FIVE

Greek and Roman Surveying and Surveying Instruments

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Background and Principles

There are two branches to surveying. One involves measuring any part of the earth's surface and any artificial features on it and plotting the result on a map or plan drawn to a suitable scale. Often, though by no means always, this work also involves recording relative heights. The other branch, which we call "laying out" or "setting out," is the reverse process, namely, positioning intended features such as boundaries or buildings or engineering works on the ground, in the correct position in all three dimensions. The surveyor often has to carry out both procedures, especially when linear features such as aqueducts or railways are to be built. First he has to record the existing shape of the terrain and then, in the light of this information, to decide the best route and to mark it on the ground.

In the Western world, although the contributions of Mesopotamia and Persia should not be overlooked,[1] the development of surveying was especially important in Egypt, where simple procedures were devised for dividing land, calculating the areas of fields, and restoring their boundaries after the Nile floods. Here grew the roots of geometry, not only in its usual secondary sense but also in its literal meaning—the measurement of land—and at the heart of this geometry lay triangles and especially similar triangles. The height of an obelisk, for example, could be learned by planting near it a vertical post and at the same time measuring the length of both shadows and the height of the post. The ratio of height to shadow length is the same for the obelisk as for the post.[2] The principle of leveling, too, was evolved. A horizontal could be established from a water surface—a crude predecessor of the spirit level—or, much more commonly, by deriving it from the vertical supplied by a plumb line. Here the basic Egyptian tool was the A-frame level, in the form of a large wooden A from whose apex a plumb line hung (Coulton 1982, 46). When this line coincided with a mark on the center of the crossbar, both feet of the A were at the same height. Such tools and methods, though modest, were no doubt adequate for most purposes.

Yet Egypt could rise on occasion to remarkable feats of precision. The four sides of the Great Pyramid, for instance, diverge from true north-south and east-west by a maximum of 5½ minutes of arc and a minimum of 2 minutes. In this case, north was probably found by building an artificial horizon in the form of a temporary circular wall, its top made exactly level by water in a trough. From a vertical post at the center a surveyor would mark the precise points on the top of the wall where a star rose and set; bisecting the resulting angle gave him true north.[3]

In the sixth century BCE the elements of geometry and of surveying were acquired from Egypt by Greek philosophers, just as they acquired mathematics from Mesopotamia and, arguably, tunnel building from Persia. But the development of more sophisticated surveying theory and of more versatile and accurate instruments had to await the creation in the early third century BCE of the famous library and museum at Alexandria—Egypt by now being a Greek kingdom—and the beginnings of more truly scientific enquiry. Surveying instruments now entered the realm of high technology for the first time; that is, they drew on scientific theory and, from practical experiment, fed back to it.

We know a good deal about Greek surveying from four technical treatises. Only one is virtually complete: Hero of Alexandria's *Dioptra*, of the first century CE but incorporating earlier material. The others comprise fragments of anonymous manuals of probably the third and second centuries BCE which are embedded in works by later writers: Julius Africanus, the so-called Anonymus Byzantinus, and (in Arabic translation only) al-Karaji.[4] Their content of practical exercises accompanied by geometric diagrams bears a close family resemblance to surveying manuals of the nineteenth and even twentieth century. For the Romans, in contrast, apart from the voluminous *Corpus Agrimensorum*, which is devoted solely to dividing, measuring, and recording landholdings,[5] the written record is sadly skimpy. Even Vitruvius, the much-admired architectural writer of the early first century CE, is not well informed about surveying. But Roman engineering works in plenty survive to show that instruments and procedures became ever more precise.

These tools were nothing like as precise, of course, as their modern counterparts. Our satellite positioning and lasers would be far beyond the comprehension of the ancient world. Its achievements are better compared with those of the nineteenth-century railway engineers, who worked with theodolite and level. Both of these instruments incorporate optics and the spirit level, which were introduced only in the seventeenth century, and ancient instruments were necessarily less compact and less accurate. The theodolite, too, measures angles; but because in Greek and Roman times trigonometry, which handles angles, was in its earliest infancy, ancient surveyors worked with Euclidian geometry. Even so, the early modern surveyor's approach to leveling was broadly similar, so if an ancient surveyor had joined the party surveying a railway in the nineteenth century, he would not have been wholly out of his depth.

Ancient surveyors, however, are elusive individuals. They seem to have fallen into four main categories. The cartographic surveyor (*chorographos* or *geographos* in Greek; no known equivalent Latin term) made maps of large areas, sometimes establishing latitudes and, indirectly, longitudes by a combination of astronomical and terrestrial methods; he also took an interest in the size of the earth and the heights of mountains. The land surveyor (Greek *geometres* or *geodaistes*; Latin *agrimensor* or *gromaticus*) worked on a smaller scale, plotting fields and laying out rectangular grids for land division or for urban streets. The military surveyor (Latin *mensor*; no known equivalent Greek term) supplied practical information to a commander and his engineers and laid out forts and the like. The engineering surveyor (Latin *mensor* or *librator*; no known equivalent Greek term) investigated terrain with a view to imposing on it roads, aqueducts, irrigation channels, or navigable canals.

The *geographoi*, it seems, were for the most part academics such as Eratosthenes or Ptolemy, who rarely ventured into the field. Of Roman land surveyors, we know the names of some. As for the rest, they are almost entirely anonymous. True, a number of their tombstones survive, but very rarely can we ascribe a particular engineering work to a named individual. Many *mensores* and *libratores* were seemingly jacks-of-all-trades, able to turn their hand to almost any need; in modern parlance, they were as much civil engineers as narrowly specialist surveyors. Certainly, military surveyors were often seconded to carry out civilian work. The profession in general seems to have been a respected one, and (to judge from the quality of its members' tombstones) reasonably well paid; in the late Roman empire, entry to it was encouraged by the granting of special privileges.

Instruments and Their Uses, with Special Reference to Greek Practice

So what did these men survey? Maps of large areas were compiled essentially by observation of the altitude of the sun and stars. Ptolemy's *Geography* goes hand in hand with the *Almagest*, his great work on astronomy, as the previous chapter has shown. A classic example of simple celestial observation—Eratosthenes's attempt to discover the circumference of the earth—was explained in chapter 3. Although we know deplorably little about the methods employed, maps of smaller areas must have been surveyed with equipment designed for terrestrial use. Such maps include cadasters of land boundaries, of which that at Arausio (modern Orange) in southern France is the best surviving example; the great marble map of Rome, the so-called *Forma Urbis*; and the long-lost maps which we know existed of Rome's aqueducts.[6] This said, however, it does seem that surveying instruments were used less for recording existing features than for creating new ones—setting out rectangular grids for city streets and land division, establishing routes for roads, meticulously fitting aqueducts into the landscape in order to obtain reasonable gradients, and, hardest of all, driving tunnels so that the ends met. On this sort of surveying we are much better informed.

On the nature of ancient surveying instruments, conventional wisdom is partially astray.[7] It assumes, blindly following Vitruvius, that the standard device for leveling was the *chorobates*. This resembled a narrow trestle table, set up horizontally by plumb lines against marks on the legs and also, for good measure, by a short trough on its top filled to the brim with water.[8] But at 6 m long it was far too cumbrous for use in the field, and it was far too crude. No instrument can be perfect, and its potential inaccuracy must always be borne in mind. When leveling for an aqueduct, for example, the resulting gradient should never be less than twice the error to which the instrument is liable, and even that can leave the surveyor hostage to fortune (see further below). To set out gradients of anything like 1 in 20,000, or 0.005%—which were not unknown, as we shall find, on Roman aqueducts—the top of the chorobates has to slope at no more than 1 in 40,000, or 0.0025%. To achieve even that approximation to the horizontal, and assuming a quite impossible perfection of manufacture, the center of the plumb line has to be aligned to within 0.0375 mm of the center of the mark. The impracticability of such precision is so obvious that no more need be said. Vitruvius had misunderstood his Greek source: the chorobates was in truth a builder's level, not a surveyor's.

Another widespread assumption is that Hero of Alexandria's *dioptra*, a complex and surely expensive instrument, was widely used for leveling (fig. 5.1).[9] In fact, it seems to have been no more than a one-off, a bright idea but a misguided one. It established the horizontal with a water level, in this case a water-filled glass tube bent up at each end. Sights were taken across the two water surfaces, where accuracy would be compromised by the inevitable meniscus. The Greeks did indeed use the dioptra—in fact, it was the only significant instrument they possessed—but they used it in a much simpler and probably more accurate version.

The word *dioptra* simply means something to look through. For surveying, the original form may have been nothing more than a narrow sighting tube suspended horizontally by wires or chains. Possibly it was first devised in Persia for maintaining alignment and gradient when driving *qanats*, water-collecting tunnels, and was possibly adopted by Greeks in the sixth century BCE. By the mid-third century BCE the tube was pivoted centrally on a circular disk. It is possible, even likely, that this development into a much more flexible instrument was stimulated by the reclamation by Ptolemy II and Ptolemy III of the Fayum depression in Egypt,[10] which involved a complex network of new irrigation canals and the allocation to farmers of a huge area of new land that had to be divided into fields. Probably by the late third century BCE the tube had evolved into the alidade, a bar that carried, at each end, projecting pinnules or vanes which served as sights. At first these vanes each had a small central hole, but, because it was difficult to align the

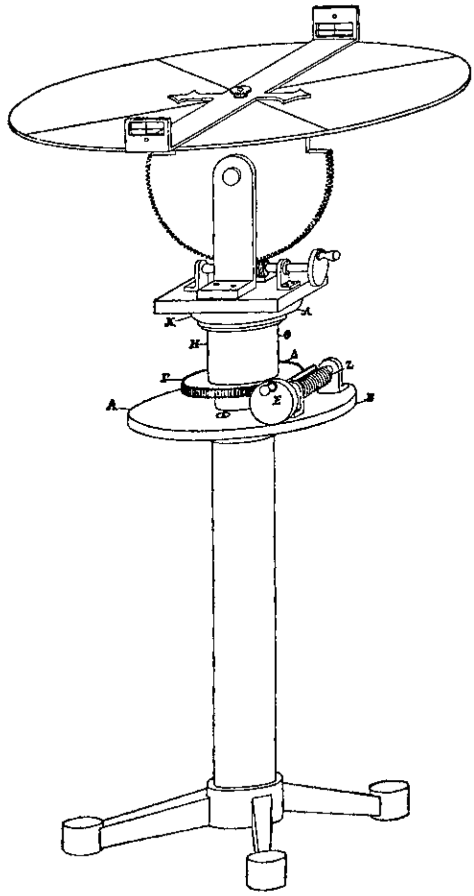

FIGURE 5.1 Hero's dioptra in horizontal mode. Reconstruction reproduced from H. Schöne, "Die Dioptra des Heron," *Jahrbuch des deutschen archäologischen Instituts* 14 (1899): fig. 1.

further hole on the target, narrow slits were added, which made sighting very much easier; such slits have remained the norm on comparable instruments to this day. This was the form of the standard dioptra. The main uncertainties about it are the material—was it metal or wood?—and the size.[11]

Because the whole subject cries out for practical experiment, a reconstruction of a standard dioptra was made, the disk being of wood and 60 cm in diameter (fig. 5.2). The sources are full enough to inspire confidence that this reconstruction is quite close to the truth. It works in either of two planes. When mounted horizontally on a tripod by means of a swiveling joint, it is used to project straight lines, in either direction or in both, for marking on the ground, and if necessary to lay out further lines at right angles to them by means of right-angled diameter lines inscribed on the disk. A quarter of the rim is also graduated in degrees, a facility used (as far as we know) for celestial observations but not for terrestrial surveying.

FIGURE 5.2 Reconstructed standard dioptra in horizontal mode. Photograph by the author.

The manuals—especially Hero's—give many examples of the dioptra's use in land surveys, in engineering works, and possibly in mapping. The area of an irregularly shaped field, for example, may be calculated by dividing it into easily measured rectangles and right-angled triangles, leaving only the small residual slivers around the edge to be estimated. A straight line can be established between two points that are not intervisible, which is useful for setting out on the surface the line of a proposed tunnel. The distance between two remote points can be measured without approaching them, which could be applicable to mapping in mountains.[12] It has been suggested that the *Forma Urbis Romae* of the early third century CE, which is remarkably accurate in terms of distances if less so in the orientation of buildings, derives from a survey made by a process of triangulation using dioptras to record horizontal angles in a fashion comparable to that of the modern plane table.[13] This hypothesis may be correct, although the manuals record no such procedures. It does also run counter to two impressions: that Roman surveyors (as opposed to Greeks) barely used the dioptra, if at all, and that its degree graduations were not used for terrestrial work. Both impressions may be wrong: the third century CE is a period much later than that of most of our sources, and changes could have occurred. We simply do not know.

An absolutely typical use for the dioptra, and one that may illustrate its capabilities, was in warfare. An army on the march is confronted by a river, and a pontoon bridge has to be made. How long has it to be? Anyone sent across with a cord to measure the distance directly is liable to be either drowned or slaughtered. On his side of the river, therefore, the surveyor sights with his dioptra a line from A to F, which is some prominent object such as a rock or bush on the far bank, and marks the line with stakes on the ground (fig. 5.3). Moving the dioptra to an arbitrary point C he aligns the diameter line with F again, and sets out the right-angled

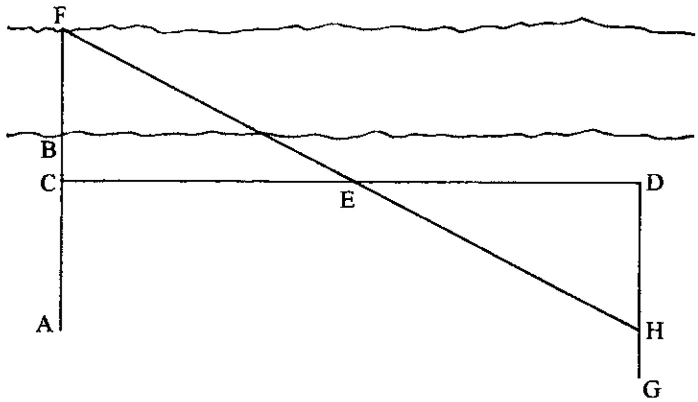

FIGURE 5.3 Measuring the width of a river. Drawing by the author.

line CD, of arbitrary length. From D he sets out another right-angled line DG. Measuring CD, he marks the halfway point E. With the dioptra at E he aligns the alidade with F and, going around to the other side of the instrument, without moving the alidade, projects that line to H, where it intersects DG. Because the triangles CFE and EHD are identical, CF equals DH, which can be measured. Subtract CB, which can also be measured, and BF is the width of the river and the length of the required bridge.[14] A practical experiment with this procedure gave exactly the right answer.

In the other mode, for taking heights, the dioptra is suspended vertically from a horizontal peg on a tripod, where it acts as its own plumb bob (fig. 5.4). One diameter line lies vertical, the other horizontal. With the alidade set on the horizontal one, sights are taken on a tall staff held upright by an assistant who, at the surveyor's direction, moves a cursor up or down it to coincide with the horizontal line of sight (fig. 5.5). The staff—Hero specifies a height of 10 cubits, or nearly 5 m—is graduated into cubits and dactyls, or feet and digits, or whatever the relevant units may be (Hero, *Dioptra* [Schöne 1903], 5).

For leveling, the Greeks started with rather inflexible methods but soon settled on one which is identical to modern practice.[15] To find the difference in height between two points A and B, place the dioptra between them, preferably about halfway, although exactitude is not necessary (fig. 5.6). Take a back sight to the staff at A and note the reading. Move the staff forward to B and take a fore sight on it there. The difference in the readings—*x* minus *y*—is the difference in height between A and B. Repeat the process as far as necessary, which, in leveling for an aqueduct, may well be a matter of miles. The total of the back sights subtracted from the total of the fore sights, or vice versa, gives the total difference in height between the two ends. If gradients are to be derived from the levels, as in the case of an aqueduct, the distances between all the stations of the staff need to be recorded, and their positions need to be marked semipermanently so that the survey line can be picked up again later. With a modern level and telescopic sights, the

FIGURE 5.4 Reconstructed standard dioptra in vertical mode. Photograph by the author.

staff can be read at a considerable distance. With a dioptra and the naked eye, it cannot. The stages have to be shorter—about 30 m seems to be the reasonable maximum—and therefore more numerous, which increases both the time taken and the opportunity for making mistakes.

Here a cautionary word is needed. Everything depends on the line of sight being precisely horizontal. On a modern instrument with a spirit level it is so, or virtually so. On a dioptra it cannot be, except by luck. Figure 5.7 shows why, in grossly exaggerated form. Suppose the radius of the disk to be 30 cm. If the pointer B of the alidade AB is only 0.1 mm above the true horizontal—an error undetectable by eye—the reading on the staff 30 m away will be 1 cm too high, but the surveyor will not know it. Fortunately there is an easy solution to the problem, not attested by the ancient sources but one which any thoughtful surveyor could have worked out. He simply takes the whole dioptra off the peg from which it hangs and, without touching the alidade, turns it through 180 degrees and puts it back the other way round. He then takes the reading again. Instead of looking through the sights from A to B, he is now looking through them from B to A, and the reading on the staff is now 1 cm too low. The mean of the two readings will be horizontal, or rather a much better approximation to the horizontal.

An experiment on this basis revealed the dioptra's accuracy, or inaccuracy. A distance was chosen, 173 m in length between two immovable stones, and was

FIGURE 5.5 Reconstructed standard dioptra leveling. Photograph by the author.

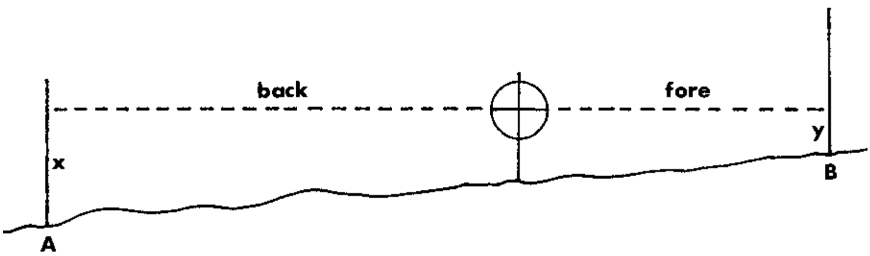

FIGURE 5.6 Principle of leveling. Drawing by the author.

leveled with a modern level. Repeated checks in both directions established the difference in height as 13.005 m. The exercise was then repeated with the dioptra. Results improved with practice, ending with an average difference of 13.127 m, or 12.2 cm too great. Over 173 m, this represents an error of 1 in 1,418 or 0.07%, which, despite all the precautions taken, is still a very significant one. It was caused no doubt by inexperience on the part of the surveyor, by the relative shortness of the alidade—the longer the distance between the sights, the better—and above all by the fact that, although the disk is suspended from a long sleeve rather than a simple ring, it tends to swing if there is any wind at all.

The more accurate the instrument, needless to say, the better. But the degree of accuracy required depends on the task in hand. Let us suppose the surveyor is leveling between two points, 100 m apart, for an aqueduct. The dioptra tells him that one is 10 cm lower than the other: that the gradient is 1 in 1,000 (0.1%) downhill. At least, this is the theory. Let us further suppose, however, that the readings are, or might be, in error to the tune of 1 in 1,000, either too high or too low.

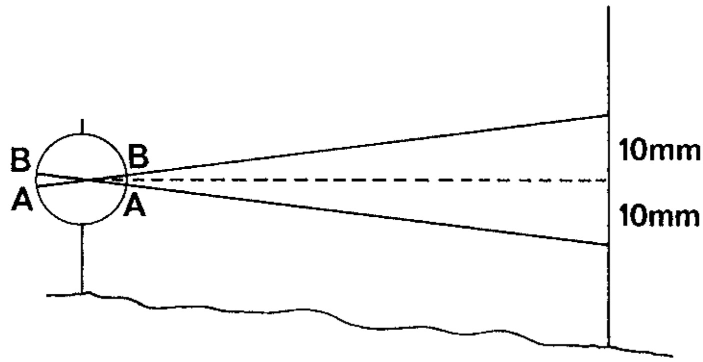

FIGURE 5.7 Averaging out errors by reversing sights. Drawing by the author.

What the surveyor fondly imagines to be a true level might therefore in reality be anything between 1 in 1,000 up and 1 in 1,000 down. Gradients are derived from levels. In subtracting 1 in 1,000 from his supposed level he will end up with an actual gradient which might at one extreme be 2 in 1,000 (i.e., 1 in 500) down, or at the other might be 0 in 1,000 (i.e., genuinely level). This is not good enough: the aqueduct might not work.

A Greek surveyor, however, would be leveling for Greek aqueducts. These, though not nearly so numerous as those of Roman date, fall into two groups, archaic (sixth century BCE) and Hellenistic (third to first centuries BCE). In both periods they normally run in pipes at a quite steep gradient: the average is roughly 1 in 100 (1.0%), and the minimum, where it is known, rarely shallower than 1 in 250 (0.4%), except perhaps in the distribution network inside a town (Coulton 1987). Roman aqueducts, however—to leap forward briefly in time—typically had very much shallower gradients, as shallow even as 1 in 20,000, or 0.005%. If, as with the reconstruction, a typical Greek surveyor's dioptra had an error of 1 in 1,418, and if he was aiming for a gradient of, let us say, 1 in 200 (0.5%), he might end up with one between 1 in 175 and 1 in 233. This is acceptable: the aqueduct could not fail to work. To survey shallow Roman gradients, however, the dioptra was too crude by far, so that, as we shall see, a very much more accurate instrument was required. The moral is that instrumental error should be, at the very worst, half the gradient intended. Ideally, it should be no more than a tenth.[16]

Nowadays, when the primary leveling is completed, its accuracy is checked by taking "flying levels" back to the starting point. In theory this will bring the cumulative height difference back to zero, although in practice a closing error is tolerated, provided it falls within strictly defined limits. If Greek surveyors had done the same, they too could have found how accurate or inaccurate their survey had been, but there is complete silence in the manuals about any such check. What the Greek world required of its surveyors was probably for the most part nowhere near as stringent as today's demands. But once again a sharp distinction must be drawn between Greek and Roman achievements and therefore, one might deduce,

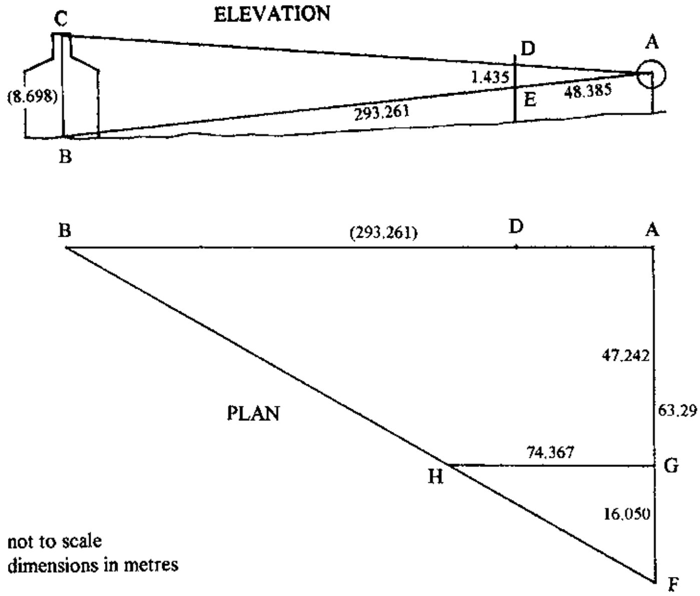

FIGURE 5.8 Measuring the height of a wall. Drawing by the author.

between Greek and Roman requirements. On Roman aqueducts, the smallest error could turn a potential success into an abject failure. For all we know (which for Roman procedures is very little), Roman surveyors may have taken flying levels to check their results.

Another use of the dioptra in the military sphere is to measure the height of a wall. A commander is besieging a city and wants to storm it. How high is the city wall? He needs to know in order to build ladders or siege towers of the right size. To try to measure it directly would be suicidal. In default of a suitable city wall, an experiment was made on measuring the height, BC (fig. 5.8), of the chimney stack of a house. This demanded two stages, both taken straight from the ancient manuals.[17] First, with the dioptra in horizontal mode at A, two lines were staked out on the ground: a certain distance toward B and, at right angles, to point F at an arbitrary distance away. With the dioptra at F, another line was staked out in the direction of B. From the arbitrary point G yet another line was staked out at right angles to AF, and the point H where it intersected FB was marked. All this was done safely out of bowshot of the chimney. The result was two similar triangles. The accessible sides were measured, and the ratio of GH to GF, in conjunction with the distance AF, supplied AB, the distance to the chimney. Then the dioptra was set up in vertical mode at A. On a staff held at D, readings were taken on the lines of sight AC (to the chimney top) and AB (to the wall foot). Two more similar triangles resulted. In conjunction with AB, just discovered, the ratio between DE (read from the staff) and AD (measured on the ground) supplied BC, the figure required. When finally the real chimney height was measured directly, it turned out to be 11 cm less than the calculation: wrong by only 0.13%. A siege tower built to the estimate would have been a hand's breadth too tall. Given that the chimney was 293 m away, this was a respectable result.

In just the same way, but on a much bigger scale, the Greeks worked out the heights of mountains. Their interest arose from their desire to understand the nature of the earth. It was commonly accepted that the earth was a sphere, yet, since mountains very obviously projected above the general surface, it could not be a perfect sphere. By finding the heights of mountains it could be shown that, relative to the diameter of the earth, they were insignificant and did not detract from the basic sphericity. Another question was the depth of the atmosphere: what height did clouds reach? The widespread acceptance that the highest peaks always rose above the clouds gave fuel to this debate.

The earliest attempts to measure mountains were limited by the lack of adequate equipment, and philosophers had to be content with informed guesses, in the roundest of round figures. But as surveying instruments improved, a more accurate assessment became possible. The procedure was probably identical to that just described, and two very precise figures are on record. In both cases the height was taken not from sea level but from some inland point which cannot be precisely located, and the accuracy is therefore uncertain. Before 168 BCE a certain Xenagoras gave the height of Mount Olympus above the town of Pythion as 1,951 m. Since the highest summit of Olympus is not visible from Pythion, he was probably measuring a nearer and lesser summit. If so, his result was, arguably, 5% in error. A little later the height of Kyllene in the Peloponnese was given as 1,703 m. From the most likely starting point, this represents an error of only 2%. Despite the difficulties of surveying in mountainous terrain, where it is hard to find reasonably level ground to lay out the base lines and triangle, these results seem impressive.[18]

Another instance, albeit less clear cut, concerns the intended canal across the Isthmus of Corinth.[19] To cut this could never be an easy undertaking, because the isthmus is over 6 km wide and rises in a ridge of solid rock nowhere less than 79 m above the sea. But a canal would save ships the long and dangerous voyage around the Peloponnese, and the project was dreamed of by a succession of rulers; work was actually begun by the emperor Nero in 67 CE. Even so, we are told, it was then stopped because surveyors had found that sea level was higher at the western end than at the east, and it was feared that the island of Aegina would be inundated by the resulting torrent. The sources in question, however, are unreliable, and in all likelihood they are anachronistically applying to Nero's attempt a story more reliably reported for an earlier one. Eratosthenes the geographer records that about 303 BCE Demetrius Poliorcetes, a Hellenistic warlord, "attempted to cut through the Isthmus of Corinth to provide a passage for his fleets but was prevented by the engineers, who took measurements and reported that the sea in the Corinthian Gulf [to the west] was higher than at Cenchreae [to the east], so that if he cut through the land between, the whole sea around Aegina, Aegina itself, and the islands nearby would be submerged, and the passage would moreover be unusable."[20]

The engineers were essentially correct. Tidal effects, exacerbated by winds, mean that the sea level west of the isthmus is always higher than that on the east, with a maximum difference—we now know—of 51 cm. There is consequently a permanent current of up to 4.8 km per hour through the modern canal, which was completed in 1893. This causes little practical difficulty, and Aegina is still there. The canal being 6.342 km long, its surface has a maximum gradient of 1 in 12,435 (0.008%), thus comparable with the gentlest gradients on Roman aqueducts, which must have taxed the skills and instruments of their surveyors to the limit. Demetrius's surveyors can only have leveled from sea level up to at least 79 m on the ridge and down again, at a date when dioptras, at least in their developed form, did not exist. It is all too easy to hail their result as a triumph. But it is not recorded what they supposed the difference in sea level to be. If it were known that they found it to be a cubit (roughly 50 cm), a triumph it could very well have been. But would so small a difference have raised fears for the safety of Aegina, 35 km away? Had the surveyors found it to be, say, 6 cubits (roughly 3 m), that would have been a massive error, which could just as easily have been in the opposite direction and made the eastern sea higher than the western. Such a finding would have been written off by posterity as a failure. We have to conclude, regretfully and at the risk of doing Demetrius's engineers a grave injustice, that their survey was probably not very accurate, and that it was only chance which made them err in the right direction.

Short distances were measured by chains, the most reliable method; or by cords, which were cheaper but liable to stretch or shrink; or by wooden rods of standard length (with metal ferrules to protect their ends) tediously leapfrogging each other. Even so, throughout antiquity and long thereafter, measuring long distances—several miles, or hundreds—was inordinately difficult. Alexander the Great on his conquests far into Asia employed "bematists," pacers, who counted their paces as they marched and noted the direction of travel and the names of places passed.[21] From their records, outline maps were compiled and descriptions of the routes published. The result was a vast improvement on anything that had gone before, but there remain severe limitations to the accuracy of pacing. It is notoriously difficult to maintain a straight path and an even pace through forest or swamp.

Geographers could reckon the distance between places on the same meridian by observing stars with the dioptra, just as was done later with the great medieval instrument that was its direct descendant, the astrolabe. The method was comparable to that of Eratosthenes, but in reverse. Geographers found a star which at a given time is vertically overhead at A, and at B, at the same time, they measured its angular distance from the zenith by means of the degree graduations on the dioptra. Here too, simple geometry gives the angle at the earth's center subtended by the radii to A and B, expressed as a fraction of the full circle. The distance between A and B is that same fraction of the earth's circumference, which the geographers thought they knew.[22]

An alternative and more flexible approach to long-distance measurement was

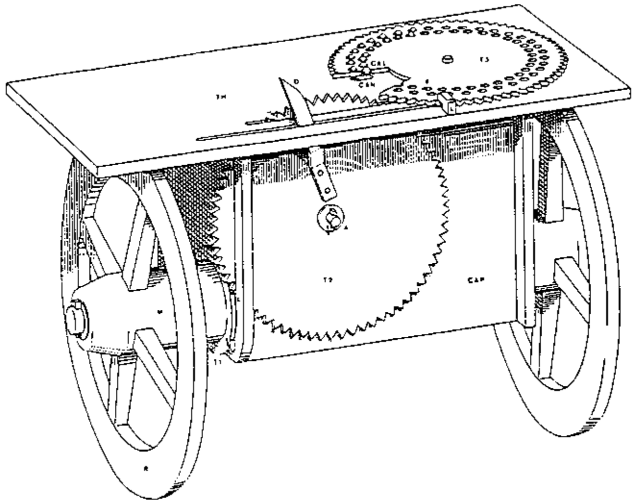

FIGURE 5.9 Hodometer reconstructed. Reproduced from A. W. Sleeswyk, "Vitruvius' Waywiser," *Archives internationales d'histoire de science* 29 (1979): fig. 1.

offered by the hodometer. This fiendishly clever geared cart, arguably invented by the great scientist Archimedes of Syracuse in the late third century BCE, is described by Vitruvius (fig. 5.9). Every mile (or whatever distance was calibrated), it dropped a ball into a metal bowl with an audible clang; and at the end of the stretch concerned the balls were counted. The hodometer is mentioned occasionally in our ancient texts, but it was certainly not an everyday part of the ordinary surveyor's equipment, if only because of the virtual impossibility of driving it in a straight line across country. It could find distances along roads, although (except on certain Roman roads) they would rarely be straight-line distances. Thus, it could provide raw material for official or semiofficial records such as Agrippa's world map, the so-called Antonine Itinerary, and the Peutinger map, all of which included such information, as well as for geographers like Marinus of Tyre and Ptolemy who were concerned with coordinates for mapmaking.[23] In a similar way, in the seventeenth century, before milestones were in place, John Ogilby measured all the main roads of England and Wales with the "waywiser," or "wheel dimensurator," which was the hodometer's lineal descendant.[24]

Instruments and Their Uses by Romans

THE GROMA

So much for the Greeks who, for all practical purposes, had only one instrument, the dioptra, for working in both the horizontal and vertical planes. The Romans, by contrast, had two different ones. While they certainly borrowed some theory from the Greeks, their instruments may well have had a native Italian origin.

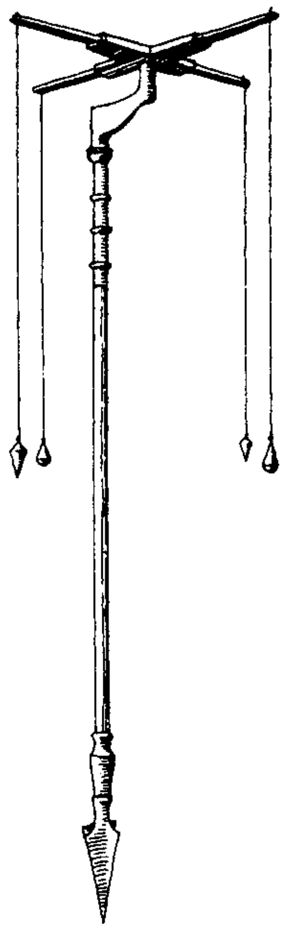

FIGURE 5.10 The Pompeii groma as reconstructed by M. Della Corte. After M. Della Corte, "Groma," *Monumenti Antichi* 28 (1922): fig. 13. Drawing by the author.

Let us look first at the *groma*, which was the exact counterpart of the dioptra in horizontal mode. Not only is it illustrated on two surveyors' tombstones, but the metal parts of one have also been recovered from Pompeii, the only ancient surveying instrument to have survived (Della Corte 1922). The principle is clear enough: a pole carrying a flat cross with a plumb bob hanging from each arm (fig. 5.10). Sighting across diagonally opposite cords gives a straight line which can be projected forward or back. Sighting across the other pair gives a line at right angles to the first. But the exact reconstruction is debatable, because it gives rise to two serious problems.[25] The first lies in the bracket carrying the cross, which seems to be a fantasy of the excavator. If there was no bracket, the cross was directly on top of the supporting pole, which would impede sighting across diagonal cords. The second problem lies in the fact that, to the surveyor, the further cord necessarily appears to be thinner than the nearer. Unlike the slit sights of the dioptra, where the further slit can easily be centered in the nearer, on the groma the further cord is hidden behind the nearer and accurate alignment seems impossible. No satisfactory solution to either problem has yet been proposed. In addition, the long plumb lines of the groma were prey, even more than the dioptra, to swinging in the wind, so much so that Hero of Alexandria proposed shielding them in tubes.

Nonetheless, the groma was indisputably the tool of the *agrimensor*, the land surveyor, for whom a whole volume of practical manuals, terse and difficult, survives in the *Corpus Agrimensorum*.[26] It is illustrated with many maps, mostly schematic and hypothetical rather than factual, and all corrupted by copying. The agrimensor's principal job was "centuriation," dividing land for allotment into a grid of squares, each usually 2,400 Roman feet on a side, and subdividing them further. He also drew maps of the resulting plots for registration with the authorities, he set up boundary marks, and he arbitrated in consequent disputes. In Italy and North Africa especially (fig. 6.1 below),[27] there are hundreds if not thousands of square miles of centuriated land still marked by roads and field boundaries, the exact counterpart of the "hundred squares" of America. With a groma and measuring cords or rods, centuriation as such was hardly a difficult task.

However, it also seems that the groma was used in setting out long, straight alignments. Staking one out by interpolation between two intervisible points is quite easy, and no instrument is needed (fig. 5.11, *a*). A surveyor at one end directs men in between to move poles this way or that until they are in line with the other end. At close range he might direct by shouting; at longer, by signaling with flags. At extreme ranges, more laboriously, fires in the form of portable braziers might be necessary. If a hill lay between the two points, setting out would be done with a groma on the hill, moved sideways by trial and error until its cords were aligned with both end points (fig. 5.11, *b*). Or a given line can be extended by extrapolation, either by sighting forward and directing where the poles should go (fig. 5.11, *c*) or by sighting back with a groma and locating it on the alignment by trial and error (fig. 5.11, *d*).

ROADS

It is natural to turn next to Roman roads. In mountainous country the Romans had the good sense to fit their roads to the landscape in order to avoid impossible gradients. But on more gentle ground, many of their roads are renowned for running straight as an arrow over hill and dale, mile after mile. When they do change direction, it is usually on a high point, which is understandable. But how were long, straight alignments set out between two low-lying towns and across a number of intervening ridges? Ancient literature is silent on this puzzle. Roman surveyors had no preexisting maps to guide them, or none that were anything like accurate enough, and they had no magnetic compasses, although they may have had a better sense of the lie of the land than is usual today.

There are many theories about the method that Roman surveyors might have

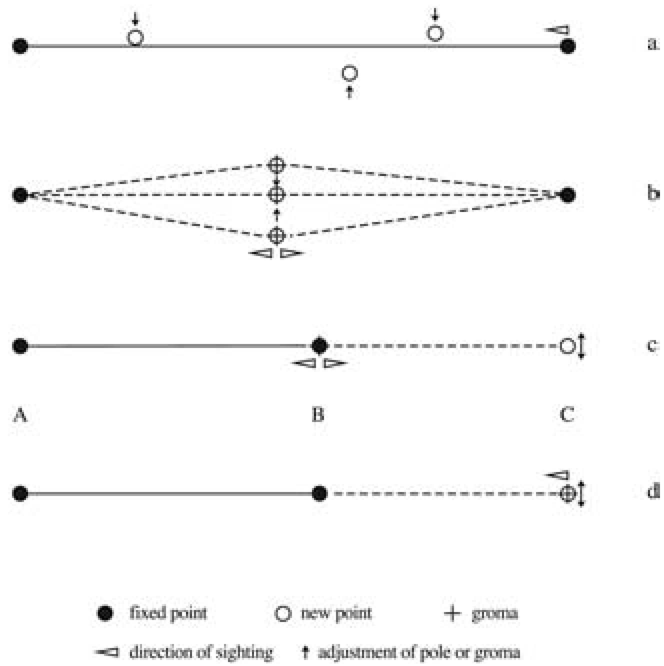

FIGURE 5.11 Simple alignment by interpolation (*a–b*) and extrapolation (*c–d*). Drawing by the author.

used. One is "*successive approximation*, in which a rough solution is refined by trial-and-error, until sufficient accuracy is achieved."[28] But how in practice might this be done? How does one bring into line marks on a succession of hilltops which might be 20 km apart, and where visibility extends only from one hilltop to the next, or to a terminus? In these circumstances, while it is straightforward to bring any three marks into line by interpolating the third between two previously fixed ones, to align (say) four marks between two fixed ones is a problem of a totally different order. The three marks at one end can be brought into line with each other and with the three at the other end; but how to align the two resulting alignments? It can be done, but only by laborious and lengthy trial and error. At least this method may account for roads which run in a succession of straight doglegged alignments; only one hill intervenes between the ends of any particular leg, each alignment being established merely by a groma on the intervening hill.

An alternative suggestion is that of dead reckoning, whereby a series of traverses at right angles to each other are set out by a groma: due east from a terminus, for example, then north, then east, and so on until the other terminus is reached. Each traverse is measured on the ground, and features such as swamps and forests are located by setting out and measuring offsets to them. All this information is transferred, true to scale, to a temporary large-scale map laid out perhaps on the floor of a room. On this map the actual route is planned and then marked, whether as a single straight line or doglegged to avoid forests or swamps. Points along the route are located on the map by offsets from the original survey line, and the length of each offset and its distance along the survey line are measured and scaled up to full size. The surveyors then set out these new offsets and locating points on the ground. These points, when joined together, mark the route of the road. With this scenario, however, many problems emerge. Unless the map is fully contoured, any changes of direction will occur at points determined only in plan, not according to height, and (except by chance) they will not coincide with high points; thus, a conflict with observed fact is created. Moreover, since the initial survey has to be done on the ground and the road has to be built there too, to design it from a laboriously compiled map would seem to introduce an unnecessary and potentially misleading intermediate stage. It divorces the surveyor from the field, where he can see how well his route fits the terrain much better than he can in the office. Above all, there is the difficulty of measuring long distances across country with any accuracy. Errors will inevitably be made and transferred to the map. Further errors will arise in transferring the chosen route back to the ground.

A vastly simpler method would be to start off from one terminus for the road, marking out by a groma a straight line in the direction which aims, at the best guess, at the other terminus and measuring the distances along the way. Suppose this line misses the destination by 4 miles to the east. At the halfway point as measured, the alignment therefore needs to be moved west by 2 miles, at the three-quarter point by 3 miles, and so on. The operation would be much faster than by successive approximation or by dead reckoning; but it is still unsatisfactory because it involves measuring the whole route.

Instead, I propose another theory. It depends, like so much ancient surveying, on similar triangles. Let us suppose the surveyor wants to stake out a direct route from A to B, which he knows lies roughly east of A, and his best guess is that it lies a little north of east. By extrapolation he projects a line AX in that direction, sighting from high point to high point (fig. 5.12). When it becomes clear that his line passes well north of B, he returns to A and projects two new alignments AY and AZ further to the south, designed to bracket B, and he stakes them out as he goes. Then from B he projects two lines back on the reciprocal bearings until they intersect AY and AZ at C and D. The diagonal between C and D is measured, and the point E halfway along it is marked. Because ACE and BDE are identical triangles, as are ADE and BCE, AEB is a straight line. To fill in further points on this line, the same process can be repeated on a smaller scale or can be interpolated in the usual way, as the terrain directs. It would be a laborious job; but with the means at the surveyor's command, any method would be laborious. My theory is no more than that, but it seems plausible, and the cross-country measurement involved is minimal—only from C to D.

Use of the word "bearing" begs a question, however. Today we take bearings by various means, such as measuring them on a map or using a magnetic compass.

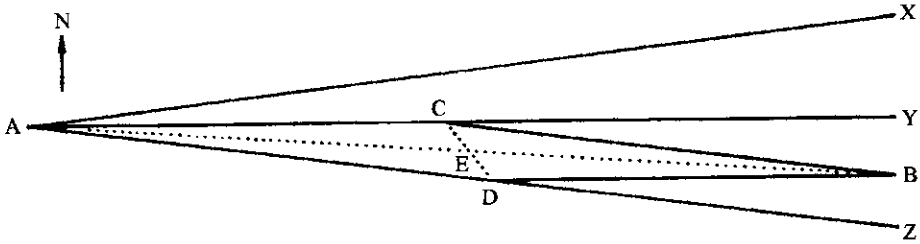

FIGURE 5.12 Surveying alignment by geometric construction. Drawing by the author.

In Roman times neither means was possible. So how did Romans deal with bearings? As far as we can tell, terrestrial surveying simply did not measure angles in degrees. There were of course terms for the cardinal points, but not for divisions between them like our south-southwest, for example, which means precisely 202½ degrees. Instead, Romans described an angle in terms of the sides of the right-angled triangle which subtends it. It is more convenient if one of these sides is aligned north-south; as we have noted, a north-south line could be established with great accuracy.

Let us consider the same diagram, but opened up for greater clarity (fig. 5.13). I suggest that when the surveyor set out the lines from A he recorded their direction as exactly as he could, by setting out on the ground a north-south line and linking it to their alignments with right-angled triangles (as large as practical), which he then measured. Thus, the direction of AY is easy—due east, where the ratio of the triangle's sides is 1 to 1. For AZ, the ratio is (let us say for the sake of simplicity) 1 to 2—that is, 1 unit south from A and 2 units east. For setting out the return lines, the surveyor used the reciprocals. BD is easy again—due west. BC is the reciprocal of AZ, namely, 1 unit north from B and 2 units west.

As an illustration (fig. 5.14), Stane Street in Britain is the Roman road from London (Londinium) to Chichester (Noviomagus), 80 km away and separated by a number of ridges (*BAtlas* 8G3–G4). For the first 20 km from London (L) the road aims exactly at Chichester's east gate (C). Thereafter it diverges for very good geological reasons. But the Romans had clearly worked out—by the method just outlined?—what we would call the bearing, that Chichester lies 20 units south of London and 13 units west. In modern terms, 13/20 is tan 33 degrees, and we would say that Chichester lies 33 degrees west of south from London, or 213 degrees relative to north. Although less cumbrous, our modern system comes to exactly the same thing.

The ultimate straight alignment, surely the longest of the ancient world, is the Roman frontier established between the rivers Main and Rems in Germany in about 155 CE. Over a distance of 81.259 km its palisade and ditch deviate only once, for a distance of 1.6 km, to avoid a deep valley (*BAtlas* 12C3–C4). This apart, a very precise modern survey of the southern part reveals that the mean deviation

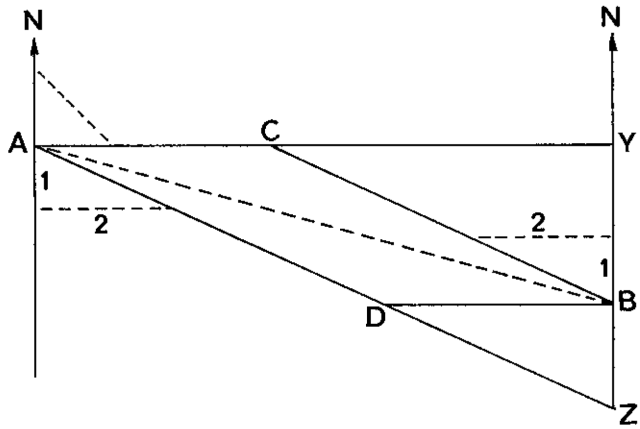

FIGURE 5.13 Recording bearings by triangle sides. Drawing by the author.

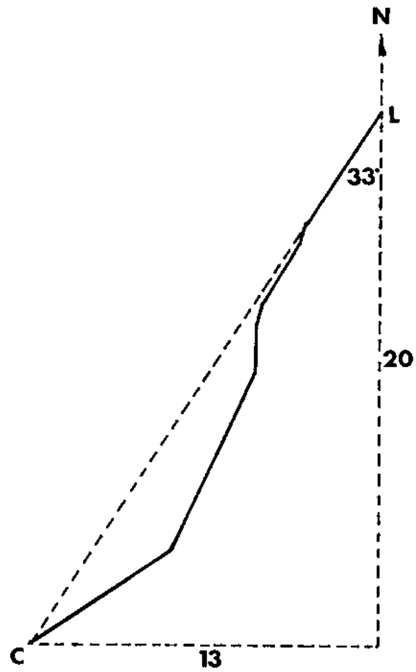

FIGURE 5.14 Stane Street. Drawing by the author.

from a truly straight line was ± 1.9 m. Why the frontier was made so painstakingly straight (military perfectionism run riot?) is perhaps hardly relevant to us. Of greater concern is how it was set out in country that was probably even more heavily wooded than it is today. All the methods rehearsed above would have been difficult or, if they involved measurement, impossible. The most likely answer is the simplest possible: that the precise location of the ends of the alignment was unimportant, and that the setting out began with a chosen alignment between two high points which was extrapolated in both directions.

THE LIBRA

In the vertical plane the Romans worked with the *libra*. We know deplorably little about it (Lewis 2001, 109–19). There is no surviving description or illustration. It does not feature in the *Corpus Agrimensorum*, which for all practical purposes is unconcerned with altitudes. As a surveying instrument, the libra is in fact mentioned only once, by Vitruvius (8.6.3): "leveling is done with dioptras or *librae aquariae* or the chorobates." It is often assumed that *libra aquaria* means a water level like that on the chorobates or Hero's dioptra. But beyond these two instances there is no evidence for the water level in the Greek and Roman world, and taking a true horizontal off a water surface, unless it be impractically long, is almost impossible. It seems therefore that the *libra aquaria* was not a level leveled by water, but a level for leveling water—in other words, an aqueduct level.

Vitruvius's mention of the chorobates is, as we have seen, irrelevant to surveying, and his mention of the dioptra seems irrelevant to Roman surveying. We cannot dismiss his mention of the libra, however, because Latin had a number of words and phrases of the same derivation whose widespread use shows that the libra was well established long before his time. *Ad libram* meant horizontal, *librare* to make horizontal or to take levels with an instrument, *libramentum* a gradient, *libratio* the taking of levels, *librator* a surveyor. Thus, Pliny the Elder in the first century CE describes aqueducts for bringing water to gold mines in the Spanish mountains (*NH* 33.74–75): "Gorges and crevasses are crossed on masonry bridges. Elsewhere impassable crags are cut away to hold wooden troughs. The workmen, hanging on ropes to cut the rock, look from a distance more like birds than beasts. It is usually suspended like this that they take the levels (*librant*) and mark out the route, and man brings water where there is not even room to plant his feet." This circumstance more or less rules out the water level and the A-frame level, which have to be placed on a solid surface, and it strongly implies a self-suspended level that can be held in the hand or even hung from a rope in front of the surveyor.

This interpretation also accords with the history of the word *libra* itself, which from its basic meaning of a weight came to denote a pair of scales or a balance, as in the sign of the zodiac. Here lies the major clue to the form of the instrument. To weigh accurately, the beam of a balance must be exactly horizontal, and it seems reasonable to deduce that this was the imagery behind the name of the surveying instrument. A libra for leveling was therefore made on the lines of a balance beam: a long iron alidade with projecting slit sights at each end, suspended from a knife-edge above its center (figs. 5.15 and 5.16). In principle it is identical to the dioptra in vertical mode. But its surface area is so much less that it hardly moves

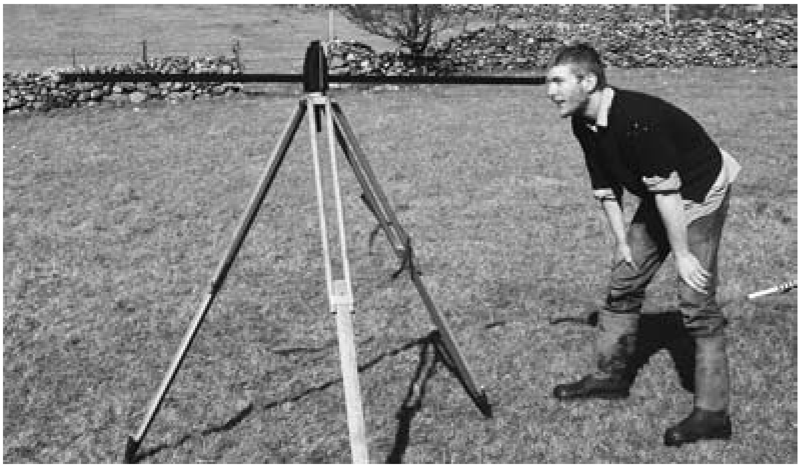

FIGURE 5.15 Reconstructed libra. Photograph by the author.

FIGURE 5.16 Reconstructed libra, detail. Photograph by the author.

in a wind. Indeed, it is so finely suspended that a fly settling on one end affects the reading on the staff. And because it is so much longer—1.83 m—it is much more accurate. Tested against a modern level, once again reversed to take double readings to counteract any in-built imbalance, its average error over the same course of 173 m was 1 in 57,000 (0.00175%), compared to the dioptra's 1 in 1,418 (0.07%). The best result was identical to that achieved with the modern level. This was a relief, because while, as we have noted, the dioptra is good enough for setting out the steep gradients of ordinary Greek aqueducts, this libra—although its design is very much more conjectural—could reasonably survey the extremely shallow gradients found on Roman ones.

PLATE 4 The world map (incorporating some revisions in northwestern Europe), drawn according to Ptolemy's second method, from Claudius Ptolemy, *Cosmographia*, based on a manuscript edited and with maps by Donnus (Dominus) Nicolaus Germanus (Ulm: Johann Reger, 1486). The Newberry Library, Gift of Edward E. Ayer. Reproduced with permission.

PLATE 5 Pont du Gard. Roman aqueduct (UNESCO World Heritage Site, 1985) on Gardon River. Photo: S. Vannini. Pont du Gard, Nîmes, France. © DeA Picture Library / Art Resource, NY.

PLATE 6 Peutinger map: furthest left of the eleven surviving parchments. Southeastern England appears top left. Southwestern France appears immediately below it, and then further below (extending across the entire segment) the narrow channel for the Mediterranean Sea. ÖNB/Wien, Cod. 324, segm. 1. Reproduced with permission.

PLATE 7 The city of Rome and routes fanning out from it on the Peutinger map. ÖNB/Wien, Cod. 324, segm. 4+5. Reproduced with permission.

PLATE 8 Imperial orbs excavated in Rome and associated with the self-proclaimed tetrarch Maxentius. Photograph by Clementina Panella, reproduced with permission.

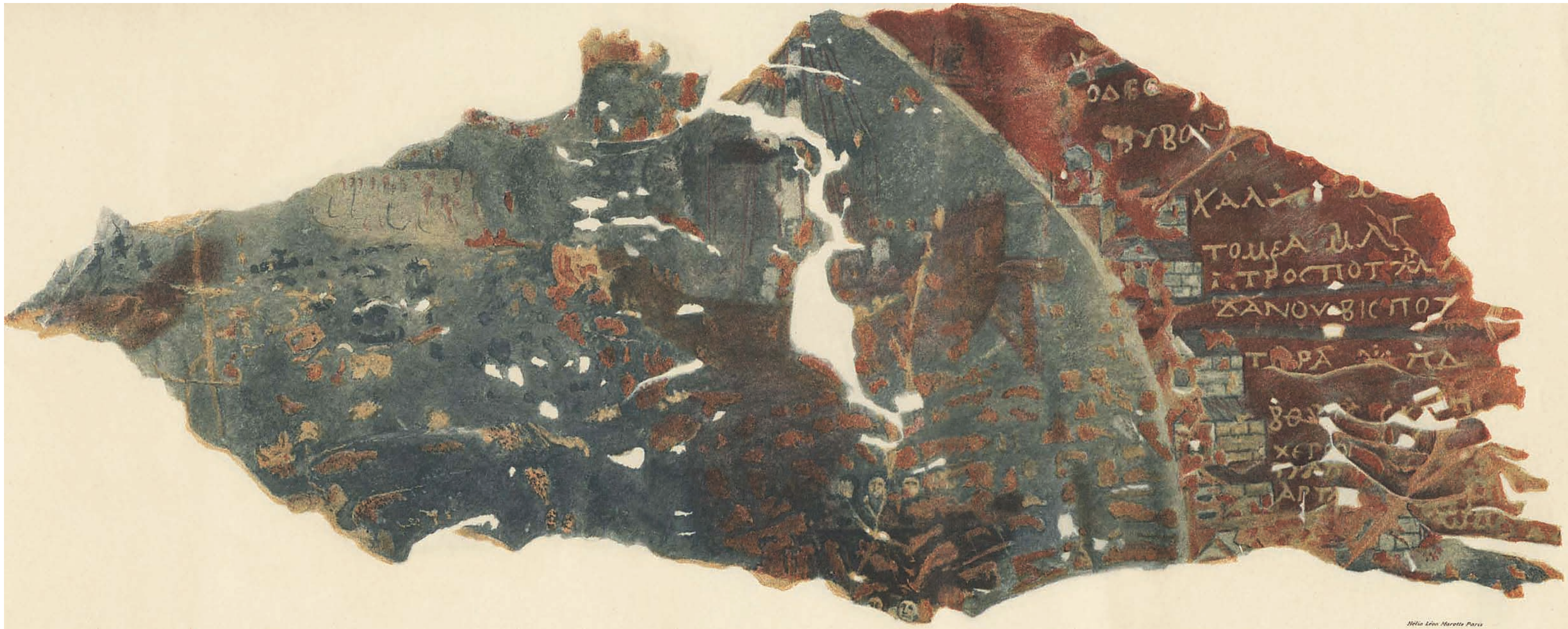

PLATE 9 The Dura parchment (Paris, Bibliothèque Nationale de France ms. Supplément grec 1354[2], V). Insert illustration bound with F. Cumont, "Fragment de bouclier portant une liste d'étapes," *Syria* 6, no. 1 (1925): 1–15.

AQUEDUCTS

Where the libra's origins lay, and the stages of its evolution, we cannot tell and probably will never know. Surviving Latin literature does not go far enough back. Conceivably the libra was inherited from the Etruscans, conceivably it was a truly Roman invention. But it does not seem to have been, so to speak, the alidade borrowed from a Greek dioptra, because it would appear that it existed before the standard dioptra evolved. The gradient of the first aqueduct supplying the city of Rome, the Aqua Appia (312 BCE), is not known. That of the next, the Anio Vetus (269 BCE), averages about 1 in 370 (0.27%) overall but, as is usually the case, varies, and it includes kilometer-long stretches at about 1 in 5,000 (0.02%).[29] Over such distances, so shallow a gradient seems to have been deliberate rather than accidental, and it is too shallow for a dioptra to have achieved.

This is not to say that very shallow gradients are to be found on every Roman aqueduct. There is no particular virtue in them. On the contrary, other things being equal, it is easier to lay out an aqueduct on a steeper gradient because surveying errors can be more readily accommodated, whereas with a very small slope an aqueduct can be rendered unworkable by the slightest of mistakes. What dictates the gradient is the local geography, namely, the height of a suitable source of water above the destination and its distance along a practicable route. In hilly and well-watered country the difference in height is likely to be considerable, the distance short, and the gradient therefore relatively steep; in flatter terrain, the reverse. The Greeks were happy with steep gradients because their aqueducts were usually pipelines which could not overflow. Roman aqueducts had open channels—in minor cases literally open, but usually lined and vaulted over to keep the water clean—so that on steep slopes overflowing was a potential problem. Consequently, if a steep gradient was forced on Romans by the terrain, they often introduced cascades: vertical steps separated by relatively level sections, which killed the velocity of the water. Cascades apart, if one had to guess at a "usual" gradient, it would be somewhere between 1 in 333 and 1 in 1,500 (0.3 and 0.066%).[30]

This is the context in which to view Vitruvius's much-debated statement (8.6.1): "Let the bed of the channel have a minimum gradient [*libramenta fastigata*] of half a foot per 100 feet [*in centenos pedes semipede*]," that is, 1 in 200, or 0.5%. The inevitable corollary is that the average gradient was steeper and the maximum steeper still. Outside Greek lands, this is simply inapplicable to the Roman aqueduct, on which 1 in 200, far from being the minimum, was more like the maximum. The favorite explanation of this anomaly is that Vitruvius's figure has been corrupted in the manuscripts. This line of argument finds support in Pliny the Elder's section on aqueducts (*NH* 31.57). In all other respects it closely follows Vitruvius, but it states that the minimum gradient should be 1 in 4,800 (0.021%), a figure nearer the truth for Pliny's own time. On the other hand, a later writer, Faventinus, who also drew on Vitruvius, goes further in the opposite direction and recommends a minimum of 1 in 67 (1.5%).[31]

These anomalies are readily explained. First, Vitruvius drew almost all his material on aqueducts not from his own experience, or directly from Roman sources, but from Greek ones which he did not fully understand. Indeed the precise source for his statement about gradients has apparently survived in a fragment of Philo of Byzantium, a Greek of the third century BCE who wrote, among much else, an almost entirely lost book titled *Water Conducting*. Vitruvius drew on Philo for other material too. This fragment, which survives in a medieval Arabic treatise, prescribes a minimum slope for irrigation channels of 12 fingers in 100 cubits, which again is 1 in 200.[32] Second, the contradictions between the Roman writers are simply resolved if Vitruvius's figure was not spelled out in words but given as an abbreviation, which (as so often happened with this ever-fruitful source of confusion) was miscopied or misread by later generations. I suggest that his *in centenos pedes S* (½ ft per 100 ft) was read by Pliny as *in centenos pedes Ɔ* (¼ inch per 100 ft), and by Faventinus as *in centenos pede S* (1½ ft per 100 ft). If so, there is only one statement from antiquity about minimum gradients. Originating with Philo, copied by Vitruvius, miscopied by Pliny and again by Faventinus, it really applies to unlined irrigation channels in the Middle East and has nothing whatever to do with built Roman aqueducts.[33]

Aqueducts are particularly difficult to survey because they have to be fitted to the landscape not only in plan but also in the third dimension. It does not matter if, within limits, a road goes up- and downhill. If an aqueduct goes uphill, however, it will not work—unless it is under pressure in pipes, as in the case of inverted siphons, which sometimes carried them across valleys. On the question of how aqueducts were planned, Greek and Roman literature is virtually silent, just as it is about how roads were planned. The surveying manuals, useful though they are, always focus on the relatively small problem and never on the larger challenge. However, common sense suggests that the operation involved three distinct stages.[34]

First, springs of suitable volume and quality had to be located, ones which seemed to be high enough for their water to flow by gravity to the town; at the other end, a site had to be chosen for the receiving tank at, ideally, a point high enough to supply the whole of the town. Second, the exact difference in height between these two end points had to be discovered by meticulous leveling, and if that difference, taken in conjunction with the likely length of the channel as demanded by the terrain, gave a reasonable gradient, then the surveyors could proceed to the third stage.

This stage was to set out the route on the ground so that, in the interests of cost, it was as short as possible, demanded a minimum of expensive engineering works such as tunnels or arcades, and had a gradient as constant as the shape of the land allowed. These requirements often conflicted. To save heavy engineering, the length of the route might have to be greater, but then a gradient which was acceptable on a more direct line might become unacceptably shallow on a longer route. The work for this stage was no doubt divided into several phases, the first defining a few key intermediate points, the subsequent ones progressively filling in more and more detail. In every phase there would be alternative routes to be considered, advantages and drawbacks to be balanced, and compromises to be reached. The surveyors, moreover, must have had to build up their own maps as they went. For certain, on a long and difficult aqueduct the whole process would take a great deal of time and fieldwork. One is reminded of Robert Stephenson who, in determining the best route for the London & Birmingham Railway in 1831, walked the full distance (181 km) more than twenty times (Smiles 1862, 306).

We know that the surveyors, their work done, left the route marked out with stakes. Presumably the same or different stakes were also marked to indicate the levels. It was then for the builders to take over. But how accurately could they, or did they, follow such marks? Although there is no evidence, it seems likely that (then as now) they used boning or sighting boards to maintain a given gradient. These consist simply of two pieces of wood nailed together in the shape of a T. Someone sights from one surveyed level mark to the next; in between, boning boards are driven into the ground along the route or beside it, until the top of each T coincides with the line of sight. The floor of the channel is then built up to this level. On the Eifel aqueduct supplying Colonia Agrippinensis (*BAtlas* 11G2, modern Cologne in Germany), constructional differences and changes of gradient suggest that contracts were let for lengths of about 3 Roman miles, and steps in the floor (the biggest is 35 cm) at each end of one such section show how gangs had failed to match their work with that of their neighbors. It was clearly possible for surveyors' careful work to be marred by shoddy work by the builders.

It is the shallowest-graded aqueducts which provide the best yardstick of the capabilities of the libra, and that at Nemausus (*BAtlas* 15C2, modern Nîmes in France), which incorporates the renowned Pont du Gard, is perhaps the most instructive (fig. 5.17).[35] The source lies 14.6 m higher than the receiving tank in the city and 20 km away as the crow flies. On a direct line the gradient, if constant, would be 1 in 1,370 (0.073%). How close the Roman surveyors got to this theoretical figure there is no way of telling, nor can we know along what line they took their preliminary levels. But, assuming their work to be accurate, they would know that in no circumstance could the overall gradient be steeper than 1 in 1,370. In fact, anything like a direct route is totally forbidden by the upland massif of limestone which intervenes: tunnels through it would be impossibly long. The only practicable route skirts the upland in a great bow which more than doubles the distance to 50 km and more than halves the overall gradient to 1 in 4,000 (0.025%). The length is considerable, but far from a record—the longest of the aqueducts supplying Constantinople (modern Istanbul in Turkey) reaches a phenomenal 336 km.[36]

Ideally, height should be lost consistently: when the channel had run a quarter of the total distance, it should have lost a quarter of the height available. But the actual gradient of the Nîmes aqueduct is far from constant. Apart from many

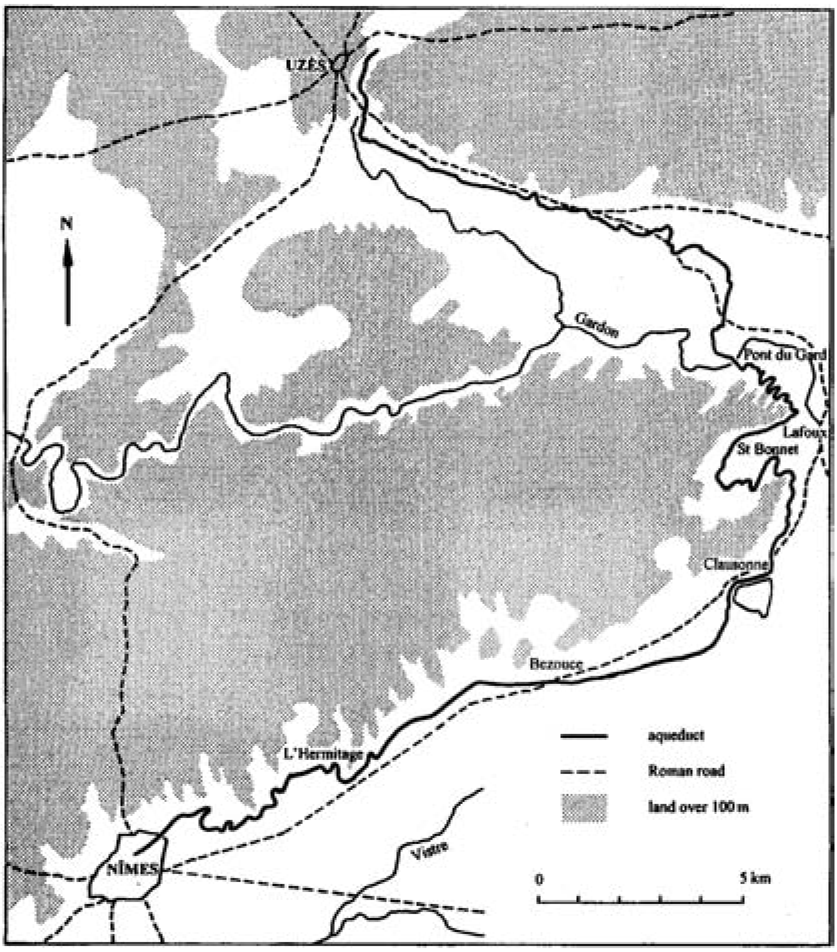

FIGURE 5.17 Nîmes aqueduct. Drawing by the author.

localized variations, the top section is relatively steep—at an average, 1 in 2,542 (0.04%). This section ends at the Pont du Gard, which is sited at the best point (in engineering terms) for crossing the valley of the river Gardon (fig. 5.18 and plate 5). As built, 47 m high above the river, it is the tallest bridge, as far as we know, ever undertaken by the Romans. Perhaps the engineers decreed "so high but no higher." However, in fixing its height well below the overall gradient, they gave the surveyors the luxury of a steeper gradient above it, but the penalty of a shallower one below. At the Pont du Gard they had used up about half of the height available in only about a third of the distance. Put more starkly, they still had 34 km to go and only 6 m of height left at their disposal.

For the 5 km immediately below the Pont du Gard the ruling gradient is almost 1 in 8,000 (0.0125%). Here a succession of small valleys descends from the upland, and the channel negotiates them by means of a series of reentrants with hairpin bends at each end (fig. 5.19). Presumably the cost of tunneling through the spurs

FIGURE 5.18 Pont du Gard. Roman aqueduct (UNESCO World Heritage Site, 1985) on Gardon River. Photo: S. Vannini. Pont du Gard, Nîmes, France. © DeA Picture Library / Art Resource, NY.

or bridging the valley entrances, which would have shortened the distance and helped the gradient, was considered too great. In this broken terrain, where the route is so tortuous that rarely can one see more than 100 m of it at once, surveying must have been a nightmare. Small wonder that the gradient changes frequently; at one point, indeed, it actually runs uphill, climbing 4.4 cm in 1,608 m. The effect on the water flow would be little worse than if it were level, but, whether the surveyors or the builders were responsible, it cannot have been intended. Space forbids detailed analysis of the rest of the route; but two stretches of roughly 8 km each are at virtually 1 in 20,000, or 0.005%, a fall of only 5 cm per kilometer.

The aqueduct had its teething troubles. Typically, at points where a steeper slope meets a gentler one below, water slows down, backs up, and may overflow. That happened in this case, and considerable lengths of the vaulting had to have their walls heightened, as did the trough of the Pont du Gard itself. But in the end the system worked, if only just. One is tempted to wonder if it did so more by luck than by good management. The surveyors and their instruments were surely tested to their limits. Nonetheless, with gradients as shallow as these, the Nîmes aqueduct illustrates the extraordinary precision of which Roman surveyors were capable. Whether they were fully aware of how fine the tolerances were, how close they were to failure and shame, we shall never know.

There are only two known instances of aqueducts which did not work. One is at Lindum (*BAtlas* 8G1, modern Lincoln in Britain), where there is no sign that

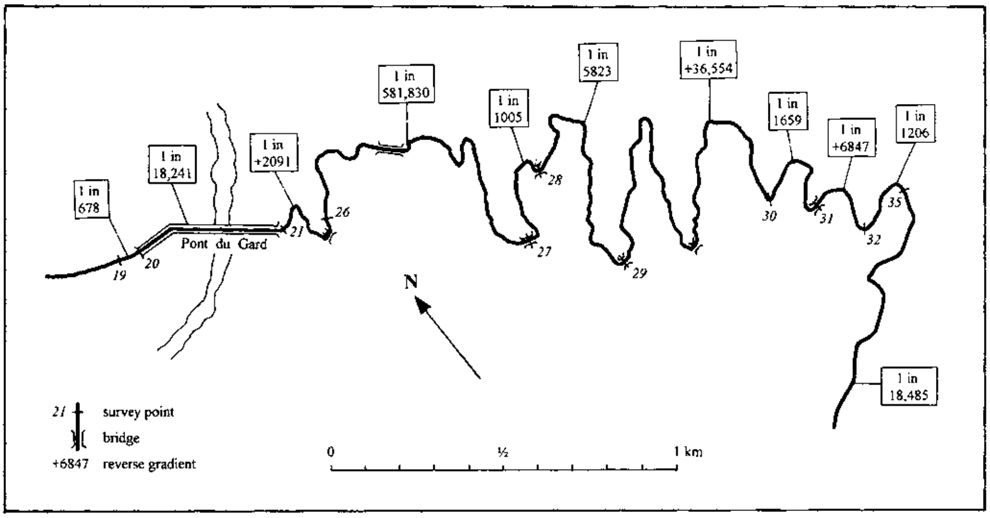

FIGURE 5.19 Hairpins on Nîmes aqueduct. Drawing by the author.

water ever flowed along its pipeline, but Lincoln was very much an oddity, in that its source lay 30 m *below* the tank in the city. The intention must have been to push the water up by machine—we know of two other cases where this was done—and most probably the machinery proved inadequate. It was hardly a surveyor's error (Lewis 1984). In the other instance, recorded in literature rather than by archaeology, the finger of suspicion does point at the surveyor. Pliny the Younger reported to the emperor Trajan in 112 CE that Nicomedia in Asia Minor (*BAtlas* 52F3, modern Izmit in Turkey) had made two attempts at building an aqueduct, and that both had been abandoned and largely demolished. Please send me, he asked, a surveyor or engineer "to prevent a repetition of what has happened" (*Letters* 10.37). The problem sounds like an engineering one, and of engineering problems the most likely is bad surveying. Our confidence in the surveyors of Nicomedia is not improved by their claim, also reported by Pliny (*Letters* 10.41–42, 61–62), that a nearby lake was less than 20 m above the sea. In hard fact, the lake surface averages 32 m above the sea, which is about 20 km away. If the local surveyors were as inaccurate as that, one can readily believe that they were responsible for the aqueduct fiasco.

TUNNELS

The surveying and driving of tunnels must count among the most difficult of engineering projects. Not only are conditions of work underground unpleasant and dangerous, but to establish and maintain the required gradient and alignment through solid rock also demands skills of a high order. The tradition of tunneling goes back to at least the eighth century BCE in Persia, where qanats, often several kilometers in length, brought water from underground aquifers to the surface for irrigation (Goblot 1979). These were probably the inspiration, either directly or through Egypt, for a small group of archaic Greek tunnels in the sixth century. Meanwhile, numerous tunnels (*cuniculi*) were dug in Etruria, most of them to drain waterlogged valleys; possibly they, too, reflected Persian practice transmitted through Greece. Later, the Romans adopted tunnels on a truly ambitious scale, for draining lakes, carrying roads, and above all as components of aqueducts.[37]

Some tunnels, like the qanat or the mine adit, were single ended, with only one mouth opening to the surface. Most were through-tunnels which passed through an obstruction such as a mountain ridge. These were of two sorts. The more difficult was the two-ended tunnel, where the depth of rock above was too great to sink shafts, except perhaps near each end for the purpose of alignment. The best known example, 1.036 km long, is that built about 530 BCE by Eupalinus to bring water to the town of Samos in the Aegean (*BAtlas* 61D2). The longest of all, on the Anio Vetus aqueduct near Rome (*BAtlas* 43C2–D2), was about 2.25 km. Two-ended tunnels permitted only two working faces, where the available space severely limited the number of workers. In consequence such tunnels took a long time to complete, and the difficulties of ensuring that two long headings met were considerable.

In the other, much more common type, the shafted tunnel, a series of shafts was sunk from the surface and their feet were linked by relatively short headings underground (fig. 5.20). This technique, employed on the qanats, was adopted wherever possible thereafter. In terms of length it culminated in the Roman aqueduct supplying Bononia (*BAtlas* 40A4; modern Bologna in Italy), 20 km long and entirely in a shafted tunnel. Shafts allow easy removal of spoil, better ventilation and, once the tunnel is finished, access for maintenance. More important still, each shaft increases the number of working faces by two. Despite the extra material to be removed, shafts therefore speed up the work, and the headings, because they are shorter, are less at risk of missing each other.

The difficulties inherent in tunnel surveying are considerable. Both the alignment of the final route and its level (which by definition is still invisible and inaccessible) have first to be established on the surface, both have to be marked in such a way that they can be projected underground once work has begun, and finally both have to be followed as driving proceeds. Tunnelers cannot see where they are going, and the scope for error is very great. Even though alignment and level must have been decided and followed at the same time, they are best discussed separately. For alignment, the procedure deduced for the Samos tunnel serves as a good example. Once the location of the two mouths had been determined, a straight line between them was set out across the intervening mountain by interpolation or successive approximation. To project this line underground, two markers were needed at each end, and not too close together. Each mouth certainly acted as one marker, but both are on steep slopes. So at the northern end the second marker was placed, on the alignment, on the opposite side of the valley. At the southern end, where this was impossible, a shaft was sunk on the alignment just inside the mouth. As the

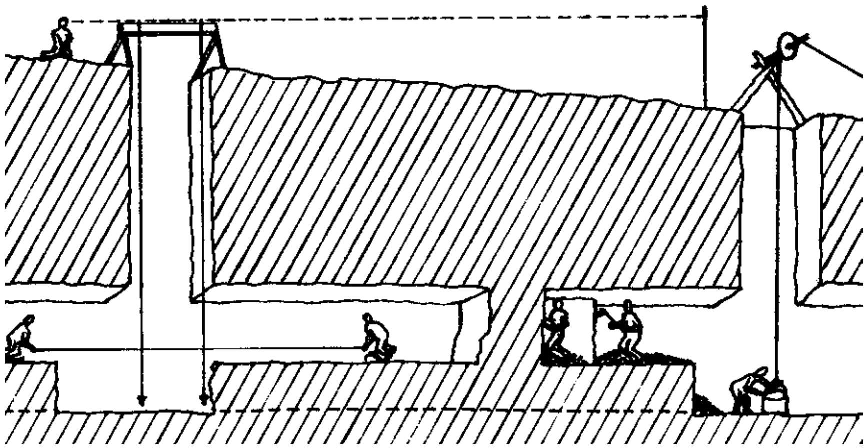

FIGURE 5.20 Shafted tunnel. After G. Fabre, J.-L. Fiches, and J.-L. Paillet, *L'aqueduc de Nîmes et le Pont du Gard: Archéologie, géosystème et histoire* (Nîmes, 1991), 85.

two headings advanced, they were aligned by sighting backward on the northern mouth and marker and on the southern shaft and mouth, respectively.

Whereas two-ended tunnels were almost always straight (or meant to be), shafted tunnels were often doglegged, the changes of direction occurring at shafts because it was down them that alignments were transferred. It seems likely that the ancient world used the method standard both on qanats and on more modern tunnels. A plank was laid across the shaft head and oriented precisely on the correct alignment. From it two plumb lines hung down to the shaft foot, where they necessarily assumed the same alignment. If the alignment changed at that shaft, similar planks and plumb lines also projected the new line down. The tunnelers, digging away from the shaft in both directions, followed the alignments indicated. As long as the tunnel mouth or the shaft foot could be seen from the working face, they knew the heading was straight. Usually a small pilot heading was driven first, later to be opened up to full bore.

Establishing the level was more difficult. The first step was to fix the relative heights of the mouths, allowing for the intended gradient. For a two-ended tunnel the surveyors might take levels over the hill to be pierced or, as probably at Samos, follow the contour around the hill. On shafted tunnels the process was more complicated, because the shaft heads lay at differing heights, but each had to be sunk to the correct horizon to meet the intended gradient underground. The surveyor would therefore level the site of each intended shaft on the surface, and from the height thus obtained and the distance along the line of the tunnel he would calculate the depth required. Maybe he drew a longitudinal section to scale and measured off the depth. Maybe he made all the shafts of equal depth below some horizontal datum, while allowing for the gradient. The traditional qanat surveyor measured the depth of one shaft with a knotted cord. He leveled from this shaft to the next one uphill, added to the cord the difference in height, and subtracted from it the height which the prescribed gradient should climb along that interval. The resulting cord was the depth of the next shaft (Hodge 1992, 205–6).

While a tunnel was under construction, the engineer had to keep a very close eye on the progress of the work. Above all, to ensure that the headings met up, he needed to know how far they had progressed and to what extent, if any, they had deviated from the intended line. It was easy to measure how far they had gone, but much harder to estimate on the surface how far they still had to go. While it was unlikely that long headings would achieve a neat, head-on meeting, it was possible to adjust their alignment in order to ensure that they would at least intersect. If one or both were deliberately angled so that their directions converged, they would be certain, provided the levels were correct, to meet. Much can be deduced from the Samos tunnel (Grewe 1998, 58–69). As the headings approached each other, Eupalinus opted for safety and made the northern heading zigzag to the west. On its return eastward (fig. 5.21, *a*) it crossed the original alignment at an angle and should have met the southern heading. But, as we now know, this was still 140 m away. Eupalinus had played his hand too soon, which implies that he had underestimated the total length of the tunnel. He therefore continued the northern heading at the same angle and turned the southern heading eastward too (*b*). Still they did not meet. At this point he probably realized that his estimate of underground distance was astray, and so he turned both headings toward each other. This should have been the final move, for he had clearly kept a careful record of how far his deviations had departed laterally from the original alignment. What he still did not know was that the northern heading was out of line with the southern: over its whole length it pointed about half a degree too far to the east. Its face was therefore always further east than expected (*c*). By this stage, however, the tunnelers could probably hear each others' pick blows through the rock, and by driving a final curved hook they were united (*d*).

Mismatches are often to be seen in shafted tunnels too, usually minor but occasionally spectacular. In La Perrotte tunnel just south of Saint Bonnet on the Nîmes aqueduct, for example (fig. 5.22), two pilot headings, only 24 m in combined length, were 1.45 m out vertically and about 2 m out horizontally when they met (Grewe 1998, 161–70). Although the junction was smoothed out, it was shoddy work, and surprising because on this aqueduct, as observed above, every millimeter of fall was precious.

There seems no reason why ordinary instruments—the dioptra and libra—should not have been used for leveling tunnels in Hellenistic and Roman times, both to determine height differences between mouths and shaft heads on the surface and to maintain the gradient underground. The much thornier question is what the Greeks used before the standard dioptra evolved in the late third century BCE. If they (and even the Etruscans) borrowed the very idea of tunnels, directly or indirectly, from Persia, we might expect them also to have borrowed the instruments for surveying qanats. For this early date we have no direct information at all on the nature of those instruments. But we do know how medieval qanat

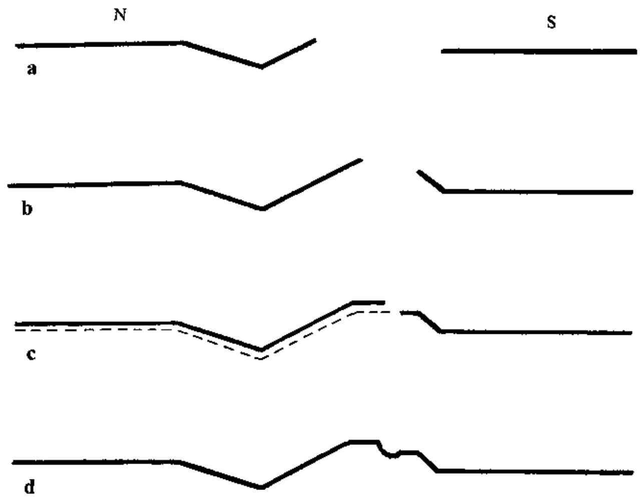

FIGURE 5.21 Samos tunnel, strategies for meeting. Based on K. Grewe, *Licht am Ende des Tunnels: Planung und Trassierung im antiken Tunnelbau* (Mainz, 1998), Abb. 88. Drawing by the author.

builders worked, and given that theirs was a highly conservative and hereditary profession, it is conceivable that their instruments were much the same as those their predecessors had always used.

Medieval qanat builders leveled height differences on the surface with a *mizan*. It required two graduated staves and a cord from whose center dangled a plumb line and a plate carrying a vertical mark. The staves were held upright a cord length apart, the cord was stretched between the tops of the staves, and one end was lowered until the plumb line coincided with the mark on the plate. This showed that the center of the cord was horizontal and its ends were therefore at the same height; the difference in readings on the staves gave the difference in height between their feet (Lewis 2001, 251–53). For underground use there was what might be called a protodioptra. A hollow brass tube was suspended from the tunnel roof, and the level was maintained by sighting through it (al-Karaji 1940, 26). How the tube was made precisely horizontal we are not told; conceivably, as suggested for the standard dioptra, it was reversed and the mean of the sightings was used. Although there is no evidence whatever in the West for the use of the mizan or, in this simple form, of the sighting tube, these qanat procedures would be entirely adequate for most of the archaic Greek and Etruscan tunnels with their quite steep gradients.

The real crux lies in the Samos tunnel. Its floor was evidently meant to be horizontal and almost is: it actually falls only 4 cm in 1,036 m, the pipeline itself running at a much steeper gradient in a trench cut in the tunnel floor. To the burning question of whether qanat instruments were capable of the accuracy seen at Samos, the only possible—and wholly unsatisfactory—answer is that we know of nothing else that was available at the time and could have done any better.

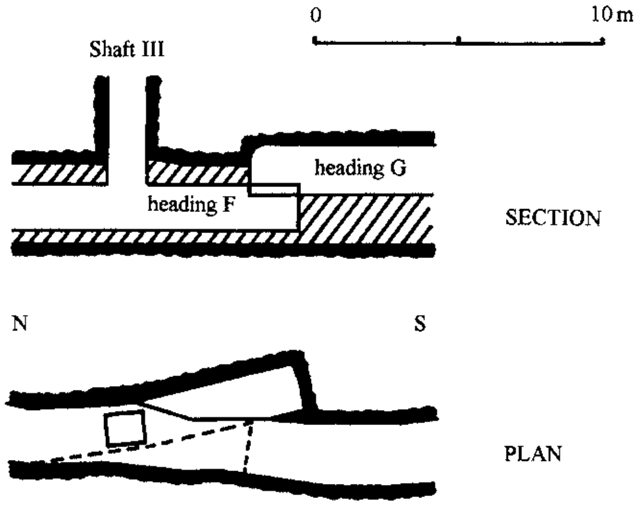

FIGURE 5.22 La Perrotte tunnel, Nîmes aqueduct. Based on K. Grewe, *Licht am Ende des Tunnels: Planung und Trassierung im antiken Tunnelbau* (Mainz, 1998), Abb. 257. Drawing by the author.

Tunneling, then, was full of challenges. At Saldae (*BAtlas* 31C3; modern Bejaia in Algeria) about 150 CE, a military surveyor named Nonius Datus was called in to rescue the municipal aqueduct project which had gone wrong—as we know from the inscribed record set up at the legionary base Lambaesis (*BAtlas* 34E2), in which Nonius himself explains: "I came to Saldae and met Clemens the procurator, who took me to the hill where they were bemoaning the poor quality of workmanship on the tunnel. It seemed that they were considering abandoning it, because the length of tunnel driven was longer than the width of the hill. The headings had evidently diverged from the straight line . . . but the straight line had been staked out across the hill." Nonius set things right, and the tunnel carries water to this day (Laporte 1997).

We may smile. But even today surveyors make mistakes. Surveying is rarely easy, and it was even more difficult in antiquity. The wonder is that the Greeks and Romans so often got it right. It is entirely appropriate that Nonius Datus's inscription features personifications of three qualities required in a good surveyor, with the name of each below in large letters: *Patientia, Virtus, Spes*—Patience, Professionalism, Hope.

NOTES

1. For the former, see chap. 1 above.
2. This was first realized, it is said, by Thales of Miletus, the pioneer Greek geometer of the sixth century BCE (Kirk, Raven, and Schofield 1983, 76–86); but significantly he made the discovery in Egypt, and no doubt he learned it from Egyptians.

3. Edwards (1985), 99, 246–47.

4. Hero, *Dioptra*, ed. Schöne (1903); Africanus, *Cesti*, ed. Vieillefond (1970); Anonymus Byzantinus, *Geodesy*, ed. Vincent (1858); al-Karaji, *Inbat al-miyah al-khafiyya* (1940). All relevant passages are translated into English in Lewis (2001), 259–302.

5. For an overview, see Dilke (1971).

6. See, respectively, Dilke (1987a), 220–25; chap. 6 below; and Frontinus, *Aqueducts* 17.

7. The least unsatisfactory of earlier accounts are Kiely (1947) and (though brief) Adam (1994), 8–19.

8. Vitruvius, *On Architecture* 8.5.

9. For discussion, Lewis (2001), 82–89.

10. See above, chap. 2, sec. V.

11. The design and evolution of the dioptra are explored in Lewis (2001), 71–82, 101–5.

12. Hero, *Dioptra* (Schöne 1903), 25, 7, and 10 respectively.

13. Rodriguez Almeida (1981), 45–48, 52n1.

14. The manuals give several procedures for measuring river widths. This is the one described by Marcus Iunius Nypsus, *Fluminis varatio* (ed. Bouma 1993), 4–28.

15. For fuller detail, Lewis (2001), 89–97.

16. On aqueduct gradients and instrumental accuracy, see Lewis (2001), 172–78.

17. Africanus, *Cesti* (Vieillefond 1970), 1.15.2; Hero, *Dioptra* (Schöne 1903), 12.

18. The complex material is collected in Lewis (2001), 157–66.

19. Talbert (2000) (= *BAtlas*), 58D2.

20. Cited by Strabo, *Geography* 1.3.11. For further details see Lewis (2001), 168–70.

21. See above, chap. 3, under "Challenges to the Study of Greek Cartography."

22. Scholiast on Ptolemy, *Geography* 1.3.3; John Philoponus, *Commentary on the First Book of Aristotle's Meteorology* (ed. Hayduck 1901), 15.5–8; Simplicius, *Commentary on Aristotle's De Caelo* (ed. Heiberg 1904), 548.27–549.10.

23. See further chaps. 6 below and 4 above.

24. Vitruvius 10.9. See further Sleeswyk (1979, 1981); Lewis (2001), 134–39.

25. See more fully Schiöler (1994).

26. For text, translation and commentary of most of the component manuals, Campbell (2000).

27. See, for example, *BAtlas* 32–33, 39–42, 44–45; note also Clavel-Lévêque et al. (1998, 2002).

28. H. Davies (1998), 4. On this complex and contentious subject see Lewis (2001), 217–45.

29. The gradients of the aqueducts of Rome are not adequately recorded: see Ashby (1935); Blackman (1978).

30. For Roman aqueducts in general, see Hodge (1992), an invaluable treatment which supplies much of the practical detail given in what follows here.

31. Faventinus, *On the Diverse Skills of Architecture* (ed. Plommer 1973), 6.

32. Ibn al-'Awwam, *Kitab al-Filaha* [Book of Agriculture] (trans. Clément-Mullet 1864), 1.131.

33. This whole matter is argued more fully in Lewis (1999).

34. Hodge (1992), 184–91; and Hauck (1988), 74–82 (a semifictional but insightful account of the building of the Nîmes aqueduct).

35. Fabre, Fiches, and Paillet (1991) is an admirable and exhaustive study; see also Lewis (2001), 181–93.

36. Crow, Bardill, and Bayliss (2008), 1; in *BAtlas* 52B2–D2 this line should extend further, to 6 km west of Bizye (B1).

37. Much the most authoritative (and splendidly illustrated) overview of ancient tunnels is Grewe (1998); many of the details in what follows are drawn from it. See also Oleson (2008), 319–33 (a chapter written by Grewe).