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How Should We Measure an Ancient Structure?

The author examines the questions of precision and accuracy in the measurement of ancient buildings, taking into account the separate requirements of both scholarship and preservation. Modern technology has changed matters significantly and promises to continue to bring change. Whereas the problem was once measuring as precisely as possible or as precisely as a scaled drawing could display, the problem is now to measure and record as precisely as required for the particular project. For each survey project, the answer must be unique, but it must be well and carefully argued with respect to the tools at hand and the subject. It is no longer appropriate to assume that the most precise measurements are necessary. Technology has advanced; now the decisions are ours.

It is possible—though certainly a simplification—to see the recording of architectural monuments as flowing from one of two traditions: scholarship or preservation. That is, scholars measure and record buildings for the purposes of understanding the structures, conveying that understanding to others, and generally advancing our knowledge of the built environment. Those who are responsible for the long-term preservation of structures, on the other hand, measure and record in order to provide necessary information to those who must repair, replace, or preserve the structure.

The precision with which scholars measure and record has often been limited by the available technology and cost. In addition, very high precision has been pointless, since scaled drawings limit the extent to which very precise information can be recorded, displayed, and retrieved. Even a scale of 1:10, much too large to permit the plan of a modest structure to fit on a page, makes it impossible to convey dimensions made to the nearest millimeter.

For those who are responsible for the preservation of structures, measuring precision must be much higher. If repairs are required, the measurement must be within the tolerances of the repair process; that is, precision must be based on the tolerances of a contractor. Depending on the structure, the building tradition in which it lies, and the construction materials, the required precision may be, simply put, as high as possible. For cut-stone structures from the classical period, for example, the absence of mortar places very high demands on reconstruction work—as it placed high demands on original construction processes. At the same time, however, contractors may assist in the measuring and recording processes, providing ways to repair or reconstruct monuments that depend less on measurements and drawings than on the craft tradition.

For both these groups—those involved in scholarship and those involved with preservation—modern technology has changed matters significantly and promises to continue to bring change. Advanced survey equipment (particularly total stations), computer-aided design (CAD) software, desktop photogrammetry, 3D scanners, and other technological aids bring not only new techniques but also new questions and even new underlying principles, often quietly and surreptitiously. Those changes require acknowledgement and open discussion to make sure that all understand the impact of the technology and explicitly reconsider work habits and assumptions in light of the technological changes.

The technological advances have worked together to magnify the total impact, and it is difficult to separate them for that reason. Therefore, the following discussion may seem artificial as the individual elements of change are isolated from one another. It is made all the more artificial by omitting discussion of 3D scanners.¹

Total stations make it possible to survey the world—whether the built environment or the natural one—with incredible precision. The coordinates of an individual point may be returned with precision to the nearest thousandth of a millimeter in each axis of the applicable Cartesian grid. This precision is seductive; users tend neither to question the utility of the precision nor the accuracy of the coordinates. (English usage tends to confuse the two terms, accuracy and precision. Precision refers to the fineness of measured distinctions; measuring the length of a block as 1.234 m. is more precise than measuring it as 1.23 m. Accuracy is the correctness of the measurement, regardless of its precision. The same block can be measured inaccurately, for instance, as 1.233 m. or 1.24 m. long, at different levels of precision.)

Starting with the question of accuracy, it must be understood that total stations have built-in limits on precision that are often ignored and that affect ultimate accuracy. Any reading is based on two angular measurements, each of which is measured to the nearest 1, 2, 5, or 10 seconds, depending on the specific instrument. The precision with which the angle is measured, in turn, should limit the precision that any calculation can generate, since no calculation can produce a result more precise than its least precise component. However, the calculations of the total station will assume absolute accuracy of the angular readings and produce unwarranted precision. (Using trigonometric functions, one can easily determine those limits on precision.) Similarly, the remaining measurement—of the distance from the instrument to the survey point—has precision limits that can be calculated. Taken together, the calculations of precision yield the true precision that can be expected of a survey measurement. No reported survey point location exceeding that level of precision should be taken to be accurate; that is, if such a location is accurate and more precise than the calculated limits permit, the accuracy is a matter of chance.

Since very precise—and necessarily inaccurate—point locations will be reported by a total station, any survey project should include two processes. First, calculations based on the characteristics of the particular instrument and the survey conditions should be

carried out to determine real precision potential. Second, a rounding-off process based on real precision should be applied to all incoming data. Only then can the results be accurate, with precision determined by the capabilities of the instrument.²

Turning to the issue of precision, the question shifts from what is possible to what is necessary. Assuming that survey locations received from a total station are precise (and accurate), for the sake of argument, to the nearest tenth of a millimeter, how useful is that precision? Does it matter if one knows that a block of the Parthenon is 2.1345 m. long rather than 2.134 m.? Does that extra precision provide real information or only the appearance of scientific precision? For the mason trying to carve an adjacent block, the distinction may be important, but he will use construction tools, calipers for instance, rather than measuring tools to determine the shape of a replacement block. For anyone else, it seems impossible to argue that understanding is enhanced by the extra precision. This is especially true when the measurement units are not absolutely certain, the tools are not preserved, and the measuring procedures are unknown—for both planning and construction—as is the case with the Parthenon.

There is, in fact, an important reason to resist unnecessary precision. Measuring with such precision implies that, for instance, the Parthenon stone was carved to its current shape according to supplied dimensions rather than being carved to fit. It may also imply an ability to measure with such precision in antiquity, something for which there is no evidence. Masons' techniques, then as now, do not rely so much on measuring as on matching stone to stone. Sub-mm. precision is thus not useful and may be positively misleading.

Indeed, why even measure to the millimeter? There is, in fact, a good reason for measuring to the millimeter. The blocks of classical architecture were fitted together without mortar, using iron or bronze clamps and dowels instead. As a result, great precision was truly necessary to the building process. Therefore, millimeter precision seems appropriate for the student of such a structure.

But what does one do about a Neolithic mud-brick hut? What level of precision is appropriate in that case? Mud-brick structures were necessarily re-coated on a regular basis as the coating deteriorated and washed off. They are often irregular as well, and square corners are all but unknown. Does it make sense to measure them with millimeter precision. Centimeter precision? I would not pretend to answer the question in the abstract, but the scholar contemplating such a structure must decide what level of precision is required — and be willing to record measurements with only that level of precision, potential methodological criticism from colleagues notwithstanding.

Roman concrete construction provides another interesting example. In many cases, Roman buildings survive as concrete wall cores with missing veneer. How precisely should such walls be recorded? It is clear that the finished surfaces are not present and that the measurable remains do not precisely locate those finished surfaces. Why would one measure such parts of a structure to the millimeter? Again, an answer in the abstract

is not forthcoming, but a scholar must have an answer—and the reasoning behind it—to guide work on such a project.³

In each of these instances the crucial factors affecting data precision are found in the nature of the structure, the architectural tradition from which it arises, and its condition. Technology has no place in determining the precision to be sought. It may provide limits, but the limits are now such that the scholars in charge need no longer ask for all the precision possible. They must now aim for the precision required.

The use of photogrammetry is very similar to the use of total stations. There are limits on precision based upon a different group of contributing factors — lens distortion, precision of lens focal length measurements, sizes of photos used, and so on. Calculations should be made to determine the precision that can be obtained so that a rounding-off process can be used for data from photogrammetry as from total stations.

The use of computer-aided design (CAD) software for recording structures brings a different but related concern about precision to the fore. The use of a CAD program makes it possible to record in three dimensions, to record the information in segments that can be combined or separated at will, and—the important issue here—to record dimensions precisely, without regard to issues of scale that would otherwise limit the representation of precise dimensions. When a CAD model is built, the computer can accept and retain the coordinates of any point, and the precision of each coordinate will be absurdly precise, perhaps to the nearest hundred-thousandths of a unit, whatever the measuring unit. The use of CAD removes any and all impact of drawing scale on the process of measuring and recording.⁴

Given such extraordinarily precise point locations, a CAD model can obviously calculate the distance between any two points with the same precision. Thus, a CAD model maintains a distinction between the distance from point A to point B of 1.12343 m. and the distance from B to C of 1.12344 m. Of course, the difference cannot be seen in a drawing of normal scale, but the CAD program can—and will, on command—provide such precise dimensions to any user at any time. As a result, limits on drawing precision that were once inherent in the use of scaled drawings have been removed by CAD systems.

Since the removal of limits on recording, displaying, and retrieving very precise measurements provided by CAD software coincides with the availability of very precise measurements provided by total stations and photogrammetry, the use of very precise dimensions meets no natural resistance from the technology. Nevertheless, the precision supplied by total stations or photogrammetry software and recorded in CAD models must not exceed the limits on accuracy of the total system and must be appropriate for the job at hand. As already stated, every project has its own needs for precision. Those needs should be carefully determined, explicitly stated, and properly met by the survey methods and procedures.

Whereas the problem was once measuring as precisely as possible or as precisely as a scaled drawing could display, the problem is now to measure and record as precisely as required for the particular project. That is, technology permits measuring and recording dimensions or coordinates in a grid system with such precision that we must now choose the level of precision that is appropriate or necessary for any project, knowing that the limits are no longer restrictive.

The technology offers no guidance as to desirable precision. Sadly, it may even encourage false precision. Many CAD programs will automatically pad point coordinates with trailing zeros, making it seem that a dimension such as 1.123 m. is actually 1.12300000 m. Anyone using a CAD model, in fact, might have all retrieved dimensions reported with such precision. As a result, documentation accompanying any CAD model must explicitly discuss issues of data precision (and data density) so that users will have the necessary information about the precision with which dimensions were made. Even the most carefully considered choices by a scholar in charge of a building survey will be of little value if not communicated to all who use the survey results. This requirement, of course, makes it all the more necessary for decisions about measurement precision to be made explicitly and thoughtfully.

There is a separate problem of precision that must be acknowledged. Any measurement assumes a standard unit of measure, and measuring any constructed item, from a piece of military armor to a building, in a unit other than the unit used by its designer/builder is fraught with danger. A very simple experiment may be illustrative.

I measured the same distance twice, once in mm. and once in inches. The distance was measured as 766 mm. and 30 1/8 in. Had I measured something planned and made with English measuring units as 766 mm. long, I should translate from the metric measurement to an English one (using the standard ratio of .03937 in. = 1 mm.). The measurement, expressed in the English system, is thus 30.1572 in. However, using the English system implies inches and non-decimal fractions thereof. The nearest fractional measurement is 30 5/32 (30.15625), but using it assumes that the craftsman planned and measured to the nearest thirty-second of an inch. If one assumes plans and measurements to the nearest sixteenth of an inch, the measurement would have to be 30 1/8 in. or 30 3/16; if to the nearest eighth of an inch, 30 1/8. How would one choose from those alternatives? That would depend on many factors, including the nature of the object, the time of its manufacture, and so on.

Starting from the other measurement (30 1/8 in.) and assuming that the object in question was made by someone using the metric system, I would translate in reverse (25.4 mm. = 1 in.). The measured distance thus becomes 765.175 mm. I would round that to 765 mm.⁵

Some would argue, as Costantino Caciagli did in “Viewpoint: On Precision in Architecture”, that this difficulty of measuring in foreign units is insurmountable, “In order to perform a survey that is philologically correct, it is necessary to ban every optic instrument . . . , to use instead instruments that are similar to those used in the [original]

construction.”[6] For someone like myself working with classical material, using an old measuring instrument is impossible. We know so little about the measuring instruments used in fifth century B.C.E. Athens that I must measure with modern tools; I have no ancient measuring devices and no way to make them.

Many scholars are in the same position. Indeed, I would argue that all are in the same position, since we cannot measure with the actual measuring device used for any given structure. At best, we might know the unit applied and the design of the measuring device, making it possible to measure with a replica. However, I believe the variations from one actual physical device to another would have been too great to permit the use of a replica, that a replica is no better than a meter stick.

If we cannot measure the Parthenon with an ancient Greek version of a steel tape or measure an Anasazi kiva with an Anasazi ruler or measure a Neolithic mud-brick hut with a Neolithic foot, what are we to do? I believe that we have no real choice but to measure with a contemporary standard, that only the actual measuring devices used on a particular project—not those from a similar, contemporary one or reconstructions based on contemporary evidence—could be a suitable replacement.

If we are measuring in meters, the next question is whether to measure to the nearest meter, the nearest centimeter, the nearest millimeter, or perhaps the nearest nanometer (.000000001). The answer is not simple; nor is it the same answer for all projects. We measure to the nearest light year when dealing with interplanetary space, to the nearest nanometer when dealing with computer chips. Each is the appropriate standard for its subject. I believe we should measure to the nearest millimeter when dealing with classical buildings, that the mm. is the appropriate standard there. For each survey project, the answer must be unique, but it must be well and carefully argued with respect to the tools at hand and the subject. It is no longer appropriate to assume that the most precise measurements are necessary. Technology has advanced; now the decisions are ours.

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Notes

1. The technology for 3D scanners is improving rapidly. It is certainly possible to duplicate an intricate architectural member today with a 3D scanner's information. However, the use of scanners for recording the remains of monuments has a serious theoretical problem: the points actually recorded are determined by the placement and discrimination of the scanning grid. Until and unless the operators of these scanners can choose the particular points surveyed, 3D scanners are not appropriate technology for surveying architectural monuments.
2. There are additional considerations for accuracy/precision. As one surveys a large area, the instrument must be moved. The new location—called an occupy station point—must be surveyed and the precision with which the new occupy station point can be located must be considered when determining the precision of all survey data generated from it. The process continues indefinitely, with each new occupy station point generating new limits on precision. Furthermore, this process means that points surveyed from a single occupy

station point will—compared only to one another—be accurate at a higher level of precision than possible for points taken from multiple occupy station points. Similar issues apply if a complete circuit of the subject is made, closing calculations applied, and all occupy station points adjusted to achieve proper closure.

3. The mud-brick example and the Roman concrete one bring up separate but related questions. How many data points must be taken, and how closely spaced should they be? The mud-brick wall is unlikely to be a straight one, but the deviation from straight is unintentional. How many points along the wall should be measured? Similarly, the shape of the broken top of a Roman concrete wall core is an accident of cruel fate. How many points defining the line of breakage need to be measured? There are similar questions for any project; it is preferable to make such questions explicit so that they can be answered carefully and not accidentally.
4. The precision with which a CAD system can maintain coordinates depends on the internal data structure chosen, but all standard CAD systems maintain coordinates at levels of precision beyond the scholar's capacity to measure.
5. The two arguments about measurement translations ignored important issues of significant digits and their impact on the calculations. The point was to illustrate the problems inherent in any effort to work in two different measurement systems.
6. Costantino Caciagli, "On Precision in Architecture", *Nexus Network Journal* 3, 1 (Winter-Spring 2001): 11-15.

About the Author

Harrison Eiteljorg, II, is a classical archaeologist whose interests have been centered on the work of the ancient architect and the architecture of the Athenian Acropolis, especially its entrances. He has written about the older entrances to the Acropolis (*The Entrance to the Athenians Acropolis before Mnesicles*) and is now directing a project to create a stone-by-stone computer model of the Propylaea, Mnesicles' entrance structure (see <http://propylaea.org>). Dr. Eiteljorg has also been an early and enthusiastic user of computer-assisted design software as an aid to the study of ancient structures, establishing the Center for the Study of Architecture (<http://csanet.org>) to encourage the wider use of CAD software in the study of architectural monuments.