

**Surveying a Sixteenth-Century Full-Scale Working Drawing.
The Tracing for the Sail Vault at the Vestry of Murcia Cathedral¹**

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Abstract

Full-scale tracings, drawn in plaster surfaces or engraved in stone walls and floors, were used frequently in Renaissance construction, in order to control the execution of ashlar masonry. In many occasions, these tracings furnished the shape of the templates used in the dressing process, either in true size or orthogonal projection.

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A large example of these tracings appeared in 2009 in the vestry of Murcia cathedral, when the sacristy drawers were disassembled in order to execute a conservation treatment against woodworm. At first sight, the tracing seemed to be related to the vault over the vestry, built in 1525 by Jacopo Torni l'Indaco, one of the first examples of ashlar sail vaults in Europe; a number of surveys confirmed that the tracing corresponds with the vault quite precisely. After an introductory section dealing with tracings and dressing techniques, the authors explain the measuring methods used in the surveys, describe the tracing, compare the tracing and the built vault, and discuss the relevance of the tracing for the history of dressing methods in European ashlar masonry.

Keywords: Renaissance construction, ashlar masonry, working drawings, stereotomy, full-scale tracings, surveying, sail vaults, templates, squaring, Jacopo Torni l'Indaco, Murcia cathedral

Full-scale tracings and dressing methods in Gothic and Renaissance ashlar masonry

Full-scale tracings were used frequently in Gothic architecture in order to control the execution of architectural elements. The earlier preserved examples represent ornamental elements such as bases, roses, gables or window traceries (Barnes 1972; Bucher 1977; Fergusson 1979). Documentary sources attest the use of large-scale tracings for complete vaults (Ruiz c. 1550, f. 46v; Zaragoza 2010, pp. 195, 208; Natividad 2010, p. 116) although none of them has been preserved, as far as we know.

This lack of surviving Gothic vault tracings seems to be justified by two different reasons. First, as Rabasa (2000, 96-121) has pointed out, the construction of Gothic vaults can be carried out using only a general tracing for the vault, including the axes of the ribs in plan and some schematic elevations. Detail drawings were unnecessary: springers were dressed using an overlay of independent templates, one for each rib,

while the keystones were carved with the help of a schematic tracing of the axes of the ribs in a surface of operation, usually the upper surface of the keystone (Willis 1842 [1910], p. 23-25; Rabasa 1996). It can be surmised that, for quadripartite vaults, masons could dispense with the general tracing, relying on the symmetry of the vault; by contrast, these full-size drawings were necessary when building the complex tierceron vaults of Late Gothic.

Second, vault tracings were executed frequently on planks laid on scaffoldings, as Rodrigo Gil de Hontañón attests (c. 1550, f. 25). Such tracings allow the mason to control the dressing of voussoirs and keystones, transferring the geometry of the vault to a block of stone by means of bevels and other instruments. Besides, these tracings were also used, according to Rodrigo Gil, to check the placement of the voussoirs, hanging plumb lines from the axes of the ribs and verifying that they fall over the corresponding line in the tracing or placing the struts for the keystones on the line intersections in the tracing, so that the vault is constructed literally over the tracing (Rabasa 2009). Placing such tracings in the church floor is impractical for a number of reasons: struts would be too long; the scaffolding makes the operation difficult; the precision of the plumb line decreases with the height of the vault; communication between an operator at the church floor and another one in the scaffolding is not easy. Thus, we can assume that executing these tracings on planks must have been the usual practice; of course, this explains the disappearance of full tracings for Gothic vaults.

By contrast, the tracings for ornamental elements were usually carried on in floors or walls, either on a plaster bed or directly on stone, using large rulers, compasses and ropes (Hernán Ruiz c. 1550, f. 13; Harvey 1968; Holton 2006; Zaragoza 2010; Natividad 2010). In many occasions, they were placed in secluded parts of buildings, such as tribunes, rooftops or spaces under staircases (Barnes 1972; Ruiz de la Rosa 2000; Ruiz de la Rosa 2002; Taín 2009). In England, dedicated rooms set aside for this purpose, known as tracing houses, have been preserved in the cathedrals in York and

Wells; there are also written references to the trasura in Westminster Palace (Hastings 1955, pp. 58-59; Harvey 1968; Shelby 1971; Colchester 1974; Holton 2006).

The Renaissance inherited many of these practices. Tracings at full scale were used frequently, up to the eighteenth century (La Rue 1728, p. 1; Mariás 1983-1986, vol. 4, p. 53; Bustamante 1994, p. 247, at the end of note 204; Freire 1998; Taín 1999; Taín 2003a; Taín 2003b; Calvo et al. 2005a). The tracing houses of the cathedrals of Seville and Santiago de Compostela have been found in the last decades; there are also documentary references to the ones at the Escorial or the cathedral of Granada (Gómez-Moreno 1963, p. 90; Pinto 1993; Taín 2002; Taín 2009; Bustamante 1994, p. 228, near the end of note 118). The manuscript of Alonso de Vandelvira (c. 1580, f. 23r, 23v) includes an updated version of Rodrigo Gil's technique for placement control: the mason must hang plumb lines from the voussoir corners, checking that they correspond precisely to line intersections in the tracing. A Baroque tracing placed under the triple staircase of the Monastery of Santo Domingo de Bonaval in Santiago de Compostela attests that such technique was used at the 17th century (Taín 2006).

However, classical architecture requires quite different methods of geometrical control. Simply put, the geometry of the Gothic vault stems from a linear basis, the network of the ribs; precise control of rib intersections is essential, but severe surfaces can be materialised loosely starting from the ribs. By contrast, Renaissance ashlar vaults require careful dressing of all voussoir surfaces, except the extrados, so that each piece fits closely with its neighbours. In the first decades of the sixteenth century this issue was new for Spanish masons, apprenticed in the Gothic tradition. Also, the Italian or Italianate artists working as first masters in some important construction sites of Southern Spain, such as the cathedrals of Murcia and Granada and the palace of Charles V in the Alhambra had no experience on this problem, since the use of ashlar masonry in vault construction is not usual in Central Italy.

Thus, in order to control the dressing of the voussoirs of ashlar vaults, French and Spanish Renaissance masons were forced to devise in a short lapse of time a number of innovative and efficient geometrical methods. These procedures can be grouped in two broad categories: dressing the voussoir starting from a block using orthogonal projections, or carving it directly with the help of true-size templates (Derand 1643, pp. 3, 5; Frézier 1737-1739, vol 2, pp. 11-15; Palacios 1990, p.18-20; Calvo 2003). When dressing by squaring, Renaissance masons started from a block of stone and used orthographic projections for each face of the voussoir, so that the faces of the starting block were coincident with horizontal and vertical planes in the final voussoir, either material or virtual. With the help of a square placed on each face, the mason could materialise planes or cylinders, inverting the projection process; the intersection of two planes or cylinders gave an edge of the voussoir. This is why the method is called "squaring", although the process can be carried on without using the square (Rabasa 2007, p. 32-37). In the most complex cases, a second carving stage was required to dress a ruled surface or a portion of a sphere passing through the edges of the voussoir (Frézier 1737-1739, vol. 2, p. 13).

According to Philibert de L'Orme (1567, f. 73v), this technique involves "a great loss of stone", since the volume of the starting block can be many times greater than the volume of the final voussoir. Aiming to reduce such waste, Renaissance masons used when possible an ingenious procedure: a face of the starting block was aligned with a plane passing through the corners of the intrados face of the voussoir, which usually is not horizontal; in this way, the block fits as closely as possible the final voussoir. In order to do so, Renaissance masons used true-shape rigid templates of the intrados and bed faces, obtained by rotation or triangulation, and flexible templates of the intrados faces, obtained by development of the intrados surface.

In particular, intrados templates for hemispherical and sail vaults were constructed by means of a sophisticated operation. Since a spherical surface is not

developable, masons inscribed a number of cones in the intrados surface of the vaults, one for each course, using bed joints as directrices, so that a particular cone passes through two consecutive bed joints, and each generatrix meets the upper and the lower bed joint of the course that corresponds with this cone. In such a layout, the vertical line passing through the centre of the sphere acts as the axis of all the cones, but the vertex of each cone is placed a different height. Masons prepared templates for the intrados surface of the vault starting from the tracing, by an economical procedure: they drew a generatrix in the cross-section of the vault passing through two consecutive bed joints; the vertex of the cone can be placed at the intersection of this generatrix with the vertical line passing through the centre of the sphere. Once this is done, a portion of the cone can be developed simply by drawing two arcs of a circle with the centre on the cone vertex, passing through consecutive bed joints. In order to obtain what we consider nowadays to be a correct development of a cone, the mason should calculate the length of the developed bed joint and place accurately the end generatrix of the template. However, such a computation involves the tricky problem of the rectification of the circumference; the main theorist of French Renaissance architecture, Philibert de L'Orme, does not mention this issue in his discussion of sail vaults, while the most representative writer in Spanish Renaissance stereotomy, Alonso de Vandelvira, eschews the issue completely, saying that "you will close these arcs at will, provided they pass through the cone vertex" (De L'Orme 1567, 111v-115v; Vandelvira c. 1580, ff. 60v-61r, 81v-82r; see also Guardia, c. 1600, ff. 69v, 84v; for evidences of the use of this method in practice, see Ruiz de la Rosa, 2002; Taín 2006; Alonso 2009).

Such easygoing attitude can be quite practical, since stone usually arrived from the quarry in blocks of different lengths; for example, the main dome in the Escorial is built in this way, probably because it was intended to be covered in stucco. By contrast, when the decoration of the vault is coordinated with the voussoir length, as in the Murcia vestry vault, Renaissance masons resorted to other procedures. Hernán Ruiz does not mention the cone development method; he uses another approximate method

to develop the sphere, in order to accommodate the decoration in the surface of a sail vault (Ruiz c. 1550, 46r). Vandelvira uses a similar method in one occasion, but when dealing with a quarter-of-sphere vault he also hints at the use of a *cerce*, that is, a ruler with a curved edge; the procedure can be extrapolated to hemispherical and sail vaults. (Vandelvira c. 1580, 68r, 116r-116v; see Calvo 2005a, pp. 88-89) In other occasions, masons seem to have used the squaring method for hemispherical vaults. Philibert de L'Orme employs it for surbased vaults (1567, f. 118), although he includes cone developments in the same drawing. This eclectic attitude is even clearer in a sheet of the manuscript of Alonso de Guardia (c. 1600, f. 69v), including two different diagrams for hemispherical vaults. One of them resembles Vandelvira's drawing for the cone development method, while the other features the typical rectangular enclosures of the squaring method; it is easy to surmise that the anti-economical squaring method was used only when there was a need to coordinate joints and decoration. We will come back to this issue when analysing the tracing at the vestry of Murcia cathedral.

The vault over the vestry of Murcia cathedral

The sacristy at Murcia cathedral is a square room placed at the first stage of a massive bell-tower. An inscription in the cornice of the vestry mentions "Anno Domini MCCCCXXV die XV Novembris". This date is coherent with archival documents and other evidence. Chapter records register payments for the tower from 1519 on, including the salary for Francisco Florentino, while a plaque on the North façade of the tower dates the start of construction in October 29th, 1521; this apparent contradiction can be solved if we accept that it was construction above ground what begun in this year. Thus, it is safe to surmise that the vestry was consecrated on November 15th, 1525, and the vault which spans the room was built along 1525 (Baquero 1902, pp. 29-36; González Simancas 1905-1907, vol. 2, pp. 85-94, 555-556; González Simancas

1911, pp. 519-521; Gutiérrez-Cortines 1987, pp. 112-129, 135-136; Vera 1993, pp. 14-19, 29-31, 106-107, 169-175; Calvo 2005, pp. 79-92).

Anyhow, the vault was not executed under the direction of Francisco Florentino, since he was dead in April 1522, when the chapter appointed Jacobo Florentino as first master of the cathedral. This artist was known in Italy as Jacopo Torni l'Indaco; he had been apprenticed as a painter in Ghirlandaio's workshop, worked with Pinturricchio in the Stanze Borgia and been called by Michelangelo to help him in the Sistine ceiling (Vasari 1568, vol. 1, part 2, pp. 524-525; Sricchia Santoro 1993; Tolnay 1945; Wallace 1987). Later on, he arrived in Spain in 1520 to work in the Royal Chapel at Granada Cathedral, where he was commissioned to paint a number of panels for the Santa Cruz altarpiece together with Pedro Machuca, the architect of the palace of Charles V. Although his training and his Italian activity seem restricted to painting, in the Royal Chapel he was also responsible for a stone Annunciation over the vestry door and a number of architectural decorations such as vestry drawers, an organ case and a wooden grille; maybe he designed also the sacristy doors and the choir stalls. Two years later, Torni was appointed first master in Murcia cathedral, acting also as master of the church of the Monastery of San Jerónimo in Granada from 1525. In any case, in Murcia he could do little more than build the first story of the tower, since he died in Villena in January 1526 (Velasco 1564, f. 8r.; Gómez Moreno 1925, pp. 68-73; Gómez Moreno 1926, pp. 100-108; Baquero 1902, pp. 32-36; Gutiérrez-Cortines 1987, pp. 61-66; Vera 1993: 155-163; Calvo 2005a, pp. 36-41; Calvo 2005b).

There is no direct information about the craftsmen that must have collaborated with Torni with the complexities of masonry construction in the tower and, in particular, in the sacristy vault. The most fitting candidate is Juan de Marquina, but there is little documentation about his activities in the years of the construction of the first stage of the tower. He had worked with Enrique Egas, an outstanding Gothic master, at the Royal Hospital at Santiago de Compostela around 1509 (Rosende 1999,

104-105). Later on, he worked at the Royal Chapel in Granada along with Francisco and Jacobo and many other masters. In 1521 he was living in Granada and signed a contract for the choir of the parish church at Moratalla with Francisco Florentino. Two years later he was living in Murcia, as the document for the acquisition of a slave attests; by the way, Torni bought another slave the same day. This has led a number of researchers to connect Marquina with the cathedral works in this period, although no actual document has arisen to prove this link; by the same years, from 1522 to 1528, he had a lease on the mountains near Nerpio and sold wood to the Archbishopric of Granada. At the early fifteen-thirties he was working in Granada, where he was in charge of the door decorations of the Imperial College, San Cecilio and, quite possibly, the ones at San Andrés and the College for Noble Girls; he also worked at the Royal Hospital. However, he fitted best in the role of foreman or *aparejador* and worked in such position at the Palace of Charles the V in Granada from 1533 to 1553. (Gómez-Moreno 1925, 283-284; Gutiérrez-Cortines 1987, 61, 95, 328-330, 356; Rubio Lapaz 1990).

The lower section of the vestry is dominated by a richly sculpted set of drawers in walnut wood, begun by Torni, continued by his successor at the post of first mason, Jerónimo Quijano and restored after a fire in 1689 by Gabriel Pérez de Mena; at the same time, the vault was repaired by Toribio Fernández de la Vega. (Baquero 1913, 47-53, 445-447; Gómez Piñol 1970; Vera 1993, 125-131). The sacristy is covered by an ashlar masonry vault resting on four wall arches. At first sight, the vault itself is divided in two sections. From the springing to the level of the wall arch keystones, four naked pendentives support the vault. A thick round garland connects the four keystones, decorated with vegetables resembling the contemporary work of Giovanni della Robbia, such as the ones in the Virgin with the Holy Child and Saint John and a garland with emblems at the Bargello, or the Lavabo at the vestry of Santa Maria Novella. The Murcia garland is not exactly circular and departs slightly from the wall arch keystones; maybe this trait can be the result of on-site retouching. Over the garland, the vault is

decorated with ribs and channels, similar to the ones at the Old Sacristy in San Lorenzo or the Pazzi Chapel; however, the space between the ribs is noticeably smaller, and the general effect reminds Bramantesque examples such as the presbytery of Santa Maria del Popolo in Rome or the tribunes at Santa Maria delle Grazie in Milan (Gutiérrez-Cortines 1987, 135-136; Vera 1993, p. 107; Calvo et al. 2005a, pp. 80-81).

The stonecutting work of the vault is executed with great care, making good use of the limestone from the Raiguero quarry, near Orihuela; a few decades later, when the areas of the Cartagena diocese belonging to the Crown of Aragon were segregated to form the bishopric of Orihuela, the chapter lost control of the Raiguero quarry and had to resort to lesser grade materials for other sections of the cathedral (Vera, 1993, p. 91; Vera 1997). In particular, the joints between voussoirs in the same course of the vestry vault are placed precisely either at the axes of the ribs or at the middle of the channels. This was not standard practice in 16th-century Spain; for example, in the hemispherical and quarter-of-sphere vaults at the crossing and presbytery of Santiago de Jumilla, built between 1538 and 1566, probably under the supervision of Quijano, the placing of such joints departs visibly from the axes of ribs and channels (Gutiérrez-Cortines 1987, p. 237-241; Calvo et al. 2008). This detail is connected with the issue of cone developments or alternative methods to dress the voussoirs; if the mason closes the intrados templates at his will, as suggested by Vandelvira, he cannot control the length of the voussoir to adjust it to the predefined spacing of the ribs.

The general shape of the vault poses another interesting issue. Gutiérrez-Cortines (1987, pp. 136) remarked the shallow height of the upper portion, considering it independently from the pendentives; although this description fits the decorative scheme of the vault, three years later Palacios (1990, p. 188-191; see also Vera 1993, pp. 106) included it in a section of his book on Spanish Renaissance stereotomy dealing with sail vaults. Thus, he implied that the entire intrados of the vault was defined by the

same spherical surface, cut by the four vertical planes of the walls. We will come back to this issue when dealing with our survey of the vault.

The tracings on the walls of the vestry

In the nineteen-eighties, if not before, Alfredo Vera (1985) noticed the presence of woodworm in the vestry drawers. A report from this period highlights the "alarming decay of what is probably the most important piece of furniture in the Murcia Region, of international interest ... woodworms have attacked not only the structure of the drawers set, which is completely perforated, but also the sculpted panels ... so it is necessary to disassemble the piece ... implementing a system for damp suppression in order to prevent the further development of woodworm".

It took no less than 25 years to execute Vera's proposal. He stressed again the woodworm attack in two further reports and in the ambitious and lavishly published Master Plan of the cathedral (Vera 1989; Vera 1991; Vera 1994, 317, 356). Around 2000, when the Spanish Ministry of Culture planned a restoration of the drawer set, the cathedral Dean remarked the presence of woodworm again. At this moment, the drawers were subject to a treatment against woodworm, without disassembling the set, and also the floor was treated to prevent damp; however, these measures proved to be ineffective.

Only in 2009 the disassembling proposed by Vera in 1985 took place, almost by chance. Early in that year, a project for a number of interventions in different points of the cathedral led Juan Antonio Molina Serrano, architect; Juan Carlos Molina Gaitán, building engineer, and José Antonio Sánchez Pravia, archaeologist, to notice again the alarming levels of dampness in the sacristy. The original project was modified in order to carry on, at long last, measures for damp contention on the vestry walls; this required, as Vera had foreseen in the eighties, to disassemble the drawers. Since this operation

demanded highly specialised supervision, the project team asked for the collaboration of José Antonio Buzes, at the central office of the Spanish Historical Heritage Institute at Madrid.

Two further projects have been necessary to solve the problem as carefully as the importance of the piece demands; the first one, involving the treatment against woodworm itself, was directed by Buzes in Autumn 2009 and Winter 2010, while the second one, outlined by Buzes, with site supervision by Laura Ceballos, for the reassembling of the drawer set, started in June 2010 and is still going on when we are writing this paper, in March 2011.

When the drawers were dismantled in 2009, a great number of objects were found behind the drawers, including many ceramic fragments, glass, wood, paper, photographs, frames of films, and even a Spanish fan, which are to be documented in a specific study. Also, and more significant for our purposes, a fair number of drawings in red chalk and incised tracings were visible in the four walls of the vestry. Both the East and West walls included a number of isolated lines and some small groups of concentric arcs and tangent circles. However, the North wall held by far the richest sets of incisions and drawings. At first sight, these marks could be classed in three categories. Many of the red chalk drawings seemed to be connected with the drawers, in particular with the Corinthian pilasters that articulate the whole composition. As for the incised drawings, on a first inspection most tracings in the North wall followed a radial pattern spanning the whole wall, around 7 m wide. This suggested from the start that these incisions could belong to a tracing for the vestry vault. However, taking into account the state of the wall, this could not be determined until the wall was cleaned in Summer 2009. In this moment, as a first measure, a rectified photograph was prepared; we will analyse it in the next section when discussing the surveys of the vault and the tracing.

Other incisions did not fit at first sight into a general pattern. Some of them may be drawn as placement marks for the drawers, in particular sets of horizontal and

vertical lines in the North and East wall; this issue is out of the scope of this article and may be treated in a separate study when the reassemblage of the drawers is completed, using 3D laser scanning of the drawers set. Other incisions may belong to working drawings that are lost for the most part and in consequence, are unrecognisable, while a number of incisions and drawings in red chalk seem to belong to simple masonic exercises in tracing, such as the sets of concentric arcs and tangent circles in the East and West walls. The same can be said about a flower-shaped composition in the North wall; quite probably, it was intended to practice the use of the compass, taking into account that the side of the hexagon equals the radius of the enclosing circumference, and thus, the whole circumference can be spanned with six arcs of the same radius as the circle. Such didactic tracings are common in Murcia cathedral, in particular in its Gothic sections (Pozo et al. 2009); thus, the roses beneath the sacristy drawers imply that this system of masonic instruction was well alive into the Renaissance.

Measuring the vault and the tracings

The vestry vault was surveyed by Miguel Ángel Alonso in 2002, with the help of a research grant from the Colegio de Arquitectos de Murcia; the results were included in a research report written the same year and published in a book on Renaissance vaults in Murcia cathedral in 2005 (Alonso 2002; Calvo 2005a). Although Alonso had used previously analytical photogrammetry for other vaults in Murcia cathedral, such as the one at the funerary chapel of Gil Rodríguez de Junterón (Alonso 2001), the survey of the vaults on the vestry area was carried on using a laser total station, in order to increase precision. During the temporary closure of the cathedral for an exhibition, a total of 1355 points were surveyed, including the corners of all voussoirs and the edges of the ribs.

This survey established clearly two important facts about the vault. First, from the constructive point of view, it is a sail vault, as Palacios and Vera had implied; that is,

the intrados of the vault, both in the naked pendentives and the ribbed upper section, is a portion of a hemisphere cut by four vertical planes coincident with the walls. A section by a vertical plane passing through the diagonal of sacristy area shows clearly the continuity between the pendentives and the upper section, broken only by the added garland. Of course, this statement does not invalidate Gutiérrez-Cortines description of the vault as formed by two different sections; although from the geometrical standpoint the vault is generated by a single main surface, from the formal point of view it is a surbased vault over pendentives.

The survey showed also the precision of the stonecutting, in particular in the upper section, over the garland. The first five courses over the garland are divided in twenty eight sections by the ribs. It is interesting to notice that the axes of the four ribs that reach the keystones of the wall arches do not pass through the axes of the keystones; rather, in these four ribs, the left edge of each rib passes through the symmetry plane of the keystone, with an error of 1,5 cm. In the first and third courses over the garland, the joints between the voussoirs in the same course are coincident with the axes of the ribs, while in the second and fourth courses the joints are placed at the middle of the channel. Taking into account that the width of the rib at the third course is 12 cm, this fact shows clearly the quality of the Raiguero stone and the stonecutting technique. The exception that proves the rule is given by the fifth course. Here the rib, 10 cm wide, is too narrow to be cut in half by the joint; the joint is placed inside the channel, not on the axis, but rather set 6 cm to the right of the axis of the channel, in order to break the continuity of the joints and prevent cracks in the masonry. Finally, the sixth course is again divided by joints at the middle of the channels; however, taking into account the lesser width of the voussoirs, the spacing of the joints equals twice the distance between the ribs, and each voussoir spans two half channels and a whole space between ribs.

When the tracings and drawings appeared in Spring 2009, a survey of the four walls of the room was prepared by AeroGraph Studio, under the supervision of Juan Carlos Molina Gaitán. Taking a number of points as fixed references, four photographs, one for each wall, were rectified in order to obtain a measured, true-shape orthographic projections of each wall. The marks in the walls were traced over these photographs in order to prepare a CAD file, including both the red chalk drawings and the incised tracings.

The team in charge of the conservation of the drawers and the archaeological supervision furnished a copy of these drawings to the Research Group on Stonecutting and Stereotomy in the Universidad Politécnica de Madrid, who had studied similar tracings in the funerary chapel of Gil Rodríguez de Junterón and surveyed the sacristy vault, in collaboration with researchers from the Universidad Politécnica de Cartagena. The CAD drawing for the North wall was overlaid upon the plan of the vault, at the same scale, taking the centre of the roundel at the vault keystone and the intersection of the radial lines in the drawing as references. This operation made clear a remarkable coincidence between the vault and the tracing. In particular it was evident that the radial lines in the main drawing, measuring about 7 m, represent the edges of the ribs in the upper portion of the vault, and the main group of concentric arcs represent the bed joints, both in the upper section and the pendentives. However, the distances between points in the tracing and the corresponding points on the built vault grew gradually from the centre of the vault, taken as a reference point, to the exterior, reaching a maximum of 6 cm.

Thus, it could not be discarded that this methodology was introducing some kind of systematic error. In order to measure as accurately as possible the tracing and the vault, we decided to carry on a survey of the tracing using a laser total station, taking also some additional measures of the vault with the same instruments. Other methods of measurement, such as multi-image photogrammetry and 3D laser scanning were

discarded for this purpose for different reasons. Multi-image photogrammetry, although a powerful and convenient instrument for the documentation of stereotomic pieces (Alonso 2010), was not precise enough. Typical errors for multi-image photogrammetry in pieces of these size stand in the range of 1-2 cm (Natividad 2010, pp. 42, 46). This precision can be sufficient for stereotomic members with medium-sized to broad joints, but the joints in the vestry vault are rather thin; besides, our aim was to measure the tracing and the vault with the greatest precision possible using available instruments, in order to gauge the precision of the stonework in Torní's period.

Laser scanning, on the other hand, can furnish precisions almost as high as a total station, but poses the problem of the granularity of the net of points. The laser scanner used by our group furnishes a matrix of 2990 by 679 points. If applied to the whole tracing, this would have led to a separation between points of around 5 mm. Of course, it is possible to scan the tracing by sections, preparing a number of point clouds and assembling them in post-process, but there are practical limits to this method. Besides, the small depth of the tracings, less than a millimetre, made quite difficult to represent them in the scanning; for example, the marks in the operating surface in a keystone in Santa Catalina church in Valencia were not detected by the scanner, although the scanning involved only the keystone, taken by means of four point clouds, and obviously the scanning distance was less than any practical distance in the Murcia tracing. As for the red chalk drawings, the situation is worse, since the scanner itself cannot detect them, and they must be rendered by a photograph associated with the scanner, which leads us again to the issues posed by rectified photographs.

For these reasons, the tracings and the drawings in the North wall were surveyed again by means of a laser total station, taking 1250 points. In order to achieve the greatest possible precision, one operator stood near the wall, projecting light along the surface of the wall, trying to make incised tracings more visible, while other operator managed the total station and a third one took 38 detail photographs with a 200 mm

telephoto lens on a full-frame camera mounted on a tripod, in order to use an optimal aperture of $f/8$ and prevent any kind of shake. This allowed us to locate a number of almost worn-out incised lines that were invisible in the rectified photograph. Later on, the points gathered with the total station, with errors in the range of 3 mm, were connected with the help of the detail photographs, drawing lines and arcs. In addition to this systematic survey of the tracing in the North wall, a number of key points in the vault were taken with the same total station, in order to verify the accuracy of the 2002 survey and prevent any significant error arising from differences in the calibration of the station used in 2002 and the state-of-the-art instrument used in 2010.

Confronting the vault and the tracings

As soon as the new drawing of the tracing was prepared, it was overlaid again on the plan of the vault. Now the maximum differences between points in the tracing and the actual vault were in the range of 2 cm; it was perfectly evident that the radial lines in the main drawing, measuring about 7 m, represent the edges of the ribs in the upper portion of the vault, while the main group of concentric arcs stand for the bed joints, both in the upper section and the pendentives. However, with increased precision in the pendentives area, it was clear that the three outer concentric arcs were not horizontal projections of bed joints, but rather a cross-section of the vault, taken by a vertical plane passing by the diagonal of the area covered by the vault. This approach is quite similar to the tracings for hemispherical and sail vaults in Vandelvira's and Guardia's manuscripts. It was usual to intermingle the plan and the cross-section, in order to reduce the number of lines included in stonecutting tracings; after all, these tracings, in particular when done in floors, were slow, tiresome and painful.

By contrast, the sets of nearly horizontal and vertical lines in the wall do not fit for the most part into the pattern of the vault plan and section, as we have said before, except a vertical line that passes through the centre of the vault plan; the rest of the

nearly horizontal and vertical lines seem to belong to a working drawing for the drawers, together with the red-chalk renderings of cornices and capitals. Anyhow, it is worthwhile to remark that all horizontal and vertical lines, including the one that passes through the centre of the vault plan, show slants to the right around $1,2^\circ$. This indicates that the wall and the tracings for the vault and quite possibly, for the drawers, have rotated after the tracings were made.

This fact is consistent with historical evidence. According to documents in the cathedral archive, work in the tower seems to have slackened around 1529; this may be caused by the slant of the tower, which is quite noticeable today. Later on, in 1545, the chapter decided that "taking into account the present state of events, work on the cathedral tower was to be stopped until the chapter determines otherwise"; according to Gutiérrez-Cortines (1987, p. 129-130), the events quoted are connected with the security of the tower. Also, the slope of the cornice at the level of the vault s was measured in 2002 by Miguel Ángel Alonso, obtaining a slope of $1,65^\circ$ for the cornice plan (Calvo 2005a, p. 179) and $1,31^\circ$ for the cornice on the north wall. This indicates that the tracing was made before 1545 and thus gives additional evidence that the tracing is a working drawing for the vault.

The correlation of plan and section poses another interesting issue. In such a vault, the cross-section is divided previously in courses of equal width; then, these divisions are brought to the plan; as a result, the projected widths of the courses are different, with the first courses being apparently - but only apparently - narrower. If this procedure is not followed and the courses are evenly spaced in plan, the spatial result in space is quite messy, as the last-minute corrections made by Philibert when tracing a spiral vault make clear (L'Orme 1567, ff. 119r - 119v; see also Rabasa 2003). In contrast, the layout and spacing of the horizontal projections in the Murcia vault is impeccable. Thus, Torni or the masons involved with the Murcia vault must have used a method to transfer the divisions from the cross-section to the plan. At first sight, it is

not easy to say if they used reference lines, as any student of Descriptive Geometry would have proposed immediately twenty years ago. Reference lines are absent in Roriczer's (1486, 1490 c.) booklets; rather than using them, he instructs the reader to draw the vertical axis of the elevation of a pinnacle, construct a number of perpendiculars to this vertical axis, which are of course horizontal, and transfer the dimensions of the different elements of the pinnacle from the plan to the elevation using the horizontals placed at each level. Such a startling procedure bears the mark of stonemasons' real size tracings; in such constructions, tracing a perpendicular using a square is simpler and more accurate than a parallel; this explains the use of the perpendicular as auxiliary construction or *juzgo* (Martínez de Aranda c. 1600, pl. 16-17; Calvo 2000, vol. 1, pp. 148-153; vol 2, pp. 76-82).

In any case, reference lines were known in the mid-sixteenth century in masonic circles, as the manuscript by Hernán Ruiz (c. 1550, ff. 28r-29r, 46v-47v; see also Dürer, 1525) makes clear. In spite of careful inspection, we have been unable to locate any reference line, such as the ones used by Ruiz, Vandelvira, or nineteenth-century Descriptive Geometry treatises, in the Murcia tracing; line v1 may be taken as a reference line, but it misses point S7 by about 1 cm, and belongs probably to the drawers tracing. Thus, we have been led to deduct the direction of the transfers from elevation to plan, either by reference lines or by transfer of measurements, indirectly. Reference lines connecting the division points in the sections, either direct or implied, must be tangent to the circular bed joints in plan; this has allowed us to reconstruct them, taking into account that the enclosing arc for a right angle is a semicircle. Thus, we have joined each division point in the cross-section with the centre of the projected bed joints, drawn a semicircle from the midpoints of each of these lines, and marked the intersections of each of these semicircles with the horizontal projection of the corresponding bed joint. This operation requires some amount of trial and error, since matching each bed joint in the cross-section with its horizontal projection is not automatic, in particular in areas with many bed joints. Anyhow, seven points have been

placed by this method; they are fairly aligned along line h0, with errors less than 2 cm. Although the line joining these points is not horizontal, it is fairly parallel to the actual bed joints in the wall that supports the tracing, which present a slope of $1,36^\circ$. Such line has left only the slightest traces: there are short lines, parallel to the bed joints, at this height, near the vault centre. However, the portion of this line at the right of the vault centre, where it was most necessary, lies below the floor, that was levelled after the tower had slanted and thus is not parallel neither to the wall courses nor to the horizontal lines in the tracing.

Anyhow, if there are no reference lines in the tracing, how did the Murcia masons manage to transfer the positions of the bed joints from section to plan? There are a number of possibilities. The simplest and most likely is to use a plumb line to transfer points S1 to S7 to line h0, determining points P1 to P7 and constructing the horizontal projection of the bed joints from these points; all this, of course, providing that the slant of the tower had not shown when the tracing was made. In this case, reference lines are materialised by plumb lines, rather than actual incisions in the tracing; this hints that masons could conceive the idea of the reference line from plumb lines used to draw verticals in wall tracings. Alternatively, the masons could have used the trusquin mentioned by Viollet-le-Duc, an instrument akin to a carpenter's marking gauge, resting on a vertical line such as v0 or v1, to transfer measures to h0.

However, this operation is cumbersome, since line h0 must have been very close to the original floor. Another possibility is to transfer distances to v0 to a more practical line such as h1 or h2, reusing the drawers tracing, either by means of the plumb line or the trusquin. Of course the intersections of plumb lines p1, p2, etc. with h1 or h2 are not placed over the projections of bed joints; however, it is quite simple to measure the radii of the projected joints along h1 or h2, or any other horizontal line, and trace circles with center at C and the radii measured along any convenient horizontal line.

In any case, it is easy to understand why the portion of the vault represented in the tracing is only approximately the fourth part of the whole plan. Both the Murcia tracing and Vandelvira's or Guardia's schemes include a full cross-section of the sail vault. Since the spherical intrados surface must pass through opposite corners of the room, the diameter of the cross-section equals the diagonal of the area covered by the vault. Both Vandelvira and Guardia place the plan in the sheets of their manuscripts so that the sides of the room are parallel to the edges of the paper. By contrast, in the Murcia tracing the sides of the room are not represented, but a full representation of all courses, both in the pendentives and the upper section, spans all the room from right to left, while the perpendicular to the implied reference lines, that is, the line where the width of the courses should be measured, is approximately horizontal. This suggests the Murcia masons used a diagonal of the area to measure the width of the projected courses, placing it as a horizontal line to take measurements at ease; the method reminds the one used by Philibert de L'Orme (1567, f. 108v) for his tierceron vault. Of course, it is impossible to fit the whole diagonal of the room at full scale in one of its sides; thus, the masons represented no more than the fourth part of the vault, reusing easily all voussoirs, taking into account the geometry of the piece.

Another detail shows the care placed on the dressing process and the empirical geometrical knowledge of the Murcia masters. In a number of channels there are semicircles whose radius equals the width of the channel at each bed joint, which of course decreases as the courses approach the main keystone. Quite probably, these circles are meant to furnish the shape of a cerce or one-sided template which was in turn used to control the dressing of the channel surface. Probably a present-day architect or engineer would consider at a first moment obtaining the projection of the channel section at each course, which is an ellipse. However, such shape was difficult to construct in the early sixteenth century and useless in the dressing process, since references to horizontal planes are lost in the finished or almost-finished voussoir. Instead, the masons constructed a section of the voussoir by the bed joint, which is a

circle and is much more useful in the dressing process. To put it in Descriptive Geometry terms, they performed a rotation of the section of the channel in order to bring them to a horizontal plane. Of course, masons did not know Descriptive Geometry in the present-day sense of the word. Things rather went the other way round; the empirical knowledge of master masons has been historically one of the main roots of Descriptive Geometry, as Taton (1954) and Sakarovitch (1992a; 1992b; 1997) have pointed out.

Also lacking in the Murcia tracing, even after careful inspection, are the templates constructed by means of cone developments in Seville rooftops, the drawings at Segovia cathedral or De L'Orme, Vandelvira and Guardia's schemes. They should be placed, at least, at the upper right part of the tracing, but the isolated lines on this portion of the tracing do not fit the expected direction of the cone developments. Of course, such lines may have disappeared, or the Murcia masons may have used another method of surface development. But all this leads us again to the issue of dressing methods and their evolution in the first stages of the Spanish Renaissance, that will be the focus of the next section.

Early Renaissance stonecutting methods in Spain

The tracing for the sail vault at Murcia vestry provides an remarkable opportunity to advance our knowledge of Early Renaissance stereotomy, for a number of reasons. First, it predates the earliest Renaissance stonecutting literature in Europe, the manuscript of Hernán Ruiz (1550 c.) and the one attributed to Pedro de Albiz (1550 c.); thus, it casts light over a dark age in the evolution of stereotomic technique, between the first stages in the adaptation of Mediaeval stonecutting lore to the needs of Renaissance architecture and the appearance of the first written accounts of classical stereotomy.

Besides, the tracing is quite large and reasonably well preserved and fits precisely an important masonry piece, which is it for itself quite significant in the introduction of Renaissance building technique in Spain. The small differences between the vault and the tracing can be accepted as fairly tight construction tolerances, even by present-day standards. Thus, it is quite clear that the tracing is not a preliminary step in the design process, as the drawings for the dome in Segovia cathedral (Alonso 2009), but rather the actual working drawing for the vestry vault.

Taking into account all these reasons, the comparison between the tracing and the vault furnishes quite valuable information about the evolution of stereotomic methods in the Renaissance. For example, the tracing suggests that reference lines were not used in full-scale stereotomic drawings of the period in Spain. As we have seen, reference lines are absent in Roriczer's schemes, but are used by Dürer (1525) here and there, in particular when constructing a half-ellipse through orthogonal affinity and when preparing a double orthogonal projection of a cube in order to draw a shadowed perspective. Quite remarkably, Dürer mentions stonemasons in both occasions; this hints strongly that the use of reference lines originated in masonic circles, and spread through Germany around the period between 1486 and 1525. As far as we can tell from the available evidence, the introduction of reference lines in Spanish stonecutting was somewhat slower: neither the tracing for the vestry vault, nor the tracings for the chapel of Junterón nor the one for a dome in the rooftops of Seville cathedral (Calvo et al. 2005a 137-170; Ruiz de la Rosa 2002) include visible reference lines. By contrast, reference lines are quite conspicuous in the manuscripts of Hernán Ruiz and Pedro de Albiz, and also in a drawing for the appraisal of a vault in Priego de Cuenca, connected to the circle of Albiz and Francisco de Luna, Andrés de Vandelvira's father-in-law (Albiz c.1550, f. 6r, 9r, 11r, etc.; Ruiz c. 1550, 28r-29r, 47r-47v; Rokiski 1980; Rabasa 1996).

As we have seen, the tracing at the vestry does not include cone developments, at least in the preserved portion; neither does the tracing in Junterón's chapel, nor Hernán Ruiz's manuscript. By contrast, cone developments are present in the tracing at the rooftops of Seville cathedral, constructed by Vandelvira's method and even going further: the template ends, that Vandelvira placed at masons' will, are simply lacking. The absence of cone developments in the Murcia tracings suggests that the masons in charge of these pieces dressed the voussoirs for the sail vault at the vestry and the quarter-of-sphere vault the entrance of Junterón's chapel using the squaring method.

This would explain the careful layout of bed joints and ribs in the Murcia tracing. Strictly speaking, horizontal projections of bed joints are not necessary in Vandelvira's method and seem to be absent in the tracing in Seville rooftops (Vandelvira c. 1580, f. 61 r.; Ruiz de la Rosa 2002). Once he has constructed an intrados template, the mason can dress a portion of spherical surface with the help of a cerce and apply the template over it in order to mark the edges of the intrados face; after this is done, he can dress the bed joints and the joints between the voussoirs in the same course using a *baivel*, that is, a special square with a curved arm (Palacios 1990, p. 135-141; Rabasa 1996). By contrast, horizontal projections are essential when dressing the voussoirs of a spherical or sail vault by the squaring method. The mason can start by dressing a wedge-shaped block starting from the plan; the sides of the wedge furnish the joints between the voussoirs in the same course. Then, he can apply a template, taken from the cross-section, to these joints, in order to mark the edges of the intrados face; after this, the intrados can be dressed using a cerce, without the need for an intrados template. Such method is not economical in labour nor material, as Philibert de L'Orme had remarked, but this waste is not significant in the vestry vault, taking into account its radius and the number of courses. Besides, the squaring method allows precise control of voussoir length and rib placement. Such desire for exactitude is also shown by the use of rotations of channel cross-sections, in order to control their dressing.

All this allows us to review some assumptions about the use of stonecutting methods in Early Spanish Renaissance. Both the squaring method and the use of templates seem to have been introduced more or less simultaneously; the choice between both systems is not connected clearly with chronology or technical merit, but is rather tied to the use of decoration. Naked vaults, such as the vault over the staircase that leads to the Seville rooftops, can be constructed easily using templates obtained through the sophisticated cone development method, as far as there is no need to control the voussoir length. By contrast, when dressing the voussoirs for decorated vaults, or vaults where precise control of voussoir length is essential, the squaring method furnishes automatically such control, at the price of some degree of material waste. This may have led Alonso de Vandelvira and the somewhat sloppy draftsman of Segovia cathedral to combine both methods, including horizontal projections in a tracing by the cone development method, suggesting the use of plans and elevations for voussoir length control, or using a compass to obtain voussoirs of the same length; of course, the last method does not solve the problem, since nothing guarantees that a number of voussoirs of the same arbitrary length will fill the circle, and the last voussoir would need to be adjusted.

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References

- Albiz, Pedro de, attr. 1550 c. Manuscrito de cantería. Madrid: Biblioteca Nacional de España, Ms. 12.686.
- Alonso Rodríguez, Miguel Ángel, Ana López Mozo, and José Calvo López. 2001. Levantamiento de las bóvedas de la capilla de Junterón de la catedral de Murcia. Paper read at III Jornadas de Fotogrametría Arquitectónica, 11-15/16, at Valladolid.
- Alonso Rodríguez, Miguel Ángel, Enrique Rabasa Díaz, and José Calvo López. 2002. Las bóvedas de la sacristía y antesacristía de la catedral de Murcia. Murcia: Biblioteca del Colegio de Arquitectos de Murcia.
- Alonso Rodríguez, Miguel Ángel, José Calvo López, and Enrique Rabasa Díaz. 2009. Sobre la configuración constructiva del crucero de la catedral de Segovia. In *Actas del Sexto Congreso Nacional de Historia de la Construcción*, edited by S. Huerta et al. Madrid: Instituto Juan de Herrera.
- Alonso Rodríguez, Miguel Ángel, and José Calvo López. 2010. Sobre el levantamiento arquitectónico mediante fotogrametría multiimagen. In *XIII Congreso Internacional de Expresión Gráfica Arquitectónica*. Valencia: Universidad Politécnica de Valencia.
- Baquero Almansa, Andrés. 1902. *Rebuscos*. Murcia: Hermanos Perelló.
- Baquero Almansa, Andrés. 1913. *Catálogo de los profesores de las Bellas Artes Murcianos*. Murcia: Nogués.
- Barnes, Carl F. 1972. The gothic architectural engravings in the cathedral of Soissons. *Speculum* 47 (1):60-64.
- Bucher, François. 1977. A rediscovered tracing by Villard de Honnecourt. *Art Bulletin* 59 (3):315-318.
- Bustamante García, Agustín. 1994. *La octava maravilla del mundo. Estudio histórico sobre el Escorial de Felipe II*. Madrid: Alpuerto.
- Calvo López, José. 2000. 'Cerramientos y trazas de monte' de Ginés Martínez de Aranda. Tesis doctoral, Universidad Politécnica de Madrid.
- Calvo López, José. 2003. Orthographic projection and true size in Spanish stonecutting manuscripts. In *Proceedings of the First International Congress on Construction History*, edited by Santiago Huerta. Madrid: Instituto Juan de Herrera.
- Calvo López, José. 2005a. *Cantería renacentista en la Catedral de Murcia*. Murcia: Colegio Oficial de Arquitectos de Murcia.

- Calvo López, José.** 2005b. Jacopo Torni l'indaco vecchio and the emergence of Spanish classical stereotomy. In *Teoria e Pratica del costruire: saperi, strumenti, modelli*. Ravenna: Università di Bologna - Fondazione Flaminia.
- Calvo López, José, Miguel Ángel Alonso Rodríguez, and María del Carmen Martínez Ríos.** 2008. Levantamiento y análisis constructivo de la cabecera de la iglesia de Santiago de Jumilla. In *XIX Jornadas de Patrimonio Cultural de la Región de Murcia*. Murcia: Consejería de Cultura.
- Colchester, L. S., and John Harvey.** 1974. Wells Cathedral. *Archaeological Journal* 131:200-214.
- Derand, François, S. I.** 1643. *L'Architecture des voûtes ou l'art des traits et coupe des voûtes ...* Paris: Sébastien Cramoisy.
- Dürer, Albrecht.** 1525. *Underweysung der messung mit dem zirkel und richtscheyt ...* Nuremberg: s. n.
- Fergusson, Peter J.** 1979. Notes on two engraved cistercian drawings. *Speculum* 54:1-17.
- Freire Tellado, Manuel J.** 1998. Los trazados de montea de factura renacentista del edificio de los escolapios de Monforte de Lemos (Lugo). In *Actas del Segundo Congreso Nacional de Historia de la Construcción*. Madrid: Instituto Juan de Herrera.
- Frézier, Amédée-François.** 1737-1739. *La théorie et la pratique de la coupe des pierres et des bois ... ou traité de stéréotomie ...* Strasbourg-Paris: Jean Daniel Doulsseker-L. H. Guerin.
- Gil de Hontañón, Rodrigo.** 1540 c. Manuscrito. Madrid: Biblioteca Nacional.
- Gómez Piñol, Emilio.** 1970. *Jacobo Florentino y la obra de talla de la Sacristía de la Catedral de Murcia*. Murcia: Universidad.
- Gómez-Moreno, Manuel.** 1925. En la Capilla Real de Granada. *Archivo Español de Arte y Arqueología*:225-288.
- Gomez-Moreno, Manuel.** 1926. Documentos referentes a la Capilla Real de Granada. *Archivo Español de Arte y Arqueología*:85-128.
- Gómez-Moreno, Manuel.** 1963. *Diego Siloé. Homenaje en el IV centenario de su muerte*. Granada: Universidad de Granada.
- González Simancas, Manuel.** 1905-1907. Catálogo Monumental de España. Provincia de Murcia. Madrid: Centro de Estudios Históricos.
- González Simancas, Manuel.** 1911. La catedral de Murcia. Noticias referentes a su fábrica y obras artísticas. *Revista de Archivos, Bibliotecas y Museos* 24 (3ª época, 5-6): 510-538.
- Guardia, Alonso de.** 1600 c. Manuscrito de arquitectura y cantería. Madrid: Biblioteca Nacional.
- Gutiérrez-Cortines Corral, Cristina.** 1987. *Renacimiento y Arquitectura religiosa en la antigua diócesis de Cartagena*. Murcia: Colegio de Aparejadores y Arquitectos Técnicos.
- Harvey, John.** 1968. The tracing floor in York Minster. *Annual Report of the Friends of York Minster* (40):1-8.
- Hastings, Maurice.** 1955. *St Stephen's Chapel and its place in the development of perpendicular style in England*. Cambridge: Cambridge University Press.
- Holton, Alexander.** 2006. The Working Space of the Medieval Master Mason: the Tracing Houses of York Minster and Wells Cathedral. In *Proceedings of the Second International Congress on Construction History*, edited by M. Dunkeld et al. Cambridge: Construction History Society.
- La Rue, Jean-Baptiste de.** 1728. *Traité de la coupe des pierres où par méthode facile et abrégée l'on peut aisément se perfectionner en cette science*. Paris: Imprimerie Royale.

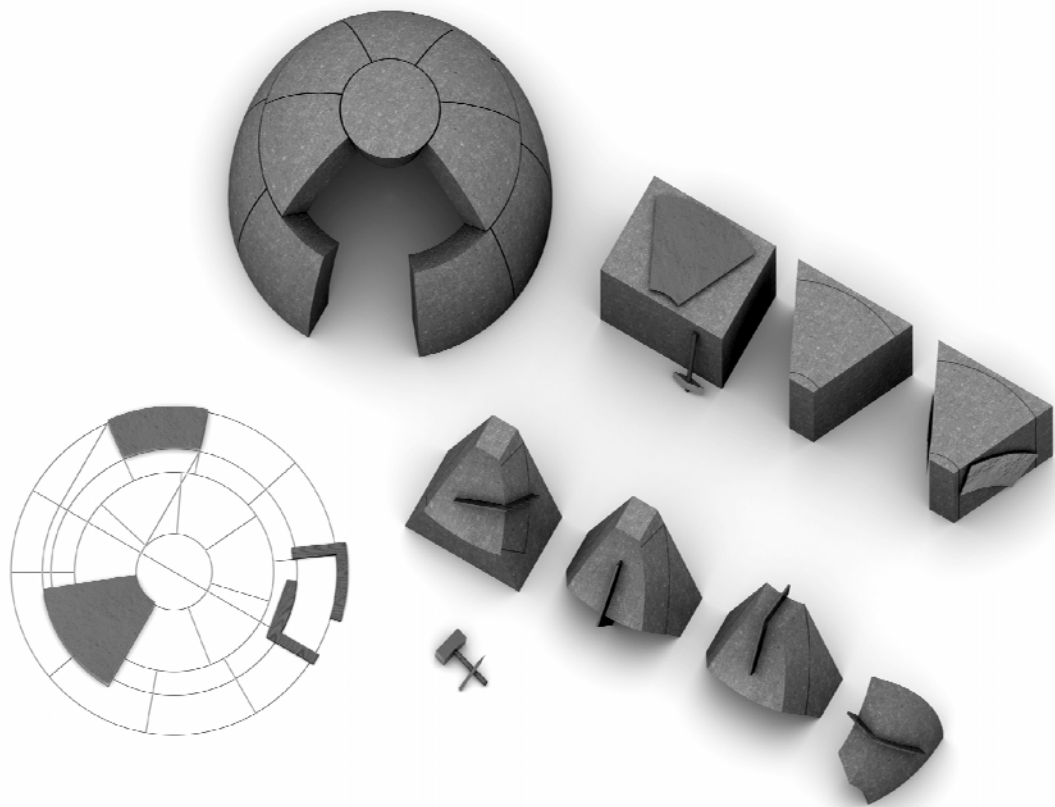
- L'Orme, Philibert de. 1567. *Le premier tome de l'Architecture*. Paris: Federic Morel.
- Marías, Fernando. 1983-86. *La arquitectura del Renacimiento en Toledo (1541-1631)*. Toledo: Instituto Provincial de Investigaciones y Estudios Toledanos.
- Martínez de Aranda, Ginés. 1600 c. Cerramientos y trazas de monte. Madrid. Servicio Histórico del Ejército.
- Natividad Vivó, Pau. 2010. Levantamiento y análisis estereotómico de las Torres de Quart de Valencia. Trabajo fin de máster, Universidad Politécnica de Valencia, Valencia.
- Palacios Gonzalo, José Carlos. 1990. *Trazas y cortes de cantería en el Renacimiento Español*. 1st ed. Madrid: Instituto de Conservación y Restauración de Bienes Culturales. Ministerio de Cultura.
- Pinto Puerto, Francisco, and Alfonso Jiménez Martín. 1993. Monteas en la Catedral de Sevilla. *Revista de Expresión Gráfica Arquitectónica (EGA)* (1):79-84.
- Pozo Martínez, Indalecio, Alfonso Robles Fernández, and Elvira Navarro Santa Cruz. 2009. *Marcas, dibujos y letreros en la catedral de Murcia*. Murcia: Ediciones Tres Fronteras - Consejería de Cultura.
- Rabasa Díaz, Enrique. 1996. Técnicas góticas y renacentistas en el trazado y la talla de las bóvedas de crucería españolas del siglo XVI. In *Actas del Primer Congreso Nacional de Historia de la Construcción*. Madrid: Instituto Juan de Herrera.
- Rabasa Díaz, Enrique. 2000. *Forma y construcción en piedra. De la cantería medieval a la estereotomía del siglo XIX*. Madrid: Akal.
- Rabasa Díaz, Enrique. 2003. The single coursed ashlar vault. In *Proceedings of the First International Congress on Construction History*, edited by S. Huerta Fernández. Madrid: Instituto Juan de Herrera.
- Rabasa Díaz, Enrique. 2007. *Guía práctica de la estereotomía de la piedra*. León: Editorial de los Oficios.
- Rabasa Díaz, Enrique, and José Calvo López. 2009. Gothic and Renaissance Design Strategies in Stonecutting. In *Creating shapes in civil and naval architecture. A cross-disciplinary comparison*, edited by H. Nowacki and W. Lefevre. Leiden-Boston: Brill.
- Rokiski Lázaro, María Luz. 1980. La cabecera de la iglesia de Priego (Cuenca). *Dibujos y tasación*. Cuenca (17): 27-34.
- Rosende Valdés, Andrés A. 1999. *El Grande y Real Hospital de Santiago de Compostela*. Madrid: Electa.
- Roriczer, Mathes. 1486. *Büchlein von der fialen Gerechtigkeit*. Regensburg: s. n.
- Roriczer, Mathes. 1490 c. *Geometria Deutsch*. s. l.: s. n.
- Rubio Lapaz, Jesús. 1990. Una aproximación a la trayectoria arquitectónica de Juan de Marquina a partir de una documentación inédita. *Murgetana* (80):5-14.
- Ruiz de la Rosa, José Antonio, and Juan Clemente Rodríguez Estévez. 2000. Monteas en las azoteas de la Catedral de Sevilla. Análisis de testimonios gráficos de su construcción. In *Actas del Tercer Congreso Nacional de Historia de la Construcción*. Madrid: Instituto Juan de Herrera.
- Ruiz de la Rosa, José Antonio, and Juan Clemente Rodríguez Estévez. 2002. 'Capilla redonda en vuelta redonda' (sic): Aplicación de una propuesta teórica renacentista para la catedral de Sevilla. In *IX Congreso Internacional Expresión Gráfica Arquitectónica. Re-visión: Enfoques en docencia e investigación*. A Coruña: Universidad de A Coruña.
- Ruiz el Joven, Hernán. 1550 c. Libro de Arquitectura. Madrid: Biblioteca de la Escuela de Arquitectura de la Universidad Politécnica de Madrid.

- Sakarovitch, Joël. 1992a. La coupe des pierres et la géométrie descriptive. In *L'Ecole Normale de l'an III Leçons de Mathématiques, Laplace-Lagrange-Monge*, edited by J. Dhombres. Paris: Dunod.
- Sakarovitch, Joël. 1992b. The Teaching of Stereotomy in Engineering schools in France in the XVIIIth and XIX centuries: an Application of Geometry, an 'Applied Geometry', or a Construction Technique? In *Entre mécanique et architecture*, edited by P. Radelet-de Grave and E. Benvenuto. Basel-Boston-Berlin: Birkhäuser.
- Sakarovitch, Joël. 1997. *Epures d'architecture*. Basel-Boston-Berlin: Birkhäuser.
- Shelby, Lon R. 1971. Medieval masons' templates. *Journal of the Society of Architectural Historians* 30:140-154.
- Sricchia Santoro, Fiorella. 1993. Del Franciabigio, dell'Indaco e di una vecchia questione: II. *Prospettiva* (71):12-33.
- Taín Guzmán, Miguel. 1999. *Trazas, Planos y Proyectos del Archivo de la Catedral de Santiago*. La Coruña: Imprenta Provincial de la Diputación de A Coruña.
- Taín Guzmán, Miguel. 2002. Las monteas de la Catedral de Santiago de Compostela: de la arquitectura a la escultura. In *Correspondencia e Integración de las Artes. XIV Congreso Nacional de Historia del Arte*. Málaga.
- Taín Guzmán, Miguel. 2003a. The drawings on stone in Galicia: Types, uses and meanings. In *Proceedings of the First International Congress on Construction History*, edited by S. Huerta Fernández. Madrid: Instituto Juan de Herrera.
- Taín Guzmán, Miguel. 2003b. Las monteas en Galicia: propuesta de una tipología. *Goya* (297):339-355.
- Taín Guzmán, Miguel. 2006. Fifteen Unedited Engraved Architectural Drawings Uncovered in Northwest Spain. In *Proceedings of the Second International Congress on Construction History*, edited by M. Dunkeld et al. Cambridge: Construction History Society.
- Taín Guzmán, Miguel. 2009. "La utilización de monteas en la construcción en piedra: El caso gallego". In *El arte de la piedra*. Madrid: CEU Ediciones, p. 171-202.
- Taton, René. 1954. *Histoire de la géométrie descriptive*. Paris: Université de Paris.
- Tolnay, Charles de. 1945. *Michelangelo. The Sistine Ceiling*. Princeton: Princeton University Press.
- Vandelvira, Alonso de. 1585 c. Libro de trazas de cortes de piedras. Madrid: Biblioteca de la Escuela de Arquitectura de la Universidad Politécnica de Madrid.
- Vasari, Giorgio. 1568. *Le vite de' più eccellenti pittori, scultori et architettori italiani*. Firenze: Giunti.
- Velasco, Lázaro de. 1564. Traducción de los diez libros de arquitectura de Vitrubio. Cáceres: Biblioteca Pública del Estado.
- Vera Botí, Alfredo. 1985. "Informe sobre la cajonería de la catedral". Archivo General de la Región de Murcia (AGRM), C 5438.
- Vera Botí, Alfredo. 1989. "Informe sobre la catedral de Murcia". Private library of Juan Carlos Molina Gaitán.
- Vera Botí, Alfredo. 1991. "Informe sobre la Catedral de Murcia. Intervenciones de máxima urgencia". AGRM, 3367/2.
- Vera Botí, Alfredo. 1993. *La Torre de la Catedral de Murcia. De la teoría a los resultados*. Murcia: Academia Alfonso X el Sabio.
- Vera Botí, Alfredo, et. al. 1994. *La catedral de Murcia y su Plan Director*. Murcia: Colegio de Arquitectos.
- Vera Botí, Alfredo. 1997. La piedra caliza de la Catedral de Murcia. *Loggia* (2): 81-86.

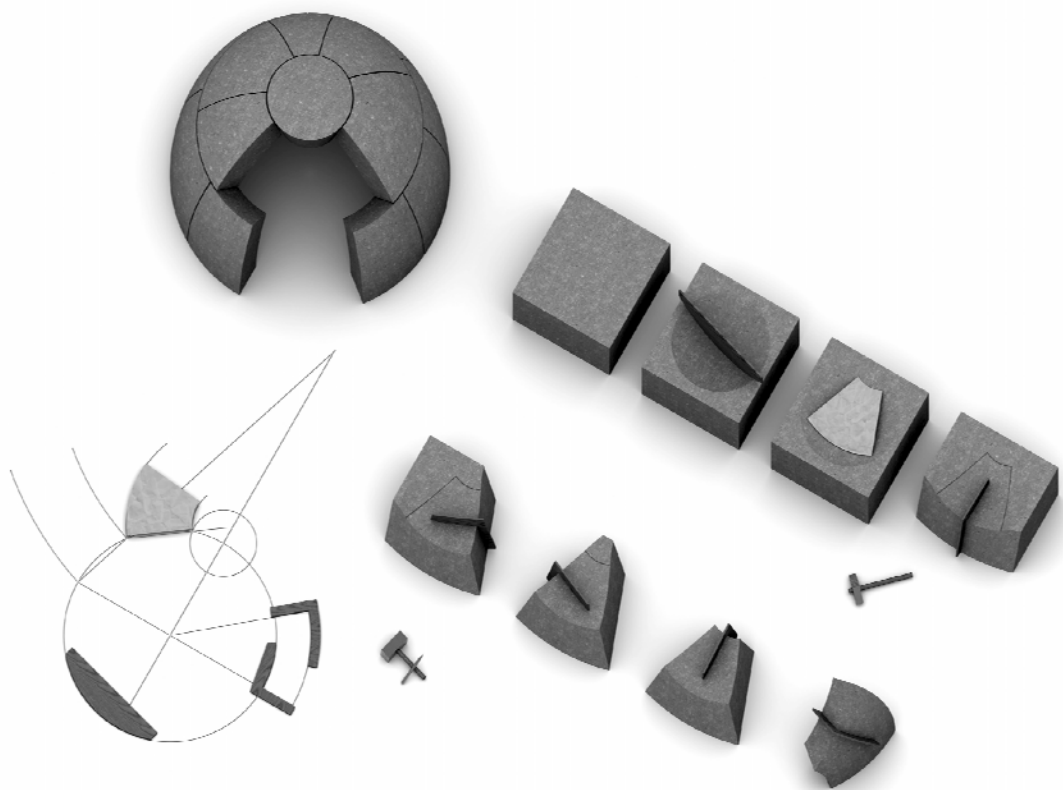
- Wallace, William E.** 1987. Michelangelo's assistants in the Sistine Chapel. *Gazette des Beaux-Arts* 110 (1427):203-216.
- Willis, Robert.** 1842. On the construction of the vaults of the Middle Ages. *Transactions of the Institute of British Architects* 1:1-69.
- Zaragoza Catalán, Arturo.** 2010. Cuando la arista gobierna el aparejo: bóvedas aristadas. In *Arquitectura en construcción en Europa en época medieval y moderna*, edited by A. Serra Desfils. Valencia: Universitat de València.



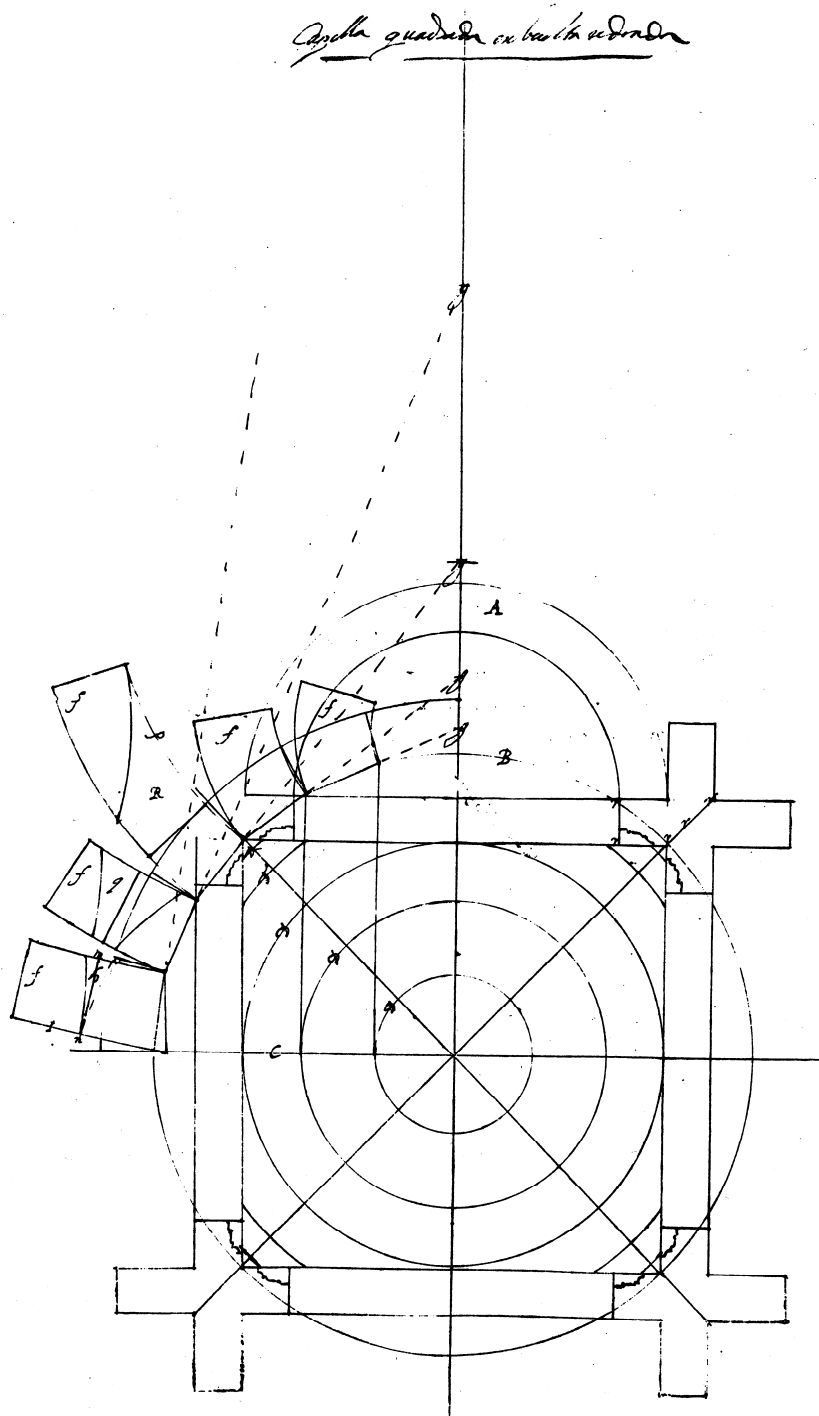
*1. Tracings for hemispherical vaults at the parish church of Santa Columba in Carnota.
Photograph by Miguel Taín Guzmán*



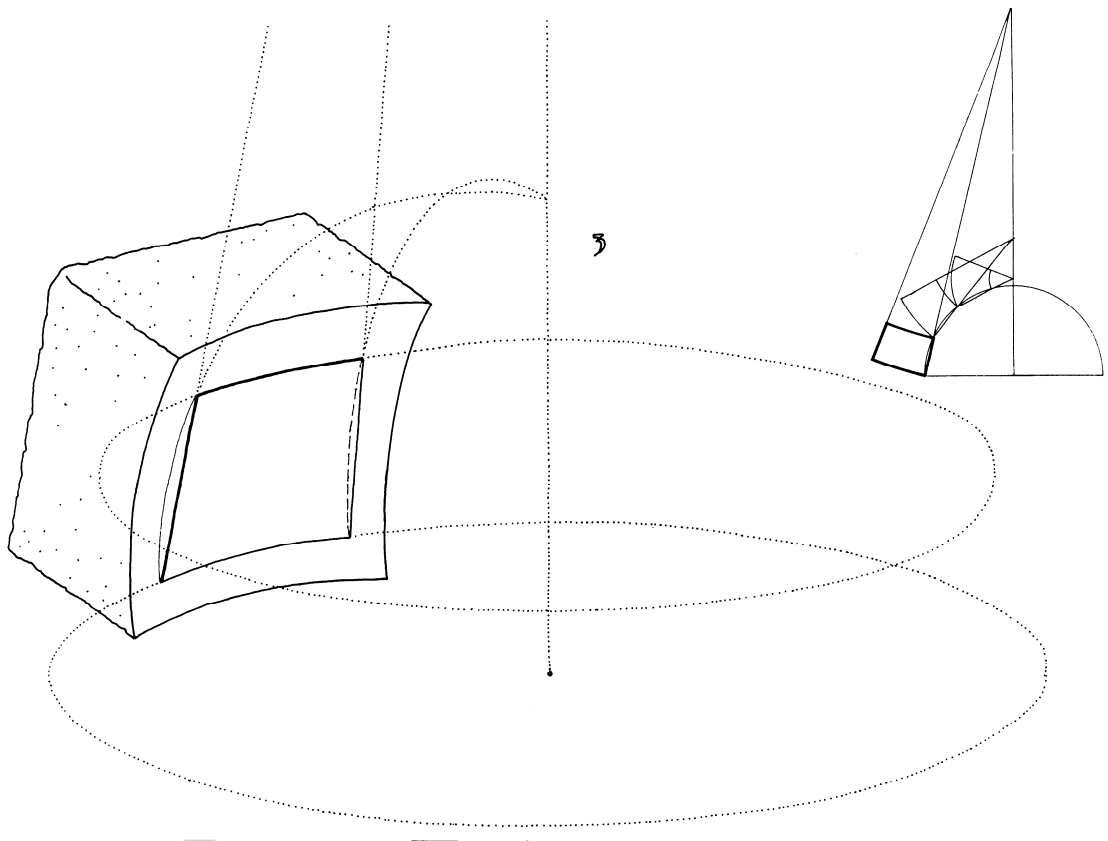
2. Dressing a voussoir for a hemispherical vault by squaring. Rendering by Pau Natividad Vivó.



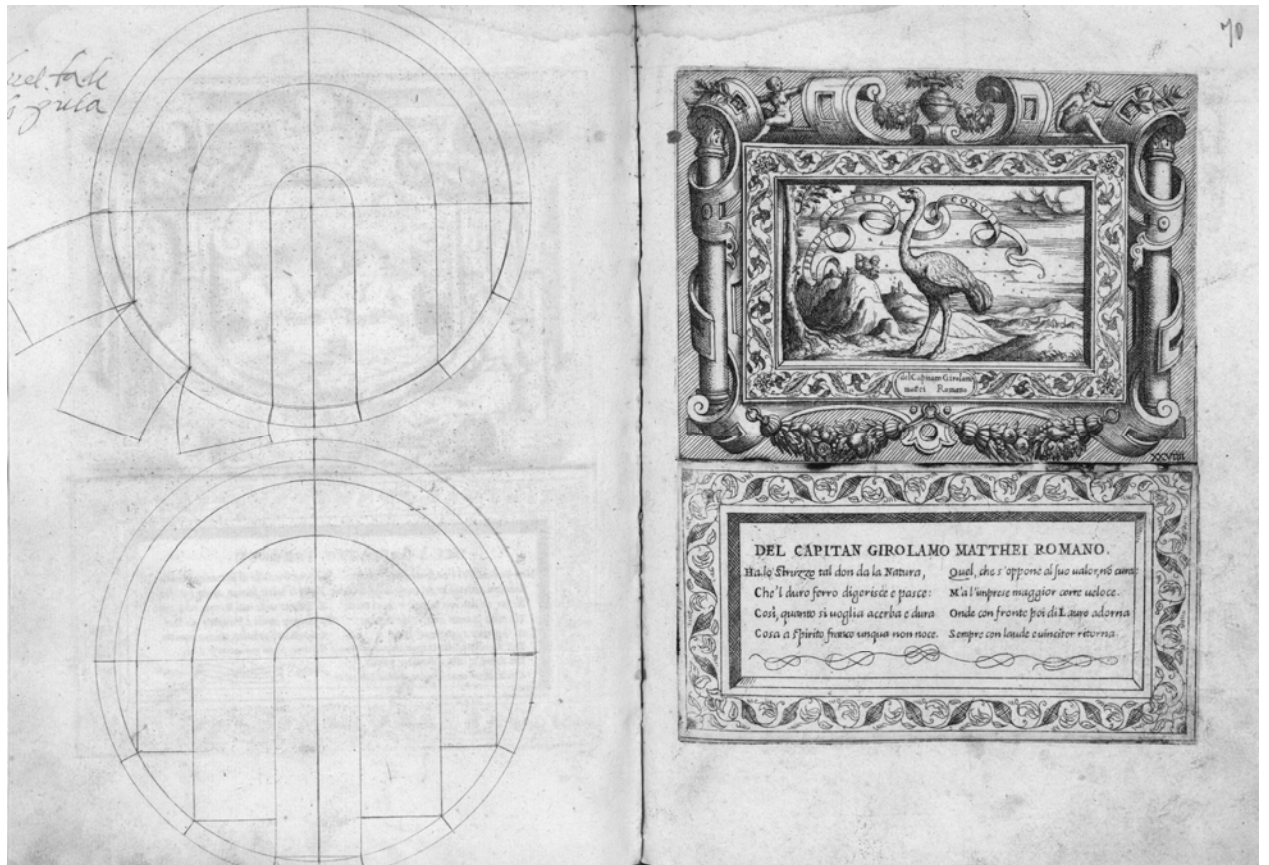
3. Dressing a voussoir for a hemispherical vault by the direct method. Rendering by Pau Natividad Vivó.



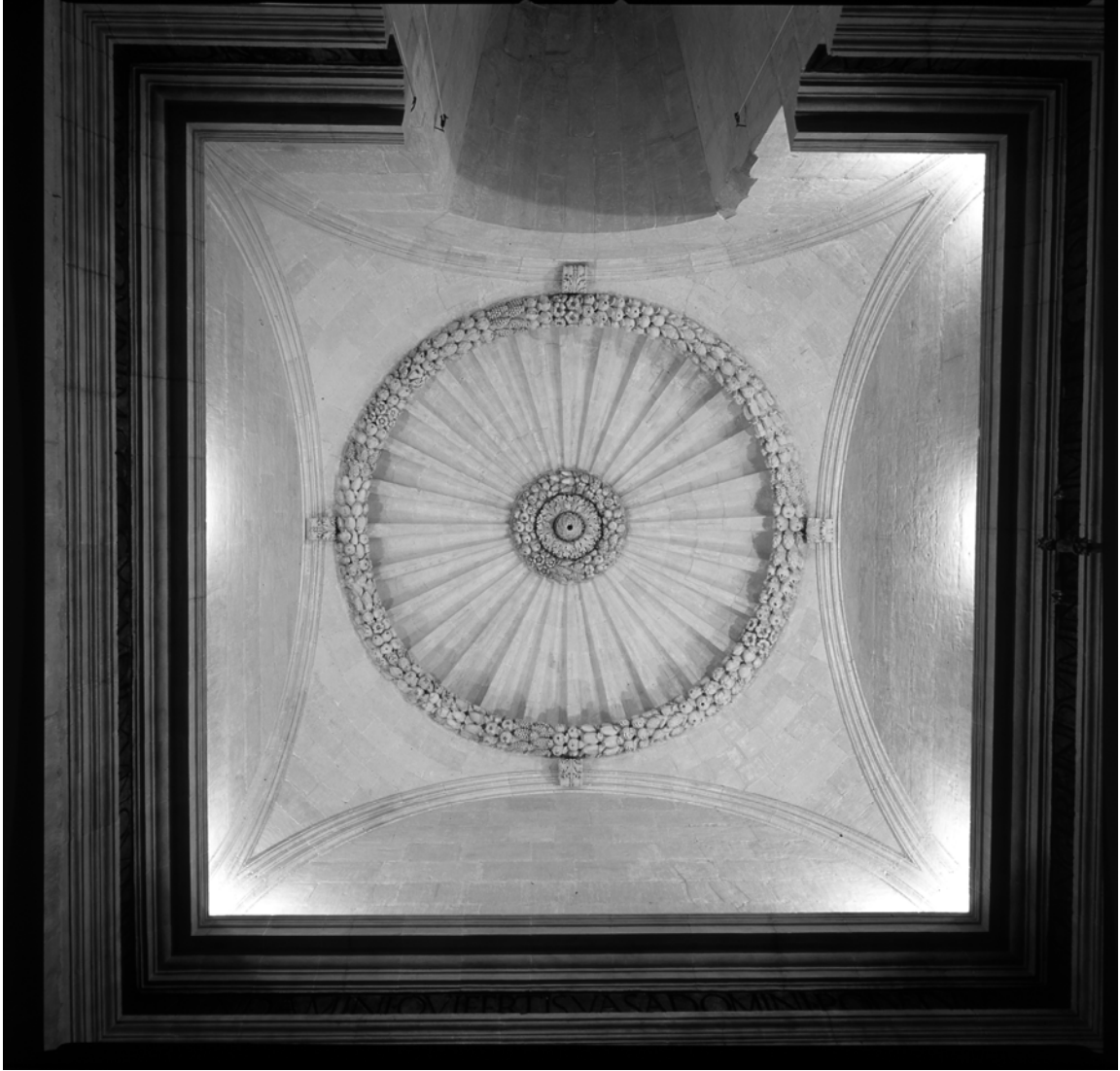
4. Tracing for a sail vault. Alonso de Vandelvira, *Libro de trazas de cortes de piedras*, c. 1580, f. 82r.



5. Inscribing cones on the intrados surface of a hemispherical vault. Drawing by Enrique Rabasa.



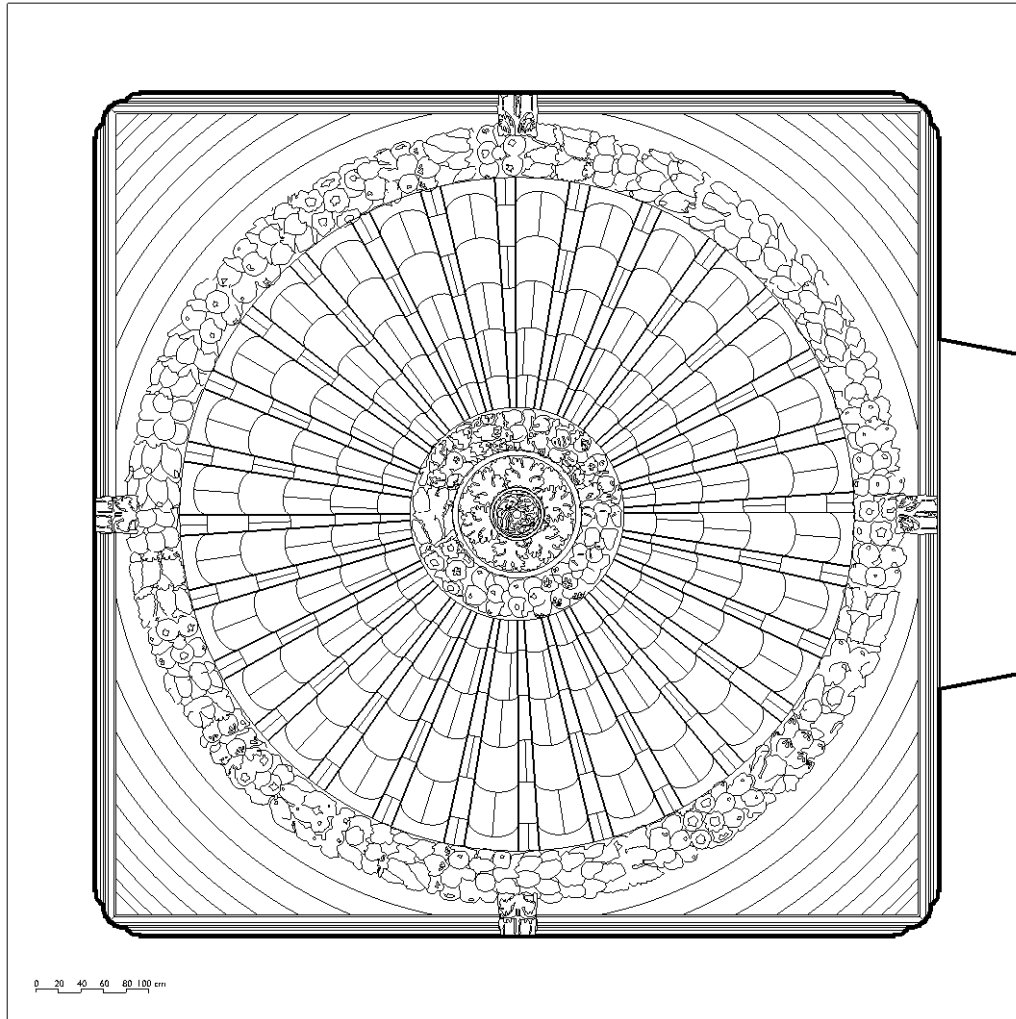
6. Tracings for hemispherical vaults. Alonso de Guardia, *Manuscrito de arquitectura y cantería*, c. 1600, f. 69v.



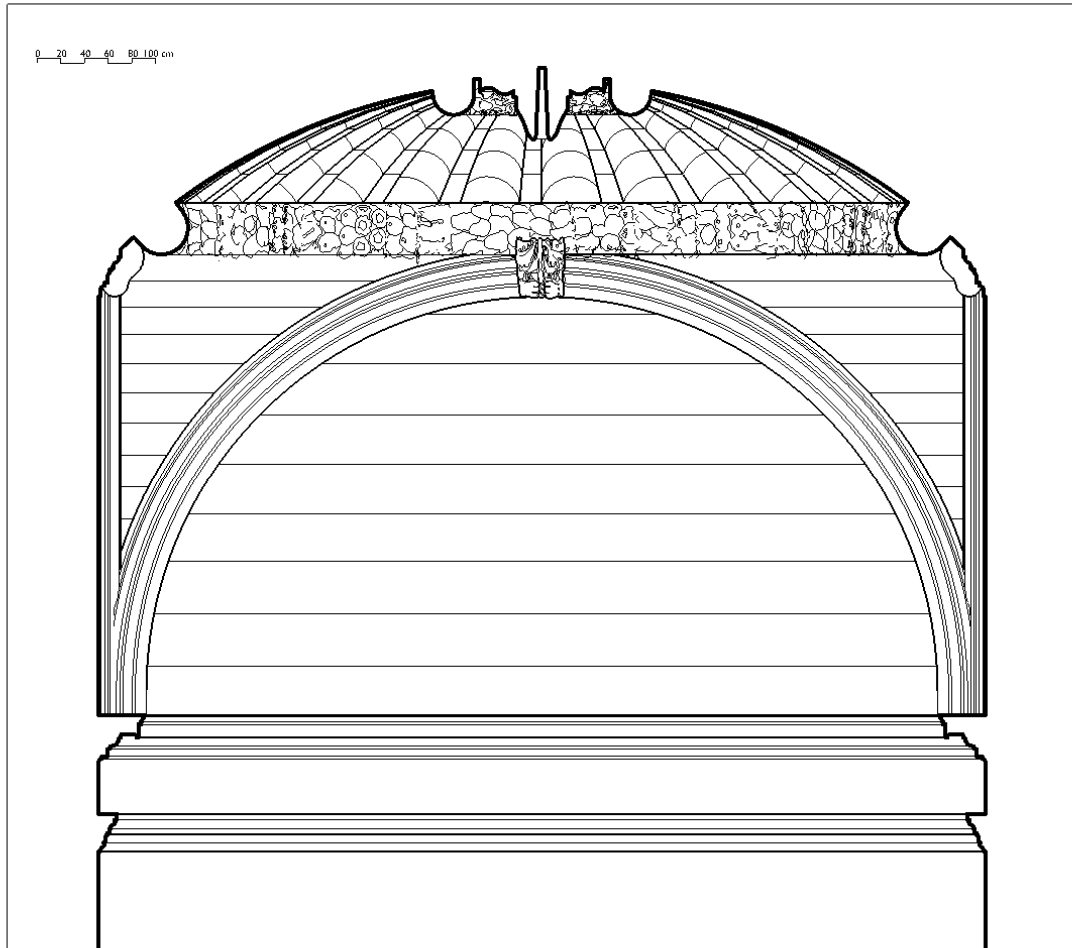
7. Sail vault over the vestry of Murcia cathedral. Jacopo Torri l'Indaco, 1525. Photograph by David Frutos.



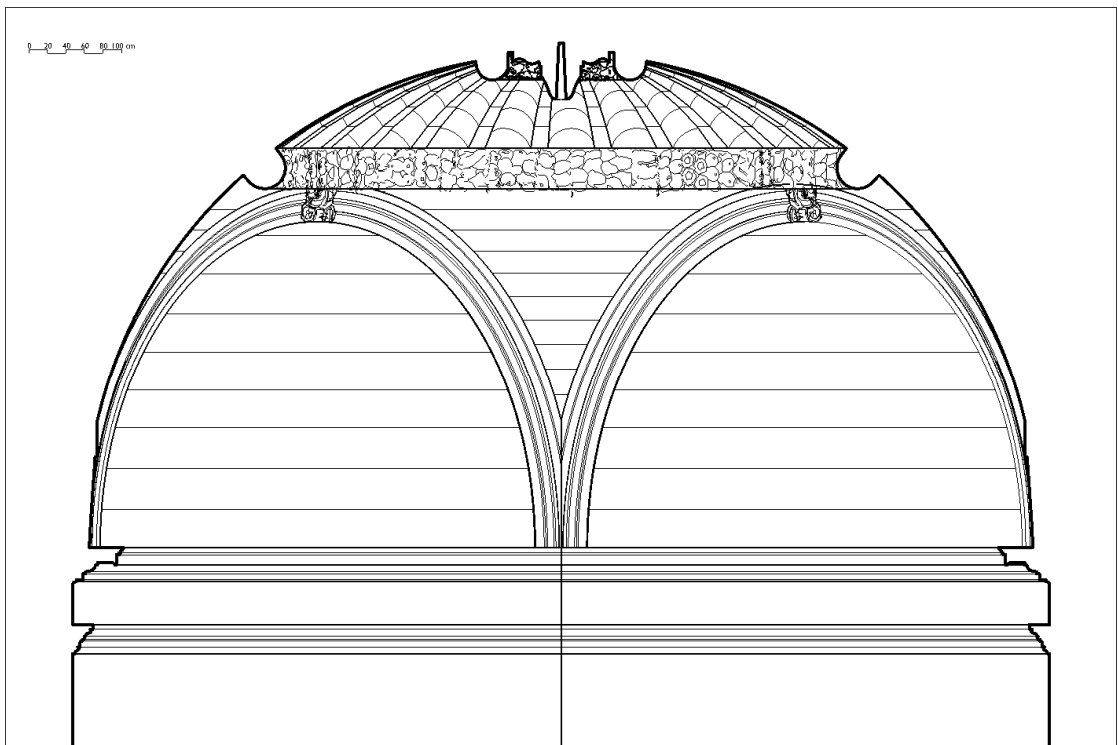
8. Main vault at the Pazzi Chapel. Filippo Brunelleschi or Michelozzo Michelozzi, c. 1450.
Photograph by José Calvo-López



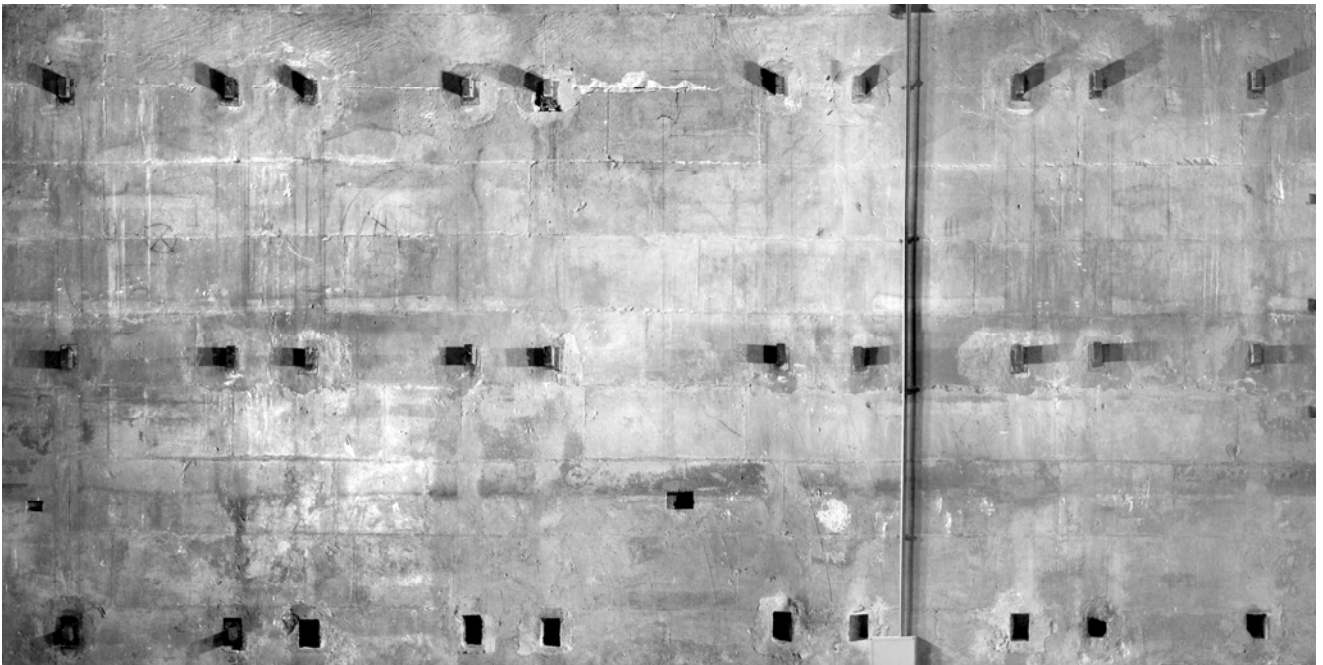
9. Sail vault over the vestry of Murcia cathedral. Plan. Survey by Miguel Ángel Alonso.



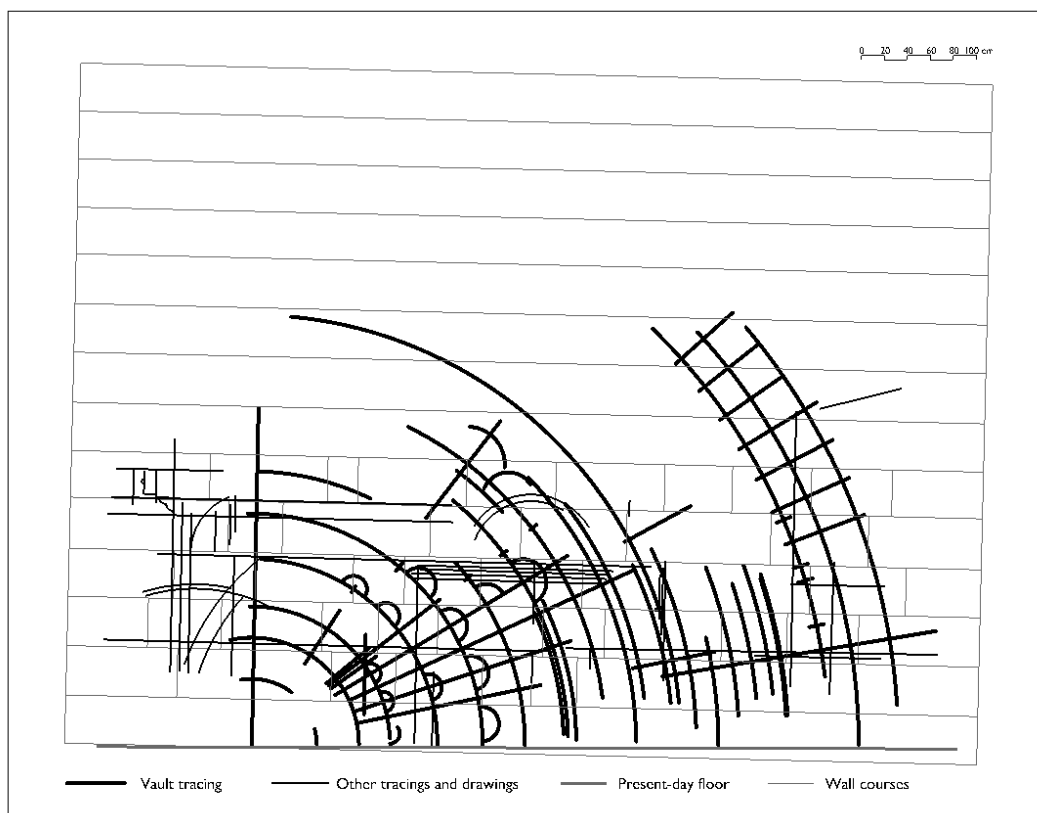
10. Sail vault over the vestry of Murcia cathedral. Cross-section. Survey by Miguel Ángel Alonso.



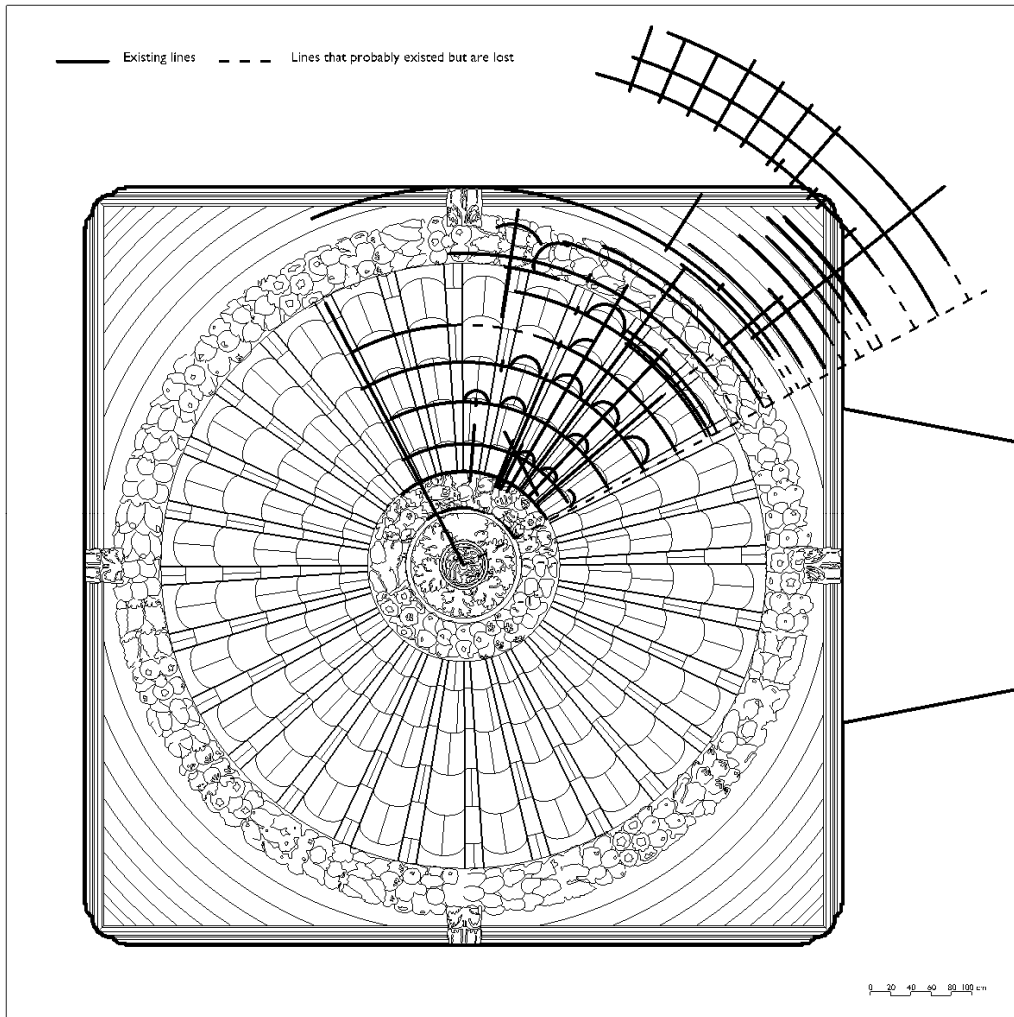
11. Sail vault over the vestry of Murcia cathedral. Section by a vertical plane passing the diagonal of the vestry area. Survey by Miguel Ángel Alonso.



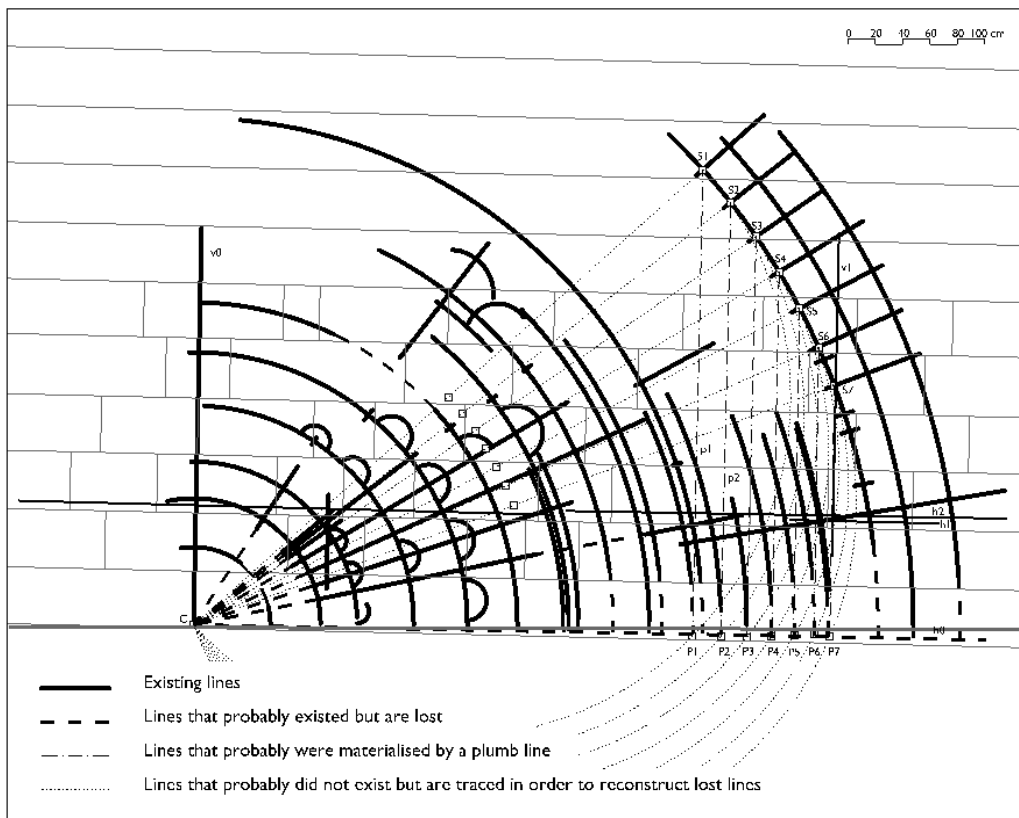
12. Tracings and drawings in the north wall of the vestry of Murcia cathedral. Rectified photograph by AeroGraph Studio.



13. Tracings in the north wall of the vestry of Murcia cathedral. The slant to the right is caused by movements of the bell-tower. Survey by Miguel Ángel Alonso and Pau Natividad.



14. Tracing for the sail vault in the vestry of Murcia cathedral, drawn over the vault plan at the same scale. Drawing by Miguel Ángel Alonso and José Calvo-López.



15. Analysis of the tracing for the sail vault in the vestry of Murcia cathedral. Drawing by Miguel Ángel Alonso and José Calvo-López.