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PREFATORY NOTE

A very limited technical knowledge of engineering subjects, and lack of access to several authorities that I should have been glad to consult, have kept me from undertaking anything more than a short general description of the principal instruments, whether Roman, Greek, or Etruscan in origin, that were used by Roman engineers in land-surveying and leveling, in laying out sites for camps and towns, and in the construction of roads and aqueducts. I hope, however, that this brief sketch may prove of interest, not only to students of Roman antiquities, but also to present-day surveyors and engineers, the worthy successors of those old Roman Agrimensores who in the early Republic were men of priestly rank and under the Empire were clothed with magisterial powers.

EDWARD NOBLE STONE

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Seattle, Washington
February, 1928

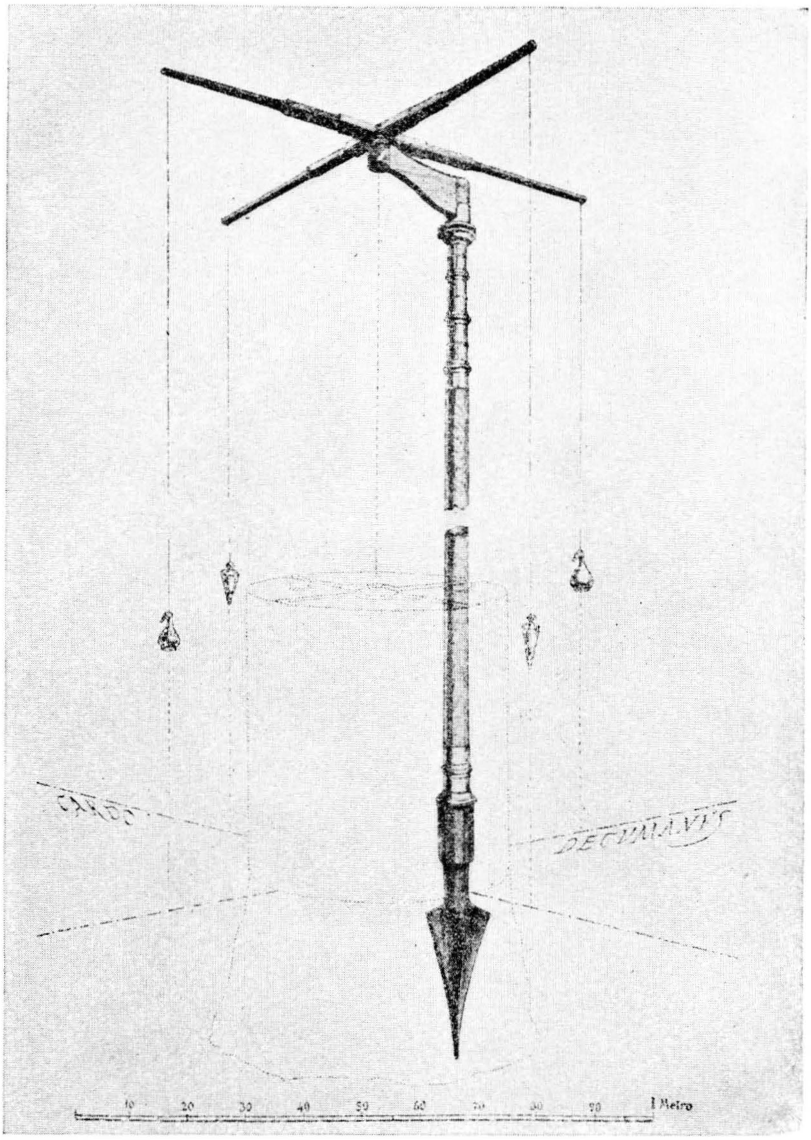

FIG. 1. Pompeian Groma. Reconstruction by Matteo della Corte.

ROMAN SURVEYING INSTRUMENTS

I.

INSTRUMENTS FOR DETERMINING THE TRUE MERIDIAN

In the age of Caesar and Cicero the star Polaris (Alpha of Ursa Minor) was about ten degrees farther away from the celestial pole than it is at the present time. The pole-star of that day was Beta of the same constellation, a star of lesser magnitude than Alpha, and therefore more difficult to locate. This is probably the reason we find no mention made by ancient writers of the determination of true meridians by ranging two plumb-lines or rods with the pole-star. Roman surveyors depended on the sun to give them their true bearings, and two devices (essentially one in principle) were utilized for this purpose, the Sun-dial ("Horologium," "Solarium") and the "Gnomon" or Pole.

A. Sun-dials

Sun-dials of many kinds were in common use among the Romans, and Vitruvius[1] gives quite full directions as to the methods to be employed in constructing and setting them up, calling attention to the fact that a dial can be accurately set only by taking the equinoctial shadow.

When a sun-dial was once correctly set, the points of compass could be determined from it, at least roughly; but the fact that it was not portable prevented its being generally employed as a surveying instrument. A modified form of the sun-dial, however, is mentioned by Vitruvius as being used in laying out the streets of a city. "In the center of the walls," he says, "[i. e., in the center of the city-site], let a marble plate be set up by means of a level, or else let the spot be made so smooth that a plate is not needed. On the exact center of that spot let a bronze gnomon be set up as a 'shadow-hunter' (called in Greek σκιαθήρας). At about the fifth hour of the forenoon the tip of the shadow of this gnomon must be taken and marked with a point. Then, with a pair of compasses extended to the point which is the mark of the shadow's length, beginning at this point a circumference must be described around the center. And likewise in the after-

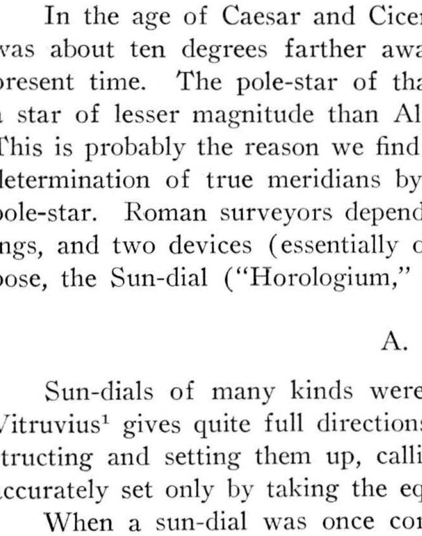

Fig. 2. Vitruvius's Method for Finding the Meridian.

[1] Vitruvius, *De Architectura*, 9, 7.

noon the lengthening shadow of the gnomon must be watched, and when it touches the line of the circumference and the afternoon shadow becomes equal to that marked in the forenoon, this shadow, too, must be marked with a point. From these two points arcs must be drawn, with the compasses, to their point of intersection; and through this point of intersection and the exact center of the circle a line must be extended to indicate the north and south quarters [i.e., the meridian]." Vitruvius gives further directions for marking on the circumference the eight principal points of the compass, or "eight winds." "Then," he continues, "it is evident that the lines of your streets and alleys should be laid out on the dividing lines between the quarters of two winds. For by this plan the disagreeable force of the winds will be shut off from the dwellings and blocks."[2] (Fig. 2.)

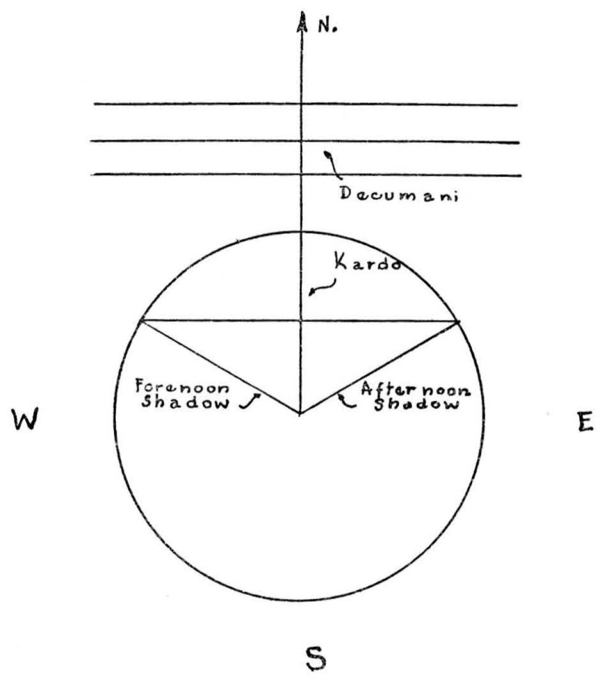

FIG. 3. Hyginus's Method for Finding the Meridian.

B. THE POLE, OR "GNOMON"

The method most commonly used by Roman surveyors in establishing a true meridian consisted in the construction of what was really a huge sun-dial, having a considerable area of level ground for its plate, and a tall pole in the place of the pin. This method (or rather, two modifications of the same method) is thus described by Hyginus:[3]

"In the first place," he says, "we will describe a circle on the ground in a level place, and in the center of it we will set up a 'sciotheras,' whose shadow will fall within the circumference part of the time; for this is a more accurate method than catching the shadow caused by the rising and the setting sun. We will watch the shadow as it wanes after sunrise. Then, when its tip arrives at the line of the circumference, we will mark that point in the circumference.

[2] *Ibid.*, 1, 6—8.

[3] Thulin, *Corpus Agrimensorum Romanorum* (*Hygini Gromatici Constitutio Limitum*), 152.

Likewise we will watch the shadow as its tip passes out of the circle [in the afternoon], and again mark that point in the circumference. When, therefore, we have marked the two points, in the places where the shadow enters and leaves the circle, we will measure a straight line from point to point of the circumference, and we will mark the middle point of this line. Through this middle point a straight line must be produced from the center of the circle, by extending which we shall have the Kardo [i. e., the 'principal meridian' of a survey]; and at right angles to this we will lay off the Decumani [i. e., the east and west 'base lines']." (See Fig. 3.)

The modification of this method, as described by Hyginus, consisted in taking three successive lengths of the shadow, either in the forenoon or in the afternoon, and then determining the meridian by means of a complicated geometrical formula involving the use of a circle and several triangles.

These methods of finding the true meridian could give absolutely correct results only at the time of the summer or winter solstices; yet they seem to have been employed with a fair degree of accuracy.[4]

[4] Hyginus's method is still sometimes used. William M. Gillespie, in his *Treatise on Surveying* (Part I, page 165, 1904 edition), describes a similar method, and refers to its use by Roman surveyors. This method is also described in Ernest McCullough's *Practical Surveying* (p. 115.)

II

INSTRUMENTS FOR MAKING LINEAR MEASUREMENTS

A. The "Pertica," or "Decempeda"

The "Pertica," or "perch," was a pole of seasoned wood, ordinarily ten Roman feet (9.71 English feet) in length, whence its other name of "Decempeda." Such a rod, when protected at the ends by metal shoes or ferrules,[5] is a very accurate instrument for making linear measurements. Poles twelve, fifteen, and even seventeen Roman feet (about sixteen and one-half English feet) in length were also sometimes employed. (The 17-foot "pertica," as a unit of land measure, may have been the origin of the English "rod, 'perch,' or pole" of the old arithmetic tables.) The longer poles were used in subdividing public land where the soil was of inferior quality, larger *sortes,* or lots, being assigned in such cases.[6] In running lines with the Groma (see page 223), the Pertica could also be used as a range-pole.

Cicero, Horace and other Roman writers make frequent mention of the Decempeda.[7] In his thirteenth Philippic, Cicero refers to a certain Lucius Antonius as a "most accurate 'decempedator' ['ten-foot-pole-man']," or surveyor of both public and private lands.[8]

B. Cords or Ropes

The ten-foot pole was a very convenient instrument for making measurements on slopes or over broken ground, with the aid of the plumb-bob;[9] but in open, level country its use must have been slow and tedious. It was natural, then, that ancient surveyors should seek some longer measuring device, and we learn from Hero of Alexandria that cords or ropes were used for this purpose. Hero does not say what lengths of line were thus employed, nor how their subdivisions were marked, but he does give us a good description of the method then used to keep the cord from shrinking or lengthening. "The rope," he says, "is stretched taut between two stakes, and after it has been kept in this position for a considerable length of time it is stretched again.

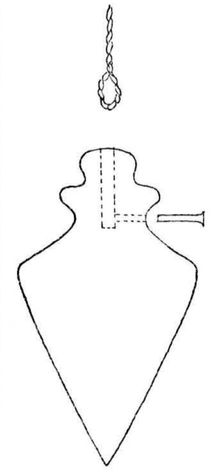

Fig. 4. Roman Plumb-bob.

[5] See footnote 18, page 224.

[6] Cf. Brandis, *Decempeda* (Pauly-Wissowa, *Real-Encyclopädie der classischen Altertumswissenschaft,* iv, 2254).

[7] Cicero, *Pro Milone* 27, 74; *Philippicae,* 14, 4, 10; *Academicae Quaestiones,* 2, 41, 126: Horace, *Carmina,* 2, 15, 14.

[8] Cicero, *Philippicae,* 13, 18, 37.

[9] Roman plumb-bobs, or "perpendicula," were similar in shape and size to those now in use. Figure 4 (taken, in part, from Daremberg and Saglio's *Dictionnaire des Antiquités Grecques et Romaines*), represents a specimen from southern Gaul. An opening in the top permits insertion of the looped end of the string, which is held in place by a short wire or pin thrust through a transverse opening below.

When this process has been repeated several times the rope is rubbed with a mixture of beeswax and resin. It is better, however, instead of stretching the rope between two stakes, to suspend it vertically for a long time with a sufficiently heavy weight attached to it."[10]

A cord thus treated was probably as accurate a measuring device as the old-fashioned Gunter's chain, or the Engineers' chain, with their two hundred or more wearing surfaces and easily bent links.[11]

I find no mention of marking-pins in connection with either the pole or the cord, but something of that sort must necessarily have been used.

C. THE "HODOMETER"

There was another instrument for making linear measurements, in use among both the Greeks, and the Romans, called the "Hodometer," or "road-measurer." In principle, it closely resembled a modern odometer, cyclometer, or taximeter. Both Hero of Alexandria and Vitruvius give full directions for the construction of this instrument. The latter says:[12]

"The subject that I will now take up in my treatise is a device, not devoid of utility and designed with the greatest cleverness, which has been handed down by earlier writers; a device by means of which, either while sitting in a carriage on the highway or when sailing on the sea, we are enabled to know how many miles of our journey we have covered. Its arrangement is as follows: Let the wheels of the carriage be four and one-sixth feet in diameter, so that, when the wheel has received a definite mark on its exterior and starting from this mark begins to make one revolution on the surface of the road, when it comes back to the definite mark from which it started it will have covered the exact distance of twelve and a half feet.[13] When these wheels have thus been made ready, then to the nave of one wheel, on its inner side, let a drum be solidly fastened, having a single tooth projecting beyond the surface of its cylinder. Above this, let there be firmly attached to the body of the carriage a box holding a revolving drum set perpendicularly and mounted on a small axle. To the face of this drum, let teeth, four hundred in

[10] Hero, *Αὐτόματα* (*Vet. mathem.*, 1694, p. 245), quoted by A. de Rochas, in Daremberg and Saglio's *Dictionnaire des Antiquités Grecques et Romaines* (Art. *Geodesia*).

[11] "A well made rope, (such as a 'patent wove line,' woven circularly "with the strands always straight in the line of the strain), when stretched wetted, and allowed to dry with moderate strain will not vary from a chain more than one foot in two thousand, if carefully used."—William M. Gillespie, *A Treatise on Surveying,* Part I, page 15 (1904 edition.)

[12] Vitruvius, *De Architectura,* 10, 9.

[13] These numbers are obviously incorrect. The text of Vitruvius (ed. V. Rose) reads: "rotae......latae per mediam diametron pedum quaternum et sextantis," and: "spatii habeat peractum pedum XII s." Some editors omit "et sextantis" from the first phrase and "s" from the second, a change which produces no better result mathematically. Charles Singer, in his chapter on "Roman Science" in *The Legacy of Rome* (edited by Cyril Bailey), says that Vitruvius gives 3⅛ as the ratio of the circumference of a circle to the diameter. This ratio would require that "et sextantis" be omitted from the first phrase, but "s" ("semis") retained in the second. It may be that Vitruvius himself originally wrote "pedum XIII" instead of "pedum XII s". This reading would involve an error in the circumference of a trifle over one English inch.

number, be fitted at equal intervals, so as to engage the tooth of the lower drum. Moreover, to the side of the upper drum let another single tooth be fitted, projecting beyond the other teeth. Again, let there be set above this a horizontal drum, toothed in similar fashion and inclosed in a box, with its teeth engaging the single tooth that has been fastened to the side of the second drum; and in this drum let there be as many holes as are the miles that the carriage can travel in one day's journey; if more or less, this will not interfere with the result. And in all these holes let marbles be placed, and in the case or box holding the drum let there be made a hole connecting with a small tube, through which, when they come to that spot, the marbles that have been placed in the drum can fall one by one into the body of the carriage and into

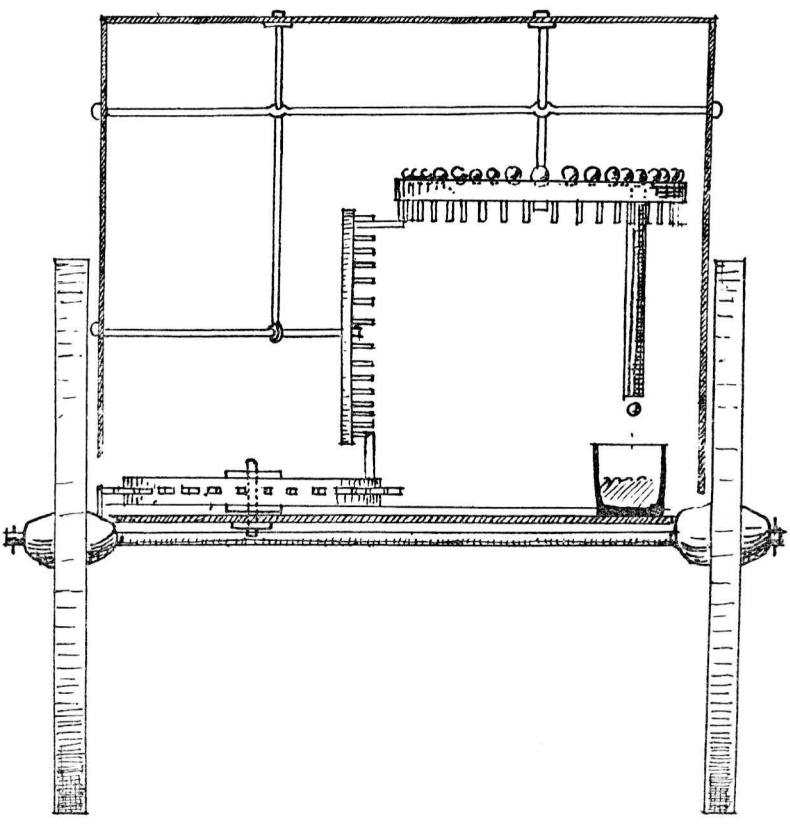

FIG. 5. Vitruvius's Hodometer.

a bronze vessel set underneath. Thus, as the wheel in its progress carries with it the lowest drum, and as the tooth of this at each revolution by striking the teeth of the upper drum forces it along, it will bring it about that when the lowest drum has revolved four hundred times the upper drum will have been driven around once and the tooth that is fitted to its side will have pushed forward one tooth of the horizontal drum. Since, therefore, with four hundred revolutions of the lowest drum the upper one will have been turned around once, the ground covered will equal five thousand feet, that is, one [Roman]

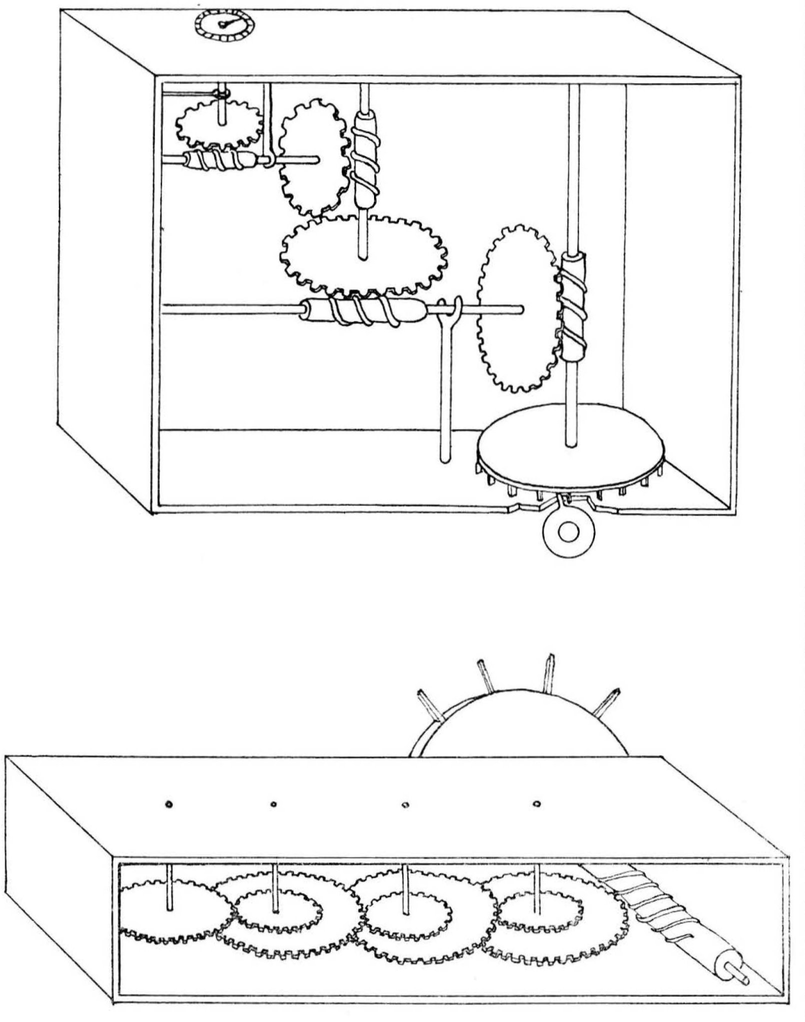

FIG. 6. Hero's Hodometers. (After Schöne).

mile. Hence, as often as a marble falls, by the sound that it makes we shall be notified that we have gone ahead one mile. Moreover, the number of the marbles gathered from below will show the number of miles covered in the day's journey." (See Fig. 5.)

Vitruvius goes on to tell how this device may also be used as a sort of "patent log" in navigation, being then connected with the axle that passes through the sides of the ship and is furnished with paddle wheels at each end.

Hero, also, describes two similar instruments for automatically recording distances traveled by land or by sea.[14] In one form of Hero's Hodometer, however, worm-gearing is employed instead of toothed wheels only, and a dial and pointer, instead of marbles falling into a bronze bowl, serve to indicate the number of miles covered. (See Fig. 6.)

The Hodometer was not used merely as a taximeter, but it was also sometimes employed by engineers for the rapid measurement of long distances, as, for example, in laying off the base of a triangle along one bank of a river whose width is to be determined, the angles at each end of the base being measured with the Dioptra. (See page 227.)

A Hodometer is listed by Julius Capitolinus in the inventory of valuable objects formerly belonging to the Emperor Commodus and sold after his death.[15]

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[14] Περὶ Διόπτρας, xxxiv, xxxv (pp. 292—314.)

[15] *Hist. Aug. Scriptores.* (Quoted by A. de Rochas, in Daremberg and Saglio's *Dictionnaire des Antiquités Grecques et Romaines;* Art. *Geodesia.*)

III

INSTRUMENTS FOR MEASURING OR LAYING OFF HORIZONTAL ANGLES

A. The "Groma"

The instrument most commonly used, during the whole period of Roman history, for measuring or laying off horizontal angles, was the Groma,[16] the invention of which is generally attributed to the Etruscans, though some authorities think that the Etruscans learned its use from the Greeks. From its shape, this device was also sometimes called the Stella ("star").

While this instrument is frequently mentioned by Roman writers, no detailed description of it has been found in ancient literature, and until the second decade of the present century theories as to its form and dimensions were, for the most part, based on a rude representation of a Groma found on the tombstone of a *mensor* (surveyor) near Ivrea (the ancient Eporedia), in Piedmont, in the year 1852.[17] (See Fig. 7.) Even as authoritative a work as the 1923 edition of Harper's *Dictionary of Classical Literature and Antiquities* bases its very incomplete description of the Groma on this crude picture. Most Latin lexicons, and other similar works, likewise give only vague or absolutely false definitions of the word "Groma"; and the more modern ones are, strange to say, the more misleading in their statements. Leverett's *Lexicon* (1847) defines *groma* as "an instrument for measuring fields"—a correct definition, as far as it goes, but applying equally well to the Pertica or half a dozen other instruments. But Harper's *New*

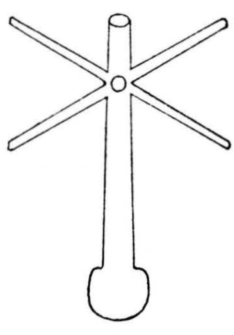

Fig. 7. Conventional Representation of Groma (from a Roman Tombstone).

[16] The word "groma" is supposed to be a corruption of the Greek γνώμων or γνῶμα, though some authorities connect it with *grumus*, "a little mound of earth." But as the Romans probably got the instrument from the Etruscans, it is possible that its name also is of Etruscan origin.

It is, perhaps, inexact to speak of the Groma as an instrument for "measuring" horizontal angles. Only right angles could be actually measured with it; but in determining the areas of *"subseciva"* (small tracts of land with irregular boundary-lines, such as river banks), which were generally cut up into a series of right-angled triangles, the cross could be swung around so as to lay off a line at any desiraed angle to the "Kardo" or the Decumani." In such a case, the side opposite each acute angle was measured, rather than the angle itself. (See also page 231).

[17] This representation is reproduced (under the article *Geodesia*) in Volume II of Daremberg and Saglio's *Dictionnaire des Antiquités Grecques et Romaines* (from which Figure 7 has been copied), also in both Smith's and Harper's dictionaries of classical antiquities. The name of the surveyor was Lucius Aebutius Faustus. His epitaph is given in the *Corpus Inscriptionum Latinarum* (V, 6786).

The discovery, half a century later, of what were thought to be the remains of a Groma, near Eichstätt, in Bavaria, led the German scholar Hermann Schöne to attempt a complete reconstruction of the original, an account of which was published in 1901 (*Jahrbuch d. K. D. Arch. Inst.*, xvi, 127-132). This reconstruction was only partially successful, however, and it is now thought very doubtful whether the Eichstätt fragments really were parts of a Groma.

Latin Dictionary (1907) tells us that *groma* means "a surveyor's pole or measuring-rod"—a perfectly good definition of the Pertica, but no more applicable to the Groma than to a modern transit or surveyor's compass. The *Oxford English Dictionary* and the *Encyclopaedia Brittanica* (under the articles "Gromatic" and "Gromatici," respectively) also refer to the Groma as a measuring-rod or pole.

In the year 1912, however, the office of a Roman surveyor, still containing many of the implements[18] of his profession, was unearthed at Pompeii. Among the articles found there was a Groma, the metallic portions of which were in a fair state of preservation. The wooden parts had, of course, disappeared, except for a few fibers adhering to the metal; but the noted Italian archaeologist, Dr. Matteo della Corte, was able to put the scattered pieces of the instrument back in their original relative positions, supplying new wooden parts whose dimensions are probably very close to those of the lost ones. Dr. Della Corte published a monograph on the Groma in 1922,[19] the main points of which were very fully reproduced by the late Professor Francis W. Kelsey, in a review of Della Corte's work written in 1926.[20]

While the Groma was used in Roman times for many of the same purposes as was the Surveyor's Compass fifty or a hundred years ago, it more nearly resembled, in form and functions, the old-fashioned Surveyor's Cross, which was also in use during the nineteenth century. (See Fig. 8.) Like the last named instrument, the Groma had two cross-bars, solidly set at right angles to each other and revolving around a spindle; in the case of each instrument, the spindle was supported by a Jacob's staff; furthermore, when either instrument was in use the staff was set a little to one side of the stake, stone, or other monument over which the center of the instrument was to be brought; but while the staff of the Surveyor's Cross was planted obliquely in the ground and the spindle brought into a vertical position by means of a ball-and-socket joint, the staff of the Groma was set in an upright position and the center of the instrument brought over the desired point by means of a swinging arm. The Surveyor's Cross had four sight-vanes projecting perpendicularly upward from the extremities of the cross-arms; the Groma had, instead, four plumb-lines suspended beneath these four extremities.

[18] Among the articles discovered were two pairs of drawing compasses, a rule, a small ivory box the cover of which could be used as a sun-dial, ink-bottles, stylus, and the metallic ends of a Decempeda, or measuring-rod. Professor Kelsey suggests that the presence of both stylus and ink-bottles would indicate that the surveyor used waxed tablets for taking his notes, but papyrus for making his permanent records, drawings and maps. Della Corte identifies the owner of these implements as a certain Verus, supposed to have been employed by the military tribune Titus Suedius Clemens in making surveys relative to the restoration to the city of certain *loca publica* held by private individuals. These surveys were made shortly before the destruction of Pompeii in the year 79 A.D.

[19] In *Monumenti Antichi pubblicati per cura della R. Accademia dei Lincei,* vol. xviii (1922).

[20] *Classical Philology,* xxi, 259-262 (July, 1926). For details regarding the form and dimensions of the Groma, I am largely indebted to this article by Professor Kelsey, and through the courtesy of the University of Chicago Press I am able to use his picture of the Pompeian instrument as Figure 1 of this bulletin.

The Groma, then, with its accessories, consisted of the following main parts: (1) a cross (the "Groma" proper) with arms of equal length (about three feet, or one and one-half feet each side of the point of intersection, which was pierced by a socket); (2) four plummets (*pondera*) suspended by cords (*fila or nervial*) from the extremities of the arms; (3) a swinging arm

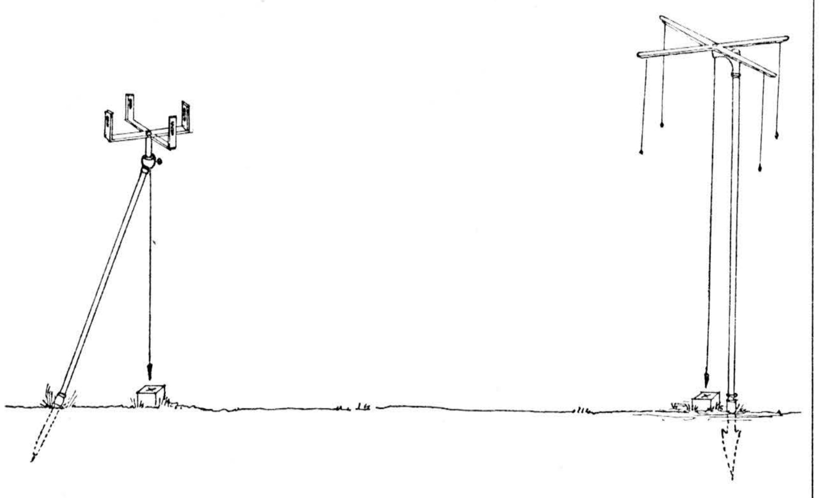

FIG. 8. Surveyor's Cross (19th Century) and Groma (1st Century).

(*umbilicus soli*), with a bronze spindle projecting upward from its outer end, on which the cross, or Groma proper, could be mounted by means of its socket; and with a bronze socket of its own, at its inner end, which slipped over another spindle firmly set on the head of the Jacob's staff, so that the arm, when mounted, stood out at right angles to the staff; (4) a Jacob's staff of wood, six or seven feet in length, the bottom of which fitted into a heavy pointed iron shoe (*ferramentum*) having tapering vertical flanges on its sides to aid in driving it firmly into the ground, while the top supported a bronze spindle which received the socket of the swinging arm. The weight of the staff, with shoe and spindle, was some seven or eight pounds.

The swinging arm (*umbilicus soli*) was a wooden bar, strengthened by metal strips fastened to its upper and lower sides. The cross-arms of the Groma proper were also of wood, but were held rigidly in place by a metal frame which also contained the socket that slipped over the spindle attached to the outer end of the swinging arm; they sloped slightly upward from the point of intersection, so as to swing clear of the *umbilicus soli.* Of the weights (*pondera*), one pair closely resembled modern plumb-bobs in both shape and size, but the others were of somewhat different form. (See Fig. 1.)

Although no ancient writer has left a description of the Groma, we do find a few directions for setting up the instrument and taking sights with it. For the most part, these directions are included in the rules and instructions for laying out and subdividing the public lands, compiled for the benefit of prospective surveyors.

One writer[21] tells the student first to plant the Jacob's staff (*ferramentum*) near the boundary-stone from which an observation is to be made, but in such a position that the staff itself will not be on the base-line or on the line that is to be run perpendicular to the base-line. Then he must swing the arm of the instrument (*umbilicus soli*) over the top of the stone, and adjust it so that a plumb-bob dropped from the outer spindle will fall directly upon the center of the cross that is cut into the top of the stone.

A passage from Frontinus[22] gives instructions for taking the next steps. "Carefully direct all the sights," he says, "bringing one of the pairs of strings or plumb-lines, which hang with their plumb-bobs from the extremities of the cross-arms, so exactly into line [with the back 'flag' or range-pole] that the further string of the pair will be hidden from sight and the nearer one only visible to the eye." Then, by sighting across the other pair of strings, a line may be laid off at right angles to the base-line. With the instrument still in the same position, and using the first pair of strings, a fore-sight is taken to the next measured point of intersection of base-line and perpendicular. The instrument is moved ahead to this point and placed in adjustment, a back-sight and fore-sight are taken, and a perpendicular laid off. This process is repeated until the end of the base-line is reached. At each point of intersection a monument is set up, the exact point being determined by means of the plumb-bob and then marked by a cross cut into the top of the stone.

Hero[23] warns surveyors of the necessity for observing great care and accuracy in the manipulation of the Groma. He writes as follows: "In as much as some persons make use of the so-called 'Star' [see page 223] for a limited number of the processes of surveying, I feel that it is proper for me to call to the attention of those who may attempt to use the instrument the results of employing it, so that they may not, through ignorance, be unconsciously guilty of errors. Those who have already tried the instrument have, I think, experienced difficulty in using it, because the strings from which the plumb-bobs hang do not come to rest quickly but continue to swing for a considerable time; this is especially true when a brisk wind is blowing. Therefore some surveyors, for the sake of avoiding this inconvenience, make hollow wooden cylinders and endeavor, by letting the weights hang inside these, to keep them from being struck by the wind. However, if there is any contact between the weights and the sides of the cylinders, then the strings do not remain in a position exactly perpendicular to the horizon. But even if the surveyor succeeds in maintaining the strings in a perfectly vertical position, it does not follow in every case that the planes in which the two pairs of strings

[21] *Schriften der römischen Feldmesser* (ed. Blume, Lachmann, Mommsen, Rudorph), i, 287. (Quoted by Schulten in Paully-Wissowa's *Real-Encyclopädie der classischen Altertumskunde*, Art. *Groma*.)

[22] Juli Frontini *De Arte Mensoria* (*Corpus Agrimensorum Romanorum*, ed. Thulin, 16 and 17).

[23] Περὶ Διόπτρας, xxxiii (pp. 288-290).

lie are absolutely perpendicular to each other." This is because insufficient care has been taken to see that the cross of the Groma is absolutely level; and Hero goes on to show, by a geometrical figure and demonstration, that correct results cannot be obtained under such conditions.

B. THE "DIOPTRA"

Like the modern Engineer's Transit, the "Dioptra" was adapted not merely to the measuring or laying off of horizontal angles, but of vertical ones as well, and it could also be used as a leveling instrument.

The Dioptra was of Greek origin, and the only description we have of the instrument was written in Greek, by Hero of Alexandria.[24] The Dioptra was, however, used by Roman surveyors at least as early as the beginning of the Empire, for it is specifically mentioned by Vitruvius,[25] who had served as a military engineer under Julius Caesar.

Most modern authorities seem to think that the Roman form of the Dioptra was inferior to the type described by Hero. But the elder Pliny[26] refers to the use of Dioptras in making astronomical measurements, from which one would infer that the Roman instrument was as fully equipped as the Greek one for taking accurate observations.

Hero's treatise on the Dioptra fills some sixty-six pages in the Teubner edition; unfortunately, however, certain extremely important details concerning the construction of the instrument are lacking, and the editor of the text, Dr. Hermann Schöne, is of the opinion that a portion of the earliest manuscript of the work (estimated by him as being either two or four entire pages) had been lost before the extant copy was made. From the existing portions of Hero's description of the instrument itself, and from his very full explanation of its use in solving most of the problems of plane surveying and leveling, Dr. Schöne has made a complete reconstruction of the Greek Dioptra, which, in the absence of any definite evidence to the contrary, we can regard as applicable to the Roman instrument also.

According to Hero, instead of a tripod the Dioptra had for support a small pillar, probably some five or six feet in height. His account does not tell how this pillar was made to stand firmly in a vertical position, but a manuscript drawing (See Fig. 9) shows three metallic cones projecting obliquely

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[24] Ἥρωνος Ἀλεξανδρέως Περὶ Διόπτρας (*Heronis Alexandrini opera quae supersunt omnia;* vol. iii, *Rationes Dimetiendi et Commentatio Dioptrica*: recensuit Hermannus Schoene. Leipzig, 1908).

[25] *De Architectura,* 8, 5.

[26] *Naturalis Historia,* 2, 69, 69.

In the short but very interesting account given by Ernest McCullough, in Chapter VI of his *Practical Surveying,* of the evolution of the Engineer's Transit from the Dioptra, the author refers to the latter instrument as a large surveyor's cross for setting out perpendiculars. Like most other writers on this subject, he seems to have confused the Roman type of Dioptra, in part at least, with the Groma. Such confusion was almost unavoidable, in view of the infrequent and vague references made to the Dioptra by Roman writers, and the fact that the real nature of the Groma was not understood until within the last decade.

from the bottom of the pillar, somewhat resembling the shoes of three tripod-legs, so that it was probably manipulated in much the same manner as a modern tripod. The drawing also shows a plummet for determining the verticality of the pillar, exactly like the device that Hero describes later in connection with the leveling-rod.

"The construction of the Dioptra," says Hero, "is as follows. A support is made in the form of a small pillar, having a round spindle projecting from its top. Around this spindle is fitted a circular bronze plate whose center is the same as that of the spindle. Furthermore, over the spindle is set a bronze cylinder, which can revolve smoothly around the spindle, and which has a cogged wheel firmly attached to its under side, somewhat less in diameter than the cylinder itself. On its upper side the cylinder has a plinth, made, for the sake of appearance, in the form of the capital of a small Doric column. Engaging the teeth of the cog-wheel, is a small tangent-screw, the supports of which are made fast to the large bronze plate. . . . . On top of the plinth are two vertical bronze standards, far enough apart so that another cog-wheel [or half-wheel] can be fitted in the space between them; and on the top of this same plinth, and between the bases of the standards, a tangent-screw is made to turn, being held in place by small supports fastened to the face of the plinth. . . . . In the space between the standards [and fastened to the upper end of the cog-wheel, which was either semicircular in shape or else flattened on the upper side], a bar is fitted, some four cubits [about six feet] in length, and of such breadth and thickness that it will fit the space [between the standards] and that this point will divide its length into two equal parts. In the upper surface of the bar a groove is cut, semicircular or rectangular in cross-section, and long enough to receive a bronze tube about twelve dactyls [eight inches] shorter than the bar itself. To the two ends of the bronze tube are joined two other vertical tubes, so that it looks as if the long tube were bent upward at each end. The height of these vertical pieces must not be more than two dactyls [one and one-third inches]. Next, the bronze tube must be covered with a flat bar, which will fit over the groove in such a way as not only to hold the bronze tube firmly in place but also to improve the appearance of the instrument. To each of the vertical ends of the tube already mentioned a small [hollow] glass cylinder is fitted,

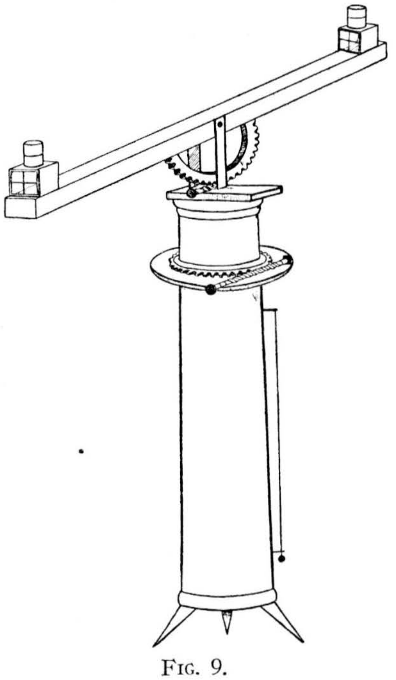

FIG. 9.

of like thickness with the tube itself and about twelve dactyls in height. Then the glass cylinders are made absolutely fast to the vertical ends of the tube, with wax or some other covering, so that when water is poured in through one of the cylinders it cannot leak out anywhere. The long bar is fitted with

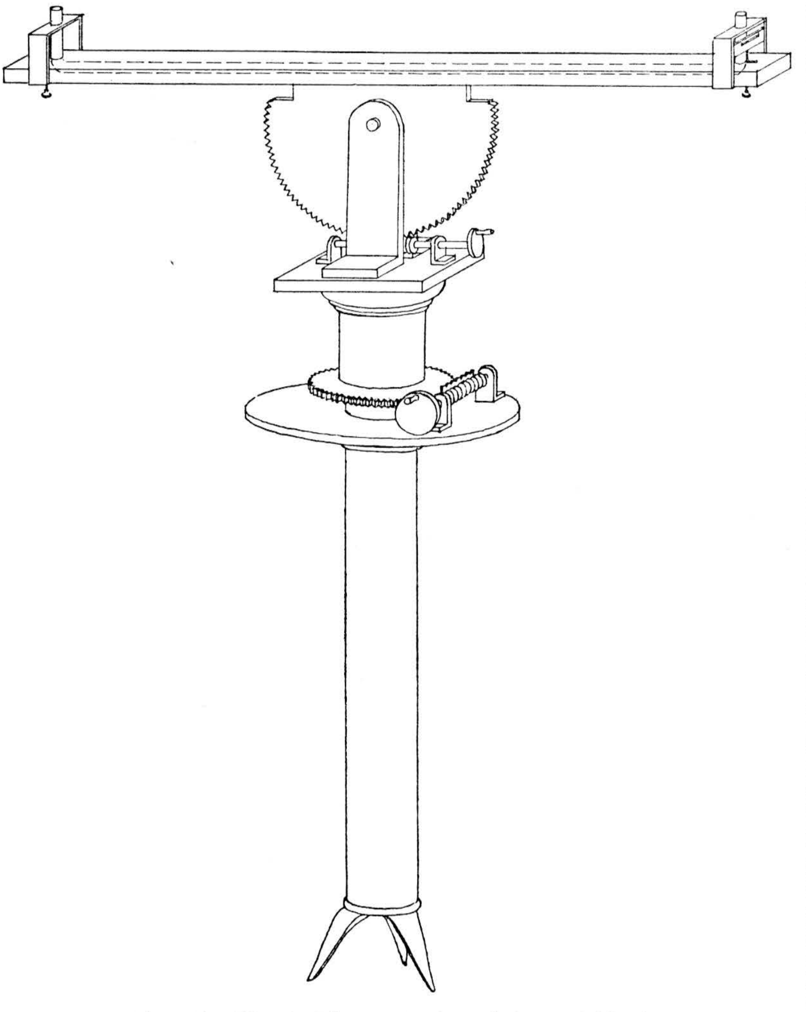

FIG. 10. Hero's Dioptra (Adapted from Schöne).

two small frames at the points where the glass cylinders stand, in such a way that the cylinders pass through the frames and are firmly held in place by them. In these frames are set small bronze plates, which slide up and down in channels cut in the walls of the frames; they have slits cut in their centers, through which sights may be taken. On the bottom of each of these plates is fastened a small cylinder, about half a dactyl in height, and into these little cylinders are fitted revolving rods of bronze, the length of which is the same as the height of the frames around the glass cylinders. These rods extend down through holes made in the grooved bar. A thread is cut in each of these rods, engaging a small nut that is made fast to the bar. Thus, then, if one turns the part of the rod that projects below the bar, the metal plate with its opening for sighting, will be moved up or down; for the end of the rod next to the metal plate is provided with a small head which fills a little socket cut on the inside of the cylinder."

From this description, it appears that the Dioptra was designed primarily to be used as a leveling instrument, and I shall speak of it further under that head. (See page 238.) But from the large number of problems in surveying and astronomy[27] that Hero lists as capable of being solved with the aid of the Dioptra, it is clear that the instrument also possessed some of the properties of the modern transit. Hero speaks of describing a circle on the large plate[28] and dividing this circle into three hundred and sixty degrees, so that angles could be definitely measured by revolving the sighting-bar over the plate. From

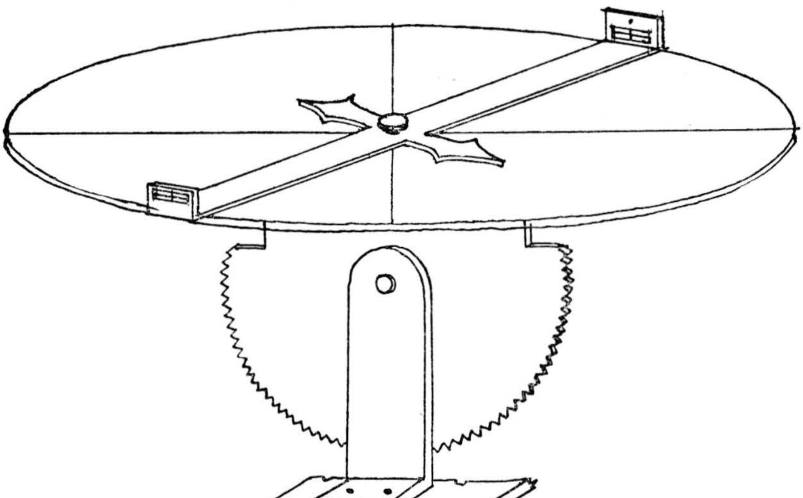

FIG. 11. Attachment for Reading Angles, as Conceived by Schöne.

[27] Among these are the following: To find the horizontal distance and the difference in elevation between two inaccessible points; to calculate the length and direction of a tunnel to be cut through a hill, when the two extremities of the tunnel have been determined; to locate the point on top of a hill from which a vertical shaft can be sunk so as to strike a tunnel running through the hill; from a single point inside a given tract of irregular shape, to subdivide this tract into smaller tracts of any desired number and size; to measure a field without entering it; to determine the width of a stream when the further bank is inaccessible; to measure the angular distance between two stars, etc.

[28] Περὶ Διόπτρας, xxxii (pp. 286-288).

this statement, Schöne concludes that a separate attachment was used for this purpose. (See Fig. 11.) But it would be equally possible to describe the circle on the plate that was fastened directly to the top of the supporting pillar; then a short pointer, projecting from the lower edge of the revolving bronze cylinder to the circumference of the inscribed and divided circle, would enable the observer to read the angle. Such an arrangement would obviate the necessity for any additional attachment.

It was only in connection with astronomical observations, however, that the ancients actually measured angles in terms of degrees. There appears to be no record of such measurement being made for other purposes, though the Dioptra certainly had some mark or attachment for setting off right angles. Trigonometry, it is true, had already been developed to a considerable extent by the Greeks before the beginning of the Christian era, but it was used by them only as an aid to astronomy. For all kinds of terrestrial surveying the principles of geometry only were employed by Greek and Roman surveyors, as in chain surveying at the present day. Even had the ancients possessed such aids to accurate measurement as the telescope or the vernier, the Roman system of numerical notation (as well as the Greek one) was too complicated and clumsy to permit any general use of involved arithmetical or trigonometrical formulas and tables.

A single problem in plane surveying will serve as an illustration of the trigonometrical method used by a modern surveyor equipped with a transit, and the geometrical one employed by a Greek or Roman engineer using either the Dioptra or the Groma. Hero states the problem thus:[29] "Given two visible [and accessible] points to determine the horizontal distance between them, also their positions."

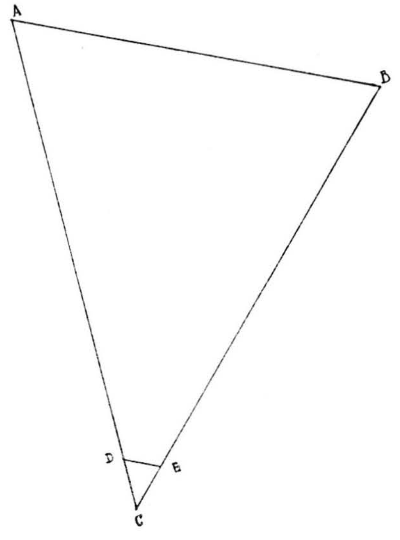

FIG. 12.

A modern engineer might set up his transit at any point, C, (Fig. 12) from which A and B, the two points in question are visible and accessible, read the angle C, and measure AC and BC. He might then obtain the angles A and B and the length of AB by using the following formulas:

$$\tan \tfrac{1}{2}(A-B) = \tan \tfrac{1}{2}(A+B) . \frac{BC-AC}{BC+AC}.$$

$$\tfrac{1}{2}(A+B)+\tfrac{1}{2}(A-B)=A;\ \tfrac{1}{2}(A+B)-\tfrac{1}{2}(A-B)=B.$$

$$AB=BC\frac{\sin C}{\sin A}.$$

[29] *Ibid.*, x (pp. 222-226).

Hero, on the other hand, gives the following three methods for solving the problem:

"Let A and B be the two given points (see Fig. 13), and let the Dioptra be set up at C, the point where we are standing; and let the sighting-bar be revolved until the point A is visible through it. The line AC is, then, a straight line. At right angles to this line, I lay off, by means of the Dioptra, the line CD. I keep moving the Dioptra along this line until the point B appears through the sighting-bar when this is set at right angles [to CD]. The Dioptra now happens to be at E; therefore, BE is perpendicular to CD, and AC is parallel to BE. Now I measure the distance from C to A, and likewise that from E to B. If, now, the distance AC happens to be equal to the distance BE, I will also decide that the distance CE is equal to AB. But we can measure CE, for it is on the side where we are standing. Suppose, now, that the distances are not equal, but that BE is, say, twenty cubits shorter than AC; in that case, I extend BE from E, where we stand, twenty cubits, giving EF. Then AC and BF will be equal. But they are also parallel, so AB is equal and parallel to CF. We can measure CF, which will give [the length of] AB, and it is clear that we can determine the position of AB, since we have found a line parallel to it."

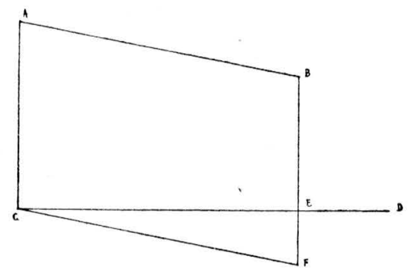

FIG. 13.

His second and third methods are simpler than the first.

"I set up my Dioptra," he says, "at any convenient point, say, at C (see Fig. 12). Now I lay off with the Dioptra the line AC, and likewise BC. I measure off from C a certain portion of AC, one-tenth, for example, giving CD; likewise, the same fraction of BC, giving CE. Then a line joining D and E must equal one-tenth of the length of AB and also be parallel to AB. I can now measure DE, since it lies in our vicinity. Thus I have both the position and the length of AB.

"But it is possible to determine the distance AB in still another manner. I set up the Dioptra at C (see Fig. 14), and extend the line AC by any convenient fraction of its length, giving CD; and in the same manner I extend the line BC by a like fraction of its length, giving CE. Then DE is a like fraction of AB and parallel to it. Now I can measure DE, and the position and length of AB will be found."

Just how sights for making measurements in a horizontal plane were taken with the sighting-bar is not fully explained by Hero. If, as Schöne thinks, a separate attachment was used for this purpose (see Fig. 11), it was probably equipped with cross-hairs or cross-wires, or it may have had something like the sight-vanes of a Surveyor's Compass, furnished with vertical slits. But if no special attachment was required for laying off lines and angles in a horizontal plane, the same movable plates or vanes must then have been used that were employed in leveling. (See page 228.) The manuscript drawing of the Dioptra (see Fig. 9) shows what looks like a set of cross-wires in each of the frames at the ends of the sighting-bar, but these lines may have been intended to represent cross-slits cut in the movable plates. However, whether they were wires or slits, the two vertical ones could not have stood directly in

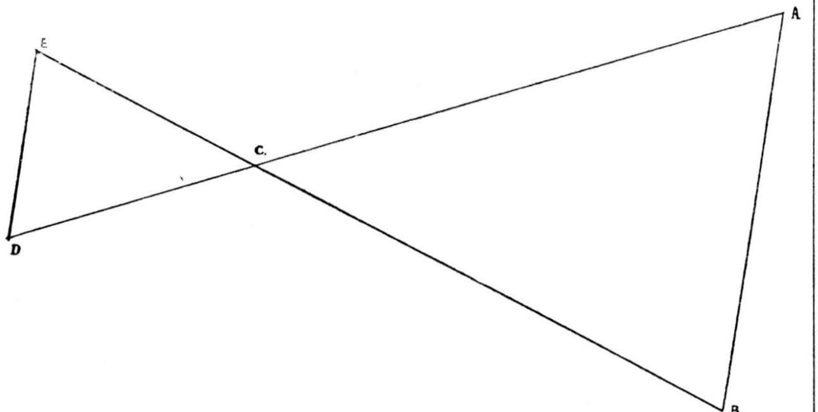

FIG. 14.

line with the vertical glass tubes of the water-level, as the drawing seems to indicate. The bronze and glass tubes may have been located a little to one side of the longitudinal median line of the bar, but parallel to it; or the vertical slit, or wire, or hair, in each of the frames may have been a little to one side of the line of the tubes. But even if the line of sight passed half an inch to one side of the horizontal axis of the Dioptra, this slight deviation would not affect the accuracy of the instrument as much as a trifling maladjustment of the telescope standards may affect the accuracy of a modern transit. When a back-sight is taken with a transit, in running a long "tangent," such lack of perfect adjustment may cause serious errors, whether the telescope be "plunged" or the horizontal plate revolved through 180 degrees. But to take a back-sight with the Dioptra, it was merely necessary for the ancient surveyor to step around to the other end of the sighting-bar, without having to move any part of the instrument, as both fore-sights and back-sights could be taken from either end of the bar.

IV

INSTRUMENTS FOR MEASURING OR LAYING OFF VERTICAL ANGLES

A. The "Lychnia"

Sextus Julius Africanus and Hero the Younger mention a device for measuring altitudes, which was so simple in construction and so easy to use that it must have been employed long before the invention of more complicated instruments, like the Dioptra. We do not know what the Romans called it, but in Greek it was known by the somewhat fanciful name of *Λυχνία*, or "lamp-stand." This instrument is described by De Rochas,[30] who follows the accounts of the two writers just named.

The Lychnia consisted merely of a ruler or bar, the center of which was loosely fastened to the side of a Jacob's staff, near the top of the latter, so

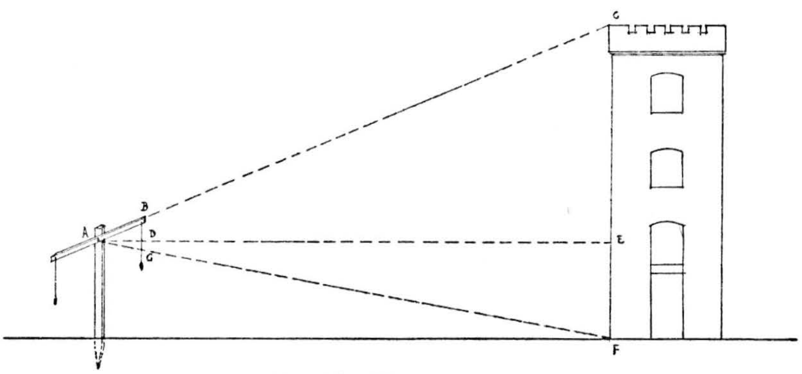

Fig. 15. The "Lychnia."

that the bar could be revolved in a vertical plane. Plumb-bobs were suspended from each end of the bar. To ascertain the height of any perpendicular object, such as a tower for instance, whose base was accessible, the instrument was first set up at a convenient distance from the tower; next (according to De Rochas), the bar was brought into a horizontal position and a sight taken along the top of it to the point E (see Fig. 15), which was then marked; the distance AE was measured, also the height EF. (De Rochas does not explain how the position of D was preserved; but all that would be necessary would be to stretch a string from A to E and fasten it at both ends.) The bar was next revolved until the line of sight struck C, the top of the tower. BD and AD were measured. Then, CE : BD=AE : AD. CE+EF=the height of the tower.

A simpler method would have been to omit AE and EF altogether, to

[30] In Daremberg and Saglio's *Dictionnaire des Antiquités Grecques et Romaines* (Art. *Geodesia*).

sight first at F, stretch a string from A to F and measure it, then sight at G and measure BG and AG. Then, CF : BG=AF : AG.

B. THE DIOPTRA

As we have already seen from Hero's description, the sighting-bar of the Dioptra could be revolved in either a horizontal or a vertical plane, so that this instrument could be used exactly like the Lychnia in measuring altitudes, in establishing grades by "shooting in" or "plunging" instead of leveling, etc.

V

LEVELING INSTRUMENTS

Ancient leveling instruments fall into two classes: (1) those depending on the principle that a line perpendicular to a vertical line is a horizontal line, and (2) those depending on the principle that the surface of a liquid in repose is horizontal. In those of the first class, some kind of a plumb-line was always used; those of the second class were furnished with either a groove or a tube, into which water was poured.

A. The "Norma" or Square

The carpenter's or mason's square, or "Norma," was made in several styles, almost any one of which could be used for taking short sights in leveling. Figure 16 shows one form of the Norma.[31] When a plumb-line suspended from the hole in the short arm at the top exactly covered the narrow vertical groove cut across the oblique leg and the cross-bar, a sight could be taken along the top of the short arm or along any straight-edge on which the two legs rested.

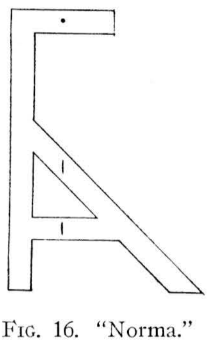

Fig. 16. "Norma."

B. The "Libella" or Level

One form of hand-level used by carpenters and masons and called the "Libella" (see Fig. 17) could also be employed as a surveyor's level. In principle, it resembled the Norma; and in form and use, it was practically identical with the modern miner's triangle.[32] It consisted of three bars firmly fastened together in the form of a capital A, and so adjusted that when the two feet rested on a horizontal plane a plumb-line suspended from the apex of the two legs would exactly cover a vertical line drawn across the front of the cross-bar. Sights were taken along the upper surface of this cross-bar.

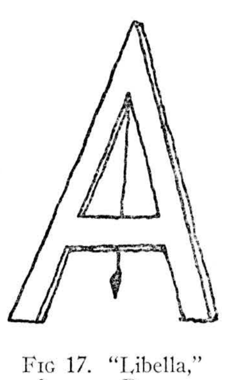

Fig 17. "Libella," from a Roman tombstone. (After Saglio.)

C. The "Chorobates"

The "Chorobates," (see Fig. 18) like the two instruments just described, was brought into a horizontal position with the aid of plumb-lines; but, unlike the others, it could also be adjusted by applying the principle that the surface of a liquid at rest is horizontal.

[31] *Ibid.*, iv, 102 (Art. *Norma*).

[32] "The early miners in California set grade pegs on hundreds of miles of ditches and roads with this primitive instrument." Ernest McCullough, *Practical Surveying*, p. 74.

Vitruvius particularly recommends the use of the Chorobates in leveling, considering it superior in accuracy to both the Dioptra and the "Water Level."[33]

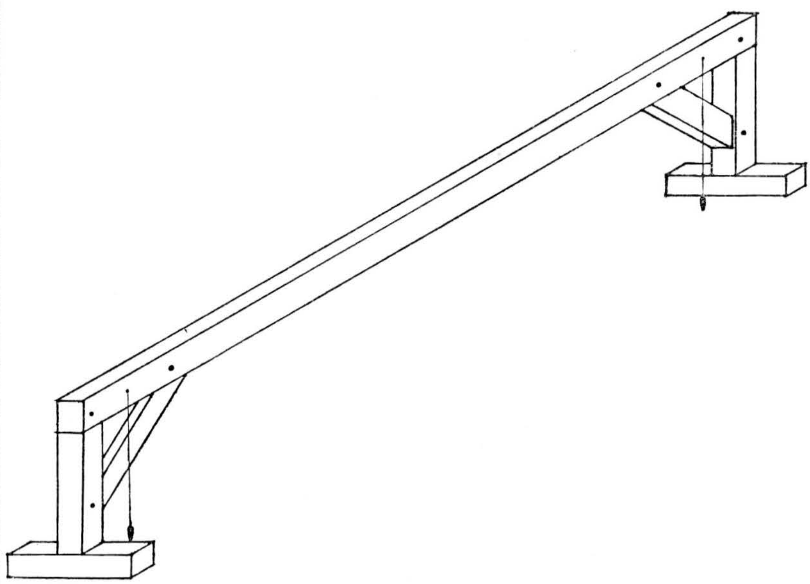

FIG. 18. The "Chorobates."

"The Chorobates," he says, "is a straight-edge about twenty feet long. It has legs, both made in the same manner and fastened perpendicularly to the ends of the straight-edge; also braces mortised to the straight-edge and the legs. These braces have marks drawn vertically across them, also plumb-lines hanging across them, one from each end of the straight-edge. When the straight-edge is in adjustment these plumb-lines will touch the vertical marks on the braces simultaneously, showing that the instrument is level. But if the wind interferes and because of the constant motion of the lines it is impossible to get an exact adjustment, then let the straight-edge have a groove in its upper surface, five feet long, a digit wide, and a digit and a half deep. Let water be poured into this groove; if the water touches the upper edges of the groove uniformly, it will be known that the straight-edge is level."

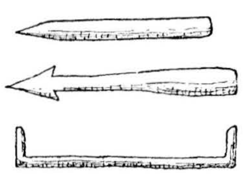

FIG. 19.

[33] *De Architectura*, 8, 5.

Just what Vitruvius means by "water-levels" ("libris aquariis") is uncertain. Some sort of an air-bubble-level may possibly have been known to the Romans, at least in later times, as a picture from a fourth century inscription found near Rome shows an object somewhat resembling a modern spirit level. (See Fig. 19, from Daremberg and Saglio's *Dictionnaire des Antiquités Grecques et Romaines*, Art. *Libella.*) But the expedient that he recommends for use in windy weather makes the Chorobates itself a water-level.

D. THE DIOPTRA

The greater length of the plane by which the surveyor directed his line of sight may have rendered the Chorobates more accurate as a leveling instrument than the Dioptra, but certainly the former must have been exceedingly cumbersome and awkward to handle. It could be brought into adjustment only by slowly and cautiously wedging or blocking up one end till the plumb-lines finally settled over the vertical marks on the sides of the braces. Furthermore, it would have to be readjusted whenever two or more sights were taken from the same station at different horizontal angles.

The Dioptra, on the other hand, with its two tangent screws and its two screws for raising and lowering the sighting-plates, was probably capable of being adjusted and manipulated almost as rapidly as a modern Dumpy level.

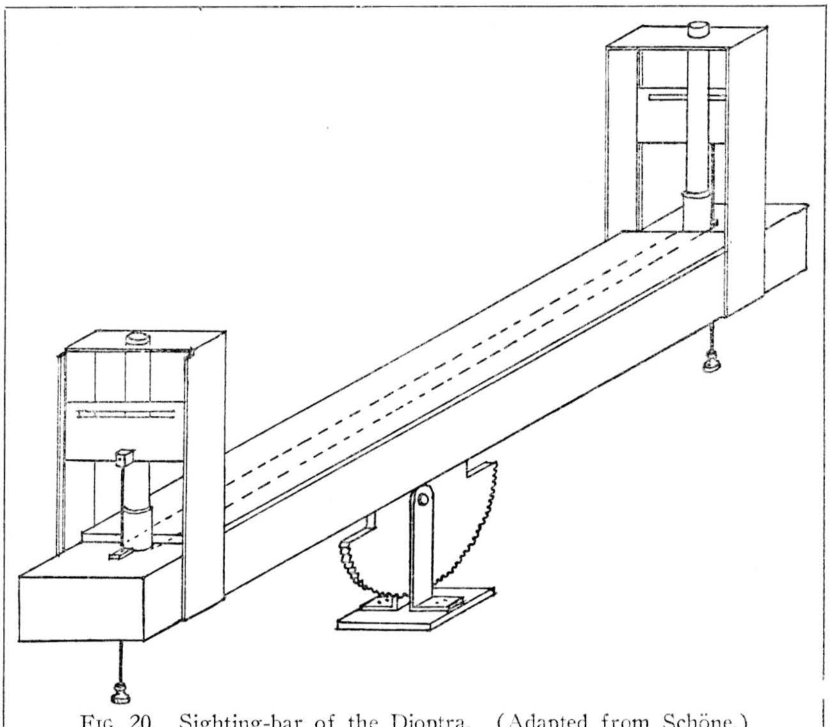

FIG. 20. Sighting-bar of the Dioptra. (Adapted from Schöne.)

The construction of the two bronze sighting-plates is described in the extract from Hero's treatise on the Dioptra given on page 228. Schöne's edition of that work contains several drawings of that portion of the instrument, one of which is reproduced here, with slight changes. (See Fig. 20.) In sighting, the screws under each plate were turned until the horizontal slit in each was exactly opposite the surface of the column of water in the glass cylinder before it.[34] (See Fig. 21.)

[34] Περὶ Διόπτρας, vi, (p. 206.)

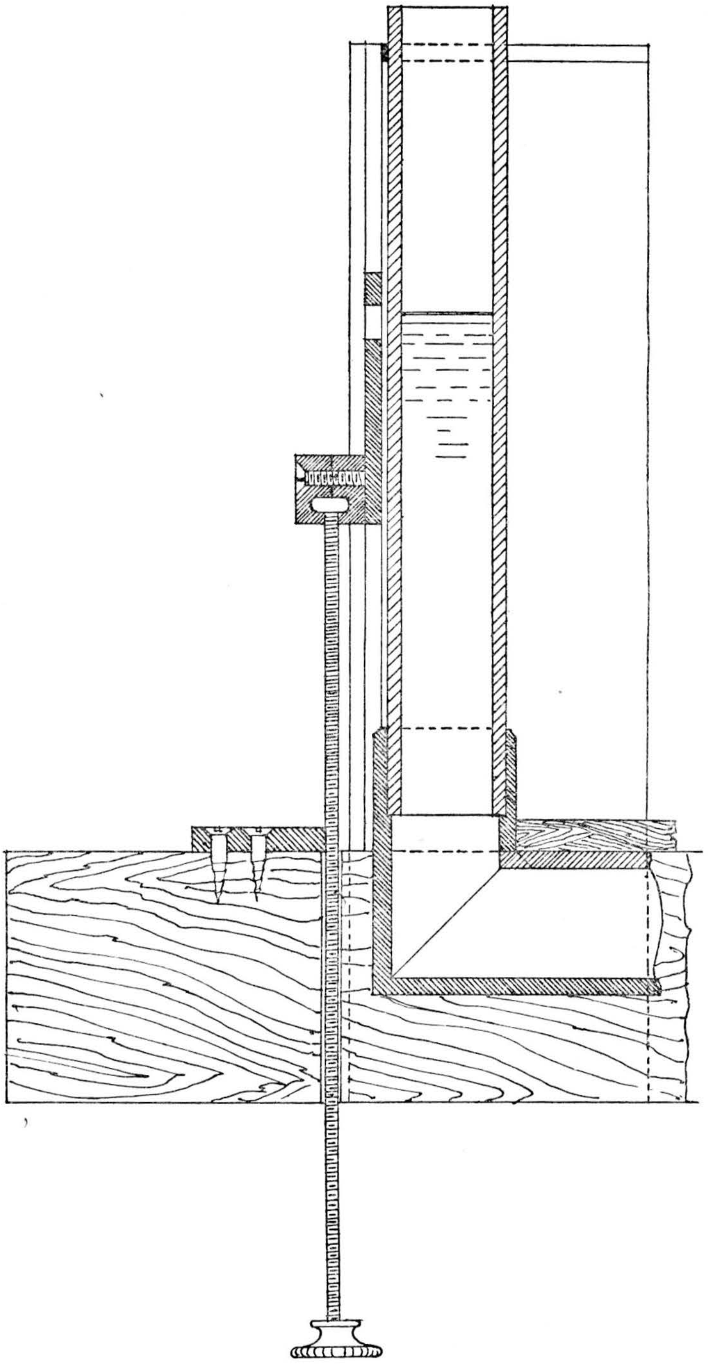

Fig. 21. Cross-section of Sighting-plate, Frame, Water-tube, etc. (After Schöne.)

E. LEVELING RODS

According to Hero's description, the leveling rods used by the ancients were not very dissimilar to those in use at the present day. The lack of the telescope precluded the use of "self-reading" rods, hence target-rods only are mentioned. After concluding his account of the Dioptra itself, Hero continues thus:[35]

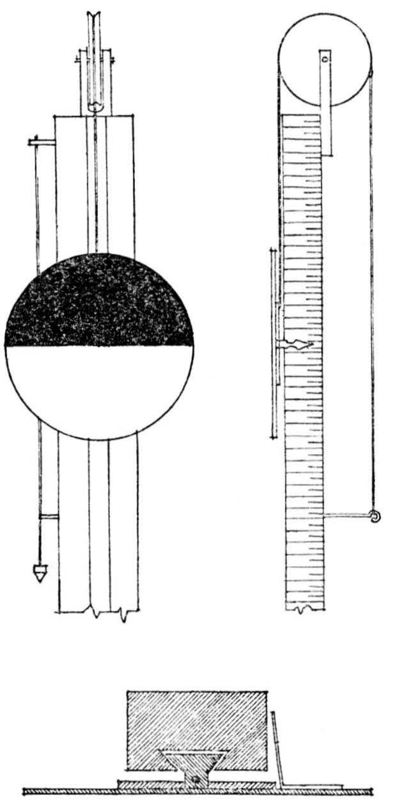

FIG. 22. Hero's Leveling Rod, Front and Side Views and Cross-section. (After Schöne.)

"The construction of the Dioptra having been explained, we will now speak of the rods and targets employed in connection with it. Two rods[36] are prepared, about ten cubits [a little over fourteen feet] in length, five dactyls [about four inches] in breadth, and three dactyls [a little more than two inches] in thickness. Down the middle of the broad side of each of these rods, throughout its whole length, a dovetail groove is cut, with its narrower side outward. Inside this groove is fitted a slide, in such a manner that it can move easily along the groove without falling out. To this slide is nailed a target having a diameter of from ten to twelve dactyls [seven and a half to nine inches]. The circular face of this target being divided by a line drawn at right angles to the length of the rod, one semicircle is painted white, the other black. To the slide there is fastened a cord which passes over a pulley mounted on the upper end of the rod, and down the side of the rod opposite to the one where the target is placed. Now, if you rest the rod in a vertical position on the ground and pull the cord from the back side, then you will move the target upward; but if you let the cord out, then the target is carried downward by its own weight; for the target should have a lead plate nailed to the back of it, so as to be carried down automatically. Next, the rod must be carefully marked off, beginning from the lower end, into as many cubits, palms and dactyls[37] as are included

[35] *Ibid.*, v, (p. 205.)

[36] Two rodmen were evidently employed, as is frequently the case nowadays, to save time between back-sights and fore-sights.

[37] These are Greek, not Roman, units of measurement. A cubit (πῆχυς, "forearm") was about 17.46 inches, a palm (παλαιστή) a trifle over 2.9 inches, and a dactyl

in its length; and at each point of division lines are cut in the side of the rod to the right of the target. The target will also have a pointer fastened to [the back of] it at the height of its horizontal diameter, and this pointer will reach to the lines cut in the side of the rod. The rods may be held on the ground in a perfectly vertical position in the following manner: On the side of the rod opposite the one where the measuring scale has been cut is fastened a peg about three dactyls long. Near its outer end a hole is bored through from above, to receive a cord having a plumb-bob hanging from it. Further down the rod another peg is fastened, the end of which is the same distance out from the rod as the hole just mentioned. In the outer end of the latter peg a vertical notch is cut, and when the cord just fits into this notch it will show that the rod is in a vertical position." (See Fig. 22.)

Hero next describes the process of leveling, at considerable length. In principle, his methods are identical with those used by engineers and surveyors today. His first problem is, to find the difference in elevation between two points, A and B, separated by a considerable stretch of uneven ground, also, to find the relative elevations of some eight "turning-points" lying between A and B. This involves moving and adjusting the Dioptra eight times. To arrive at the final result he records all the back-sights in one column and all the fore-sights in another; the difference between the sums of the two sets of figures is the difference in elevation between the points A and B.

(δάκτυλος, "finger-breadth") about three-fourths of an inch. The πῆχυς corresponded roughly to the Roman "cubitum," the παλαιστή to the "palmus," and the δάκτυλος to the "digitus."

As different systems of linear measurement were long in vogue in different parts of the Empire, a Roman surveyor would ordinarily employ the system in use in the locality where he was working.

VI

ACCURACY OF THE WORK OF ROMAN SURVEYORS

As to the degree of accuracy attained by Roman surveyors and engineers, abundant evidence is furnished by such existing monuments as roads, bridges, aqueducts and public buildings. Two specific and striking examples of their efficiency, however, are given in an article published some years ago in *Nature*,[38] from which I have taken the liberty of making the following rather lengthy quotation:

"In the *Zeitschrift für Vermessungswesen* (Heft 21, 1911) Prof. E. Hammer discusses the precision with which the nations of antiquity were able to mark out lines on the surface of the earth with the means at their disposal. Taking, first, that portion of the frontier of the Roman Empire[39] which existed as a straight line about 80 kilometres long from near the River Rems in Würtemburg to the district of Walldürn in Baden, he investigates the question whether this line was laid down approximately straight by chance, or whether it was intended to be a straight line, and special care was taken to arrive at this result. Points on the line were located and their position plotted on the cadastral maps (scale 1:2500), from which their coordinates were determined. From these, the direction-angle of portions of the line was calculated, and also the mean departure of points on the boundary line from a true straight line. For a portion amounting to 29 kilometres of the whole length, the mean error in position of a point on the boundary was found to be ± 2 metres, which indicates a surprising accuracy in carrying such a line over rough ground, while for a portion of it an even greater precision was attained.[40] Further observations by Prof. Leonhard, not yet published, on the remaining 50 kilometres of the boundary, indicate that the same accuracy is there maintained. The Romans must have fixed a few principal points in prominent positions by signals at night, and then interpolated intermediate points; the observed accuracy could never have been attained by prolonging a line.

"A second case is that of the amphitheatre at Pola,[41] laid out by a Roman architect or land-surveyor, which has been recently studied by an Austrian surveyor, Herr Hofrath A. Broch. Using a plan on a scale of 1:250, he investigated the accuracy with which the amphitheatre as constructed approached an ellipse. Taking twelve points on the curve, their mean error in position from an ellipse was but 15 cm., in spite of the weathered surfaces of the stone contributing to the uncertainty. The axes of this ellipse were $2a=129.9$ m. and $2b=102.6$ m., or in the ratio of very nearly 9:7, as in the case of many Roman amphitheatres."

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38 Vol. 88, p. 158; Nov. 30, 1911.

39 Surveyed, marked and fortified by order of the Emperor Domitian. Cf. Julius Frontinus, *Strategematon*, 1, 3, 10.

40 Compare the provisions of the offical instructions for the survey of the public lands of the United States, which permit, in closing up the sides of a township, a lateral error of 50 links, a trifle over ten metres, in a six-mile meridional or latitudinal section line, or about nine and two-thirds kilometres.

41 The city of Pola, situated about 50 miles south of Trieste, was destroyed by Augustus, but afterward rebuilt by him at the request of his daughter Julia, and renamed Pietas Julia in her honor. The amphitheatre to which reference is made was built about 200 A. D. and is remarkable as being the only Roman amphitheatre whose outer walls have been preserved intact.