
RESEARCH ARTICLE

Divining Proportions in the Information Age

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The process of reverse engineering proportional systems of historic buildings has long been fraught with problems. One cannot assume, without knowing the specific conditions of acquisition, that existing plans are accurate enough to sustain the scrutiny necessary to resolve differences among potential proportional schemes. Yet producing a new survey with conventional measurement instruments could take weeks, if not months, and only in the best of situations would it be possible to acquire data in the upper reaches of the building—information required to avoid arbitrary dimensional rectification. With the advent of high-speed and high-precision laser scanning, however, the situation has changed dramatically.

Introduction

For students of medieval proportional systems who lack such documentary evidence as James Ackerman had, in relative abundance, for his groundbreaking 1949 study of the Cathedral of Milan, the only choice has been to turn to the buildings. Yet Ackerman warned that such an exercise was destined to fail: ‘the analysis of remaining monuments,’ he wrote, ‘provides insufficient evidence for [the] task’ (Ackerman 1949: 85).

Ackerman’s pessimism probably had much to do with the quality of survey data readily available for medieval monuments. One could not assume, without knowing the specific conditions of acquisition, that existing plans were accurate enough to sustain the scrutiny necessary to resolve differences among potential proportional schemes. Had the buildings in question been completely and carefully surveyed? Were the resultant plans and sections plotted using the drafting techniques necessary to minimize error? To what extent were measurements rectified — i.e., arbitrarily corrected — out of a desire to represent the building in a supposed perfected state, or from a lack of sufficient survey data to represent the building as it actually stood?

The scholar of proportions had two solutions when faced with the difficulty of establishing the representational reliability of drawings created by others. He might dismiss the problem by arguing that precision in plan and section was in any case not essential: since proportional systems were more often than not imperfectly executed in the buildings themselves for a host of reasons having to do with the reality of the construction site, a certain inaccuracy in an existing plan might be tolerated as a result. Though this might be satisfactory in a general sense — in order, for example, to locate a double square in the nave of a given building — more

complex situations could not be resolved with any clarity. It was simply impossible to know precisely by how much a proposed proportional scheme was distant from the constructional reality of the building.¹

In this case the only choice was to undertake a new survey of the building in question using the most precise means available. Yet this could take weeks, if not months, and only in the best of situations would it be possible to acquire data in the upper reaches of the building: scaffolding is expensive and encumbering.

Today, over a half a century later, Ackerman might have had a different response. Though we are faced now, as much as we were then, with a dearth of documentary evidence for proportional planning, our ability to look to the buildings with confidence — and rapidity — has changed radically, in large part thanks to laser scanning technology.²

Acquisition, assembly, and sectioning are the three primary components of laser surveying.

Acquisition

There are two primary means of measuring distance with a laser: a) by calculating the time of flight for a laser pulse to be sent, reflected from a surface and returned, and b) by calculating the phase shift induced in a sinusoidally encoded beam after travel, reflection, and return. Each technique presents certain advantages and is chosen generally as a function of the type of scanning work to be accomplished. Time of flight measurement, for example, has been the preferred approach for distances that extend beyond 150 meters. The technology is advancing with impressive rapidity, however, driven by a greater demand for speed, accuracy, and portability, and limitations are regularly overturned as scanner hardware evolves.³

In a typical scanner the laser beam is distributed over a range of 360 degrees horizontally and 270 degrees vertically by a rotating mirror, and acquires the distance between itself and every surface that it can ‘see’ at a rate that can approach one million measurements per second (**Fig. 1**).⁴ The result is what is called a ‘cloud’ of points (**Fig. 2**). The

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Fig. 1: Leica Geosystems ScanStation C10 at work on the south flank of the Cathedral of Saint-Pierre in Beauvais, June 2013. Photograph: Andrew Tallon.

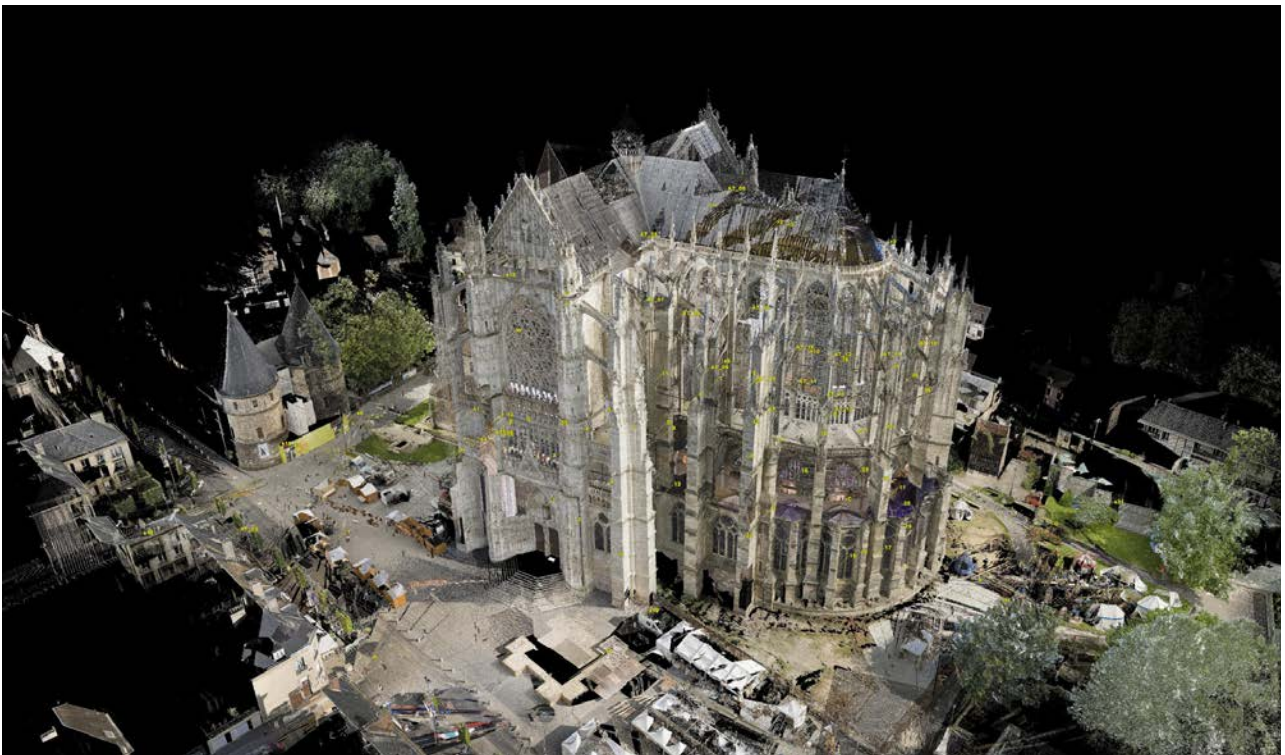


Fig. 2: Cathedral of Saint-Pierre in Beauvais, laser scan, June 2013: point cloud. Targets are labeled in yellow. Each pixel in the image represents a measurement; the points have been color mapped using textures acquired photographically. Image: Andrew Tallon.

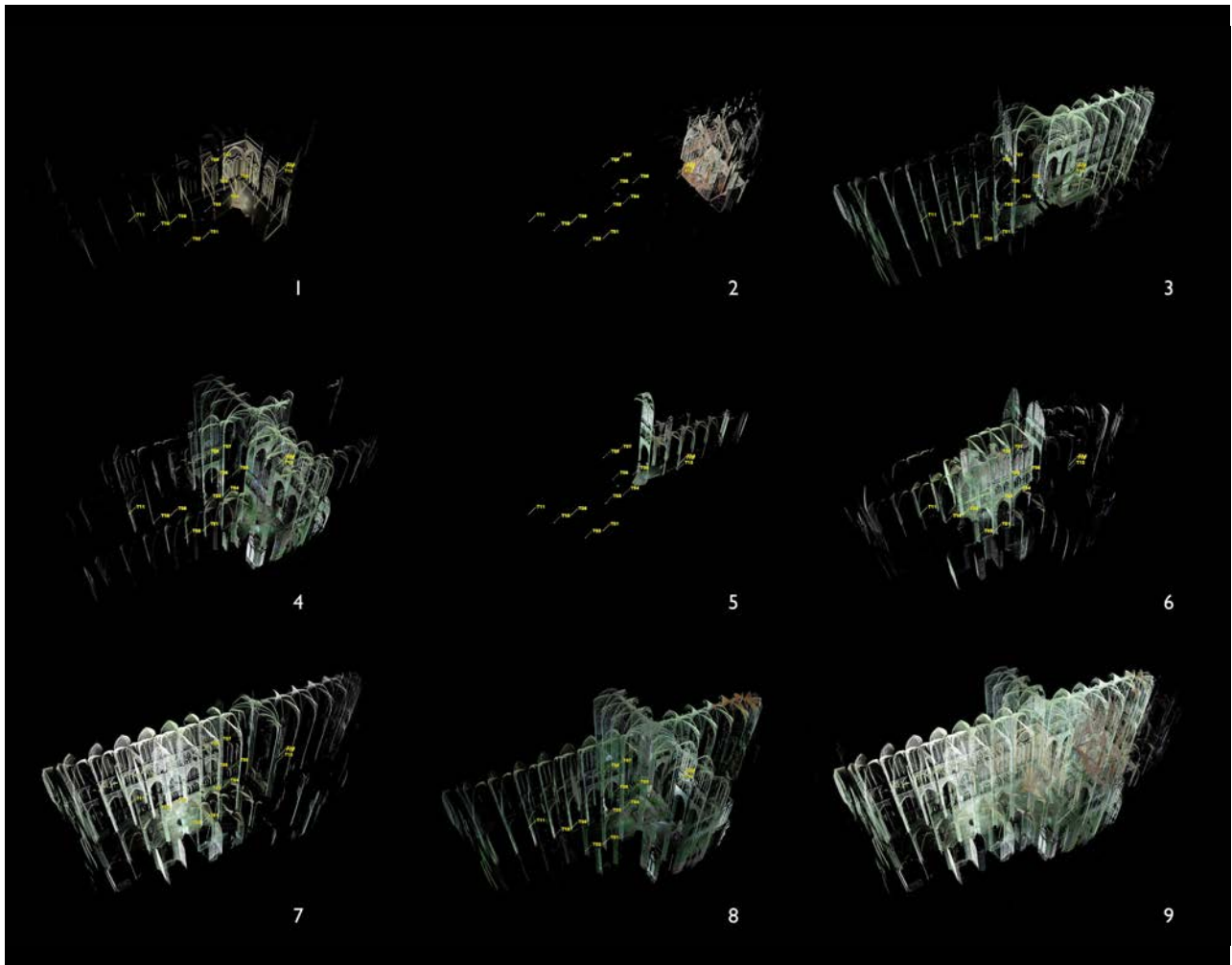


Fig. 3: Cathedral of Notre-Dame in Amiens, partial laser scan, June 2009: individual scan positions with targets (1–8) and final registration (9). Image: Andrew Tallon.

maximum positional error for each of these measurements, which in the latest long-range scanners is often fewer than five millimeters, is a function of the laser acquisition technology employed, the error-correction abilities of the scanner, and atmospheric conditions (lasers can produce erroneous data when passing through raindrops, for example).

Scan resolution is a key consideration. Scanning with lower point density will take less time, but with too few points the details of the building will be impossible to reconstruct from the data. A resolution of a point every five centimeters, for example, may be sufficient to locate the plane of a wall and even the curvature of a vault, but it is largely insufficient to represent the detailed forms of a capital or base, which require point densities of millimetric order. For this reason multiple resolutions are often most practical: the general details of walls, floor, and vaults might be acquired with relatively low density (and thus relative rapidly), with denser and slower windowed scans (i.e., a subset of the scanner acquisition sphere) reserved for key details.

While an individual cloud will supply a great deal of information, it is but a single viewpoint; to produce a survey of sufficient density and to minimize occlusions it is

necessary to displace the scanner. Each scanner position, or station, must be fixed to a network of control points (**Figs. 2 and 3**).⁵ Control points are most often supplied by reflective targets that can be accurately scanned and then recognized by the onboard scanner software; typical error in target recognition is on the order of two millimeters.⁶ It is also possible to use architectural elements in the building as control points, which presents certain advantages in terms of rapidity (no targets need be placed), but at the potential cost of precision. Scanning a target that is recognized by the scanner as such is straightforward; assuring that the corner of a particular abacus is scanned at sufficient density to properly resolve its vertex, for example, is less so.

The amount of time required to scan an entire building is a function of the technology used, the scan resolution, conditions of building access, the size and complexity of the building, and the efficiency of the operator. In 2008, for example, a survey of 52 stations undertaken by the author at Bourges Cathedral took fully nine days to acquire (Tallon forthcoming). In 2013 the author produced 74 stations at the Cathedral of Beauvais – with a twenty-fold increase in measurement density – in just three days.⁷

Constraint ID	Scan/field	Scan/field	Type	Status	Weight	Error	Error Vector	Group
1	Station-001 (south transept) Station-001 (south transept) Leveled	Station-006 (south transept east aisle center) Station-006 (south transept east aisle center) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.002 m	(-0.001, 0.000, -0.001) m	Ungrouped
1	Station-001 (south transept) Station-001 (south transept) Leveled	Station-007 (south transept east aisle south) Station-007 (south transept east aisle south) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.002 m	(0.000, 0.001, 0.001) m	Ungrouped
1	Station-001 (south transept) Station-001 (south transept) Leveled	Station-008 (ambulatory bay 3) Station-008 (ambulatory bay 3) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.002 m	(0.000, -0.001, -0.001) m	Ungrouped
2	Station-001 (south transept) Station-001 (south transept) Leveled	Station-002 (north transept) Station-002 (north transept) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.002 m	(0.000, -0.002, 0.001) m	Ungrouped
2	Station-001 (south transept) Station-001 (south transept) Leveled	Station-005 (north transept west aisle) Station-005 (north transept west aisle) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.003 m	(0.001, -0.002, -0.001) m	Ungrouped
2	Station-001 (south transept) Station-001 (south transept) Leveled	Station-006 (south transept east aisle center) Station-006 (south transept east aisle center) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.002 m	(-0.001, -0.002, -0.001) m	Ungrouped
A	Station-001 (south transept) Station-001 (south transept) Leveled	Station-002 (north transept) Station-002 (north transept) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.001 m	(0.001, -0.001, -0.001) m	Ungrouped
A	Station-001 (south transept) Station-001 (south transept) Leveled	Station-003 (crossing) Station-003 (crossing) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.002 m	(0.001, 0.001, 0.000) m	Ungrouped
A	Station-001 (south transept) Station-001 (south transept) Leveled	Station-004 (south transept west aisle) Station-004 (south transept west aisle) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.001 m	(0.000, 0.001, 0.000) m	Ungrouped
A	Station-001 (south transept) Station-001 (south transept) Leveled	Station-005 (north transept west aisle) Station-005 (north transept west aisle) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.001 m	(0.001, 0.000, 0.001) m	Ungrouped
A	Station-001 (south transept) Station-001 (south transept) Leveled	Station-006 (south transept east aisle center) Station-006 (south transept east aisle center) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.002 m	(0.001, -0.001, 0.000) m	Ungrouped
A	Station-001 (south transept) Station-001 (south transept) Leveled	Station-008 (ambulatory bay 3) Station-008 (ambulatory bay 3) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.001 m	(0.001, 0.000, -0.001) m	Ungrouped
A	Station-001 (south transept) Station-001 (south transept) Leveled	Station-009 (ambulatory bay 4) Station-009 (ambulatory bay 4) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.002 m	(0.001, -0.001, -0.001) m	Ungrouped
A	Station-001 (south transept) Station-001 (south transept) Leveled	Station-010 (ambulatory bay 5) Station-010 (ambulatory bay 5) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.001 m	(-0.001, 0.000, 0.000) m	Ungrouped
A	Station-001 (south transept) Station-001 (south transept) Leveled	Station-011 (ambulatory bay 6) Station-011 (ambulatory bay 6) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.001 m	(0.001, 0.000, 0.000) m	Ungrouped
A	Station-001 (south transept) Station-001 (south transept) Leveled	Station-012 (ambulatory bay 7) Station-012 (ambulatory bay 7) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.002 m	(0.002, 0.000, 0.000) m	Ungrouped
A	Station-001 (south transept) Station-001 (south transept) Leveled	Station-023 (choir west) Station-023 (choir west) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.002 m	(0.002, 0.000, 0.000) m	Ungrouped
A	Station-001 (south transept) Station-001 (south transept) Leveled	Station-024 (organ) Station-024 (organ) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.001 m	(0.000, 0.001, -0.001) m	Ungrouped
3	Station-001 (south transept) Station-001 (south transept) Leveled	Station-003 (crossing) Station-003 (crossing) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.002 m	(-0.001, 0.001, 0.001) m	Ungrouped
3	Station-001 (south transept) Station-001 (south transept) Leveled	Station-004 (south transept west aisle) Station-004 (south transept west aisle) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.002 m	(-0.001, 0.000, 0.001) m	Ungrouped
3	Station-001 (south transept) Station-001 (south transept) Leveled	Station-006 (south transept east aisle center) Station-006 (south transept east aisle center) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.003 m	(-0.001, 0.002, 0.002) m	Ungrouped
3	Station-001 (south transept) Station-001 (south transept) Leveled	Station-009 (ambulatory bay 3) Station-009 (ambulatory bay 3) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.003 m	(-0.002, 0.002, 0.002) m	Ungrouped
3	Station-001 (south transept) Station-001 (south transept) Leveled	Station-009 (ambulatory bay 4) Station-009 (ambulatory bay 4) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.003 m	(-0.001, 0.003, 0.001) m	Ungrouped
3	Station-001 (south transept) Station-001 (south transept) Leveled	Station-010 (ambulatory bay 5) Station-010 (ambulatory bay 5) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.002 m	(-0.001, 0.002, 0.001) m	Ungrouped
3	Station-001 (south transept) Station-001 (south transept) Leveled	Station-020 (north chapel west) Station-020 (north chapel west) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.002 m	(-0.001, 0.001, 0.001) m	Ungrouped
3	Station-001 (south transept) Station-001 (south transept) Leveled	Station-002 (north transept) Station-002 (north transept) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.001 m	(0.000, 0.000, 0.000) m	Ungrouped
B	Station-001 (south transept) Station-001 (south transept) Leveled	Station-003 (crossing) Station-003 (crossing) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.004 m	(0.000, -0.004, 0.000) m	Ungrouped
6	Station-001 (south transept) Station-001 (south transept) Leveled	Station-002 (north transept) Station-002 (north transept) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.001 m	(0.001, -0.001, 0.000) m	Ungrouped
6	Station-001 (south transept) Station-001 (south transept) Leveled	Station-003 (crossing) Station-003 (crossing) Leveled	Coincident - Vertex - Vertex	Dn	1.0000	0.001 m	(-0.001, -0.001, 0.000) m	Ungrouped

Fig. 4: Cathedral of Saint-Pierre in Beauvais, laser scan, June 2013: list of constraints for the interior registration, with corresponding error. Note that one of the constraints has been disabled because its error was greater than three millimeters. Image: Andrew Tallon.

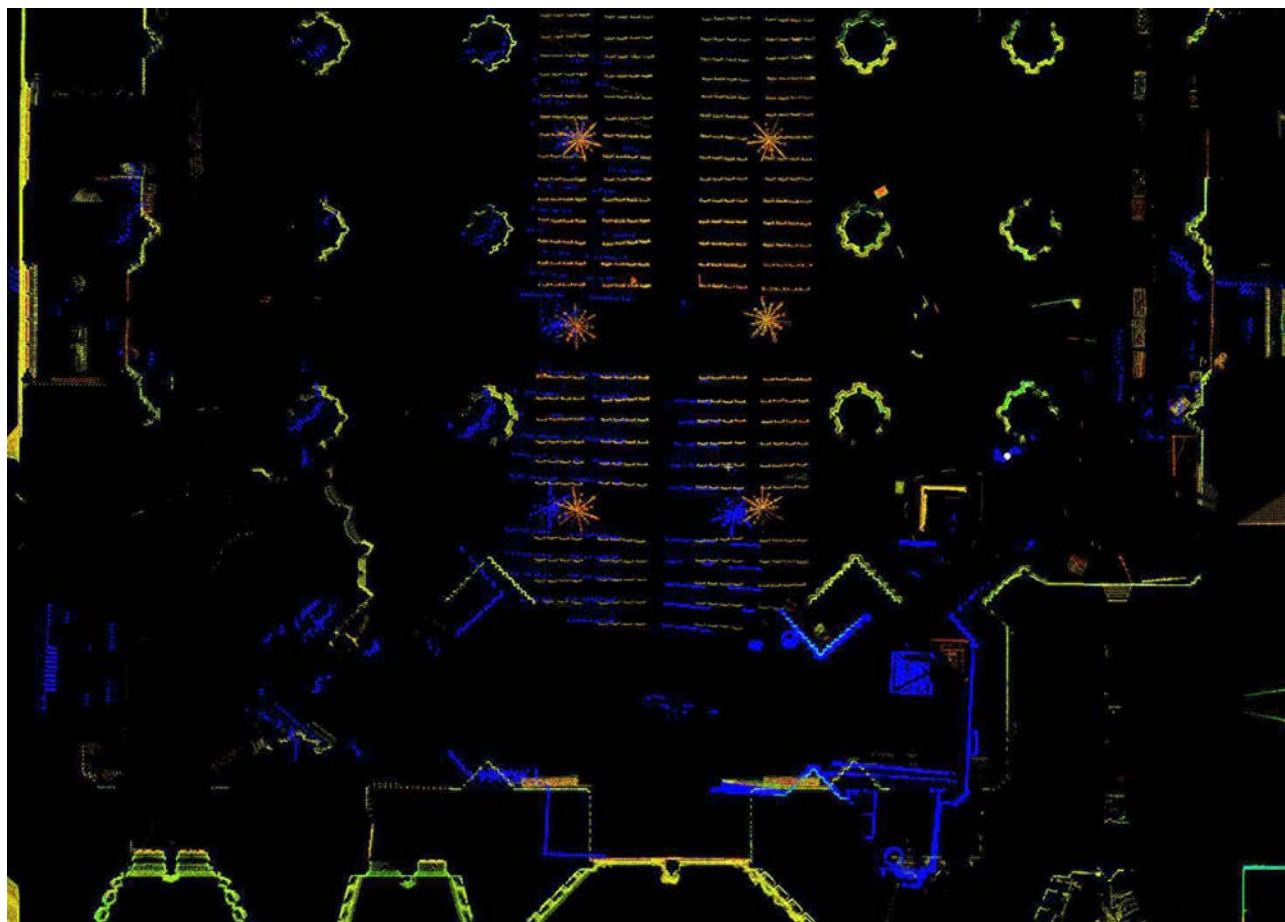


Fig. 5: Cathedral of Saint-Etienne in Bourges, laser scan, May 2008: alignment problem due to misnamed target in the westernmost bays of the nave. Image: Andrew Tallon.

Assembly

Once the desired stations and requisite control points are acquired the data must be registered – that is, assembled by computer.⁸ The software undertakes a series of interpolations to create a match among the various control points, or constraints, with the least error.⁹ It is often necessary to suppress certain constraints.

Scan-processing software offers two ways to understand and minimize error accrued during the process of assembly. First, it indicates the extent to which individual

registration constraints are distant from their positions as indicated by the final interpolation (Fig. 4). Second, it is possible to inspect visually the resultant registration for errors. Because laser scanners are often operated in full-dome mode, scanning through their entire spherical range, they tend to produce measurements that overlap with those of many other stations. When the scan data for a wall plane, for example, are examined at close range, it will be possible to see if the measurements of this wall as acquired in these various stations are coincident within

a range of error that is consistent with that of the laser itself (typically around five millimeters). If they are not, the flawed data must be traced back to the station to which they belong, and the constraints carefully verified to determine the source of the problem. **Figure 5** illustrates a dramatic error of several meters in the west end of the nave at Bourges Cathedral, the result of a target mistakenly given the name of another: the data in blue are meant to align with those in green.

Sectioning

Once the data are registered, sections, plans, and views can be created by limiting visible points. The rectangular excerpt of the plan of the abbey church of Saint-Denis in **Figure 6**, for example, is limited in vertical terms to the crypt and an adjoining meter of the chevet; it is graded in color according to elevation. Because the scanner generates points, not planes, all surfaces are transparent; it becomes possible to observe that the chevet piers (in orange) are not aligned with those of the crypt (in blue). If we assume that the builders in fact attempted to position one directly over the other, the disjunction could be attributed to a faulty positional translation necessitated by the presence of the crypt vaults and complicated, perhaps, by portions of the previous church still present on the site. An apparent miscalculation such as this would be of great interest if it could be taken as a benchmark for planning precision – for the builders' ability to control constructional error elsewhere in the church.¹⁰

In a similar way, a section through the nave of the abbey church of Saint-Leu-d'Esserent (**Fig. 7**) reveals information about the building with far greater clarity than could be had with the conventional tools of steel tape, plumb bob, or total station, for which multiple measurements of this density would be laborious at best. Such a section – a representation as visually explicit as it is precise – makes it possible to quantify, with a level of detail on the order of five millimeters, the vault-induced outward deformation of the building (Tallon 2012: 173–93).¹¹

Analysis

Any such subset of the cloud data can be imported into computer-aided design software such as AutoCAD, for the iteration of potential proportional schemes, using the robust shape generation and mensuration tools proper to such programs. The chevet plan of the Cathedral of Notre-Dame in Paris (**Fig. 8**), from a scan undertaken by the author in 2010, will supply an example (Sandron and Tallon 2013: 30–31, 183). The data reveal that the columns in the hemicycle and ambulatory of Notre-Dame were located using a series of concentric circles with proportional radii – as would be done subsequently at the geometrically proximate cathedrals of Bourges (**Fig. 9**) and Coutances.¹² Further, the scan data indicate that certain plinth faces among the intermediate ambulatory piers are curved according to the radius of the circle used to place them (A and B in **Fig. 10**).

This is a detail that is difficult to see in the building, and is easily overlooked when measuring by traditional

means: had one assumed, for example, that the plinths were square like their adjacent counterparts, one might well have fixed them in plan using their corner points alone. Finally, not only does the outermost concentric circle in the choir of the Cathedral of Paris probably locate the outer extremity of the original choir buttresses, but there is a direct correspondence between the penultimate circle and an equilateral triangle that appears to have determined the sectional envelope of the choir (**Fig. 11**).¹³ The entire spatial and structural system might thus be accounted for in plan.

Given the resemblance in plan and section of the cathedrals of Paris and Bourges, it could be expected that the transverse matrix at Bourges would also have been determined using an equilateral triangle. Yet this is a difficult hypothesis to sustain because of the perpetual uncertainty, in the absence of documentary evidence, concerning the key points of reference for an imposed geometrical shape. Should the base of the triangle spring from the inner faces, the outer faces, or the centers of the outer walls? To which vertical points must the triangle altitude correspond to be considered legitimate? The transverse vault rib, the severies just above, or the extradados of the vault?

That no accurate section of Bourges existed until recently (**Fig. 13**) has not made the quest any easier. Eugène-Emmanuel Viollet-le-Duc, for example, derived the sectional proportions of the building using a drawing he had copied, apparently without having visited the building, from a highly confected section made by diocesan architect Hippolyte Roger in the early nineteenth century.¹⁴ Viollet-le-Duc's image was widely disseminated, as was a rectified version (**Fig. 12**) published by Georg Dehio and Gustav von Bezold (Dehio and von Bezold 1894: plate 376).¹⁵ In the late 1950s Robert Branner and Pierre Capron took a series of measurements of the building for Branner's doctoral dissertation (Branner 1953). Capron then created a new section drawing (**Fig. 13**) that was printed on a large fold-out piece of paper placed at the back of the 1962 edition of Branner's monograph (Branner 1962: plate 1).¹⁶

These were the drawings that Peter Kidson probably had at his disposal – though he did not identify which he used – when he attempted to address the questions posed above in an article published in 2000 (Kidson 2000: 147–56). Kidson proposed that the distance between the exterior faces of the outer choir walls at Bourges was calculated using 30 perches of 1.42 meters, each equal to five 28.5 centimeter-long feet – an unusual unit whose origin he did not discuss.¹⁷ The altitude of an equilateral triangle with a side of 30 is 26 – two numbers, Kidson argued, that were chosen for a specific reason (Kidson 2000: 155). The ratio of 26 to 15 (half of 30) was the most precise arithmetic approximation in common use for $\sqrt{3}$, a number necessary to calculate the triangle altitude (altitude = $\frac{1}{2} \cdot \sqrt{3} \cdot \text{side length}$). Kidson believed that Bourges had been dimensioned literally according to the formula – an idea that he found particularly compelling because of an apparent conceptual link with the cathedral in Paris. An

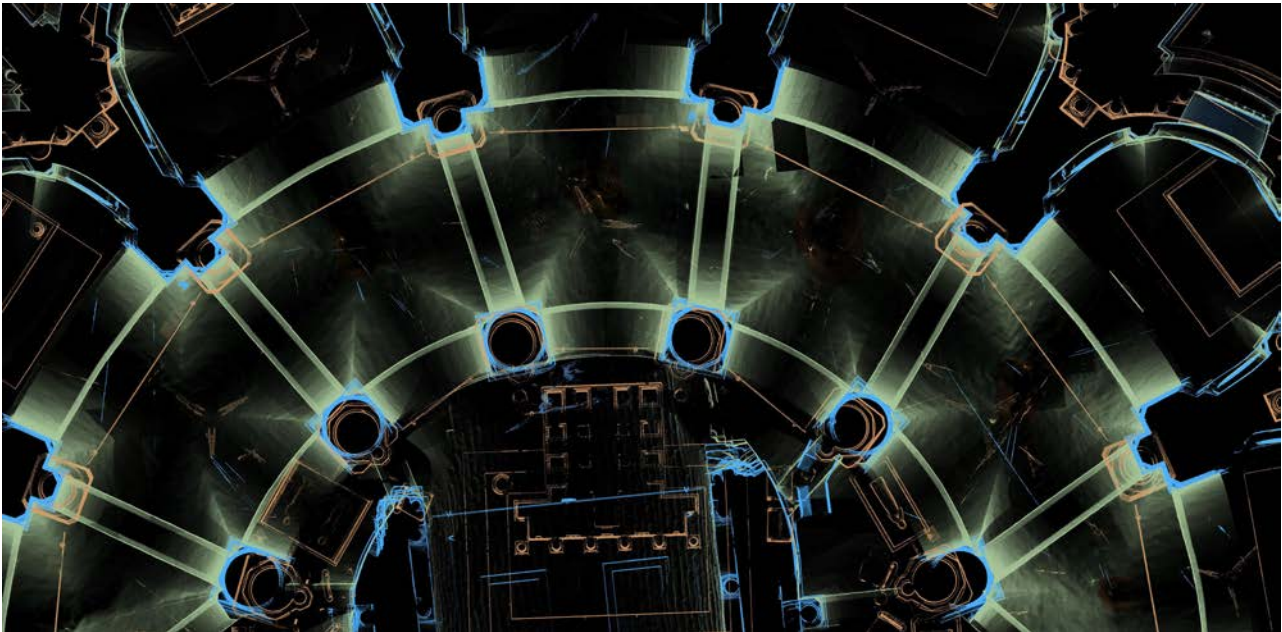


Fig. 6: Abbey church of Saint-Denis, laser scan, June 2011: color-coded plan and section of the sanctuary and crypt. The crypt piers and bases are in blue, the crypt vaults are in green, and the sanctuary piers and bases are in orange. Image: Andrew Tallon.



Fig. 7: Abbey church of Saint-Leu-d'Esserent, laser scan, June 2011: section through the nave. Image: Andrew Tallon.

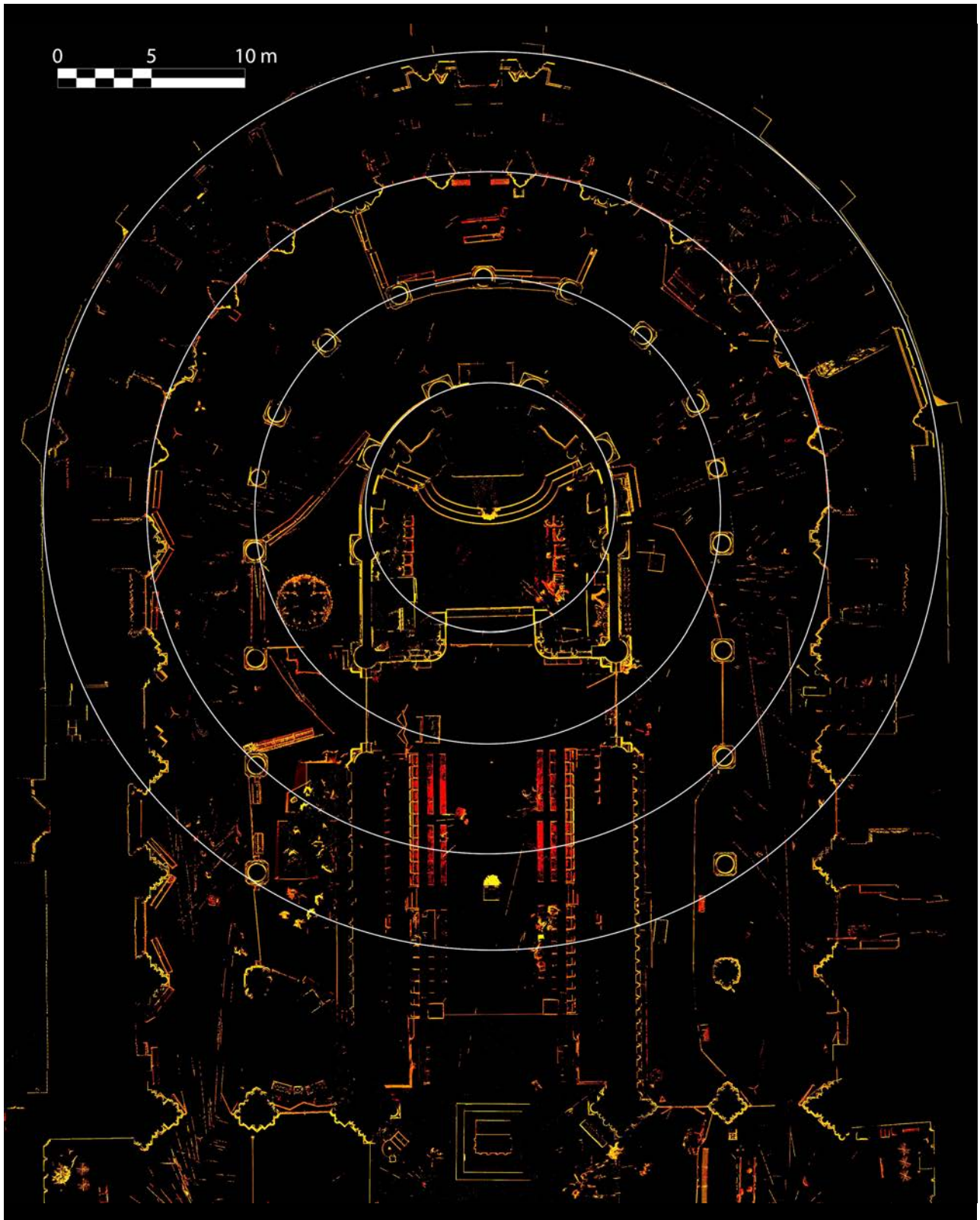


Fig. 8: Cathedral of Notre-Dame in Paris, laser scan, January 2010: plan of the choir with concentric circles of proportional radii. The circles have radii of 6.65 m, 12.42 m, 18.19 m, and 23.96 m. Image: Andrew Tallon.

equilateral triangle with sides of 26 perches corresponds, in Kidson's words, 'as nearly as no matter' with the sectional matrix of Notre-Dame (Kidson 2000: 155).

Kidson's triangle does indeed align well with Branner's section (**Fig. 13**) and 'as nearly as no matter' with that of Dehio (**Fig. 12**); the same must have been true for

whatever section of Notre-Dame he tested. Yet when imposed on a laser-generated section of the choir of Bourges (in white in **Fig. 14**), the correspondence is less compelling. The exterior faces of the outer choir walls are ten centimeters further apart than dictated by the 1.42 meter perch – admittedly a fairly minimal difference.

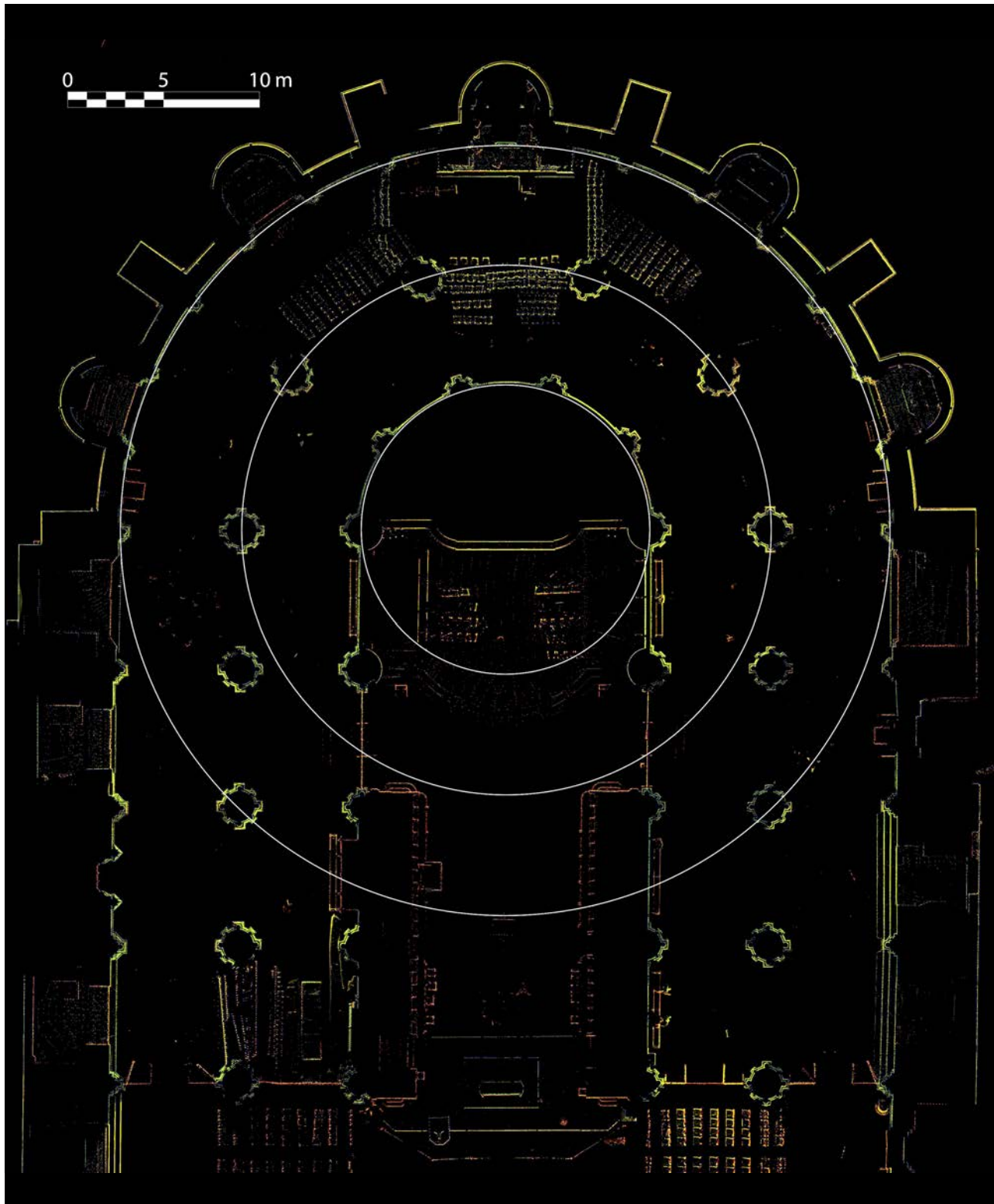


Fig. 9: Cathedral of Saint-Etienne in Bourges, laser scan, May 2008: plan of the choir with concentric circles of proportional radii. The circles have radii of 7.53 m, 13.8 m, and 20.07 m. Image: Andrew Tallon.

Yet what to make of the triangle peak, which extends 40 centimeters above the vault extrados?¹⁸ As for the correspondence with Notre-Dame in Paris, is the actual width of the choir, expressed in Kidson's enigmatic perch units, 25.6, sufficiently close to 26 to forge the link?

Another triangle lurks in the wings, that generated from the outermost concentric circle of the plan of **Figure 9**,

with diameter of 40.14 meters (in red in **Fig. 14**). Yet its peak falls 98 centimeters *below* the vault keystone – not much of an improvement in correspondence with respect to the triangle proposed by Kidson. There are two potential morals of this story: first, it may be time to abandon the supposed equilateral triangularity of Bourges in favor of a scheme that better reflects constructional

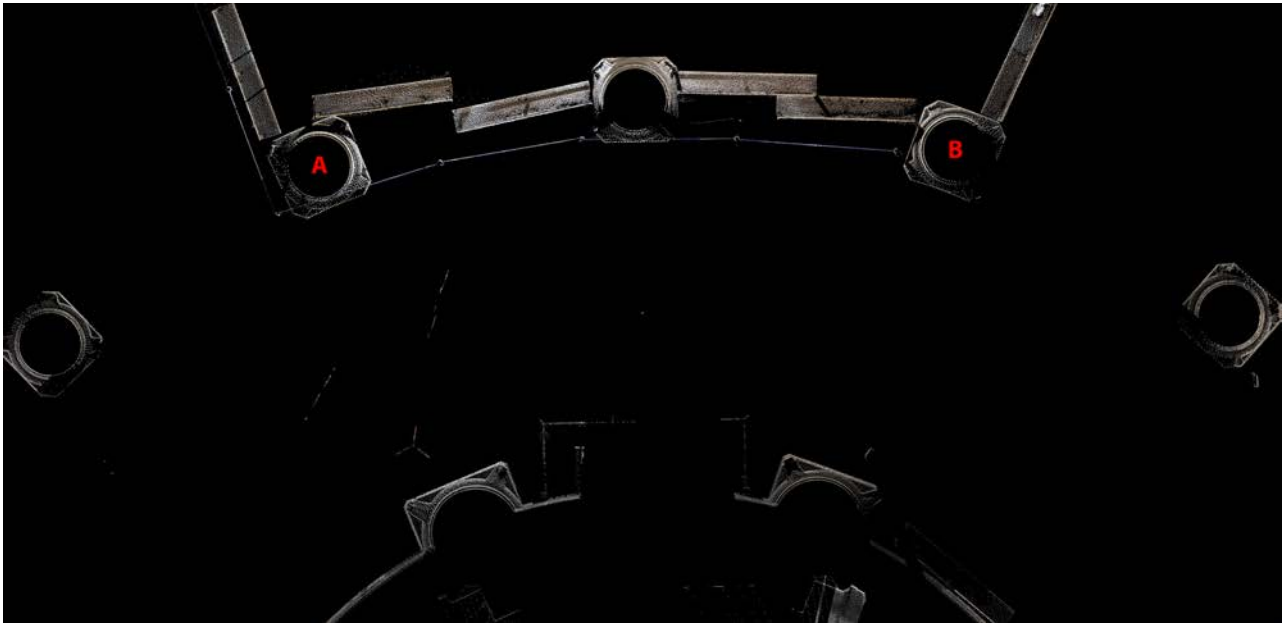


Fig. 10: Cathedral of Notre-Dame in Paris, laser scan, January 2010: the inner faces of the intermediary aisle columns that frame the axial bay (A and B) are curved. Image: Andrew Tallon.

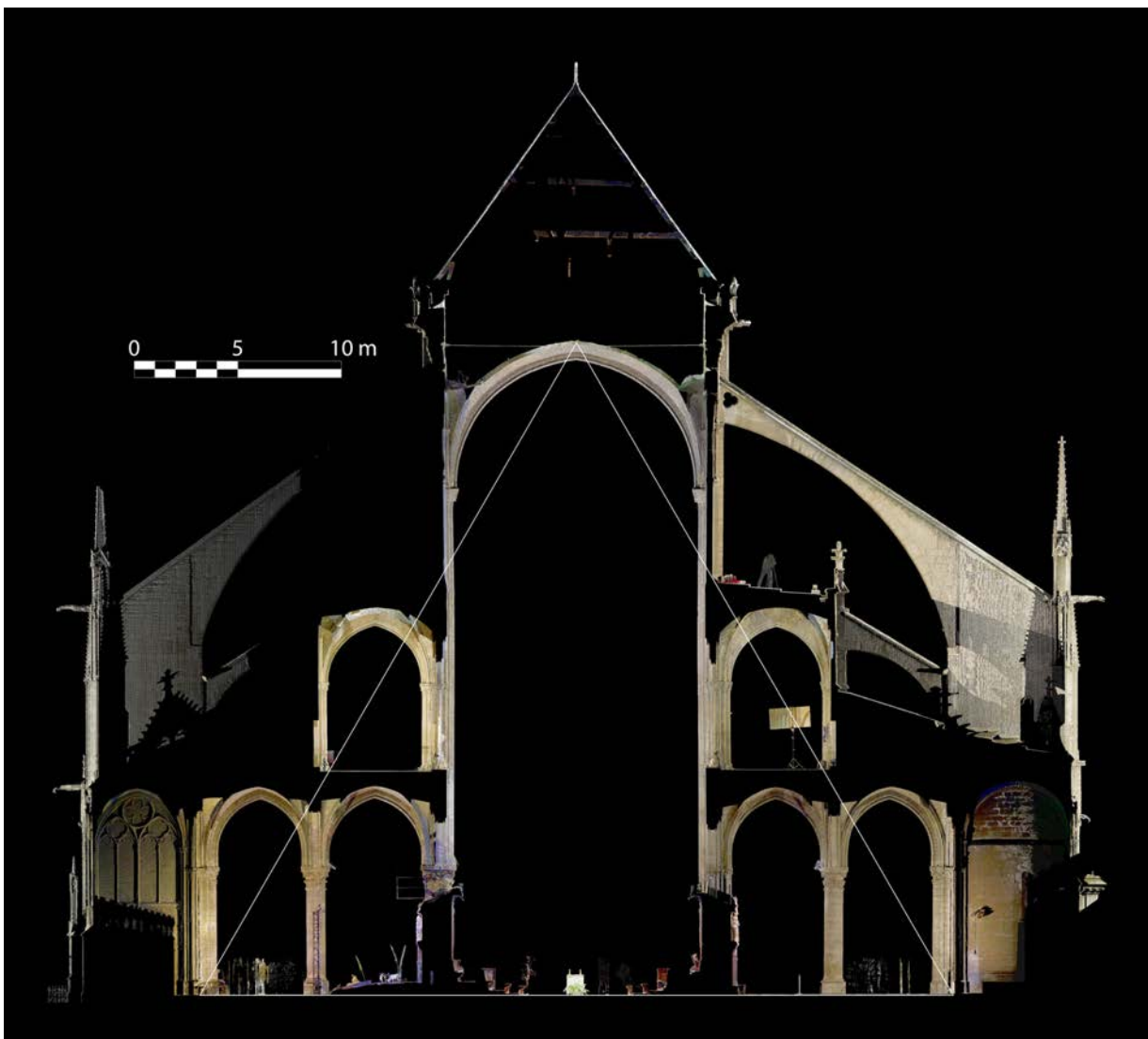


Fig. 11: Cathedral of Notre-Dame in Paris, laser scan, January 2010: section through the third straight bay east of the chord of the hemicycle with superimposed equilateral triangle. Image: Andrew Tallon.

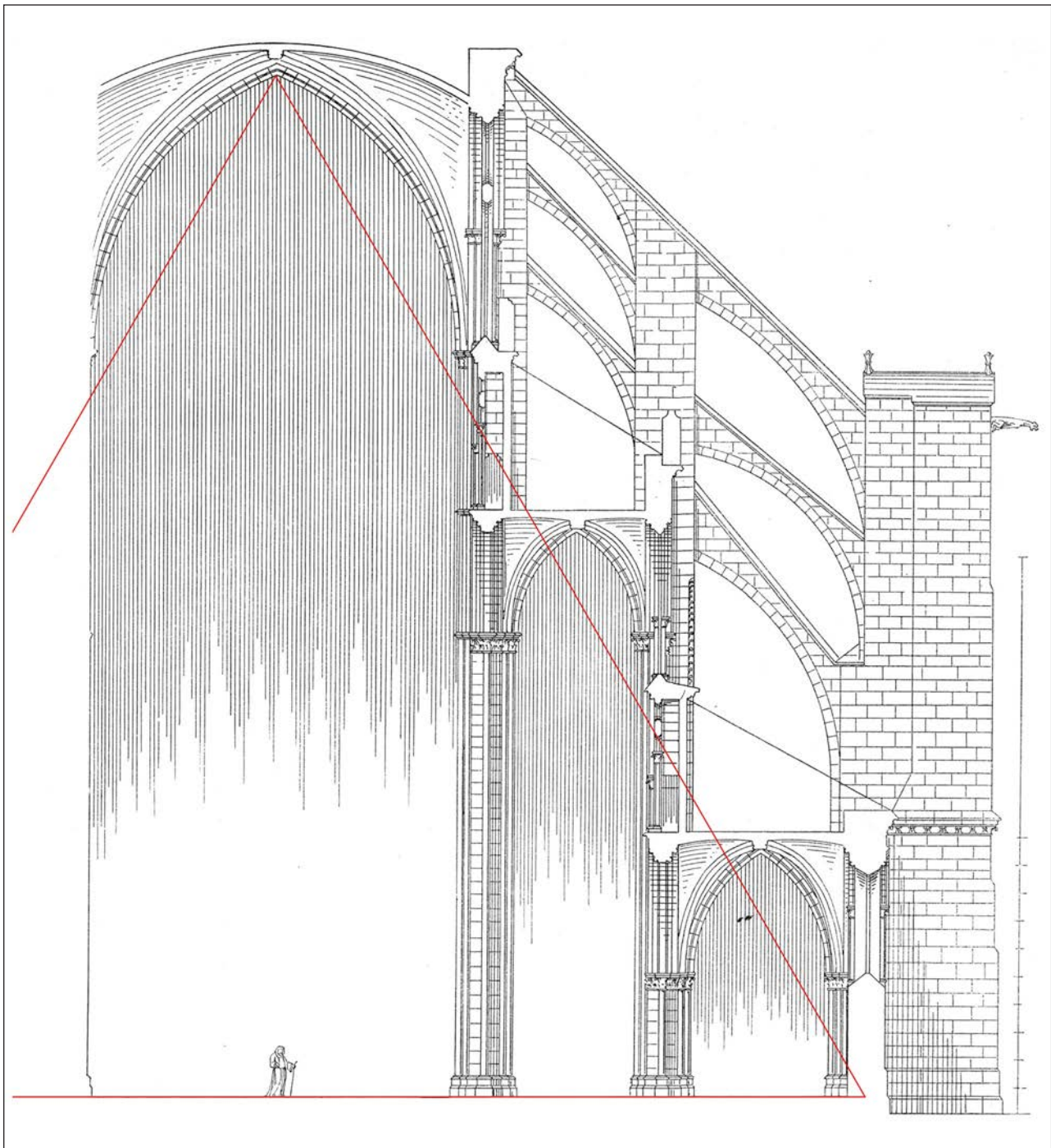


Fig. 12: Cathedral of Saint-Etienne in Bourges, section drawing (Dehio and von Bezold 1894: plate 376), with equilateral triangle superimposed by Andrew Tallon.

reality – one that can account for the disposition of the inner and outer aisles, for example.¹⁹ Second, and perhaps more importantly, working with existing plans and sections for which the precise conditions of acquisition and rendering are unknown is sufficiently fraught with problems as to render the prospect untenable, as Ackerman seems to have suggested. Had Kidson seen the imperfect consonance of his triangle with the actual building, as indicated here by the laser scan, he might have been reluctant to propose what in retrospect appears to be a foot unit concocted to fit the formula.

In the alignment of proposed proportional schemes with an actual building, how close is close enough? 40 centimeters? Or 4 centimeters? Laser scanning cannot tell you this – but it *can* tell you where you stand. By making it possible to represent structures in a highly accurate, explicit, and time-efficient way, laser scanning supplies the means to combat imprecision and its correlate, the numerical wizardry sanctioned thereby – and thus has potential to revolutionize the venerable but vexed process of reverse engineering proportional systems directly from the building fabric.²⁰

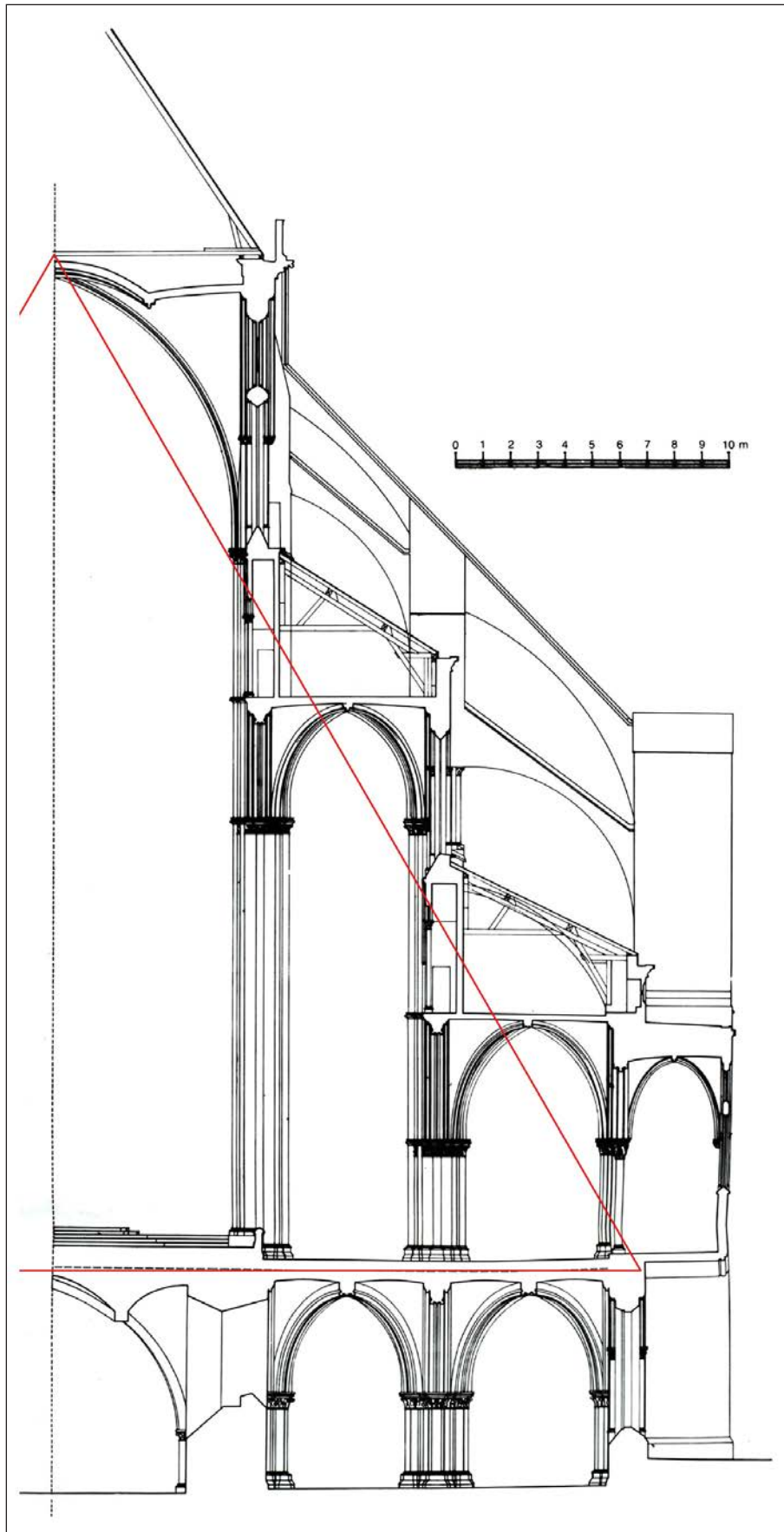


Fig. 13: Cathedral of Saint-Etienne in Bourges, section drawing (Branner 1989: plate 1), with equilateral triangle superimposed by Andrew Tallon. Note the distortion introduced into the southern outer aisle, chapel, and buttress by a fold in the paper – another hazard of using existing plans.

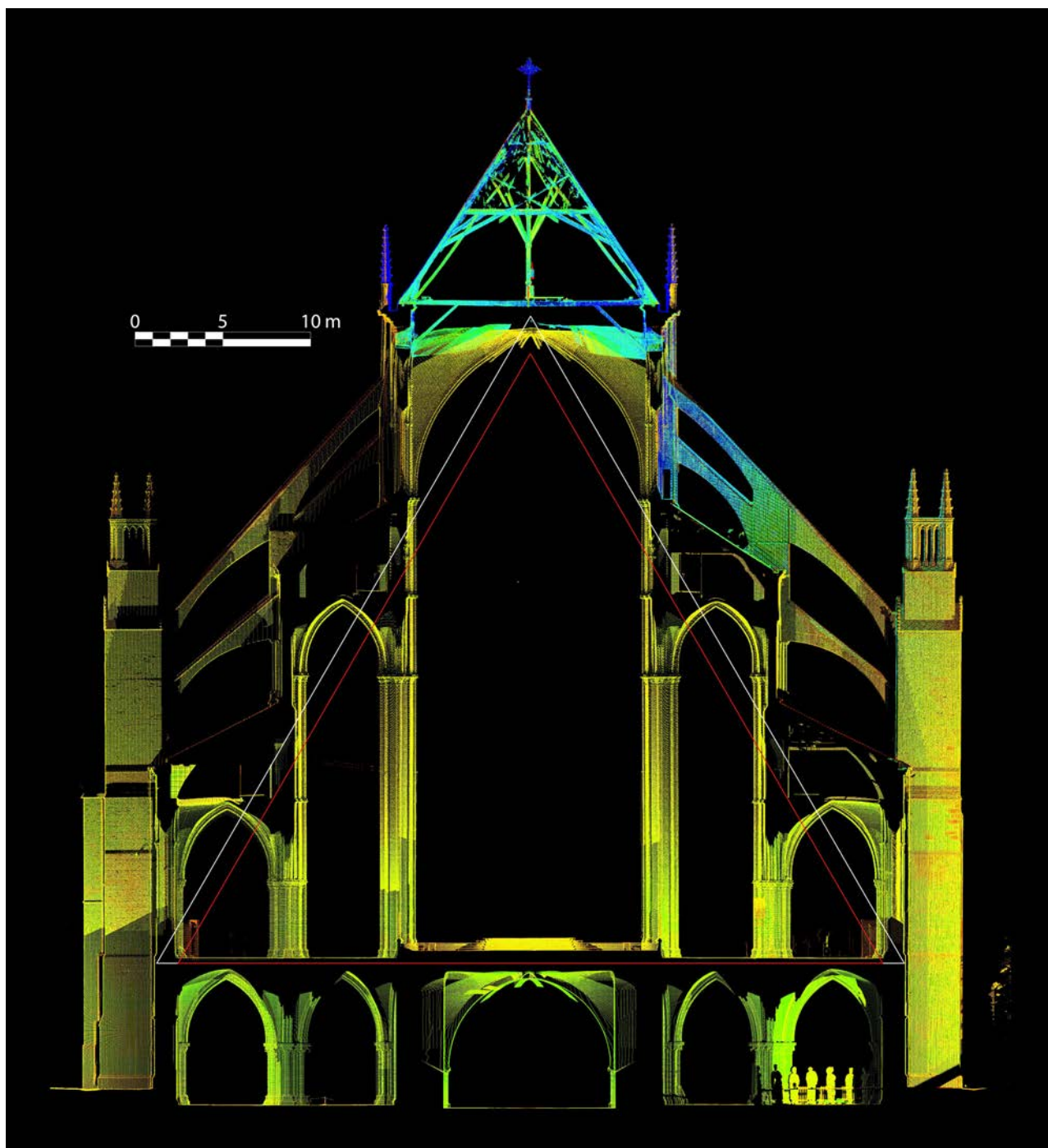


Fig. 14: Cathedral of Saint-Etienne in Bourges, laser scan, May 2008: section through the chord of the hemicycle with superimposed equilateral triangles. In white, the hypothesis of Peter Kidson; in red, an alternative hypothesis based on the diameter of the outer circle in Figure 9. Both triangles are placed 30 centimeters below the current pavement to match its original level. The section includes scan data of the roof acquired by the 3d surveying and imaging company Art Graphique et Patrimoine; I am grateful to directors Gael Hamon and Didier Happe for permission to use them. Image: Andrew Tallon.

Acknowledgments

I am grateful to Matthew Cohen and Michael Davis for their helpful comments.

Notes

¹ Nigel Hiscock's account of his struggle with these problems is particularly revealing: Hiscock (2000: 293–98). See also Fernie (1990: 230).

² For a discussion of the changes brought by photogrammetry and laser scanning to the discipline of architectural surveying and drawing see Sartor (2011: 90–103). See also Davis (2011: 219–33).

³ The four major manufacturers of laser scanners used for surveying purposes are at present Leica Geosystems (<http://www.leica-geosystems.com>), Faro (<http://www.faro.com>), Trimble (<http://www.trimble.com/3d->

- laser-scanning), and Riegl (<http://www.rieglusa.com>). For further discussion of the technical aspects of laser scanning, see García-Gómez et al. (2011: 25–44).
- ⁴ As with Leica Geosystem's current top-of-the-line scanner, the P20.
- ⁵ It is standard practice to use a total station in conjunction with a laser scanner to supplement this control point network, although the technology is advancing in such a way that this method may soon be outmoded. Leica Geosystems's Nova series, for example, combines the functions of total station and laser scanner.
- ⁶ It is possible, in some scan processing software, to recognize a series of targets, distributed liberally throughout the building, *after* the scan has been completed. While this practice increases the speed of operation in the building, because no time is spent scanning targets or other control points, it can entail several important risks: first, that an insufficient number of targets might be placed; second, that a given target might not be scanned with sufficient resolution to be properly recognized by the scan processing software; and third, that a target critical for registration might be lost, unbeknownst to the operator, when someone visiting or working in the space inadvertently interrupts the laser beam at the very moment that the scanner passes over the target in question – something that happens with unfortunate regularity.
- ⁷ At Bourges, 123,204,667 measurements were acquired; at Beauvais, 2,915,108,374. I am grateful to Leica Geosystems France for having supplied me with their latest laser scanner, the P20, for the Beauvais survey; to El Mustapha Mouaddib at the University of Amiens and Stephen Murray for their collaboration; and to Columbia University graduate student Nicole Griggs for her assistance with acquisition. Supplemental scans were produced using a Leica Geosystems C10 and a Faro Focus Focus3D X 330.
- ⁸ Typically, the software used for registration is that published by the manufacturer of the survey machine. The software used by the author is called Cyclone, by Leica Geosystems.
- ⁹ Certain scan processing software packages are able to recognize common forms and planes in raw scan data through superimposition and error calculation to create constraints, but the technique depends on high scan density and large planar surfaces and is ultimately less precise than when targets are used.
- ¹⁰ On the question of planning precision at Saint-Denis see Crosby (1987: 233–41); Kidson (1987: 11–17); Van Liefferinge (2011: 147–57); and Bork (2013: 55–68). See also Cohen (2008: 18–57).
- ¹¹ For a more general discussion of deformation and its analysis, see Tallon (2013: 530–54).
- ¹² The circles at Notre-Dame have radii of 6.65 m, 12.42 m, 18.19 m, and 23.96 m; the difference in radius between each adjacent circle is exactly 5.77 m. The octagon-based theory of Stefaan van Liefferinge (2010: 496–502) is untenable given its lack of correspondence with the building fabric.
- ¹³ The buttresses were later extended outward by roughly 1.5 m, according to Viollet-le-Duc (1856: 293). See Tallon (2007: 150–53).
- ¹⁴ Roger's section is published in Martin and Cahier (1841–1844). For Viollet-le-Duc's sectional analysis, see (Viollet-le-Duc 1864: 546–49); his transverse section of Bourges is found in Viollet-le-Duc (1854: 199, Fig. 34). The earliest section – though only partial – appears to be that by François-Narcisse Pagot of 1833 (Charenton-le-Pont: Médiathèque du Patrimoine 82/18/1002 no. 14305).
- ¹⁵ Dehio and von Bezold, though they often redrew sections, had good reason to rectify this image in particular: the drawing as printed in the *Dictionnaire* was somewhat skewed. Two further transverse sections, little known outside the world of the *Monuments historiques*, were created in 1889 by Paul Boeswillwald (Charenton-le-Pont: Médiathèque du Patrimoine 82/18/1002 no. 14302) and in 1943 by G. Desmarest (Charenton-le-Pont: Médiathèque du Patrimoine 82/18/2004, no. 81194).
- ¹⁶ The section drawing published in 1962 is missing a scale reference; it was included in the posthumous English edition (Branner 1989: plate 1).
- ¹⁷ Kidson (2000: 155–56) noted only that he had had 'occasion to argue that one of the more widely used masonic yardsticks had a length of ca. 1.42 m' that 'could be subdivided in various ways to produce a series of documented foot measures; and it is a moot point whether in any given case the conceptual unit was the foot or the yardstick'. Unfortunately his discussion of this perch, during the Mellon Lectures of 1980, was never published.
- ¹⁸ The triangle in **Figure 14** is set at the level of the original choir pavement, 30 cm lower than at present.
- ¹⁹ Viollet-le-Duc (1864: 546), despite having employed a faulty section for his analysis, wrote that 'tout le système des proportions de la cathédrale de Bourges dérive du triangle isocèle rectangle, et non point du triangle équilatéral'.
- ²⁰ Stephen Murray's forthcoming work on the geometry of the chevet and crypt at Saint-Denis is a case in point.

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