings corresponding to the most relevant times of the year, providing an accurate and understandable visualization of the solar impact on the site analyzed (Fig. 11, 12, 13 & 14).

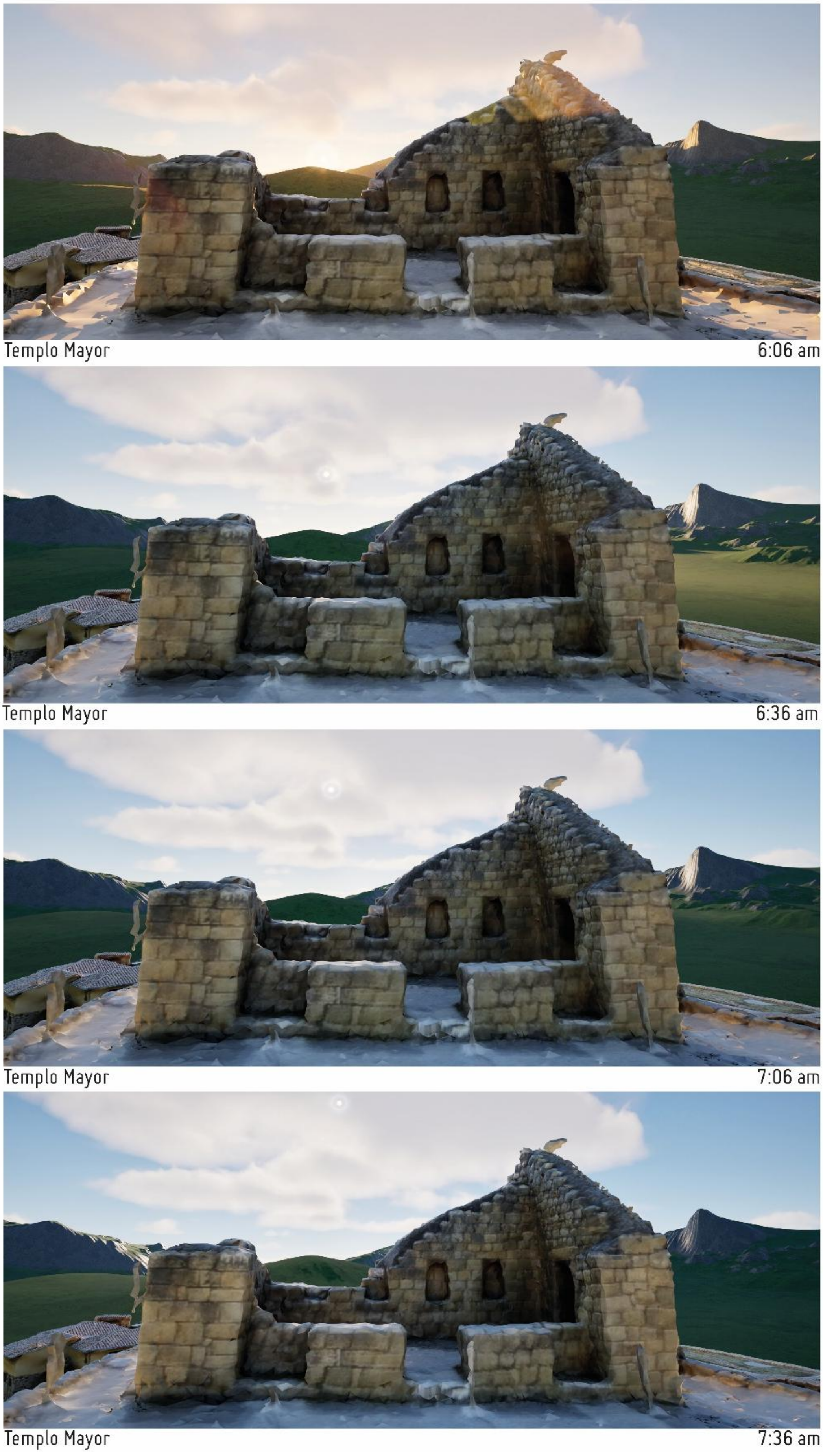

Figure 11. Simulation of the sun’s path at dawn on the winter solstice (December 21) at the Temple of the Sun

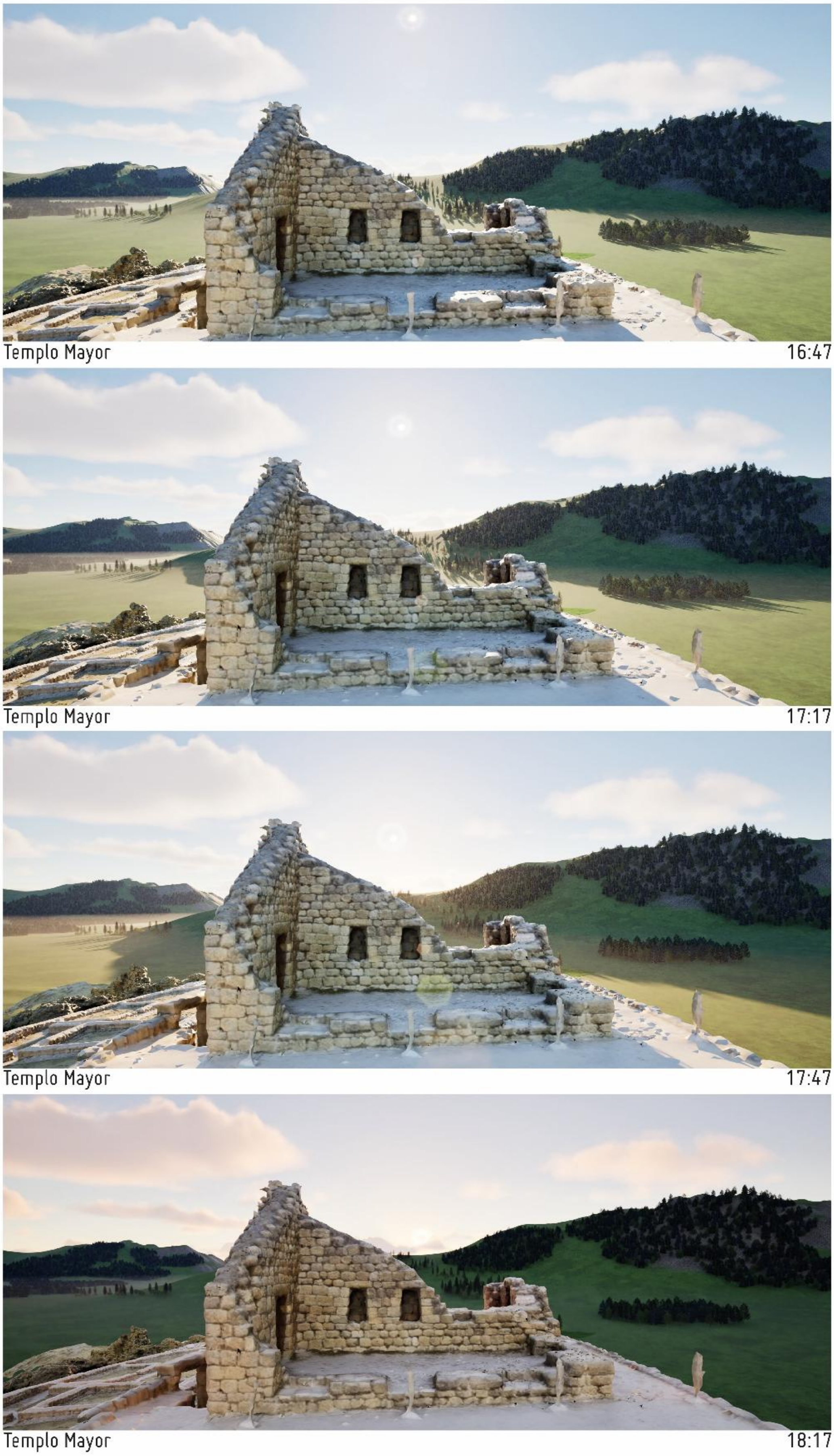

Figure 12. Simulation of the sun's path during sunset on the summer solstice (June 21) at the Temple of the Sun building

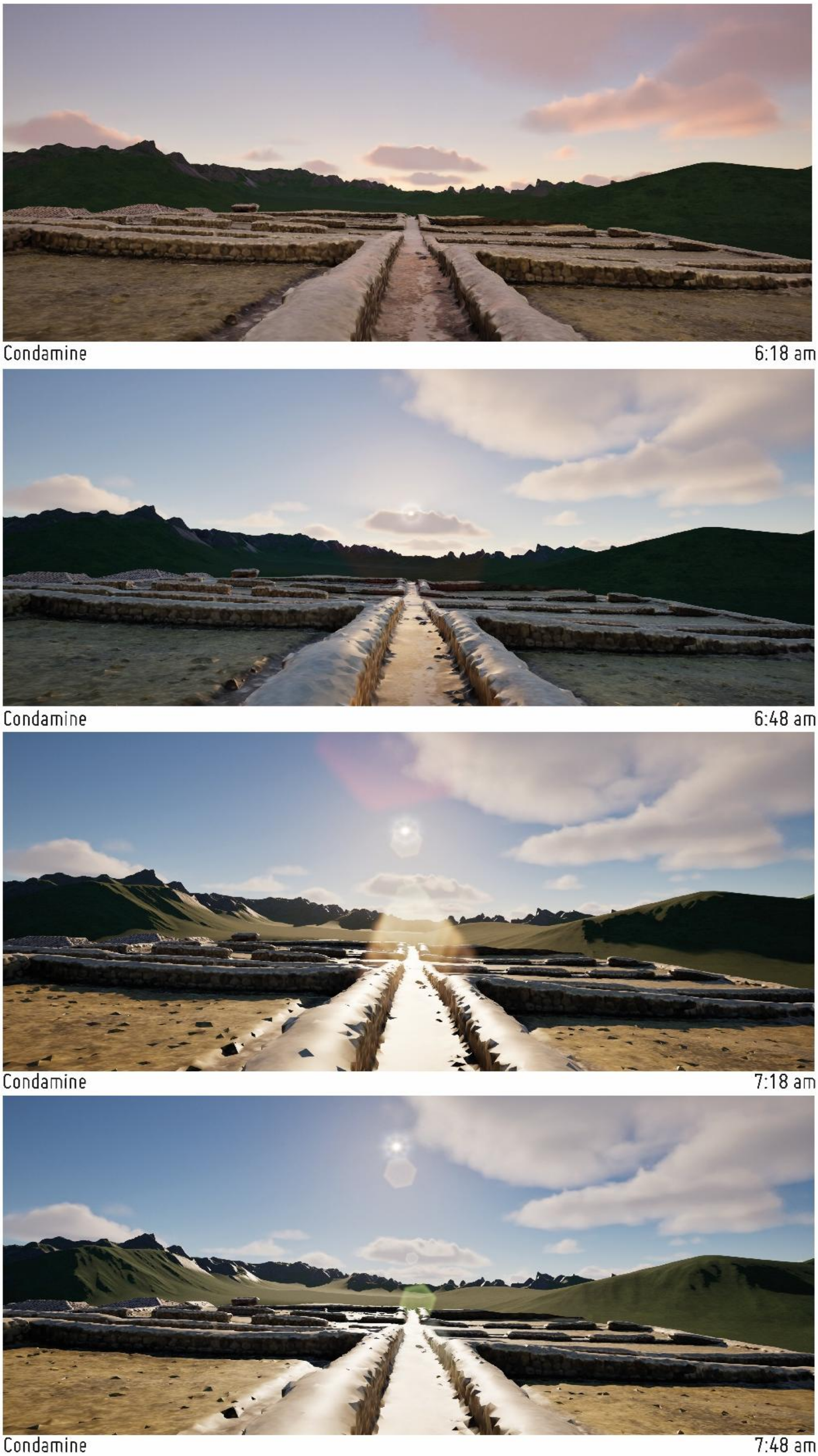

Figure 13. Simulation of the sun's path at dawn on the summer solstice (June 21) at the Temple of the Sun

Figure 14. Simulation of the sun's path during sunset on the winter solstice (December 21) at the Temple of the Sun building

3.2. Discussion

The castle (ellipse)

Through the analysis of various documentary sources, there is broad consensus that the Ingapirca Archaeological Complex is constructed in such a way that its structural elements are oriented to align with the solar trajectories of sunrise and sunset on the dates corresponding to the summer solstice (June 21) and winter solstice (December 21), as well as the spring and autumn equinoxes (March 21 and September 23) [6], [9], [10], [22], [32], [37], [38], [39].

In the "Report on Archaeoastronomical Research in the Central Area of Ingapirca" [35], Ziółkowski and Sadowski suggested that the building known as "El Castillo" (The Castle) would have connections with the equinoxes and solstices, based on the location and orientation of the various architectural elements that comprise it. In particular, they pointed out that certain structural angles corresponded to equinoctial events, especially in the areas known as the eastern and western Guard Corps. However, the results of this research indicate that, based on the orientation of the central axis of "El Castillo," it is highly unlikely that the structure was designed for observing the sunrise in the astronomical east (90° azimuth) or the sunset in the astronomical west (270° azimuth). This conclusion is based on geometric analysis and simulation of specific solar trajectories for the latitude of the site, which show no direct correspondence with these equinoctial positions and reveal significant errors in the azimuth angles presented in the study.

In conclusion, according to the study, both two-dimensionally and three-dimensionally, El Castillo or (Temple of the Sun) only complies with two of the azimuth angles, if the major axis (Axis 72) of the ellipse (Fig. 3) is considered as the intentional orientation in terms of its ceremonies, the orientation of the major axis coincides with the sunrise on the Winter Solstice (December 21) and with the sunset on the Summer Solstice (June 21), and does not comply with the rest of the angles whose orientation coincides with the equinoxes and with the sunrise on the Summer Solstice and the sunset on the Winter Solstice. It is unknown whether there was a solar observatory, although its orientation allowed the passage of the sun to be perceived at the times described above on both dates, but it is very unlikely that the rest of the solar trajectories could have been measured, or at least that is what the architecture of the building suggests. The referenced work (p. 109) points out a methodological limitation in Ziółkowski's work: the lack of precision surveying equipment made it impossible to determine the azimuthal orientation of the building elements with respect to true geographic north.

La Condamine

The central axis of the set of walls (Axis 54) known as La Condamine (Fig. 3) suggests, based on its azimuth, that they were also built taking solar astronomy into account. Its angle is 66.72°, which is close to the azimuth of the sun at sunrise on the summer solstice and sunset on the winter solstice, coinciding with an azimuth value of 246.72°. The other three walls (Axes 50, 53, and 55) also coincide with this orientation. The orientations of the rest of the walls in this part of the complex do not coincide with the notable values of solar astronomy.

Cellars

In the area known as Bodegas, two walls were identified, corresponding to axes 25 and 26, whose azimuths coincided with the angles of the sun's trajectory during sunrise on the winter solstice (December 21) and sunset on the summer solstice (June 21). This orientation was analogous to that of the major axis of the so-called Temple of the Sun. Such correspondence could have been the result of a coincidence or a practical decision intended to facilitate the layout of the wall during its construction. However, considering that the construction of El Castillo has been attributed to the Cañaris and that the sectors of La Condamine and Las Bodegas are associated with the Inca period, it was plausible to interpret that there was a deliberate intention to align the new constructions with the extreme solar positions, thus integrating both solstices into the same symbolic and spatial framework.

Analysis of the other elements that made up the constructions in the different areas of the complex showed that their azimuths did not coincide with the values corresponding to the solar trajectories. This lack of correlation suggested that the orientation of these structures did not respond to astronomical criteria, but possibly to topographical, functional, or construction factors. Consequently, it was inferred that, although certain sectors may have been planned considering specific solar references, most of the buildings in the complex did not have a direct relationship with astronomical phenomena, which reinforced the idea of heterogeneous architectural planning conditioned by various contextual variables.

The comparative analysis developed in this research demonstrated the methodological superiority of the approach applied over previous approaches of a predominantly descriptive or interpretative nature. The integration of aerial photogrammetry, geospatial validation, BIM modeling, and three-dimensional simulation of solar trajectories made it possible to obtain quantifiable, reproducible, and geometrically verifiable results, reducing the margin of subjectivity present in previous studies. Unlike methodologies based on in situ observations or isolated documentary inferences, the procedure implemented made it possible to systematically contrast architectural alignments with accurate astronomical data, adjusted to the latitude and topographical conditions of the site.

The findings obtained, particularly the identification of solstice correspondences and the absence of technical relationships with equinoctial events, confirm the ability of the integrated digital model to discriminate between plausible hypotheses and unverifiable assumptions. In this way, the methodology applied not only strengthened the internal validity of the research, but also established a replicable analytical framework that substantially improves the accuracy of archaeoastronomical studies in heritage architectural contexts.

4. Conclusions

The findings of the study show that the Ingapirca complex was configured using astronomical criteria that differed between the Cañari and Inca traditions, confirming its function as an active place of memory during the cultural transition. It was found that the La Condamine site features alignments associated with the solstices, suggesting that the Cañari culture had a precise understanding of the sun’s path. Likewise, it was determined that the Inca interventions, particularly in "El Castillo" or Temple of the Sun, responded to precise solar orientations linked to the solstices, ruling out interpretations based on purely formal impositions. The site can be classified as archaeoastronomical, although this condition is verified only in specific areas of the complex. In addition, the results refute the supposed direct relationship with the equinoxes maintained by historical literature.

The importance of these results lies in the fact that they provide quantitative and spatially verified evidence of the link between architecture and solar phenomena at Ingapirca, surpassing previous descriptive interpretations. The comprehensive approach, which combined cultural stratigraphy, textual sources, two-dimensional alignment analysis, and three-dimensional simulation, allowed for a more complete reading of the built landscape and its symbolic meaning.

Among the limitations is the dependence on digital models based on current terrain conditions and preserved structures, which opens up the need for future research that integrates hypothetical reconstructions, local horizon studies, and comparative analyses with other Andean sites.

The practical implications of the study relate to heritage conservation, museum interpretation, and the design of cultural tours based on verifiable solar phenomena. Methodologically, the digital workflow employed appears to be replicable.

In summary, the research establishes an innovative theoretical and methodological framework that provides evidence that Ingapirca constitutes a space for cultural interaction mediated by solar knowledge, thereby redefining its archaeoastronomical understanding.

Conflict of interest statement

The author declares that he has no known financial or non-financial interests that compete with any of the materials discussed in this document.

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Author contribution

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