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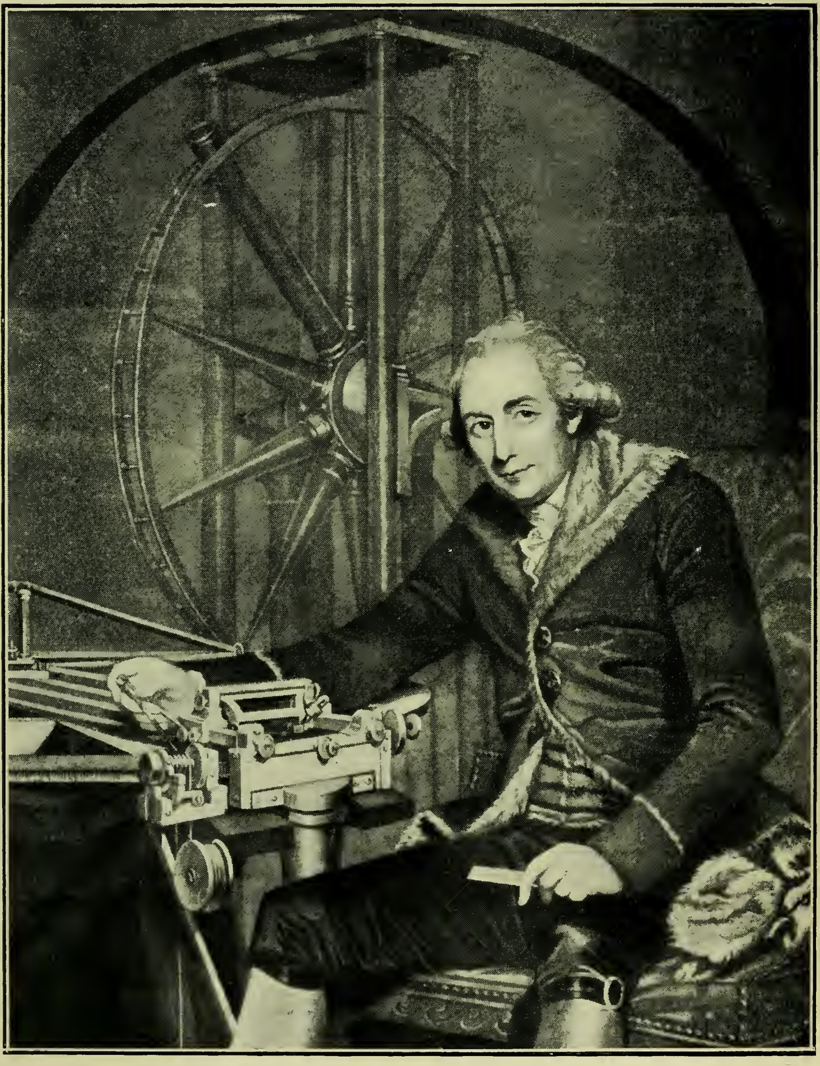
SURVEYING INSTRUMENTS



JESSE RAMSDEN AND HIS DIVIDING ENGINE

SURVEYING INSTRUMENTS

THEIR DESIGN, CONSTRUCTION, TESTING & ADJUSTMENT

BY

obert
R. M. ABRAHAM, M.I.E.E., F.R.A.S.

With 238 Illustrations

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CONTENTS

CHAPTER I

INTRODUCTION. Improvements in the design of surveying instruments — Work done by inferior instruments — Importance of accuracy.

CHAPTER II

MANUFACTURE AND CARE OF SURVEYING INSTRUMENTS. Choice of instruments—Minimum weight which can be carried in various countries—Surveys made with simple instruments—Importance of transit theodolite—Reduction in weight of instruments—Sizes of telescopes—Metals used in the construction of instruments—Lubrication—Finish of instruments.

CHAPTER III

THE OPTICS OF SURVEYING INSTRUMENTS. Achromatic lens—Acuteness of vision—Optical qualities required in telescope—Large field of view desirable — Resolving power — Magnification — Brightness of the field—Size of telescope required—Focusing for distance and for elimination of parallax—Advantages of the internal focusing lens—Variation of the collimation lines—Eyepieces—Object glasses—Centering of object glasses—Diaphragms — Fitting of spider webs — Illumination of webs — Readers — Reading micrometers—Estimating microscope—Construction of micrometers—Adjustment of micrometer magnification—Minimum focusing distance—Short focus attachment—Parallel plate micrometer— Anallatic telescopes — Stadia readings — Inclined sights—Bar subtense method—Eyepiece micrometer.

CHAPTER IV

SPIRIT LEVELS. Sensitivity of spirit levels—Machine grinding of levels —Cleanliness of the interior—Liquids used—Variation in the length of bubble—Chambered bubbles—Damping of bubbles—Value of the level divisions—Methods of mounting levels—Level tube grinding machine—Circular levels—Methods of reading the bubble—Level triers—Radius of bubbles.

CHAPTER V

Graduation of Instruments. Work done by Graham — Sisson — Bird—Roemer—Hooke—Duc de Chaunes—Ramsden—Ramsden's engine—Andrew Ross's engine—Accuracy of dividing—Construction of a dividing engine—Cutting the teeth—Compensating apparatus—Elimination of errors—Speed of dividing—Materials for divided circles—Thickness of lines—Various forms of vernier—Method of inlaying silver—Figuring of verniers—Worm and wheel in place of vernier—Method of calculating vernier values.

CHAPTER VI

Transit Theodolite. Self-checking instruments—Sizes of theodolites—Tacheometers—Centesimal dividing—Horizontal axis—Double taper axes—Independent axes—Parallel axes—Position of plumb bob—Adjustment of the vertical axis—Foot screws—Four-screw system—Three-screw system—Two-screw system—Locking plate—Railway transit theodolites—Clamps and tangent screws — Defects of various forms of clamps — Floating clamping arm—Floating tangent screw—Tripod stand—Ball and socket joint—Gradienter screw—Direct-reading tacheometer—Casella's double-reading micrometer theodolite—Electric lighting for theodolite—Effect of side illumination on the dividing—Heyde's micrometer — Adjustment of transit theodolites — Collimating apparatus for adjusting theodolites—Errors of collimation—General performance of the instrument—Field of view of theodolite telescopes—Theodolites with eccentric telescopes.

CHAPTER VII

Levelling Instruments. The ideal instrument—Dumpy level—Y level—Adjustment of the dumpy level—Adjustment of the Y level—Four-screw Y level—Casella's precise tilting level—Levels with tilting screws—American pattern precise level—Builder's levelling outfit.

CHAPTER VIII

Simple Surveying Instruments. Abney level—Tables for use with Abney level—Optical square—Brunton & Pearse's mine transit—Clinometer levels—Verschoyle's pocket transit—Hanging level—Prismatic compasses—Pocket altazimuth—Trocheameter—Perambulators—Pedometers.

CHAPTER IX

Levelling Staves. Self-reading staff—Staff with inverted figures—Target levelling staff—Precise levelling staff—Foot plates—Circular spirit levels for levelling staves—Ranging poles.

CHAPTER X

Photographic Surveying. Advantages of the photographic method of surveying—Main difficulties which affect the subject—Bridges Lee photo-theodolite—Canadian surveying camera—Method of adjusting surveying cameras—Pictures taken at an angle to the horizon—Stereo-photographic system—Measurement of base lines—Stereo-comparator—Vivian Thompson's stereo plotter—Von Orel's automatic plotter—Drawing of contours—Speed of plotting by intersection and by stereo method—Aerial photography—Photographs on inclined plates.

CHAPTER XI

Investigation of the Upper Atmosphere. Pilot balloons—Ballons-sondes—Dines's apparatus—Recording theodolite—Kite meteorgraph—Cloud attachment—Method of observing with a pair of theodolites—Method of observing with a single theodolite.

CHAPTER XII

Geodetic Surveying. Objects of geodetic surveying—Minor surveys—Situation of control points—Base line measurements—Rigid bar method—Ice bar apparatus—Invar tapes and wires—Steel tapes and wires—Length of tapes—Accuracy required—Supporting and stretching apparatus—Corrections required for height above sea level, sag and temperature—Qualities of invar—Reel for invar tapes—Annealing of tapes—Tape thermometers—Triangulation—Lengths of the sides of triangles—Theodolites used for primary triangulation—Size of theodolites—Casella's ten-inch double-reading micrometer theodolite—Secondary and tertiary triangulations, accuracy of Levelling—Precise levelling—Accuracy required—Levels run along railways—Time required and results obtained on large surveys—Levelling by theodolite.

CHAPTER XIII

Topography. Contour lines—Prismatic compass survey—Chain and level survey—Types of steel band chains—Difficulties of plane table survey—Alidades for plane tables—Potter's alidade—Trough compasses.

CHAPTER XIV

ASTRONOMICAL WORK. Determination of time by sextant—Various forms of astronomical transit instruments—Chronographs, drum type—Governors for chronographs—Electrically driven tape chronograph — Impersonal micrometer — Adjustment of transit instruments — Latitude — Horrebow-Talcott method — Zenith telescope—Adjustment of Zenith telescope—Obtaining the value of micrometer divisions—Zenith tube—Latitude variation discovered by Chandler—Longitude—Longitude by chronometer and the use of telegraph wires—Photographic method—Azimuth —Azimuth marks—Heliotropes—Eyepiece micrometer method —Circumpolar star method—Forms of targets used.

CHAPTER XV

PRISMATIC ASTROLABE. Description of Claude & Driencourt's method —The accuracy to be expected—Prismatic astrolabe attachment for micrometer theodolite—Adjustment of the instrument—Ball & Knox Shaw's star list—Weld Arnold's star list—Improvements in astrolabe by T. Y. Baker.

CHAPTER XVI

GRAVITY. Rates of pendulums—Errors introduced into the apparatus by vibration—Michelson's interferometer—Radius of the sphere —Clarke's ellipsoid—Determination of gravity at sea—Form of the earth.

CHAPTER XVII

MEASUREMENT OF MAGNETIC DECLINATION. Horizontal intensity — Dip—Kew dip circle—Adjustment of the dip circle—Method of using the instrument—Observations at sea—Dip inductors— Goolden's portable dip circle— Magnetometers—Magnetic declination—Collimator magnet—Horizontal component measurement—Vibration experiment — Torsion head — Plumb bobs — Deflection magnets — Inertia bar — Schuster dip inductor — Shaxby's inductor magnetometer.

CHAPTER XVIII

SEXTANT. Hadley's sextant—Hooke and Newton sextant—Improvements by Ramsden—Advantages of the sextant—Sextant mirrors —Britannia sextant—Method of holding index and horizon mirrors—Qualities required in dark glasses—Method of centering circles when dividing—Qualities of shades—Endless tangent screw—Appleyard's sextant—Booth's bubble sextant—Baker air sextant—Box sextant—Adjustment of sextants—Artificial horizons—Roof pattern—Casella's pattern—Glass plate horizon.

CHAPTER XIX

Wireless Time Signals for the Determination of Longitude. Atmospherics—Ordinary time signals—Rhythmic time signals—Method of transmitting time signals—Spark system—Method of reception of time signals—Methods of recording time signals—List of high power stations transmitting signals—Equipment required.

CHAPTER XX

Mine Surveying. Theodolite used—Auxiliary telescopes for theodolites—Precise plumbing—Optical plumbing—Plumbing in deep mines — Two-wire apparatus — Three-wire apparatus — Mine plumbing device.

CHAPTER XXI

Errors in the Measurement of Angles. Instrumental errors—Observer's errors—Errors of eccentricity—Taking the mean of two or more verniers—Probable error of readings—Elimination of centering error—Inconsistent readings—Necessity for stability when setting up the instrument—Accuracy of placement required—Errors in the reading of bubbles.

CHAPTER XXII

Barometers and Hypsometers. Mercury barometers—Aneroid barometers—Fortin type barometers—Mountain barometer—Calibration of aneroids necessary—Compensation for temperature-lag—Advantages and disadvantages of aneroids—Apparatus for testing and comparing aneroid barometers — Hypsometers — Accuracy of hypsometers.

CHAPTER I

INTRODUCTION

I TRUST I may be pardoned for the infliction on the public of another volume on mathematical instruments. My excuse is that a study of the books generally found in the hands of students and scientific workers has left me with the impression that the information contained in them is, in the majority of cases, antiquated and incomplete, and that the illustrations are either copied from older works, or extracted from the out-of-date catalogues of manufacturers. While the general principles upon which the designs of modern surveying instruments are based have not changed appreciably in recent years, great improvements in detail have been introduced by most of our progressive manufacturers. Although it is true that these improvements have been mainly in the direction of simplifying the apparatus, cutting down the weight, making the instruments easier to use, and increasing the accuracy of their performance, at the same time certain types of apparatus have been so modified that new methods have been developed by the users in order to take full advantage of these improvements. New materials have been introduced, enabling manufacturers to incorporate in their designs improvements which have completely changed the older methods of procedure. For example, the commercial production of invar has enabled surveyors to use geodetic methods of base line measurements for such minor surveys as city and town planning schemes. How important this has become will be realised when considering the survey of underground work in a city such as London, with its complex system of railway tunnels, water mains and sewerage schemes. For surveys of this nature, measurements of angles and distances must be carried out to the greatest accuracy which it is possible to obtain, and only those instruments which are capable of giving results of a very high order may be employed.

While it may be admitted that of the surveys made twenty or thirty years ago many show up remarkably well, the results were obtained at an enormous expense of time and money by taking the means of repeated readings on what we should now consider inferior and cumbersome instruments. Repeated readings on inaccurate instruments may give accurate results—there is no certainty and little likelihood, however, that they will. The accuracy required to-day necessitates the employment of highly skilled observers who are, or ought to be, highly paid. It is therefore of paramount importance that the work should be carried out in the shortest possible time and that the results should be undeniably correct within the prescribed limits, Accuracy is the first consideration to-day, and in designing instruments, this point must never be allowed to recede into the background. Although convenience in handling, speed, portability, etc., are of great importance, and although every finished design must be more or less of a compromise, accuracy and permanence of adjustment are the points upon which no latitude is permissible. It has been found desirable to describe in this volume a number of instruments, the design of which has not changed for many years. The reason for this lack of modification is not because these particular instruments are perfect, but probably because the demand has not been sufficiently great to make it commercially worth while to modify them. I have endeavoured to describe and illustrate only those instruments the use of which is general, and to exclude examples of many appliances which, while interesting in themselves, have not, or are not likely to, become part of the equipment of the surveyor or explorer. No attempt has been made to treat subjects such as optics in a general way, or to include material which can be found in the usual text books. An endeavour, however, has been made to accentuate points of special interest to surveyors: for example, in the section dealing with the lens system used on instruments no mention has been made of the various aberrations, etc., which are of interest to the users of photographic lenses, but stress has, on the other hand, been laid on the special points such as resolving power and magnification upon which surveyors rely.

My thanks are due to Mr Rowland Miall for his kindly help, to Messrs Cooke, Troughton and Simms, for the loan of various blocks for the illustrations, to Mr C. Green, who produced the drawings for the diagrams, and to Miss M. L. Ackerman for the transcription of the MS.

CHAPTER II

General Observations on the MANUFACTURE AND CARE OF SURVEYING INSTRUMENTS

THE choice of instruments to be carried by a survey party will depend on many circumstances, and a careful study of all the conditions before coming to a decision is advisable, and will amply repay both those who have to supply the outfit and those who are to do the field work. For exploration work, where the cost of transport and porterage especially over rough mountainous regions is very high, it is of the greatest importance to see that weight is reduced to the utmost, and in certain cases it is necessary that mere bulk shall be avoided. Local conditions should be taken into consideration whenever possible, and where the outfit has to be carried by native porters, the equipment should be so divided that each bearer will have the maximum weight which it has been found by experience he can carry without undue fatigue over the particular terrain in which the party has to travel and work. As an indication of the difference which is to be found in different countries, an Indian native can be relied upon to carry 40 lbs. for twelve hours per day. In Peru 35 lbs. is about the maximum, and in Tropical Africa 50 lbs. In Canada and the U.S.A., where the instruments are carried by white men, 65 lbs. on level ground is considered a good load per man, and in heavy or hilly ground 30 lbs. is about his limit. Pack mules can carry about one-third their own weight. The total weight of the outfit will, of course, depend on the degree of accuracy to which the survey is to be made. This point is generally settled first, and then a suitable equipment designed to fulfil the conditions within the limits decided upon. Many explorer have made wonderfully accurate maps of previously unknow territories with such simple equipment as prismatic compasse and aneroid barometers, but for any serious survey, it is no considered essential to carry a theodolite which is, withou doubt, the most generally useful instrument for this kind o work. With it, angles in altitude and in azimuth, compas bearings, levels, distances and astronomical observations fo latitude and longitude can be taken with the greatest ease, an to any order of accuracy required. The instrument, moreover is easily adjusted without subsidiary apparatus, and can b relied upon to remain in adjustment even when subjected t treatment which would render alternative instruments useless Theodolites weighing five or six pounds can now be obtaine which can be relied upon to give results accurate to within few seconds of arc. It is not surprising, therefore, that thi instrument has become so deservedly popular with surveyors **The transit theodolite** may be considered the most importan of all the appliances used by surveyors and in consequenc more thought has been given to its design and therefore mor improvements in its details have been effected than in the cas of any other single instrument of this kind. Specialize surveying instruments can, of course, do the work for whic they have been designed in either a better or more expeditiou fashion, but the theodolite can do the work of all of them wit more or less perfect results, whereas the special instrument can only do their own jobs perfectly, and the other jobs not at all

A possible exception to this is, however, the **sextant.** Thi instrument which has remained practically unchanged for fift years, is, in spite of its many serious drawbacks, a wonderfull conceived and extraordinarily efficient instrument. The fact that it can be operated without a stand makes its use essentia on board ship, where the theodolite would of course be useless. Some years ago, magnetic compasses of very elaborate design were much in favour. Their use has now practically ceased, the work formerly done by them being now carried out by the theodolite. Mining dials, circumferentors and instruments of this description have also given place to the level and the theodolite just as the watch has superseded the sundial and astrolabe.

Reduction of Weight

In order to reduce the dead weight of instruments, manufacturers have, in recent years, taken advantage of the many light alloys now commercially procurable. The production of these alloys has been studied very extensively, owing to the demand which has arisen for them in connection with automobile and aircraft construction, with the result that instrument makers have now a wide choice of excellent materials which they have been quick to take advantage of. Great care, must, however, be exercised in the use of these materials, and up to the present no light alloy has been found which is suitable for the working centres and faces. In this connexion, it must be mentioned that the perfection to which ball bearings are now constructed makes it possible in some instances to design the working parts so that use may be made of these bearings not only to allow the parts to turn more easily, but in certain cases to reduce the total weight to be moved. It is along these lines that designers are now travelling, and it is only by attention to details of this nature, that instruments have arrived at their present perfection. Although the saving of weight, as has been pointed out, is generally of great importance, in certain cases, actual weight is, on the contrary, desirable. For example, in a theodolite which is to be used in a city or in any position where the transport problem is not vital, the stability given to an instrument constructed from material of high specific gravity is of great advantage. When this additional weight is so disposed that the centre of gravity of the whole apparatus is lowered, the difference in steadiness is most marked. The modern tendency in the design of theodolites and levels is to keep as much of the weight as possible in the lower and stationary parts, and to concentrate on lightening the upper or moving parts. The weight of the upper parts of a theodolite depends largely on the size of telescope employed. It is therefore desirable to keep this important part as small as possible, and to this end, perfection of the lens system must be sought after by every means. A study of modern instruments will illustrate this point very clearly, and it will be found that theodolites and levels with long, small diameter telescopes have been quite superseded by those of short focus and large aperture. A modern level with an object glass of 10 inch focus will give better results than any of the old-fashioned Y levels many of which had telescopes as long as 22 inches.

The principal metals used in the manufacture of surveying instruments are gun-metal, containing 88 parts copper to 2 parts tin, and bell metal which is an alloy containing rather more tin, generally about 16% to 18%. The castings should be made from virgin metal and as many instruments are fitted with, or contain a magnetic compass, great care must be taken to see that no ferrous material is used in the construction or allowed to get into the castings. Nickel silver, an alloy of copper 70% and nickel 30% is used for many of the small parts such as foot and tangent screws, pinions and springs. Yellow brass, which often contains a percentage of lead, is now never used for any part. In certain types of levels and theodolites, steel is employed for the centres and other working parts, and in the rustless form is an excellent material for this purpose. Its great advantage, apart from its strength, lies in the fact that when it is hardened, it can very easily be ground and polished to a degree of perfection impossible with the softer metals, and that the wearing qualities are so remarkably good. When an instrument leaves the maker's hands, it is generally in adjustment; it always looks very beautifully finished and polished, showing that he has spent a great deal of time and taken great pains to make it perfect. He is therefore much disappointed when, if it is returned to him for repair, he sees the shocking state in which it arrives and the evidence of the rough treatment it has received at the hands of its owner. Accidents will happen to instruments, many of them unavoidable. The bulk of repairs, however, are not necessitated by accidental happenings, but by wilful misuse. Screws are overturned, parts left for years without oil, or clogged up with lubricants only suitable for the axles of carts, or the instrument has been placed wrongly in its case and the lid then forced down. A good instrument (unless accidentally damaged), should never need repair; it will never wear out, and should only need to be replaced when it becomes out-of-date. Lubrication should be carefully attended to, only the finest watch oil should be used for working parts, and then only the merest trace. Superfluous oil collects dust, leads to wear, and should be avoided. Petroleum jelly, procurable under the name of "Vaseline" is an excellent lubricant. Do not use too much of it. Lenses should be wiped occasionally with a clean linen rag, and the divided circles should be brushed with a camel hair brush every time the instrument is used. Metal polish should never be used on the divided silver surfaces, but if they have become tarnished, a slight rubbing with the finger after all dust has been carefully removed is all that should be done. Finally, if the instrument has been left out of doors in a rainstorm, it should be cleaned all over very carefully and then polished off with an oily rag. If this is done at once no damage will result, but if, however, as is generally the case, the instrument is dumped into its box and left thus for perhaps a month or two, it will very soon have to be sent back to the maker for extensive repairs.

With regard to the finish of the instrument, this varies greatly and is largely a matter of taste. Generally speaking a light colour is preferable, as the instrument will reflect the sun's rays better, and will therefore not become so hot. On the other hand, if the finish is white, which should be the best from this point of view, surveyors sometimes find the glare objectionable. A grey or khaki colour would therefore seem to be about the best compromise, and many modern instruments are now finished in that way. Some American instruments are finished by spraying the parts with a sticky varnish and then coating them over with cloth dust or shoddy. This acts as a sort of lagging and gives the instrument a very pleasant feel and appearance when new. When the instrument has been in use some little time, however, it becomes very bedraggled looking, and probably for this reason this method, which is known as "cloth finish" has not become very popular with European manufacturers.

CHAPTER III

THE OPTICS OF SURVEYING INSTRUMENTS

THE measurement of angles by optical means was a comparatively inexact science until the invention by MOOR HALL in 1724 and by DOLLOND independently in 1757 of the achromatic objective. This brilliantly conceived improvement put in the hands of scientists a weapon which enabled them to solve many difficult problems. Except perhaps for the interior focusing system of PORRO, referred to later, no improvement so remarkable has since been made. The resolving power of our modern optical systems has, of course, been constantly improved, until to-day it probably approaches the point where the personal errors in observation of the setting of contact between reference marks and objects magnified by the telescope put a period to the accuracy ultimately obtainable.

Instrument constructors have constantly been improving their products, and although the accuracy may possibly be increased still further, it is finally limited by the physiological deficiencies of the eye. HELMHOLTZ has shown that the unaided eye is capable of resolving objects only if the angle subtended by them approaches 90 seconds of arc. Other observers have put the value as low as 50 seconds. In any case, it is necessary to realize that the acuteness of human vision is limited, and that before deciding to carry out measurements to any given degree of accuracy, it is important to determine if the means to hand are suitable. Instrument makers in the past neglected to take these factors into consideration in their designs, so that we often find apparatus offered with circles and verniers marked to read say 10 seconds of arc, the optical parts of which are only capable of being used to perhaps 30 seconds with any degree of certainty. We have seen instruments fitted with spirit bubbles sensitive to 10 seconds, with verniers to set them only capable of being read to double that figure. The same fault is also found in the relative powers of the telescope and circle readings with the consequence that one instrument may often have double the weight of another giving exactly the same result.

The majority of instruments used by surveyors require to be portable, and comparatively light in weight, but as stadia methods of measuring distances and astronomical observations on second or third magnitude stars are often employed, it is essential that the optical qualities of the telescopes should be of the highest, in view of the limit placed on their dimensions by the nature of the instruments themselves. The optical design should therefore be directed towards perfection in the special points of interest to the surveyor, and all other considerations, which do not directly affect the final results, should be treated where necessary as of relatively small importance. It may be useful here to define the essential requirements and those of secondary importance. In the first place, a surveying telescope is always employed to bring the image of a mark, such as a star or staff, into its line of collimation, this image being then examined under magnification by the eyepiece. As this line of collimation is always in the centre of the field, it follows that the resolving power of the telescope is of greatest importance at this point, and if better resolution in the centre can be obtained at the expense of slight distortion at the margin, it is desirable to effect a compromise of this nature. A large field of view is always desirable, as otherwise some difficulty is experienced in getting the object into the field. The brightness of the field is important owing, amongst other things, to the fact that it is often necessary to work in failing light towards the end of the day, so that good light-gathering power enables the surveyor to get in more sights in his working day. A correct value of magnification for each particular kind of job is important but, as will be seen later, the most essential characteristic which the telescope ought to have, is good resolving power. All the various defects of aberration and chromatism which would be undesirable in a look-out telescope or a pair of field glasses are of no great interest to the surveyor unless they affect the resolving power of his instrument. **The resolving power** may be defined as the magnitude of the assistance which is given to the unaided vision to distinguish small objects. In order to compare telescopes for resolving power, it is useful to fix some unit of resolution and this may conveniently be taken as the resolution of unaided vision of a person having normal sight. The resolving power of the telescope will then be the ratio of the size of an object which he can distinctly see with the help of the telescope to that which he can see with the unaided eye. For example, if the resolving power of the telescope is 10, then an object 10 times as small can be distinguished with it as that which can be distinguished by the naked eye. The actual result which an individual will obtain with any particular telescope will depend of course on his acuity of vision so that in order to determine the distance at which he will be able to read a graduated rod with a telescope of known resolving power, it will be necessary to multiply his observations by a constant which he himself will first have to determine by taking a series of observations. Taking the mean result of a number of observers looking with the naked eye at a graduated scale placed at various distances, it has been found that they can easily distinguish and count the divisions when standing 2,000 times the spacing of the graduations distant from it. This figure of 1 in 2,000 holds good down to distances of about 20 feet. At shorter ranges, errors due to the quality of the illumination and to diffraction effects render the determinations unreliable. These short ranges are not, however, important in the case under discussion. The resolving power of the naked eye having been chosen as unity of resolution, if $d =$ size of the division of the rod and D its distance, and $R =$ resolution, then if given the distance and the spacing of the divisions on the staff the resolution required of the telescope is

$$R = \frac{D}{2000d}$$

Given the resolution and the size of the graduation the distance at which the graduations can be clearly determined will be $D = 2000dR$, and the size of the smallest division which can be seen on a staff is given by

$$d = \frac{D}{2000R}$$

The surveyor can by this method determine for himself the resolution of the telescope and can calculate the best distance at which to place his rod for the most economical result. In works and laboratories, a different method is adopted, owing to the necessity of dealing with large numbers of instruments of varying qualities under invariable conditions. The procedure is generally as follows:—A diaphragm of thin metal is perforated with sets of holes the spacing of which decreases in geometrical progression, the size of the largest set depending on the distance at which it is to be used. This diaphragm is then fixed at one end of a tunnel made of wood or sheet metal, the length of which is 2000 times the spacing of the largest hole. When the diaphragm is strongly and evenly illuminated, the largest set of dots should then be distinguishable by the naked eye, and may therefore be called R 1 as the resolving power of the naked eye is unity. It is then only necessary to point the telescope to the diaphragm and, by noting the number of the set which is only just distinguishable the resolution can at once be found. The difference in resolution between the centre and edges of the object glass can be determined at the same time, and an idea of the aberrations present in the system may be arrived at by noting the appearance of the dots as the telescope is racked in and out of focus.

Magnification

If M = magnification of a telescope
D = effective diameter of O.G.
E = diameter of exit pupil

Then $M = \frac{D}{E}$

Or, if F = focal length of O.G.
F_1 = focal length of eyepiece

then $M = \frac{F}{F_1}$

The simplest way to find the magnification is to measure D and E, the latter by placing a small microscope having a scale of known value in the focus of its eyepiece, close to the ocular of the telescope. **The brightness of the field** varies inversely as the square of the magnification and directly as the square of the clear aperture.

Thus if B = brightness of field
D = effective diameter of O.G.
M = magnification

Then $$B = \frac{D^2}{M^2}$$

To obtain the absolute value of B this expression must be adjusted by a constant depending on the construction of the telescope. As the exit pupil varies in the same way the brightness also bears the same proportion to this exit pupil. The brightness of the field of the telescope being proportional to E, if this is larger than the full aperture of the eye, nothing is gained in brightness or resolution. If, however, it is smaller than the pupil of the eye, the full resolving power of the eye is not effectively employed, and therefore the resolution of the telescope is less than the theoretical value deduced from its dimensions. A study of the magnification is of great importance to the surveyor, not only because of the effect on the resolution but also on account of the aspect of the image. Given two telescopes of equal resolution, one of large and one of small magnification, the former will give a small field and the appearance of the graduation of the staff will be large, but owing to the lack of light the webs cannot be set any better than they can on the larger instrument which has a very bright field with small but very clear and sharp divisions. Again, with the small, high magnification telescope, the difficulty in pointing it on to the object is greater and it is more affected by vibrations. On the other hand, being smaller, it is less affected by the wind, moves more easily and is altogether more desirable from a mechanical point of view. As mentioned previously, the size of telescope to be used depends largely on the conditions under which it is to be employed, but generally speaking, the instrument with a comparatively small telescope and having fairly high magnification is, in spite of its drawbacks from a purely optical view, a rather better all-round tool, because of its stability and portability and the ease with which it can be set up and transported. The opinions of surveyors differ a great deal on the subject of magnification, and there is no doubt that it is largely a question of what they have been accustomed to, but as a general indication of the preference of the majority, it may be taken that for measuring angles to an accuracy of 20 inches to 30 inches, a 5-inch theodolite with a telescope having a magnification of about 20 to 22 in conjunction with an object glass of $1\frac{7}{16}$ inch clear aperture which will give a resolution of about 20 will give excellent results and a well-balanced, sufficiently portable instrument with a field bright enough for use even in our winter climate. In levels, as their bulk is somewhat less, we can afford to use a larger object glass in the telescope. Its focal length can also be made slightly longer, thus allowing the same magnification with a lower power ocular. This has the advantage that it is easier to get correct focus free from parallax and that the brightness of the field is much increased. For ordinary levelling operations a telescope of 10 inch focus, $1\frac{5}{8}$ inch object glass, and a power of twenty will be found amply sufficient; for the most precise work there is no necessity to go beyond 12 inch focus with a $1\frac{3}{4}$ inch object glass and a power of 28. This size of telescope will be found quite comfortable to work with, and there is no point in going further, as the limit of accuracy will be determined rather by the setting of the bubble and the measurements on the ground than by the telescope itself. For stadia work, of course, the larger the telescope the better; the only question to be considered is the relative cost of the final results. With regard to the actual construction of the mechanical details of the telescope, there are several points to be borne in mind when considering the design, the most important of which are as follows:

It should be capable of being easily and accurately focused for distance and for elimination of parallax. It should be free from collimation error at any focus. It should be water-tight and where possible, well-balanced about its axis of rotation. The webs or reference marks at the focus should be easily removable for cleaning or adjusting, and should be so arranged that they can be replaced without undue disturbance of the line of collimation. Formerly, telescopes were adjusted for focus by varying the distance between the object glass and the webs either by racking out one or other or both of these parts. This system had several defects, which in badly-made instruments were serious. (1) The balance of the telescope was altered, owing to the difference in total length when focused for different distances. (2) When racked out for short distances a certain amount of overhang was unavoidable, with the result that the lack of support for the overhung part allowed it to droop, thus introducing an error of collimation. (3) It was difficult to keep the tube water-tight. (4) It was only possible to secure anallatism by the use of additional lenses, which, from their nature, caused a large loss of light and magnifying power, and what was more serious, introduced another source of possible error into the line of collimation. It cannot be too strongly emphasized, that a surveying instrument is merely an apparatus built round a line of collimation and exists only for the purpose of setting that line in any desired direction, and then measuring its setting. The introduction therefore of any device or part which is liable to deflect the line from its correct position must be carefully guarded against. Levels and theodolites have been designed from time to time in which prisms and mirrors have been utilised for the purpose of shortening the instrument or bringing the line of collimation into a more convenient position for examination. Hitherto, little success has attended these praiseworthy and often ingenious efforts, because of the difficulty of securing permanance of the adjustments. In modern surveying telescopes, the use of a movable internal lens for focusing is now universal, and fulfils most of the conditions just laid down. It is true that an internal lens introduces something in the line of collimation which may possibly disturb it, but as has been shown by several writers, the probable error is negligible. The following argument has been translated by permission from an article in *Zeitschrift für Instrumentenkunde* of 1909, which will make this point quite clear.

Variation of Collimation Line in Internal Focusing Telescope

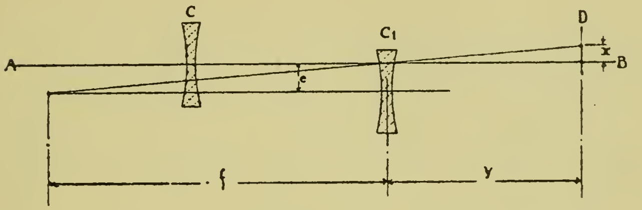


FIG. 1

Let A B be the collimation line of the telescope passing through the centre of the negative lens C in the position of solar focus, and C_1 the lens in the position it takes up when the telescope is adjusted for a near object. If C_1 moves out of alignment by an amount e, the line of collimation will be displaced from its correct position A B by an amount x, depending on the magnitude of e and the distances f and y, f being the focal length of the negative lens

as in the two triangles $\frac{x}{y} = \frac{e}{f}$

then $x = \frac{ey}{f}$

Taking a practical example, if the focus f of the negative lens is 10 inches, its distance y from the diaphragm D when set to focus on a near object is 3 inches. and its lateral displacement e is ·01 in.

$$\text{then} \quad x = \frac{ey}{f} = \frac{\cdot 01 \times 3}{10} = \cdot 003 \text{ in.}$$

It is here seen that although the lens is displaced by the large amount of 1/100 inch, the error caused at the diaphragm is very much smaller, being only 3/1000 inch. In a telescope of the ordinary type, where the object glass or the diaphragm is moved to adjust the focus, the whole of the error due to lateral displacement would be chargeable to the result.

It is evident that as the power of the negative lens f becomes less, so does the error x, but on the other hand, the distance through which it has to be moved to get down to short focus becomes greater. As, however, the slides upon which the tube carrying the movable lens can be machined very perfectly, no appreciable error need be feared from this source. When the line of collimation is the most important feature of the instrument it is obviously of advantage to fit a negative lens of low power. When, however, the instrument is to be used for tacheometrical purposes, the more powerful lens is preferable, owing to the fact that the smaller motion necessary for focusing has less effect on the position of the anallatic point to which the measurements are referred. Tests with telescopes constructed with internal lenses show that for distances over 100 ft., the errors in the stadia measurements are negligible, and as all distances up to 100 ft. are usually measured by tape or chain instead of by stadia, the corrections to be applied to the readings are only of theoretical interest. Should the surveyor ever require to make stadia measurements at short distances, and of very high accuracy, it is a simple matter to test the telescope on various measured distances, and to make a table or curve showing the corrections to be applied. Most makers of these telescopes give the value of a constant which, when added to the figure found by the webs, will correct for all distances above about 30 ft., to within two or three inches and certainly to within a smaller error than that due to the reading of the staff, under even the best conditions. Mr E. Wilfrid Taylor has described (Trans., Opt. Soc., xxv, No. 4), a perfectly anallatic internally focusing telescope, which does away with the necessity of adding a constant to the readings. As, however, two more lenses are employed in this design, it would seem that this disadvantage, and the additional complication and loss of light introduced would hardly compensate for the slight amount of labour involved in applying the necessary corrections when using a telescope of the more usual and more simple pattern.

However, from a theoretical point of view, the design is most interesting and for certain laboratory purposes would probably be of great value.

Focusing by a negative internal lens was originally designed for the purpose of obtaining great magnification with a relatively short object glass and was then known as the teleobjective. If we set up an object glass OG having a focal length F, and between OG and F place a negative lens of focus f at a distance a in front of F, then the image of a distant object, instead of being brought to a focus at F will, owing to the presence of the negative lens, be brought to a focus at a point F_1, at a greater distance, viz.: $a + b$ from the negative lens, and the image will also be magnified. The focal length of the combination F_2 will be given by

$$F_2 = \frac{Ff}{f - a}$$

The other elements may be calculated from the formula :—

$$\frac{1}{f} = \frac{1}{a + b} - \frac{1}{a}$$

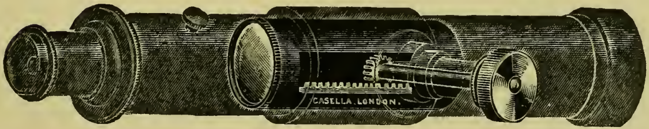


FIG. 2—Focusing Slide for Internal Lens

Focusing.—Fig. 2 shows the method of focusing for distance employed by Messrs Casella. In this design, the spiral pinion, working in a rack fixed to the carriage which supports a negative lens of low power, is extended through the axis and terminates in a milled head. This head, being on the end of the axis, is always in a convenient position for manipulation, and as it is housed in a solid part is very strongly supported. Its use also does not disturb the setting of the telescope to the same extent as in the usual design in which the milled head is fixed to the tube.

Fig. 119 shows an excellent design for the movable slide carrying the internal lens, due to Messrs T. Cooke & Sons. In this case the carriage runs on a 3-point skid which gives the smooth and straight run for the lens necessary to fulfil one of the conditions laid down.

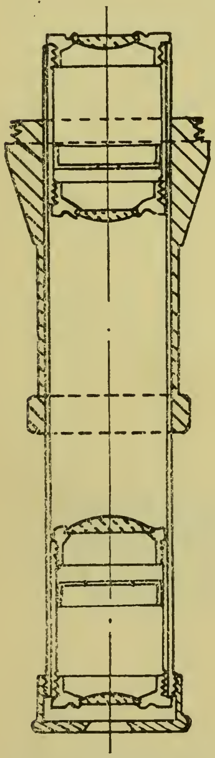


FIG. 3—Erecting four lens eyepiece

Eyepieces.—The eyepieces in use today are generally of the simple **inverting type,** although those of the erecting form are occasionally employed. If a surveyor during his training has been accustomed to an **erecting eyepiece,** he generally finds it difficult to use an inverting one, so that manufacturers are obliged to cater for these individuals, in spite of the fact that there can be no possible doubt that the inverting eyepiece is superior in every respect. The main disadvantage of the erector is that the telescope must be made longer to get an equivalent result. If the eyepiece is incorporated in the body of a transit theodolite telescope, as is sometimes done in American instruments, the shortening of the focus of the object glass is fatal to good resolution, and the loss of light occasioned by the two additional lenses is considerable. Again, with an object glass of such short focus in order to get reasonable magnification the equivalent focus of the ocular must be made much less with the result that it is more difficult to focus accurately on to the webs, thus rendering the probability of parallax error much greater. The webs also appear coarser and when a glass diaphragm is fitted, dust or moisture is magnified, giving the field a misty and dirty appearance. They are convenient, however, when used in conjunction with a prism to examine stars towards the zenith, and for that reason an illustration of the form generally employed is shown in Fig. 3. The inverting eyepiece in general use is either of the RAMSDEN or orthoscopic form. The Ramsden, which consists as shown in Fig. 4 of two plano-convex lenses placed about two-thirds of their focus apart, is an excellent form for all but the most precise work where very high magnification is required. It has the advantage of cheapness, has a flat field in the part used by surveyors, is easily cleaned, and owing to the absence of cemented components, never gets out of order. Its chief merit, however, lies in the fact that it is not necessary to place the eye very close to it, so that sun-shades and prisms can be placed between the eye lens and the eye without much loss of field. Orthoscopic eyepieces, on the other hand, can be designed to give a larger and clearer field and can therefore be more easily arranged for very high magnification. They are more expensive, and not quite so comfortable to use. Fig. 120 shows a method of adjusting the ocular for focus.

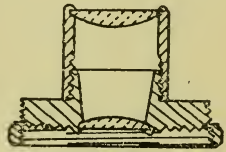


FIG. 4—Inverting Ramsden eyepiece

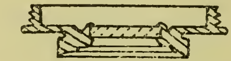


FIG. 5—Sun glass

The importance of correct focusing of the object glass on to the webs must be emphasized, as serious errors will be introduced in the readings unless parallax is eliminated. The method of adjusting for parallax is as follows:—Focus the webs very carefully by moving the eyepiece out or in. (The actual position depends on the focus of the eye and varies greatly in individuals). Then focus the object glass on to the object to be measured, moving the eye up and down or from side to side, when, if parallax is present, the webs will appear to move

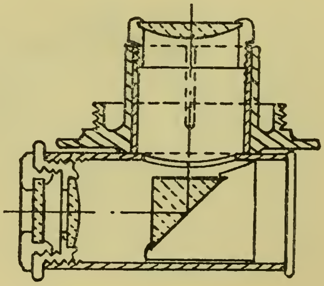


FIG. 6—Short diagonal eyepiece

across the object. If they move in the same sense as the eye then the object glass is set for an object nearer than that under examination, whereas if they move in the opposite sense, it is set for a more distant object. It should be adjusted until no relative movement takes place. Errors in the reading of as much as 30 seconds of arc may be made if this point is not carefully attended to.

Fig. 6 shows the form of low power diagonal eyepiece generally employed, except that in this case, its focus can be adjusted by the screwed ring instead of being pushed in and out as in the older design. When high power is required in the diagonal, it is usual to fix a small prism directly in front of a Ramsden eyepiece as shown in Fig. 7. This prism screws on in the place of the usual sun glass, and can be slightly rotated for convenience of observation. Fig. 8 is the form of diagonal used when it is necessary to examine objects near the zenith, as in this position it is impossible to get the eye close enough to an eyepiece of inverting form. Eyepieces carrying micrometers with movable threads are sometimes employed for stadia work, but as they are similar to those used for reading the circles of micrometer theodolites, no description of them need be given here. See p. 27 *et seq.*

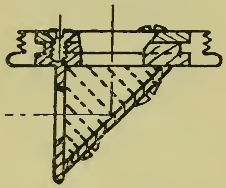


FIG. 7—Prism for attaching to eyepiece

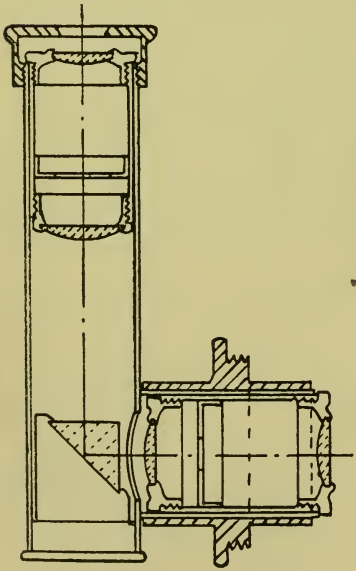


FIG. 8—Long diagonal erecting eyepiece

Object Glasses

The object glasses used in surveying instruments are always achromatic doublets, and may either be of the open contact or cemented variety. So far as actual performance is concerned, there is hardly anything to choose between the two systems. The cemented doublet is equivalent to one solid piece of glass and is therefore not easily damaged. It is watertight and when properly centered should never give any trouble. It happens sometimes that owing to extreme changes of temperature or unskilful cementing the balsam becomes starred or cracked, resulting in loss of light. When this happens, it is seldom that the surveyor can effect the necessary repairs. As the cracking of the balsam is of rare occurrence, this defect need not carry much weight, when making a choice. The open contact lens can be taken to pieces and cleaned, but the ease with which this can be done is rather a trap for the unwary, and much damage is often caused in this way. Some lenses are so designed that the units are separated by small slips of tinfoil, with the result that a space is allowed for the ingress of moisture and dirt. When the components are centered up a notch is ground at corresponding points in their edges. These notches are arranged to fit on a feather fixed inside the containing cell. If the fit is not good, or the groove is chipped, the lenses may be slightly misplaced, and their performance somewhat impaired. On the whole, the balance is probably in favour of the more robust cemented lens.

The test for definition having already been given, the only other point which requires consideration is the accuracy of centering which is necessary.

Centering of Object Glass.—As will be seen later, when discussing the adjustment of instruments, it is necessary that the object glass should be accurately centered. This is done during the manufacture of the lens by the very simple operation of revolving it in a lathe and so adjusting it that the image of a spot of light which is allowed to fall on its surface will remain stationary. The edge of the lens is then ground true to this centre before removing it from the lathe. As this operation can be carried out in a most precise manner it is seldom that the defect of inaccurate centering is found in modern instruments.

Diaphragms. Reference marks of some kind are required at the focus of all surveying instruments, and they generally take the form of spider webs or lines ruled on an optically worked glass disc. Diagrams 1 to 8 show a number of forms commonly employed.

1. Is the form mostly fitted to theodolites.

2. Is a rather better design than No. 1 as there is less confusion between the lines at the centre.

3. Is a better form of stadia than No. 4 as there is less likelihood of mistakes when the centre wire is being used for taking altitudes.

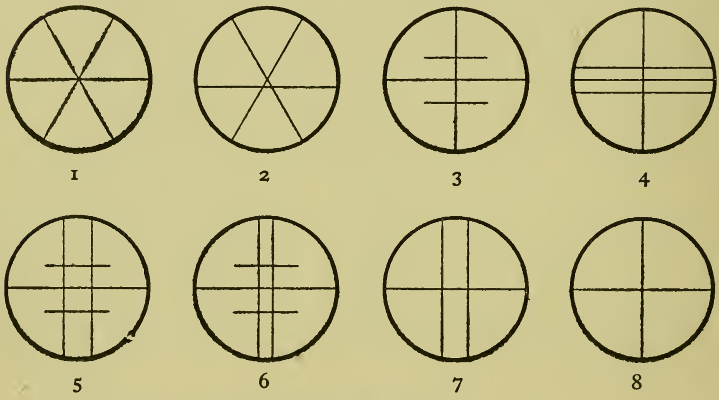


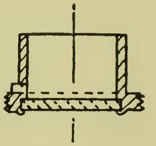
FIG. 9—Diaphragms

5 and 6. Are stadia diaphragms as often fitted to levels.

7. Is a good form of diaphragm for special work, where the distances are constant. If the spacing of the webs is such that the picket or plumb line fills almost the whole of the space, leaving merely a small band of light at each side, very accurate settings can be made.

8. Is a simple cross as fitted to most dumpy levels. For stadia work, when horizontal targets are often employed, the diaphragm is so arranged that it may be rotated through an angle of 90°.

There is a considerable difference of opinion as to the best form of diaphragm, and also as to the relative merits of webs and lines ruled on glass. The glass diaphragm is more permanent than the webs, and where stadia measurements are required, is generally preferable. It is, however, never quite so clear, it obstructs a certain amount of light, and is liable to become dirty and covered with moisture. Webs, on the other hand, give a very clear and clean image, and are much more robust than is generally supposed. Probably the best solution is to have a spider web fitted for general use and a spare ruled glass carried in a box for use in case of accident. Diaphragms are now fitted as shown in Fig. 10 and can therefore be replaced without difficulty when they have been removed for cleaning. The fitting carrying the webs or glass is inserted with a special tool which has a screw thread into which the fitting can be fixed. There is a locating pin on the fitting engaging with a slot in the adjustable holder so that when the fitting is pushed home, the webs come correctly into collimation. The extractor is then unscrewed the locating pin preventing the fitting from turning.



Replaceable mounting for glass diaphragm

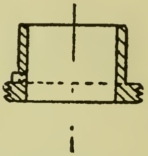


FIG. 10—Mounting for spider webs

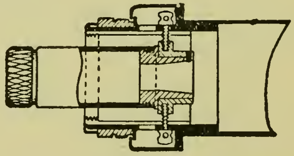


FIG. 11—Diaphragm mounts with extracting tool shown in position

Diaphragms in which the spacing of the webs is adjustable are sometimes employed, an arrangement for which is shown in Fig. 12. A fixed web is mounted in the centre and the other two webs are cemented on to the two blocks shown. These blocks may be moved towards or from the centre by turning the small adjusting screws, spiral springs serving to keep them apart at any setting.

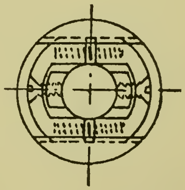


FIG. 12—Adjustable diaphragm

When observing stars with the theodolite the correct illumination of the field is a matter of some difficulty. If the light is too intense the image of the star is blotted out, while if it is too faint, the cross wires cannot be distinguished.

A number of proposals have been made to overcome this difficulty, the most successful hitherto being one made by Mr E. A. Reeves of the Royal Geographical Society.*

In this ingenious device two images of the star are visible in the field of the telescope, one seen directly through the instrument in the ordinary way and the other by a double reflection. These images only coincide when the star is in the centre of the field and move in opposite directions as the telescope is turned in altitude. This double and opposite movement increases the accuracy of the observation since if the star is not in the centre of the field the distance the images are apart is double the error of pointing.

The attachment can be fitted to any theodolite and consists of two partly silvered glass discs, one placed in the position which the ordinary diaphragm would normally occupy, and the other in front of the eyepiece. This latter glass may be adjusted by means of 4 capstan-headed screws, in order to bring the images correctly into the line of collimation.

The optical principle is as follows :—The image of the star is formed on the silvered face of the diaphragm. Part of this beam is transmitted and meets the eye in the usual way, but part of it is reflected back through the eyepiece, thus forming a second real image on the silvered face of the diaphragm. These two real images may therefore be examined under magnification by the eyepiece and very accurate pointing obtained.

Fitting of Spider Webs.—It may be of interest to describe the method of fitting spider webs to the diaphragm and the following instructions will enable anyone with a slight amount of practice to re-web a diaphragm successfully. A supply of web should first be procured as follows :—Make up a few frames about 6×2 in. of brass wire about $\frac{1}{16}$ in. in thickness as in Fig. 13. Smear the edges with shellac varnish or gum. If a small field spider is placed on the frame and then jerked off, it will remain suspended to the frame by its web. If then

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* Note *Geographical Journal*, Vol. LXIV, No. 6, for December, 1924

the frame is rotated on its longitudinal axis the web can be wound on to it as shown in the figure. Several frames can be filled and if they are kept in a tin box, such as those used for storing photographic negatives, they will remain in good condition for years. It will be found that the webs vary somewhat in thickness, but suitable pieces can be chosen by the aid of a magnifier or the eyepiece of a theodolite.*

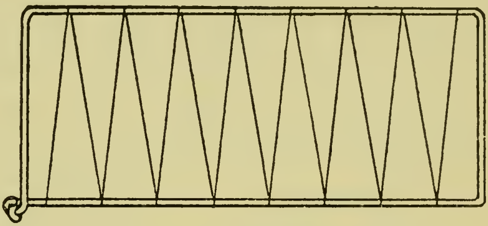

FIG. 13—Frame for holding spider webs

The brass mount of the diaphragm will, when cleaned off, be found to be ruled with grooves in the positions the webs are to take. The frame carrying a suitable length of web should be brought over the groove and gently lowered into position. The weight of the frame when laid on the table, will stretch the web sufficiently. It is then only necessary to fix each end down with a little shellac varnish dropped on with a pointed match stick. This will dry off in
a few minutes, when the other webs ca
manner. A magnifying lens on a stan
by botanists for dissection purposes w
matters, but an ordinary watch-make
eye will be quite suitable for the purp

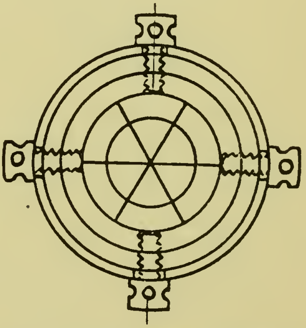

FIG. 14—Diaphragm fitted with
sp

It is such a simple job to re-web a di
prising that surveyors are content to send
repairers for this attention. The setting o a
more difficult operation. The makers have for this purpose

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* The first few feet of web spun by the spider will probably be made up of a number of very fine strands and must be discarded.

a tool which traverses the web a known distance, by means of a screw, and then lowers it into place. It is also necessary of course, to have a micrometer eyepiece which fits into the theodolite in order to measure the value of the interval to give the reading required. As, however, web stadia diaphragms are seldom used, the surveyor will not often be required to fit them himself.

Illumination of Webs.—There are several methods of illuminating the webs for night work, all of which give sufficiently good results. The simplest is probably that shown in Fig. 15, which consists of a spring ring arranged to fit over the object glass cell carrying a bent wire at the end of which is soldered a small silver ball about $\frac{3}{16}$ in. diameter. If a beam from an oil lamp or electric torch shines on to the ball, sufficient light is reflected down the tube to show up the webs against the dark field. It is not, however, easy to adjust the amount of illumination to suit the brightness of the object under examination, as, when observing stars of the third or fourth magnitude, the light on the webs may be sufficient to blot out that from the star. Another method is to paint the edge of the diaphragm with luminous compound or to have a small glass tube of radium paint inserted in the telescope tube in such a position that it shines on to the webs. Thi [illegible] ot always convenient as it gives an invariable [illegible] he best method but most complicated is [illegible] d at the end of the hollow axis or directly [illegible] n in the telescope tube. With a suitable [illegible] le to regulate the amount of light to a [illegible] f this are given in the description of [illegible]

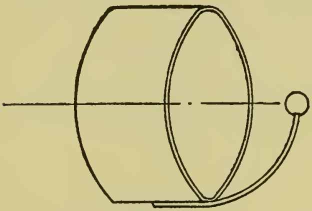


FIG. 15—Bead illuminator for telescope

[illegible] rm of magnifier is usually required to [illegible] ce of the lines of the verniers with those of th [illegible] accurately determined, and for this purpose a low power Ramsden eyepiece is probably the most convenient. In English instruments, readers of this kind are usually fitted on arms turning about the axis of rotation of the divided circle.

When readings are to be taken at night, the above forms are not very convenient and an electrically illuminated microscope, Fig. 16, is most useful as not only can it be used as a reader but the light can be employed to illuminate the webs or any other part of the instrument required. The hollow handle contains the dry battery and a small push switch is fitted to turn on the current when required. Larger instruments are generally fitted with a complete electrical illumination outfit which allows the work to be done in great comfort. A description of this will be found in the chapter dealing with micrometer theodolites.

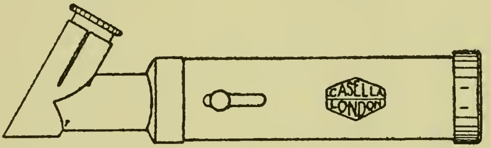


Fig. 16—Electrically illuminated reading lens

Reading Micrometers.—For reasons which will be discussed later, divided circles of surveying instruments are now seldom made greater than 12 ins. in diameter, and as it is not desirable to make graduations of less than 5-minute spacing, reading by vernier is not possible when settings to seconds of arc are required.

Verniers reading down to 5 seconds are sometimes constructed but the results obtained leave much to be desired. In the first place, it is necessary even with a circle of 10 ins. in diameter to make the lines fairly fine, if they are to be so placed that they can be conveniently read by means of a vernier, with the result that they are rather delicate and easily defaced. With the most perfectly fitting vernier a certain amount of parallax is present, which makes the readings ambiguous. There is also this difficulty. The reading is either an edge to edge or edge to flat one, and as it is almost impossible for the divider to get his graduations of even thickness right up to the edge, the accuracy of coincidence setting is impaired. Bell mouthed divisions, by which term this type of defect is known, are uncomfortable to set, and if a test is made by a number of observers, it will be found that the majority can estimate 5 seconds on a vernier with a least count of 20″ to a greater degree of accuracy than they can read a direct 5 second vernier. The power of the eye, even in untrained observers, to estimate halves, quarters and tenths is remarkable. For these reasons, there has been considerable development in the design of theodolites in which the readings are made by either mechanical or optical micrometers. Formerly, instruments of this description were confined to those of comparatively large size, and although they were sometimes fitted to those having circles of 6 inches diameter and smaller, they were, owing to the relatively small demand, merely adaptions of vernier instruments with the micrometers fitted on in the manner which the constructor found most convenient for himself. The result was, as might be expected from any built-up apparatus of this nature, unsatisfactory, both from a mechanical and optical point of view. In recent designs, the problem has been studied as a whole and suitable arrangements evolved to meet the necessary requirements

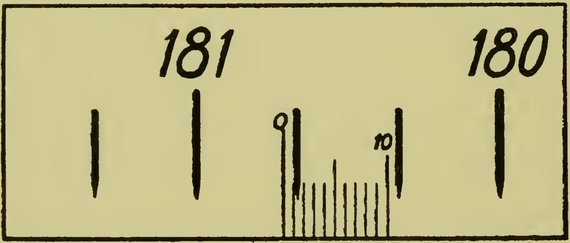


FIG. 17—Estimating microscope, direct reading = 180° · 43′

The graticule is divided to read double minutes for convenience when taking the mean of the opposite circle readings.

Thus microscope A = 180° · 21·4
B = 21·5
mean = 42·9
Therefore reading = 180° · 42′ · 54″

The simplest form of micrometer is similar to that shown in Fig. 19, but without any screw. This is generally termed an estimating microscope. It consists of an ordinary microscope having a magnifying power suited to the particular graduation to be examined. An image of the graduations is projected on to a ruled glass graticule fixed at the focal point. A Ramsden eyepiece is then used to magnify the field in the usual way and as the two sets of lines appear in contact and free from parallax a very accurate estimation can be made. An example of the field of view in this type of micrometer is shown in Fig. 17 from which it will be seen that a reading down to minutes can be estimated without difficulty. It will be obvious from the appearance of the field that this method cannot be pushed to a much finer reading and, indeed, the thickness of the actual lines on the divided circle, even for the reading given, is already less than is desirable from a mechanical point of view.

On the other hand, if the magnification is increased, the lines become coarse looking, and the setting ambiguous, and then, also, it is not possible to get the numbering of the degrees into the same field. It is necessary that the field should contain the figures belonging to two adjacent degree marks in order to make the booking of these figures easy, so that with greater magnification a subsidiary scale and microscope would be required. For the above reasons, when readings of 10 seconds or less are required, the screw micrometer microscope is more convenient. This, with a suitable design, can be constructed to give any value of reading required down to even 1/10 second. The usual readings are 10 seconds for 5 or 6 inch circles, 5 seconds for 8 inch and single seconds for 10 or 12 inch circles. With a fairly large micrometer head 1/10th of these amounts can be estimated and indeed it will be found that most users of these instruments habitually estimate the readings to 1/10th of the marked values.

Estimating microscope reading both sides of the circle in one field.

Top reading = 180° · 21′·2
Bottom „ = 0° · 21′·3
= 42·5 minutes

Mean reading = 180° · 42′ · 30″

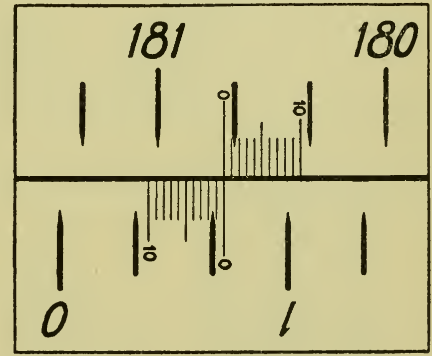


FIG. 18

Fig. 19 shows the simplest construction of micrometer microscope, an instrument having microscopes of this type being shown in Fig. 82. In order that the eye may be brought close enough to the ocular of this form of micrometer, it is necessary to bevel the divided limb and mount the microscope at right angles to the divisions. This construction, while simple, means that the microscopes cannot be well supported and as they stand out from the general body of the instrument, are very liable to damage when in use. Most makers now mount their microscopes vertically to read on a flat divided limb and bend the line of collimation by means of a prism so that the eye can be brought conveniently into the reading position. Figs. 20 and 21 show alternative methods of doing this. In Fig. 20 the prism is placed between the object glass and the movable hair lines. This has some slight disadvantage in that any disturbance of the setting of the prism will shift the field. Any movement of the prism will not, however,

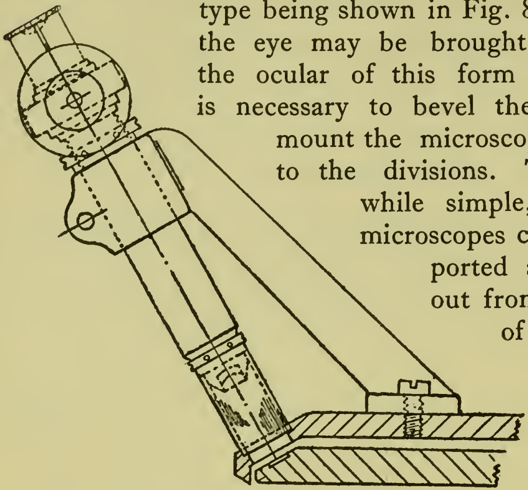


FIG. 19

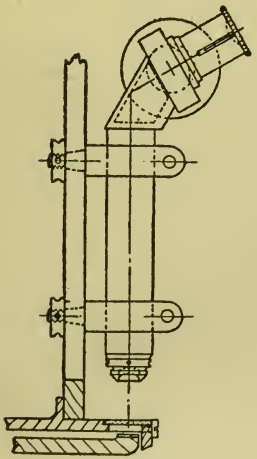


FIG. 20

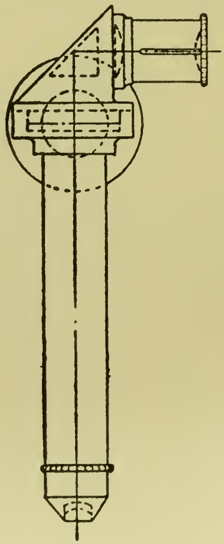


FIG. 21

appreciably affect the accuracy of the reading, as this is determined solely by the ratio of the focus of the object glass to the pitch of the screw. It may, however, affect the centering, but as the means of opposites are always taken, no error is introduced. The construction shown in Fig. 21 is free from this defect, and is rather simpler. Its main defect is that as the prism lies between the ocular and the webs, it is only possible to employ low power lenses in the eyepiece. The divisions are therefore very small and accurate setting is not so easy. A prism having one face ground convex may be employed, which gets over some of the difficulties, but on the whole the arrangement of Fig. 20 is more convenient. Fig. 22 shows a plan view of the construction of the micrometer box. In this it will be seen that the screw is held longitudinally, and when revolved, moves the frame

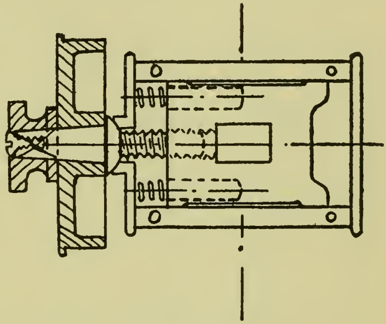


FIG. 22

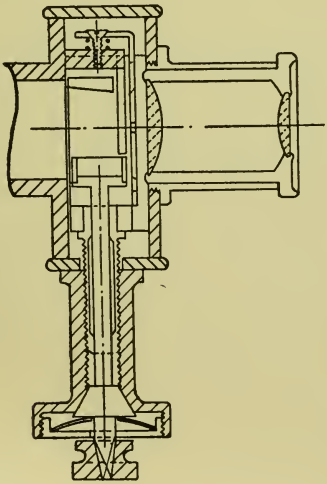


FIG. 23

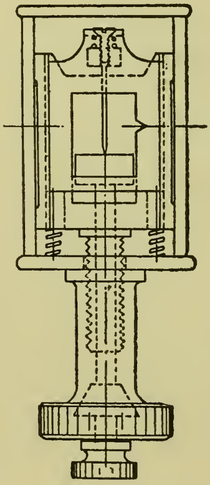


FIG. 24

carrying the fixed webs across the field. A better construction is shown in Fig. 23 in which the screw is part of the frame and moves inside the hollow nut when the latter is revolved. This design is superior to Fig. 22 because it is easier to make the bearing part of the nut longer, the slide can be better supported and when required, the axis of the micrometer screw can be in the same plane as the webs. Fig. 24 shows the construction of the micrometer as fitted to Messrs Casella's micrometer theodolite. In this instrument, the opposite sides of the divided limb and also the divided head of the drum are all in one field of view, and can be read simultaneously. When the instrument is so designed that one turn of the screw moves the webs over one division of the limb, it is only necessary to have a single zero notch as in Fig. 25. This notch serves to show when the webs are approximately at zero. The actual setting of the webs for zero is of course made on the dividing itself, and when this has been done, the micrometer head can have its zero set opposite its fixed reading mark. For this purpose the divided head is only friction tight on its spindle, and before a series of observations are taken it is convenient to set the webs and the drum to zero, so that the readings may be booked without calculation. When, however, the instrument is to be read to less than say 5 seconds with a limb divided to 5 minutes, it is necessary to arrange the pitch of the screw so that more than one turn is required to move the webs from division to division. For example, with a limb divided to 5 minutes spaces which is required to read to seconds of arc, the screw could be calculated so that it must make five turns to cover this space, that

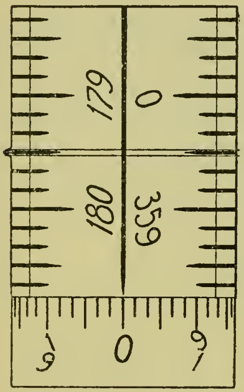


Fig. 25

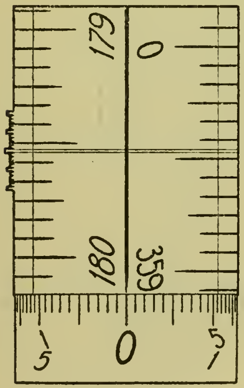


Fig. 26

is, a screw having a pitch equal to one minute. If then the drum is divided into 60 parts, each part will be equal to one second, i.e., 5 turns × 60 divisions = 300 secs. = 5 mins. It is therefore necessary in this case to be able to count the number of whole turns and parts of a turn, the parts of a turn being of course counted on the drum. In order to count the whole turn a comb, Fig. 26, is placed as close to the webs as possible, so that it is in the focus of, and magnified by, the eyepiece. This comb is of exactly the same pitch as the screw, and is made by cutting a screw thread on a rod of brass on the lathe upon which the micrometer screw was made, and then milling it down to a thin flat section from which the combs can be cut.

Adjustment of Micrometer Magnification

In a five inch circle divided into spaces of 10 minutes the distance between the division lines will be

$$5\,\frac{\pi}{2160} = \cdot 00727 \text{ inch}$$

and in a six inch circle ·00873 inch. As it would be inconvenient to cut a screw having a pitch exactly equal to or any simple proportion of the spacing of the circle, it is necessary to arrange the microscope in such a way that its initial magnification may be suitably adjusted. The micrometer screw therefor is cut to any convenient pitch, say, 50, 60 or 100 threads per inch and an object glass of suitable focus is employed in such a position that the image of the divisions which it projects on to the webs will be equal to, or 5 or 10 times as large as, the pitch, the proportion depending on the reading required and the number of spaces into which each degree is divided. If M = the magnification, p = the pitch of the screw, d = the diameter of the circle at the reading point and G = the number of spaces into which the whole circle is divided then

$$M = \frac{p\,G}{\pi\,d}$$

Taking the practical example of a five inch diameter circle divided into ten minute spaces, the reading in the micrometer to be 10 minutes per revolution, and assuming the distance from the webs to the face of the divided circle to be four inches (this latter figure will be determined by the general design of the parts), a convenient pitch of screw for an instrument of this size would be, say 60 threads per inch. Therefore

$$M = \frac{\cdot 0166 \times 2160}{15\cdot 708} = 2\cdot 283$$

As the total length of the path is four inches, the distance from the object glass to the scale will be

$$P = \frac{4\cdot 0}{2\cdot 283 + 1} = 1\cdot 22 \text{ inch}$$

and the distance from the object glass to the webs will be

$$P_1 = 4\cdot 0'' - 1\cdot 22'' = 2\cdot 78 \text{ inches}$$

The focus of the object glass will be given by

$$\frac{1}{P_1} + \frac{1}{P} = \frac{1}{F} \text{ where } F = \text{the focus}$$

or
$$F = \frac{PP_1}{P + P_1}$$

Therefore

$$\frac{1}{2\cdot 78} + \frac{1}{1\cdot 22} = \frac{1}{F} \text{ and } F = \cdot 848$$

If a lens having a focus of about ·85 inch is employed the magnification can be adjusted to the required amount of 2·283 by setting P and P_1 to suitable distances, as it will be noticed that each of these dimensions can be set at any desired figure, P by moving the whole microscope in its mount and P_1 by screwing the object glass nearer to or further away from the webs. When a prism is interposed between the webs and the object glass it will be necessary to make an allowance in the calculation depending on the refractive index of the glass employed. For ordinary crown glass it will be sufficient to add half the length of the path through the glass to the total distance. For example, if the path through glass is ·5 inch, the distance assumed in above case as 4 inches would be increased to 4·25 inches for the purpose of the calculation. The actual measured distance would of course be only 4 inches. If the distance P_1 is permanently fixed, the magnification will always be correct for the circle to which it was adjusted, as it has been shown by several writers that the expansion of the brass tube due to increase in temperature nearly balances the alteration in focus from the same cause. It is to be noted, however, that is as the graduations are radial, and therefore become further separated as they recede from the centre, care must be taken that the microscope always reads at the same distance from the centre. With the old type of instrument this was difficult to secure, as a very slight bend in the supporting arms would tilt the microscope and thus render the readings inaccurate. In the micrometer shown in Fig. 27 this can hardly happen and in the example Fig. 107 the danger is negligible owing to the fact that the whole of the optical work is housed in the body of the instrument where it is thoroughly protected from injury.

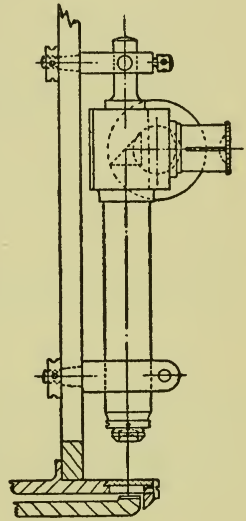
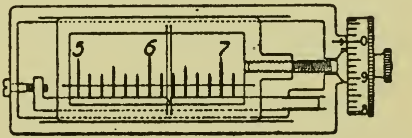
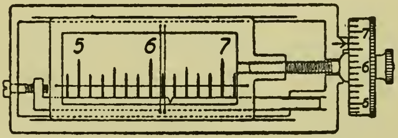


FIG. 27



Setting = 6° · 10′ plus distance from web to next division on left



Distance from web to next division shown to be six minute spaces plus four small divisions = 6′·40″. The total reading is therefore 6° · 16′ · 40″

FIG. 28

Fig. 28 shows what is undoubtedly the best form of webs for the microscope. The spacing should be such that a just appreciable amount of light is seen between each web and the graduation. In this way remarkably accurate settings can be made. It necessitates, however, an even thickness of line all round the circle, so that some makers prefer to fit points or a single web in order to hide any defect. One, or better still two, cross webs are necessary on larger instruments, in order that the reading may always be taken at the same place. A circular line ruled on the silver when the divisions are being made would be preferable if it could be made fine enough. A sufficiently fine line is, however, not easy to produce and a line as thick as the divisions themselves and crossing them is not a convenient mark upon which to set. On the whole, the cross web is quite good enough and as modern instruments are so robust, and as the value of the readings can be so easily checked, there is no practical disadvantage in this arrangement.

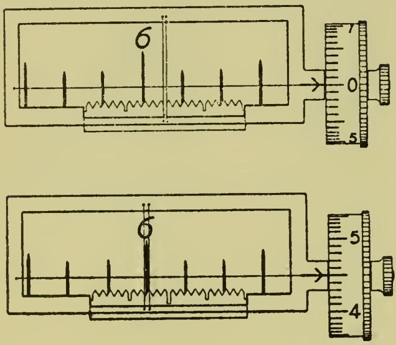


FIG. 29

In this case the circle being divided into five minute spaces the reading is 6° · 2′ · 45″ as two turns plus 45 small divisions were required to bring the webs back into the six degree division.

Minimum Focusing Distance.—When it is required to focus a telescope on to objects at very short distances, the amount by which it is necessary to separate the object glass from the webs becomes excessive, so that other arrangements have to be made. For ordinary surveying telescopes of about 10-inch focus a movement of the object slide of 1¾ inches is rather more than can be allowed with safety. If it is made greater than this, the draw becomes unsteady and the drop in the line of collimation leads to large errors.

A simple calculation serves to determine the minimum distance on which a telescope may be focused with a given extension of the draw tube. For example :—

If F = the solar focus of the object glass.
D = the distance of the object from the instrument.
D_1 = the distance from the object glass to the web.

Then at solar focus $F = D_1$

Now as

$$\frac{1}{F} = \frac{1}{D} + \frac{1}{D_1}$$

$$F = \frac{DD_1}{D_1 + D}$$

$$\text{and} \quad D = \frac{F D_1}{D_1 - F}$$

$$\text{and} \quad D_1 = \frac{F D}{D - F}$$

If, for example, a telescope of 10″ solar focus is required to be focused on to an object 10 feet distant, then the draw must be designed so that it will extend to

$$D_1 = \frac{F D}{D - F} = \frac{10 \times 120}{120 - 10} = 10{\cdot}99 \text{ inches}$$

that is, an extension of ·99 inch beyond the point of solar focus.

If we can afford an extension of 2 inches then the shortest distance at which an object can be focused will be

$$D = \frac{F D_1}{D_1 - F} = \frac{10 \times 12}{12 - 10} = \frac{120}{2} = 60 \text{ inches}$$

If we should require to focus down to say two feet, then

$$D_1 = \frac{10 \times 24}{24 - 10} = 17 \text{ inches}$$

As such an extension would not be practicable other arrangements must be made when very near objects are to be focused.

Short Focus Attachment.—As the focus of a surveying instrument must be capable of being set to infinity it is not generally practicable as has just been shown to arrange the optics to allow of a setting to much less than 8 or 10 feet. When the instrument is to be employed around buildings or underground, it is often necessary to sight on to marks as close as 3 or 4 feet. To enable this to be done, it is usual to fix temporarily a long focus single lens in front of and working in conjunction with the usual object glass. It is mounted in a tube, which fits over the cell of the object glass and is positioned by a slot and pin which prevents the tube turning on the cell. Sometimes three adjusting screws are fitted in order to allow for the centering of this auxiliary lens, but it is more usual for the maker to arrange that the combination is in adjustment when pushed home on the cell. The error of collimation can be checked by stretching a line along the ground from the centre of the instrument and by sighting on to a plumb line. The error on such short distances is, however, not likely to be serious.

There is another short distance focusing arrangement which is employed extensively on the continent of Europe. This was devised by Porro and consists of a short focus positive lens placed just in front of the diaphragm. When using the telescope on long sights this lens has of course no appreciable effect on the distance at which the diaphragm must be placed from the object glass. When, however, the target being examined is brought up to the anterior focal point of the object glass it is evident that the parallel beam which will then be formed will be brought to a focus by the small converging lens. The image can therefore be examined by means of the eyepiece and diaphragm in the usual way. It is difficult to design a lens system of this kind which will give clear images free from distortion, and the presence of a powerful lens between the object glass and the diaphragm is objectionable owing to the liability of displacement of the line of collimation.

Parallel Plate Micrometer.—This device is sometimes fitted to levels for the purpose of measuring the fractions of a space on the staff. This, as is shown diagrammatically in Figs. 30 and 31, consists of a disc of plano parallel glass, which may be turned on a horizontal axis through known angles, the amount of tilt being indicated either by an index moving over a scale or by a coarse micrometer screw and divided head.

The tilting of the glass disc displaces the image of the staff vertically and parallel to the line of collimation. If the apparatus is so arranged that the total movement over the arc moves the image exactly over one division, the fraction to the nearest staff division will be indicated directly on the arc or micrometer in a rather more exact manner than it can be estimated by eye.

If for example, the staff is divided to 1/100 foot and a movement of 10 divisions on the arc is required to displace the image by one division on the staff, each division on the arc will equal ·001 foot. As a large movement of the glass plate is necessary for a small displacement of the staff image, this method is capable of giving very close and permanently accurate results, depending as it does for practical purposes only on the thickness and the refractive index of the glass employed. Another fitting which is sometimes used by continental surveyors consists of a similar mount to the above, but carrying a prism ground to a small angle. The prism Fig. 32 is fitted in such a way that it may be easily hinged to one side without disturbing the setting of the telescope. If a reading is made on a staff first with the object glass direct, and then with the prism placed in front of it, there

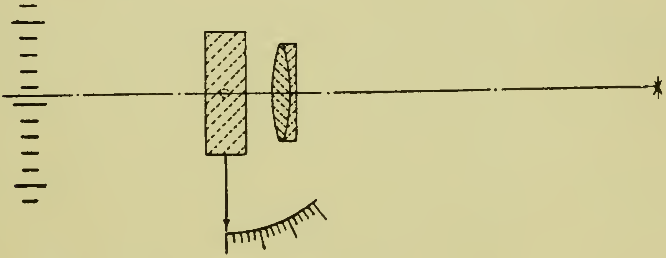


FIG. 30

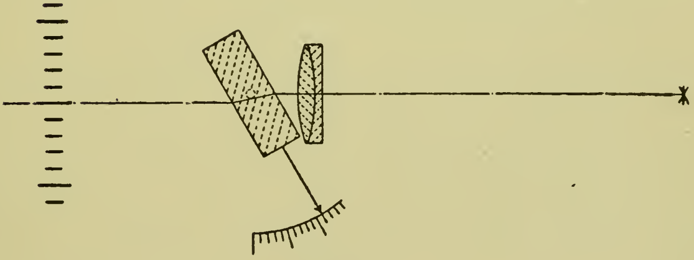


FIG. 31

will be a difference in the reading due to the deviation of the prism. The amount of this deviation can be arranged to be 1 in 100 or any other amount, depending on the angle of the prism, thus it is a simple matter to measure horizontal distances to about the same degree of accuracy as in stadia work. Slight adjustments of the deviation in a vertical or horizontal sense can be made by rotating the fitting carrying the prism, and then fixing it in the correct position.

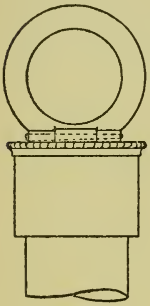


FIG. 32

The alternative method of tilting the whole telescope by a fine micrometer screw is rather less cumbersome, and probably as easy to use, but the accuracy of the reading is lost when wear takes place in the screw or the mountings. On the other hand, the glass plate being a separate fitting, which has to be carefully packed away in the level box when not in use is easily damaged and sometimes lost. Additional fittings which are only occasionally used are a continual annoyance to surveyors. They are usually dirty or out of order just when they are wanted.

Anallatic Telescopes.—For tacheometrical purposes, many surveyors prefer to use a telescope which is perfectly anallatic, that is, one which will project an image of the staff on to the webs of such a size that it is in direct proportion to the distance from the centre of the instrument to the staff. At first sight, this would appear very advantageous, but practically it merely eliminates the necessity of adjusting the booked figures by the addition of a constant to each reading. Moreover, with the modern form of focusing by means of a negative internal lens the errors in the readings are practically negligible for any distance above 50 feet. If extreme accuracy is required from this latter kind of telescope, the adjustment of the figures is a simple matter. This procedure gives the best results in practice owing to the fact that the instrumental errors are likely to be less than in any of the more complicated anallatic telescopes hitherto produced. As the question is one of considerable interest, and as a simple, perfectly anallatic telescope is for some purposes desirable, a short account of its construction is given below together with the corrections to be applied to the readings made on the ordinary simple telescope.

Fig. 33 shows how the lenses are disposed in the anallatic telescope, in which OG is the object glass and A the anallatic lens. If C is the centre of the instrument to which all measurements are to be referred, the rays G and G_1 coming from the graduated staff or target would in the absence of an object glass cross at this point The object glass being interposed, the rays are in consequence bent and cross instead at C_1, when, continuing their paths they fall on the anallatic lens A. If this lens is made with a focal length A C_1, the rays will emerge as parallel rays which, falling on the diaphragm at W W_1 may be examined by the eyepiece in the usual way. If the distance D is 100 times the distance G G_1 and the webs W and W_1 are arranged to cut the rays as shown, it is evident that the number of divisions on a staff held at G G_1 which these webs will cut will be equal to

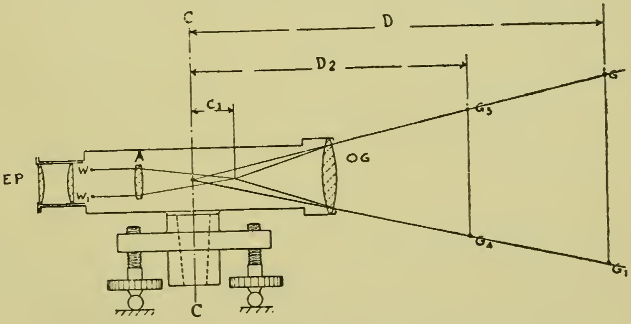


FIG. 33

$$\frac{D}{100}$$

If the staff is now moved to D_2 it is obvious that the above proportion will be unaltered and that the webs will still cut off an amount on the staff G_3 G_4 equal to

$$\frac{D_2}{100}$$

As the lens A must be made positive it follows that the equivalent focus of the whole telescope is made much shorter than an ordinary telescope of the same dimensions. It is therefore necessary when using this system either to increase the size of the telescope body or else be satisfied with a much poorer performance. In practice, anallatic telescopes are generally made longer and are fitted with a larger object glass to compensate for the loss of light. They are also mostly fitted with a rather higher power in the eyepiece to bring the magnification up to a suitable degree for stadia work. It is obvious that an ordinary simple telescope, when enlarged in the same way, will give a much better result than any anallatic telescope of this kind. It is to be noted that to focus this type of telescope for varying distances it is necessary to alter the separation between the object glass and the webs. In order that the anallatic point may remain at the centre of the instrument, the focusing must be done by moving the graticule and the eyepiece together; if, as in certain cases, it is more convenient to focus the instrument by altering the object glass and therefore varying its distance from the anallatic centre, a small correction must be applied to the readings when very exact distances are required.

When **stadia readings** are to be made with an ordinary open telescope, that is, one consisting of an object glass and eyepiece only, the anallatic point is situated outside the instrument at a point in front of the object glass equal to its solar focus.

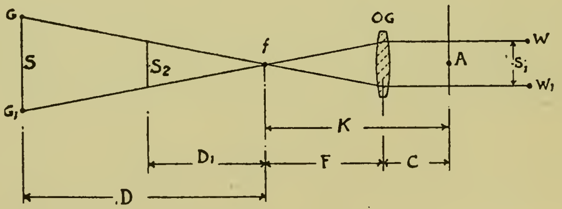


FIG. 34

A correction must therefore be added to each reading, the amount being equal to the focal length of the object glass, plus its distance from the centre of the instrument. If, for example, the focus of the object glass = 9 inches, its distance from the axis 4½ inches and the stadia interval 1 in 100, and if a space of two feet were cut on the staff, then the distance from the centre of the instrument to the staff would be

$$200 \text{ feet} + \tfrac{3}{4} + \tfrac{3}{8} \text{ foot} = 201\tfrac{1}{8} \text{ feet}$$

The preceding diagram, Fig. 34 will make this point clear. If W W_1 are the webs in the telescope, A the axis upon which it turns placed at a distance C from the object glass, F the focal length of the object glass and G G_1 the staff, then light falling on the webs W W_1 would be brought to a focus by the object glass at f and continuing would cut the staff at G G_1

Let $S =$ distance G G_1

and $S_1 =$ distance W W_1

then $\dfrac{S}{D} = \dfrac{S_1}{F}$

and $D = \dfrac{F\,S}{S_1}$

If the dimensions F and S_1 are so chosen that

$$\frac{S_1}{F} = \frac{1}{100} \text{ then } \frac{S}{D} = \frac{1}{100}$$

and $D = 100\,S$

If therefore the webs cut off 1 foot on the staff the distance D will be equal to 100 feet and the distance of the staff from the centre of the instrument will be $D + (F + C) = D_1 + K$.

If now the staff is moved to S_2 it is evident that the proportions are unaltered and that the required distance will be $D_1 + K$.

If the telescope is arranged to focus by moving the webs and eyepiece, K will be a constant, but if on the other hand the focusing is performed as usual by moving the object glass it will then be necessary to add an additional amount equal to the distance which the object glass had to be moved from the position it took when focused for parallel rays. As the amount of movement required is very small for distances above 100 feet, this correction is for most work negligible.

The exact amount may be found by the method shown on page 37.

In practice it is usual to determine the stadia interval, d, by actual experiment over measured distances of 200 or 300 feet, these distances being measured from a point in front of the centre of the instrument equal to K. The distance for an ordinary telescope is then

$$D = ds + K$$

and for an anallatic telescope

$$D = ds$$

Inclined Sights

As it is seldom that the stadia readings can be made on a rod held at the same level as the instrument, it is necessary to apply various corrections to allow for the angle to which the telescope must be tilted when the staff is at some considerable elevation or depression. There are three methods of holding the staff when taking inclined sights.

(a) With staff vertical.

(b) With staff inclined so as to be at right angles to the line of sight on the middle wire.

(c) With staff horizontal.

Those made with the staff held in a vertical position are most employed as it is difficult for the rodman to hold it at the correct angle when using the method (b) and when the staff is horizontal as in (c) some form of supporting stand is essential.

The horizontal position gives the best results but because of the necessity of transporting some form of fairly stable and therefore comparatively heavy stand is only employed where long sights are required. When the staff is held in a vertical position as in (a) and if a is the angle which a line joining the central wire to the staff makes with the horizontal, then the horizontal distance $D = ds.\cos^2 a + K \cos a$.

It is therefore necessary to note the angle a on the central wire when reading the staff. The height from the pivots of the telescope to the division of the staff cut by the central wire is given by the well-known formula

$$h = K \sin a + s.d \frac{\sin 2a}{2}$$

In the case of the perfectly anallatic telescope the above formulæ become $D = ds \cos^2 a$ and $h = D \tan a$.

When the staff is held at right angles to the line of sight the formulæ become

For the anallatic telescope $D = ds \cos a$
and for the ordinary telescope $D = ds \cos a + K$

An additional small correction should in theory be added when it is necessary to alter the distance between the object glass and the axis of the instrument to focus on to short sights.

The internal focusing telescope as usually constructed may be employed as a perfectly anallatic system for all distances over 60 or 70 feet, the errors at this distance and at all greater distances being negligible. It is generally necessary to add a small constant when exact values are required at distances less than 60 feet. This constant is easily determined by experiment as previously shown.

Bar Subtense Method

The above method of determining distances has been extensively employed in India with excellent results, and is often made use of by explorers and reconnaissance parties, as by this scheme considerable distances may be estimated rapidly with small percentage of error. The method was first employed in practice by the late Col H. B. Tanner of the Indian Staff Corps, who read a paper on the subject before the British Association Meeting in Cardiff in 1891.

It is claimed for this system that at distances up to 2 miles the maximum error expected is about 3 feet per mile when using a 6-inch theodolite. The instrument used should be low and stable and have a telescope of about 10 inches focal length with an object glass of 1¾ to 2 inches clear aperture. The subtense bars vary in length from 20 feet to 2 feet and Fig. 35 shows the form used largely in India. It is generally made in three sections for convenience in transport, these sections fitting together by means of strong iron sockets and pins. At each end of the bar a circular target of painted wood is fitted by means of iron brackets accurately placed a known distance apart. The centre section is arranged so that it may be fitted to a supporting stand and carries a sighting device which enables the rodman to align the bar with the observing theodolite. Fig. 36 shows a simpler form of subtense bar. This is made from a bamboo pole about 14 feet long having two square boards about 12 ins. × 12 ins. fixed as shown at a distance apart of 10 feet. These boards are fixed towards one end of the pole, the projecting portion of the pole which is about 2 feet long serving to support the bar when used in a vertical position. The method of use is simply to measure the angle subtended at the instrument by the bar; this angle and the length of the bar being known, the distance is calculated as follows :—

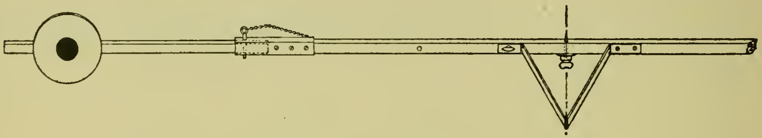


Fig. 35—Indian Subtense Bar

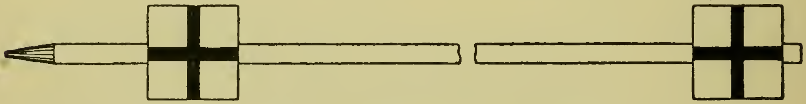


Fig. 36—Simple Subtense Bar

If a is the angle
d = distance between the targets
D = the distance required
Then $D = \frac{D}{2} \cot \frac{a}{2}$

The main advantage of this system lies in the fact that a large number of repetitions of the reading of the angle may be rapidly made, this being done as follows :—The forward signalman sets up the horizontal bar over the station mark, and then by means of the folding sight-vane, directs the bar at right angles to the observer, who then intersects and records the reading of the back signal. Then leaving the lower clamp fast, he releases the upper plate and intersects the right-hand disc of bar, the reading of which he records. He now releases the lower clamp (leaving the upper clamp fast) and intersects the left-hand disc. He again releases the upper plate and intersects the right-hand disc, and for a second time the left-hand disc with lower plate and so on, continuing the repetition, say, ten times. He then reads and records the right-hand disc. In this operation the graduated limb of the theodolite will have moved over an arc ten times greater than that subtended by the bar. He now repeats again, ten or twenty times, and records the readings of right-hand disc, and then having taken a vertical angle to the bar, and leaving lower plate fast, he intersects and records the reading of back signal with the upper tangent screw. The mean of all these repetitions will give a close approximation of the angle subtended by the bar thus allowing very accurate estimations of the distances to be made.

When the distances to be measured are greater than 2 or 3 miles, the angle subtended by a 20 foot bar becomes rather small. It is usual in this case to observe on to two poles or targets placed at a measured distance apart. These poles should be so placed that a line joining them makes a right angle with the line from the theodolite to a point midway between them. Care should be taken that the various sets of repetitions are made on different parts of the horizontal circle in order to eliminate any possible errors of graduation.

Another favourite method of estimating distances is by means of an **eyepiece micrometer** in conjunction with a bar similar to that just shown The scheme is simply to measure the small angle subtended and then calculate the length of the middle ray as before. In order that this angle may be accurately measured it is necessary to know very exactly the value of the micrometer divisions. This may be done as follows, care being taken that the telescope is set and always used at solar focus.

The subtense bar must first be set up at an accurately measured distance from the theodolite. Then the value of the turns and parts of a turn required to move the wire over the space between the targets is determined a number of times and the mean taken.

If D = the horizontal distance
d = distance between the targets of the subtense bar
M = the micrometer division as determined above.

Then the angle subtended in seconds will be

$$a = \frac{d}{D} \times \operatorname{cosec} 1''$$

The value of each micrometer division in seconds will therefore be

$$\frac{a}{M}$$

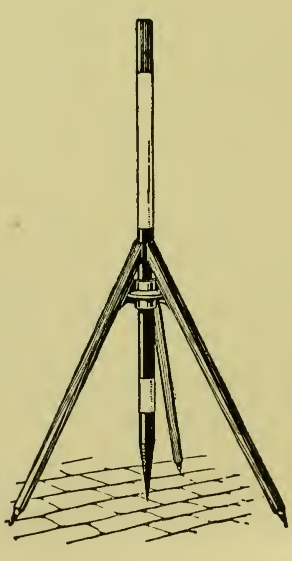


Fig. 36a—Support for ranging pole.

CHAPTER IV

SPIRIT LEVELS

AS surveying operations generally consist of taking angles and distances which require to be referred to the horizontal, the means for assuring horizontality must be efficient and accurate. The invention of the spirit level tube was one of the most important discoveries in the history of surveying. Before this event crude water levels and clinometers were the only means by which the horizontal could be determined. The level bubble put at once a new weapon into the hands of the surveyor, and enabled full use to be made of the telescope as a sighting instrument. It is difficult to conceive a more simple and perfect device and the sensitiveness to which it can be made is truly amazing. Recently, Mr Sears of the National Physical Laboratory, has successfully made use of the level bubble in his wonderful measuring machines, some of which are capable of appreciating differences of a millionth of an inch and as on many surveying operations the final accuracy depends on the exactness of the setting of the bubbles of the instruments, the subject is one which merits a great deal more attention than is usually given to it. Formerly, level makers simply picked out pieces of glass tube which happened to come out slightly curved in the manufacture. These were filled with spirit and the ends sealed up. Very soon, however, greater accuracy was demanded, and makers developed methods of grinding the interior of the glass tubes to definite radii, and were thus able to deliver levels to any degree of sensitiveness desired. It is usual to specify that bubbles should move definite amounts when tilted through definite angles, and the art has arrived at such perfection that to make a bubble which will run 1/20 inch for each 1 second of tilt is not a difficult matter.

A perfect level should have the following characteristics. It should be made of a glass which will not deteriorate with the elapse of time. Its bubble should move equal amounts for equal tilts. It must not be sluggish and it should not show any signs of creeping. The tube should preferably have a barrel-shaped interior. If not, it should be so ground that nearly half its circumference in cross section is circular, as if this is not done, there will be errors of run when it is slightly rotated on its longitudinal axis. As during the mounting and indeed during use on the instrument it sometimes happens that slight displacement from the proper position occurs, it will be seen that attention to this detail is of great importance. Machine ground levels nowadays are often barrel-shaped, and are, therefore, to be preferred to those ground by hand, as by the latter process, it is difficult to ensure that the tubes are truly circular at any cross section. English-made lead glass is a very perfect material for the level makers' purpose, as it does not deteriorate with age, as do soda glass and many of the continental varieties. Lead glass is also brilliant, hard and stable, and is not easily deformed under the influence of variation of temperature or the slight unavoidable strain due to the mounting. If the air space is to move equal amounts for equal angles of tilt, the tube must be ground to a true radius and this can only be ensured by machine grinding. There will of course be a falling off in accuracy at the ends of the run due to the distortion introduced when sealing off, so that all else being equal, the longer the bubble tube the better from the point of view of evenness of run. The sensitivity of the level for run depends on the radius of curvature, and to a slight extent on the character of the ground surface and the material with which it is filled.

The cleanliness of the interior is also of importance as it is evident that any foreign substance on the ground surface which is not miscible with the filling liquid would impair the readings. For example, a slight trace of grease in a tube filled with water would cause the air space to behave in an erratic manner. The purity of the liquid with which the level tube is filled is of the first importance, not only for the above reason, but also to prevent any change taking place in the course of time. During the manufacture of the level, it is not easy to avoid contamination of the ground surface by grease, and it is difficult to remove the last traces of it. A liquid which easily dissolves grease is, it would seem, the most desirable one to employ, and in fact, practical experience has proved this to be the case. The chief liquids used are alcohol, ether, chloroform, benzene and sometimes xylene. For the cheapest levels with bent tubes, such as are fitted to bricklayer's spirit levels, methylated spirit is used, but for surveying levels, the value of the liquid is so small compared with the other costs that it need not be taken into consideration. The most universally used liquid is now petroleum ether, distilled at about 50°C. which, owing to its low surface tension and viscosity, is a very suitable one for the purpose. A well-made level filled with this liquid is about as perfect a piece of apparatus as can well be imagined, except for one defect, which is, unfortunately, common to all liquid filled levels, and that is the effect which change of temperature has on its performance. A rise of temperature will cause the liquid and glass to expand and the air bubble to contract, thus increasing the internal pressure slightly. It is unlikely with the level as usually manufactured, that any alteration in radius or form takes place, so that the only effect which needs to be considered is that which differences in the length of the bubble will have on its performance. In the first place, the variations in the length of the bubble might be so great that the level would fail to be of service. For example, if the length of bubble is made suitable for use at a temperature of 20°C. its use in Polar regions would be impossible, as the bubble might easily be as long as the tube, while under the tropical sun it might almost disappear, so that special arrangements have to be made for these extreme cases. The usual plan is to have a small chamber fastened inside at one end of the main tube. By tilting the level, more or less air can be trapped in this chamber, so that the actual bubble length can be adjusted. The most important effect which the length of the bubble has on its performance is the damping. The longer the bubble the greater the number of times it will oscillate when disturbed from zero before coming to rest, and owing to the greater amount of control it will return more exactly to the zero position. For very exact work, therefore, long bubbles in long tubes are to be preferred, but on the other hand they are very difficult to set and the length of time necessary to adjust an instrument fitted with them becomes excessive. When the bubble becomes so short that its movements are almost dead beat, it is found that it does not always take up the same position, but creeps about in a slow and uncertain manner. The mobility of the bubble is also affected to some extent by the diameter of the containing tube, by the character of the ground surface and by the liquid employed. Manufacturers have found by practical experience the dimensions and qualities which give the best all-round results.

Mr Watts of London has devised an ingenious level which is so constructed that the bubble remains constant in length under varying temperatures. This is arrived at by giving the ground surface an elliptical section instead of the usual circular form, the bubble apparently expanding laterally instead of longitudinally. Everything else being equal, it would be advantageous for ordinary levelling operations to have a bubble which needs to be examined at one end only, but as any rotation of the tube on its longitudinal axis would render the indications unreliable, this form does not fulfil the condition laid down for a perfect level and it is difficult to see how it could be used for precise work.

Value of Level Divisions.—Levels are generally specified by the distance of run given per second of tilt. For example :—

Let R = radius of bubble tube in feet, and

T = distance of travel of bubble in inches for a tilt of one second of arc.

Then $R = 17188 \times T$

For a travel of 1/20th inch per second, the radius will therefore be

$$R = \frac{17188}{20} = 859{\cdot}4 \text{ feet.}$$

For a 5-inch theodolite which might have a bubble run of 1/20th inch per 10 seconds of tilt the radius would therefore be 86 feet.

It is to be noted that very small irregularities in the ground curve may lead to large errors in the readings. This is especially the case with short bubbles and is therefore another indication that long bubbles should be employed where possible. Fig. 37 will serve to show the reason for this clearly. If we imagine the bubble to become very small, when it meets an irregularity of approximately its own size, it will become trapped so that a very great increase of tilt will be necessary to dislodge it. The same degree of irregularity in grinding will obviously have only a very small effect on a long bubble.

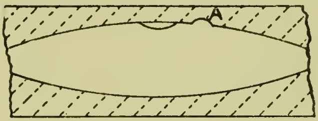


FIG. 37

Method of Mounting Levels.—Levels having small radii of curvature are used on the less important instruments, and no special care need be taken in arranging the mountings for them. They are therefore simply cemented into brass cases with plaster of Paris, which gives a sound fixing good enough for the purpose.

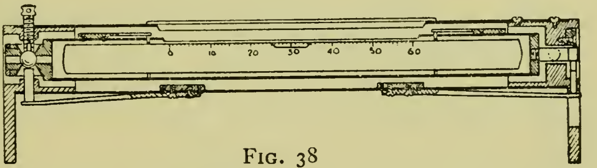


FIG. 38

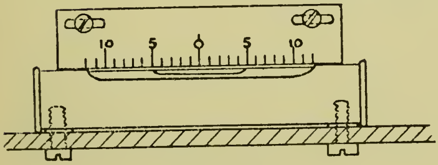


FIG. 39

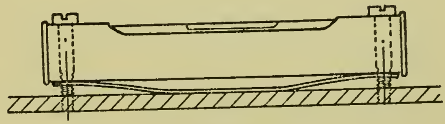


FIG. 40

For the more sensitive levels, it is necessary to design the mounting more carefully in order that no strain may be imposed on the glass tube likely to disturb it in any way either owing to the mounting itself or to temperature changes when it is being used. It is also desirable to protect it from local heating as much as possible, as if one end of the tube is at a higher temperature than the other, the reading will be affected by the difference in the density of the liquid from end to end, and by the change in its surface tension. Convection currents may also possibly tend to render the readings unreliable. The protection from temperature changes is considered sufficiently secured by giving the mounting a reflecting surface either by coating with white paint or by nickelling and by fitting an outer glass covering tube. For extremely exact work, where the accuracy of the bubble is of major importance, it would be possible to fit some form of lagging, but this would only be called for in rare cases. Figs. 38 to 43 show various methods of mounting the tube in its case.

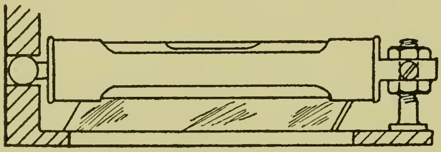


FIG. 41

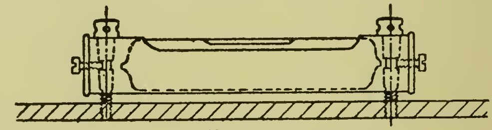


FIG. 42

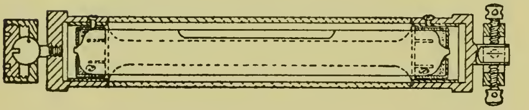


FIG. 43

Level Grinding Machine.—Fig. 44 is taken from a photograph of the machine used by Messrs Casella for the grinding of bubble tubes. In this machine the glass tube is revolved about its longitudinal axis, and a revolving lap is passed through it, thus grinding the inside surface. The linkage motion shown can be set to give the lap a movement of any radius required, thus grinding out the tube to true barrel form in a very exact and simple manner.

Circular Levels.—Circular levels are often used for approximate settings to which purpose they are well adapted, as they give at one glance the direction of dislevelment. Being very compact, they are easily incorporated in most designs and as they are cheap and robust have come into increasing use in recent years. For various reasons they cannot unfortunately take the place of the tubular level when great sensitivity is required. The curve to which the surface is ground can be made accurately to any radius required, and in fact this radius upon which the sensitivity of bubbles depends can be more exactly formed and measured than in the ordinary form of level.

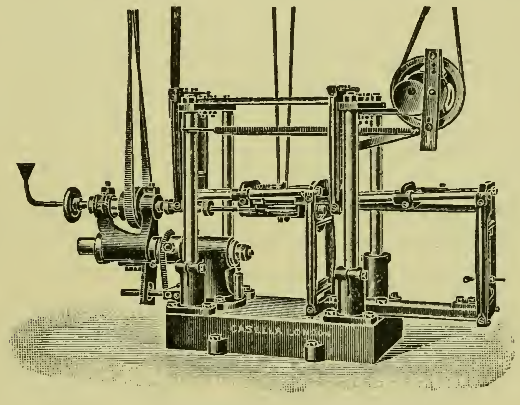


FIG. 44—Level tube grinding machine

It has been shown previously that in order to make the bubble respond quickly and accurately, it must be fairly large, but when we attempt to use a large bubble in a circular level, we find that although it is mobile and sensitive enough it is very difficult to set it to any kind of reference mark. A small bubble can be set moderately well inside a circular mark engraved on the surface or can be brought fairly well within a square. If the bubble is made small enough, it can easily be set centrally in the field of a microscope. The damping, however, becomes so great, and the controlling force so small, due to the small difference of head, that this form of reading is useless for any exact kind of work. The use of circular levels, therefore, in the present state of the art, must be confined to approximate settings. Fig. 45 is a form often used. In this the glass disc is held in its cell by a screwed portion, the joint being made by a lead washer and the filling liquid inserted through the hole in the bottom, which is then sealed by a screw and washer as shown. If the mount is made of steel or any metal having a co-efficient of expansion nearly equal to glass, the results are good, and no likelihood of leakage need be feared. In Fig. 46 the glass disc after being ground to the required radius is fused on to a blown glass cistern the pipe of which is sealed off after the liquid has been inserted. This level is quite free from any danger of leakage, but it is usually found that the sphericity of the ground surface is slightly distorted, thus rendering the readings unreliable. This latter form of level is usually fixed in its brass mount with plaster of Paris.

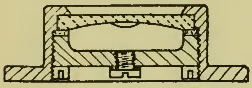


Fig. 45
Circular bubbles

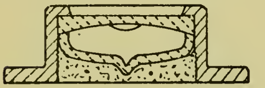


Fig. 46

Methods of Reading the Bubble.—In view of the increasing precision demanded on modern surveys it has become important to improve the accuracy of reading the bubbles and various devices have been evolved to enable this to be done quickly and to a degree of exactitude comparable with the means of setting the telescope. It is necessary in the first place to see that the illumination is sufficient and that the direction from which the light comes is such that errors of parallax are not likely to be introduced. It is essential, therefore, that the illumination be perpendicular to the plane of the bubble, and this is arranged in the simplest manner by transmitting the light through the bubble itself from underneath by means of a reflector or prism. If the bubble can be viewed directly from above a very good setting of its coincidence with the marks can be obtained, but as it is not easy to arrange this on every instrument, various devices have been evolved to bring the image into a suitable position for examination. Fig 47 shows a simple form in which a mirror is pivoted on an axis parallel to the level tube. This gives quite good accuracy of setting so long as the eye is opposite the centre of the bubble. Fig. 48 shows how

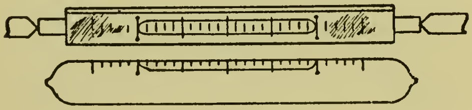


Fig. 47

the mirror must be placed if the bubble is to be read from the end, and Fig. 49 shows the form of mirror employed by Messrs Cooke to bring the two ends of the bubble closer together. For ordinary levelling operations, the mirror gives good enough results, but care must be taken to see that the eye is placed so as to eliminate parallax. The end-on mirror reading is defective also in this respect that, as the two ends are at different distances from the eye it is not easy to evaluate the means of the two readings without considerable practice. Fig 50 shows a method employed on the levels used by the French War Office which obviates some of these difficulties and which, in skilful hands, gives excellent results. Fig. 127 is the method used by the U.S. Coast and Geodetic Survey in their levels and is similar to the French type, but arranged in a more convenient form. Fig. 51 shows what is probably the best design hitherto

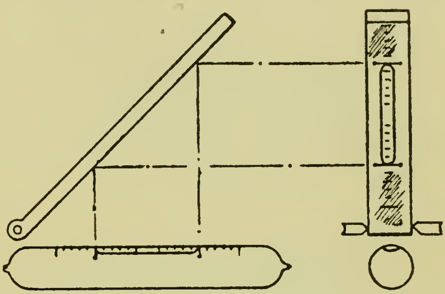


FIG. 48

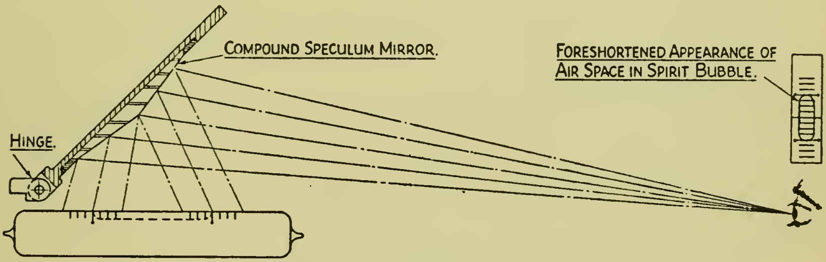


FIG. 49—Cooke's method of reading the level bubble

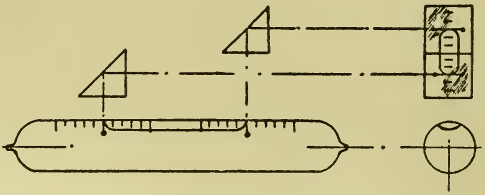


FIG. 50

produced. It is due to H. Wild, and was first placed on the market fifteen years ago by Messrs Zeiss. It would probably have come into universal use for precise work but for the fact that the patentees kept the rights of manufacture in their own hands. It will be seen that the images of sections of the two bubble ends are folded over by means of a pair of prisms and brought into juxtaposition. This image can then be viewed directly or turned to any convenient position for reading by means of a second prism. As the length of the optical path from the eye to each end of the bubble is equal, one of the defects mentioned previously is eliminated. A very exact setting of the coincidence of the bubble ends can be made, this being facilitated by the clean cut shape of the image and by the fact that the apparent movement is doubled in magnitude. There is also this collateral advantage.

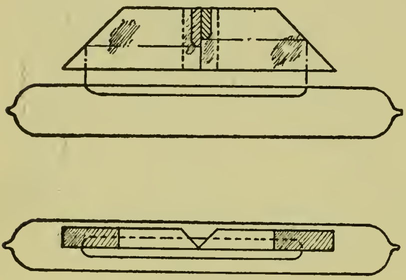


FIG. 51
Prism reading device for bubbles

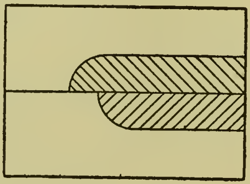


FIG 52—Appearance of the bubble ends as seen in the prism. The images move in opposite directions as the level is tilted

The adjustment of the bubble can be made by moving the whole prism system longitudinally in a similar manner to that shown in Fig. 39 where the equivalent result is obtained by moving the scale. This adjustment requires a much greater translatory movement to give the same effect as a much smaller tilt, and can therefore be done with greater ease. This becomes more important as the sensitivity of the bubble becomes greater, it being, of course, easier to set on to the magnified image of an object than on to the object itself. With this type of reading, a prism may be used to turn the image into any convenient viewing position. A level having this type of bubble reading device is shown in figure 125, page 135.

Level Triers.—Levels are tested in the workshop on an apparatus known as a "level trier," a picture of which is shown in Fig. 53. The micrometer screw which serves to raise the top frame carrying the level is usually arranged so that one revolution equals a tilt of one minute of arc, the seconds of arc being read on the divided head. This apparatus consists of gun-metal frame with two V shaped slides, long enough to take bubbles up to 18 inches (45·7 cm.) in length. This frame rests on a steel point and a knife edge at one end, and on a fine steel screw (100 threads per inch) at the other. To the latter is fitted (friction tight) a gun-metal reading head 4·75 inches (12 cm.) diameter with 100 divisions; the rotation of one division gives a movement of one second of arc. The frame rests on a cast-iron triangular shaped base plate, supported on three points, and has a levelling screw and tightening nut at one end for levelling the bubbles roughly, prior to testing with the fine screw.

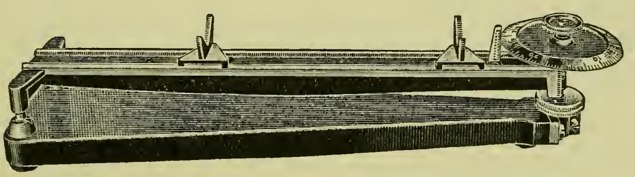


FIG. 53
Level Trier

Radius of Bubbles.—To find the radius of a bubble on this instrument the spacing of the graduations is first measured by means of a travelling microscope. Then the amount of tilt in seconds of arc, required to move the bubble over one division is determined.

Then if R = the radius of the bubble
d = the value of a division in inches
d_1 = the tilt in seconds of arc for one division.

$$R = \frac{d}{d_1 \sin 1''}$$

By testing the level at various points, with different lengths and at varying temperatures its general performance can easily be determined to a high degree of accuracy.

The actual run of the bubble can easily be tested after it is fixed in a theodolite by taking readings on the divided circle or by placing the whole instrument in the level trier, or more accurately, as follows :—

To find the value in the field of the divisions of the level. Set the instrument up to read a staff at say 500 feet from its centre and take a pair of readings, first with the bubble tilted say five divisions from the centre of its run in one direction and then an equivalent amount in the other direction.

Then if T = number of divisions of tilt
D = distance of staff
S = difference of staff readings in feet
R = value in seconds of one division of bubble.

Then $$R = \frac{S}{500 \, \frac{T}{2} \sin 1''}$$

CHAPTER V

THE GRADUATION OF INSTRUMENTS

SINCE the days of the early astronomers, the art of dividing the circle has been practised with ever-increasing success, until to-day it has reached such a state of perfection that it has ceased to be, what it once was, the limiting factor of precision in surveying and astronomical instruments. Owing to the gradually increasing accuracy of the spacing of the divisions during the past 200 years, mechanicians have been compelled to work to closer limits in the mechanical details of their apparatus, and opticians to improve the resolving power of their optical systems in order to keep pace with the progress made. When it is realised that to-day we have instruments which will measure accurately to the millionth of an inch (0·000025 mm.), and that apparatus is in contemplation which will appreciate the 10 millionth of an inch, it will be seen what progress has been made in these arts, chiefly in recent years.

Until about the year 1700, circles were divided by hand methods, of which we have no very exact account. It was not until the time of GRAHAM (circa 1730) that the dividing of circles became of sufficient importance (in relation to the other details of the instruments) to attract the attention of a number of patient workers, in whose hands the art eventually arrived at a considerable degree of perfection. Graham's method, and also that of SISSON, two of the most prominent dividers of their day, consisted in setting the radius of the circle on a pair of beam compasses, and laying out the chords of the arc of 60°, then by continued subdivision they completed the division of the circle to 5 minute spaces. BIRD, who worked for Sisson, and with Graham's assistance set up in business in the Strand, also used beam compasses; but by computing the chords of the arcs he laid down the division 85·20, and then by continual bisection was able to complete his divisions.

Roemer, about this time divided quadrants by the following method; he set a pair of compasses to approximately the smallest space required, and stepped this fixed distance along the whole of his arc. The total length of the arc was disregarded, the number of divisions being converted into degrees, minutes and seconds, by a table calculated specially for each instrument. This mode of dividing was soon found to be unreliable, as owing to the porous nature of the metal, and to the fact that the dots could never be placed exactly on the circumferential line, the errors were too irregular to permit of correction, his table being calculated on the assumption that the whole of the arc was evenly divided.

Hooke, about the same period, invented an endless screw system of dividing; but this, although now the recognised method, was at that time a failure, owing to the fact that sufficiently accurate work in the mechanical details of the apparatus was unattainable.

In the middle of the 18th century, the Duc de Chaulnes made a remarkable improvement, which has turned out to be the foundation of our present-day method of examining, and computing, the errors in divided circles. The procedure was shortly as follows:—

Two microscopes were fixed to read diametrically opposite points on the circle which was to be graduated and these were focused on to two slips of brass, each carrying a finely engraved line and fixed temporarily at the edge of the circle. The circle was then moved through 180°, and the necessary adjustments made to the brass slips and microscopes, until the opposite divisions were again bisected by the spider lines in the microscopes. A cutting frame having been fixed to the stand carrying the circle, it was then only necessary to cut the divisions in their proper positions, under control of the microscopes, and by continual trial of bi- and tri-sections in the whole of the circle, it was possible with sufficient care to fill in the sub-divisions in a most precise manner. Once having obtained an accurate master circle, it was a comparatively simple matter to make copies of it by this method ; and in fact until quite recent years, this was the only means available to most of the continental dividers for the production of circles on astronomical instruments.

Ramsden. In the years round about 1765, Jesse Ramsden, a clever mechanician of London, was dividing circles of a quality notably superior in accuracy and finish to any hitherto produced. His method, however, although capable of giving very excellent results, was too tedious and difficult, except to a man of his outstanding skill, patience and ability. He first divided his circles as precisely as possible by beam compasses. Then, after ascertaining the errors of spacing by means of the microscopes, he corrected them by pressing over the dots, backwards or forwards, by a steel point held in the hand. The demand for circles divided by Ramsden became so great that he set his mind on the problem of turning them out by what we should now term methods of "mass production." The result was the invention and construction of his automatic dividing engine. This wonderful machine functioned so perfectly that the production of accurately divided circles became a matter of comparative ease, and in consequence the strides made in the output of astronomical and surveying instruments at this period were remarkable. The efforts of Ramsden also led to extraordinary improvements in the cutting of wheels for clocks and watches ; and his name, in consequence, stands out as a landmark in the progress of mechanical achievement. It was due largely to his efforts, and to those of his co-workers at this period, that England became pre-eminent in the manufacture of precision apparatus, a position which she has never since relinquished. It may be stated, without fear of contradiction, that in the output of instruments of the first order of accuracy, England to-day holds the premier position of all nations. The circles produced on the dividing engines housed in her workshops are unsurpassed ; and her mechanicians, inspired by the tradition of hundreds of years of successful effort and progress, are to-day turning out apparatus which, in design and accuracy of manufacture, convenience in use, and beauty of finish, take second place to none.

Ramsden's Engine consisted of a wheel of bronze cut on its periphery with 2,160 teeth, into which a steel worm engaged. This was given an intermittent motion by a ratchet and wheel, the cutting of the division taking place while the worm was at rest, the cutter returning, ready to make the next stroke, during the time the toothed wheel, carrying the circle to be graduated, was moving round over the desired interval.

It was soon found that however accurately the teeth of the wheel were cut in the first place, a certain amount of wear took place, and that the resultant dividing showed errors of relatively large magnitude. Constructors then increased the diameter of their circles, and also the number of teeth cut on their periphery; but, although this procedure minimised the errors due to wear, other difficulties soon became apparent. In consequence, Andrew Ross, in 1830, devised a machine on an entirely new principle. The regulation of the motion of his circular plate was the reverse of the endless screw of Ramsden, which acts by driving. In the engine of Ross, the plate, containing 48 adjustable steel abutments on its periphery, was turned by a gut band and weight, and was stopped very precisely at every division by the contact of plane and spherical surfaces of hardened steel. As the circle was under no influence during the time the division was being cut, except that of a constant weight keeping the steel surfaces in contact, very accurate work was capable of being done on this machine. Moreover, as the steel surfaces were fitted with a screw adjustment, it was found that contact could be made to within one quarter of a second of arc, and the whole machine regulated from time to time, in such a way, that work of the very highest accuracy could be guaranteed. The area of contact, upon which the permanence of adjustment depended, was necessarily small, so that constant attention had to be paid to the wear of the steel surfaces, if work of extreme precision was required from the machine.

During the next 50 years, various machines were constructed in Europe and America, nearly all modifications of Ramsden's engine.

Recently designed engines follow the Ramsden principle, but they are constructed with circles of large diameter, the teeth are cut in the first place with the most scrupulous accuracy, and fitted with hardened and ground steel worms, optically finished on the angles of the threads. Such is the precision of the modern tools brought to bear on this work, that the wheel and worm, when lapped together, will function with a maximum error in the intervals of the divisions of less than one second of arc. For the final regulation of the engine, trial divisions are made with the machine in this stage, and tables of errors computed—these tables being used to regulate the compensating apparatus with which all the best modern machines are now fitted. This simple and very efficient device works on a similar principle to that used on measuring machines and the lead screws of precision lathes. The method is as follows.

Round the periphery of the wheel a thin steel plate is fixed, and engaging with its edge is a lever which, when it is raised or lowered, gives a corresponding lead or retardation to the worm. It is then only necessary to cut the edge of this steel plate to the curves shown by the table of errors in order to remove the small residual discrepancies from the teeth. In this way, not only can the machine be regulated to within the probable errors of observation, but also it can be kept up to this standard during the whole of its life.

It is difficult for the mind to realise the meaning of an accuracy of one-tenth of one second of arc, but a numerical example will serve to give some indication of the minute spacing this denotes on say the 5-inch circles of a theodolite. Imagine a circle four miles in diameter, with two straight lines starting at the centre and diverging at an angle of 10 degrees. At the edge of the circle they will be 1,840 feet 8·74 inches apart; increase this divergence by 1/10th second and they will then be 1,840 feet 8·8013 inches apart, a difference of ·0613 inch. This difference would amount on a 5-inch circle to ·0000012 inch.

To put it another way, a line drawn round the equator would come back within ten feet of the starting point.

Dividing machines are generally housed in a specially constructed room kept at a constant temperature. They are arranged in such a way that when the circles to be divided are fixed in place, the driving motor is started, and the cutting proceeds automatically, stopping itself when the last division has been completed.

Dividing Engine

A description of the methods employed on the construction of a dividing engine recently completed in Messrs Casella's works is here given, as it differs somewhat in detail from other published accounts. In the first place, the revolving table, centre, and stand were made and the necessary apparatus for cutting the divisions mounted up in place. On the top surface, near the edge, bands of silver had been inlaid in the usual way, and then a light cut was taken over the top face and the edge, where the teeth were to be formed while the table was revolving on its own centre. Care had to be taken in this and subsequent operations to see that all parts of the table were at an even temperature, and that the foundation upon which the machine was bolted was free from vibration due to adjacent machinery and to heavy vehicles running on the roads in the vicinity. To this end, the important parts of the work were carried out after the usual working hours, and sometimes through the night, careful control being kept of the temperature of the engine room. The next operation was to clamp an accurately divided circle of half degrees (made on another machine, the accuracy of which was known to within two seconds of arc), to the table and to fix four micrometer microscopes to read its 720 divisions. This circle was carefully centered on the table from marks made at the time the dividing was done, the centering being also checked on the divisions themselves. The cutting frame was then mounted over the silver on the main table and adjusted to give a truly radial division. The whole of the 720 divisions were then copied from the divided circle on to the table, under the control of the microscopes, allowance being made at this stage for the inaccuracies known to be in the circle being copied. The microscopes were then fixed over the divisions just made and a thorough examination of the errors was undertaken and tables made of them. This was a most laborious and trying operation, and one which would only be undertaken by a confirmed optimist or one with patience and determination different from that possessed by the ordinary individual. The next step was to engrave the degree numbers on the second silver strip, and to copy the first set of divisions on to it, allowing for the errors as shown in the tables. These new divisions were again examined and tabulated, and the machine prepared for the cutting of the teeth. This was done by clamping the table firmly with each division under the microscope and gradually forming the teeth by the following method. If a single point cutter is placed at the angle of the worm and fed into the edge of the table, a straight tooth will be formed which will not engage truly with the spiral worm but only bear on one or two places. This form of tooth would not be tolerated in a worm gear which was required to run with any approach to accuracy as the effects of wear would soon be evident. It was thought, therefore, that on a machine of this description the work should be at least as good as that carried out in ordinary engineering practice, where worm wheels are now invariably of spiral form. In order to cut the teeth as nearly as possible to the shape dictated by theory, a frame, shown in Fig. 54, was constructed and bolted down in the position which the driving worm was eventually to occupy. The actual worm which was to be used on the machine was made as shown at A and had a hole through its centre in which was fitted the shaft B. This shaft was pierced to take the cutter C which was carefully made and lapped up to such a shape that the tooth cut by it when on the frame exactly fitted the thread of the worm.

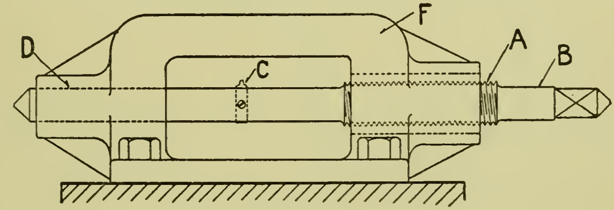


FIG. 54

The worm itself was hardened, ground, lapped and polished, and fitted to a split bronze nut which was fixed into the frame F. The other end of the spindle was fitted into a bronze bush in

F, so that when the shaft B was turned, the cutter was translated tangentially to the table at the required rate. If now the table is clamped and the cutter fed across its edge, teeth will be cut of the exact pitch required to gear with the worm, and if the cutter is of correct shape, they will be of correct form also, the whole operation being just the reverse of that which will take place when the worm is held and the table is being driven by it. As the worm used in this frame was the one which was to be finally employed to drive the table, it was then only necessary to set it by measurement tangentially to the table and the correct distance from the centre, thus (Fig. 55).

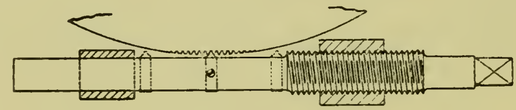


FIG. 55

The cutter was then set to take a slight cut along the face marking about three tooth spaces at the first pass and then gradually screwed farther out until finally the centre tooth was nearly of the correct depth, all the other teeth on each side of the centre being of course gradually shallower. Each division was then brought in turn under the microscope, the table clamped and the corresponding tooth cut until finally all the teeth were brought to nearly the correct depth. The cutter was now replaced by a narrow one with straight sides and the bottom of the teeth relieved thus (Fig. 56).

FIG. 56

Finally the original cutter, after having been carefully dressed, was again fitted and fed out to give a tooth of the correct depth and the whole operation repeated. By this method, not only are the teeth of the correct form, but they are all of the same depth. The worm was now mounted on its proper spindle and after fitting up the driving gear the table was revolved for a few days in order to remove any rugosities which might possibly have remained on the teeth. An examination of the teeth and the worm having shown perfect contact all round the circle, a new set of divisions were cut using the worm and teeth, and these were compared with the other set of divisions which had been tabulated. In order to test the actual working of the machine and the accuracy of the revolution of the axis before proceeding further, another set of divisions was made at a distance of a few seconds of arc from those last cut, as it was thought that an inspection of these would show at once whether the machine could be relied upon to reproduce the teeth correctly. No difference in the amount of light shown between the two sets of divisions could be detected, so that the machine was judged to be perfect in this respect, it having been found previously that the actual thickness of the lines could be considered constant within the means provided to measure them. These three sets of divisions were placed thus (Fig. 57)

Fig. 57

and as they could all be seen in the field of the microscope at one time, it was easy to compare the errors of the divisions made by the machine and those of the original dividing. In spite of the extreme care taken in cutting the teeth, it was found that

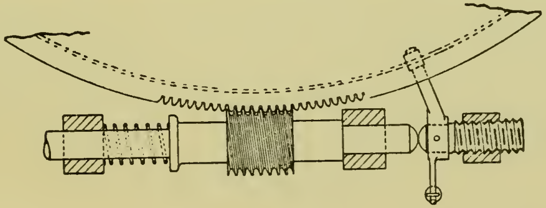


Fig. 58

at a few places differences of 0·3 second were recorded and it was thought possible to remove these residual errors by the method of compensation used on precision lathes. Figs. 58 and 59 show the form employed. This gear was made at the time the machine was built, the lever and screw being so

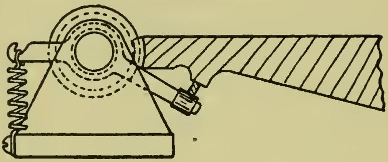


FIG. 59

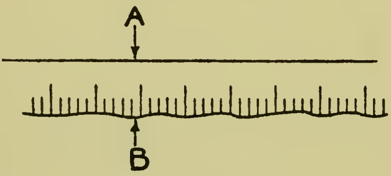


FIG. 60

arranged that a rise or fall of 10 mm. should advance or retard the table by one second of arc. The edge which was to receive the calibration curve was made from a hoop of carbon steel screwed to a spigot underneath the table and was divided into 720 parts and numbered at each degree for identification purposes. A list was then prepared from the table of errors, showing the amounts to be removed from the edge of the calibration strip so that it was a simple matter to cut a curve to these figures after its removal from the machine. The measurements were taken across A.B. (Fig. 60), the back edge of the hoop being used as the datum line. A test of the machine now showed that the errors had been reduced to about half those previously found, and by adjusting the curve no doubt most of the residual errors could be eliminated. As, however, the machine was to be used for commercial work, and was therefore designed to work automatically, it was decided to make a thorough test of its functioning under the actual conditions of use. To this end, a number of sets of graduations were divided at slightly different radii and at speeds varying from 2 to 20 strokes per minute. The divisions on one set were so placed nearly to touch those of the next set, thus (Fig. 61) so that any differences in spacing could be seen by simple inspection under the microscope. Tests all round the circle

FIG. 61

showed that at speeds of from 10 to 12 strokes per minute the super-imposed accidental errors of spacing were at a maximum as much as ± 0·15 second. These errors are due to a number of causes, the most important of which are probably as follows:

(1) Temperature variation of the circle and frame.

(2) Change in position, (probably due to differences of temperature) of the bridge carrying the cutting frame.

(3) Differences in the thickness of the oil film on the main axis of rotation.

(4) The variation of the oil film between the worm and worm wheel.

(5) Inaccurate indexing of the worm.

(6) Rise and fall of the centre spindle due to a fault in the main abutment.

(7) Slackness in the links of the cutting frame.

With regard to the elimination of these faults, Nos. 1 and 2 could be reduced by greater elaboration of the temperature control and by enclosing the whole machine in a specially designed chamber in order to neutralise the effect of the presence of the operator.

Nos. 3 and 4 would seem to present insuperable difficulties. No. 6 is not likely to be important, and as for No. 7, the links are already as perfect as it is possible to make them. Nos. 2 and 5 are considered to be the most important sources of accidental error, and as the remedy for No. 2 has been indicated the reasons for No. 5 may be discussed. By inaccurate indexing is meant the angular errors in the rotation of the worm at each stroke. It must be remembered that the motion is an intermittent one and that it is difficult to stop and start any piece of mechanism in an exact manner, this difficulty increasing with its weight and speed. As any error in the spacing of the driving ratchet or other device employed would for most of the ordinary divisions of the circle merely introduce a periodic error, it need not be considered under this heading, as errors of this description are due to quite definite causes which can be eliminated much more easily than the nebulous accidental errors. The reason for the production of angular error in the rotation of the worm is not easy to discover when the machine is working at speeds up to 10 strokes per minute. When, however, the speed is increased it is at once evident that the major portion of the error is caused by the over-running of the worm. When the driving ratchet is stopped, the worm, owing to its inertia, tends to continue its rotation, and the amount of this rotation will depend on the stopping friction. This friction is exerted at the abutment, in the journal bearings and on the surface of contact between the worm and the wheel. These are all variable, the most important, and unfortunately the most difficult to control, being the last. If the resistance to revolution of the worm is increased by adding a brake to its spindle, the machine can be run at greater speed, or its angular errors reduced, but this addition introduces its own errors and it is seen that after a time the worm tends to turn in a series of jerks. If the driving pawl is stopped just when the worm is turning freely, the worm will over-run, while if the stopping takes place at a hard spot, it will lag behind its true position. Some form of magnetic damping would seem to offer a solution and it is probable that something of this kind will need to be devised if the accuracy of automatic dividing is to be equal to that which can be done by turning the machine by hand. Several other methods of intermittent drive have been tried on other machines but they all suffer from the same defect. For quick acting machines used in coarse dividing, the Geneva stop motion similar to that used in kinematograph machines gives very good results when the parts are well made and fitted, but there are too many points where backlash can occur to allow this method to be used for the finest work.

Materials for Divided Circles

For theodolite circles silver is the metal most universally employed, and on the whole is satisfactory, but for the fact that it tarnishes rather easily. A new silver alloy has recently been discovered which is not so liable to tarnish, and promises to be an improvement on the usual alloy of silver and copper, known as coin, silver hitherto used. Platinum is, of course, the best metal, but its increase in price in recent years has prohibited its use except in exceptional circumstances. Owing to the soft nature of silver, and to the fact that it is not capable of being polished to any high degree of flatness, it is not possible to divide lines on it much thinner than 10 to 12 μ, so that when finer lines are required, it is necessary to divide on some harder material. Speculum metal, glass and rustless steel in the hardened state can be brought to a very high optical polish, and lines 2 to 3 μ thick can be produced sharp and black without any difficulty. On the softer metals, the cutting point skates over the high spots on the imperfectly polished surface and leaves a ragged line which, when an attempt is made to get it down to about 5 μ thick looks, under high magnification, like a series of dots and any accurate setting becomes impossible. Extremely fine and clear lines can be produced on a film of aniline dye floated on a glass surface, but they are hardly permanent enough for any but exceptional cases. Rheinburg has suggested that small circles might be made by photographic means, and provided that no distortion is introduced, by the lens, or in the subsequent processes, this method looks attractive and promising. There are many advantages in keeping the circles small if the necessary accuracy of reading can be maintained, and the only disadvantage they are likely to have is that their centering would be difficult to effect and to control. The accuracy of rotation of the centres upon which the circles are carried would have to be of a much higher order than can be produced in the present state of the art. At the moment, it seems that a circle of 10 inches diameter gives the necessary ease of reading and all the accuracy which can be expected from the other parts of the apparatus and the means of producing them.

Verniers

Various designs of the mounting of verniers have been produced, a number of which are shown in Figs. 62, 63, 64 and 65.

The most satisfactory from the point of view of permanence is the edge to edge form, as in Fig. 62. It is, however, not always easy to arrange this type in a convenient manner for reading.

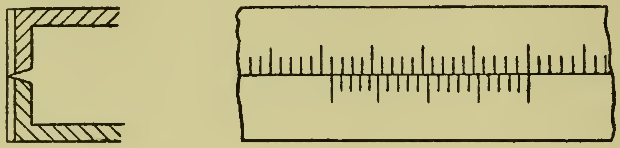


Fig. 62—Edge-reading vernier

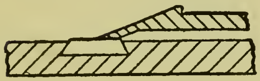


Fig. 63—Bevelled vernier

This feather edge form gives good results when new, but is very fragile, and grit getting under the edge soon impairs the sharpness of contact upon which the accuracy depends. Makers like this type because it can be adjusted so easily for length, as to make this adjustment it is only necessary to place it further away from or nearer to the centre. It is difficult to avoid a bell-mouthed appearance at the ends of the lines in this pattern.

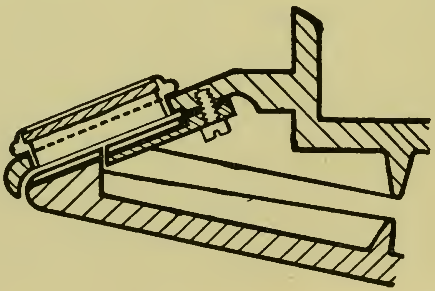


Fig. 64—Edge to edge vernier reading placed at an angle of 22°

This is the kind of vernier employed on most continental and many English theodolites for the horizontal circle. It is not so satisfactory as Fig. 62, but gives a convenient reading position for the eye.

This type shown in Fig. 65 is almost universal on American instruments. It gives very good results, but the reading position is not very convenient. It has the advantage that it is possible to look along the lines, thus allowing a very accurate setting to be made. When, however, the divisions are required to be fine, it is not possible to use this form, as it is then necessary to use a powerful magnifier which cannot be focused to read in this way. The direction from which the light falls on the divisions has an important bearing on the accuracy of the reading, especially in badly-fitting verniers where errors of parallax are added to those which are introduced when the illumination is from one side. These defects are most noticeable when the verniers are divided to read to 10 or 15 seconds, as they often are in comparatively small instruments. If a number of not very experienced students are asked to read a 10 second vernier, it will be found that their results vary more than 30 seconds from the true value; on the other hand, if a similar test is made on an instrument reading to 30 seconds, they will, on the average, be able to estimate the true position to within ± 15 seconds and with a little practice to ± 10 seconds in much less time than when using a vernier divided direct to 10 seconds. This is especially noticeable in the reading of sextant verniers which are generally divided for a least count of 10 seconds, but which, owing to the effect of the mirrors, is only equal to 5 seconds on an ordinary circle of equal radius.

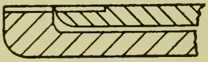


FIG. 65—Flat vernier

Method of Inlaying Silver

When a silver strip on which the graduations are to be made is to be inlaid the gun-metal circle is first roughly turned and an undercut groove formed on its surface thus :—

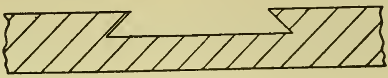


FIG. 65a

The strip of silver cut to the correct width and length is then drawn through a die which shaves off the edges and forms the strip up to the exact shape of the undercut groove prepared to receive it. It is then passed through a pair of rollers which give it the shape shown

FIG. 65b

thus allowing it to be laid in the undercut groove in this way :—

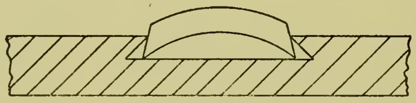


FIG. 65c

The silver is now carefully flattened out by a small hammer and planished down until it is level with the surface of the gun-metal circle, after which the whole of the face is carefully turned in a dead centre lathe.

The silver surface, after being turned in a dead centre lathe, is stoned down with "water of Ayr" stone and then divided and figured. It is then brought down to a fine dead matt surface by rubbing it with a piece of willow charcoal moistened in water. This treatment gives a sharp edge to the divisions and leaves the surface more or less flat. It should not be cleaned off with plate powder or polishing paste of any kind, as the use of material of this sort leaves the surface glossy and in time creates a hollow spot at each division, so that the accuracy of reading is much reduced. Various methods of figuring the verniers are in use at the present time, some inverse reading, some with centre reading and those known as folding verniers. The most popular, however, at present, is the straightforward figuring shown in Fig. 66. This is the easiest to read and is less likely to lead to errors in booking the figures than any other kind in use. It is of some advantage to have the figures leaning in the direction of the numbering of the circle divisions, as in the example shown of a 30′ circle with vernier reading to 1 minute. This type of vernier, which is known as the direct reading, is divided into a number of parts, each of which is shorter by a certain amount than a division of the circle. For example, 30 divisions on the vernier may be equal in length to 29 on the circle, so that starting from the zero of the vernier as each line is brought into coincidence with the next one in advance, the reading has increased by 1/30th of the main division value. Some practice is required to read verniers quickly and accurately, and mistakes are often made, even by experienced surveyors, especially when they have not been taking actual observations for some time. The mistake mostly made is not in finding the actual number of minutes or seconds but in the booking of the degree figure. This is due to reading the degrees opposite one of the sub-divisions instead of from the actual zero mark. This zero, which is of course the zero of the instrument, is generally marked with an arrow and is usually the first division of the vernier. It is placed there merely because it is the custom to do so, but it is obvious that it can equally well be placed at any other division, or it may, in fact, be beyond the vernier altogether, as shown in Fig. 67. If made in this way, the main reading is taken opposite the arrow and a quite separate observation is made of the vernier divisions. In many ways, this, when the

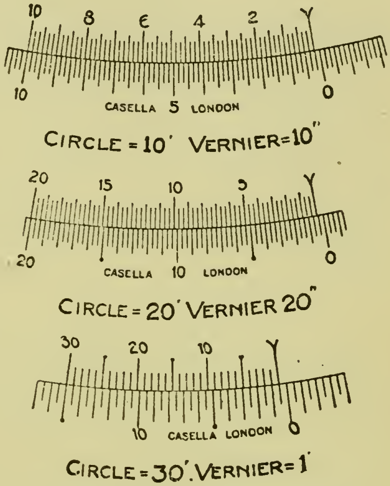


FIG. 66—Examples of Verniers

The three figures above illustrate three of the most popular forms of vernier

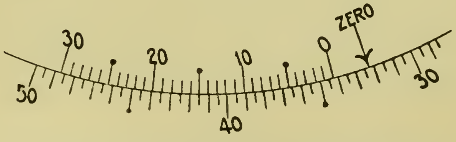


FIG. 67—Vernier with outside zero

observer gets used to it, is very convenient and simple, and once he has been accustomed to reading and booking in this way, he is not liable to make mistakes. On the other hand, the presence of two zeros in the field is confusing, and an observer not accustomed to a vernier of this sort, would probably use the zero of the vernier as the zero of the instrument. Sometimes the centre division of the vernier is used as the zero and certain advantages are claimed for this position. It is, however, largely a matter of taste, and surveyors generally choose the form they have been taught to read during their training. There is no doubt that the reading of verniers accurately and quickly is a serious stumbling block to many, so that any design which would simplify the matter would be welcomed.

Some continental theodolite makers have introduced instruments the reading of which is done by a micrometer head attached to a worm which engages with teeth cut all round the circle. This arrangement gives a very simple and clear reading, but has the great disadvantage that it is subject to wear. Moreover, to give the same accuracy as a vernier, the teeth on the circle must be as truly placed as are those of the engine used for dividing the circle. This is of course commercially impossible, and is a point often forgotten by designers of instruments when they suggest the worm and wheel or the micrometer screw as an alternative to the divided circle.

Once the circle is truly divided and placed on the instrument, the graduations themselves are not subject to any wear which would render them inaccurate ; they therefore remain always a true reproduction of the engine upon which they were made. For this reason, we must look to new methods of reading the circle for improvements in accuracy. The present tendency lies in the direction of optical micrometers, the details of which have been discussed in another chapter.

Method of Calculating the Vernier Values

It is usual to arrange the vernier so that its length is divided into one more space than an equal length on the limb.

If $n =$ the spaces on the vernier
$n - 1 =$ the spaces on the limb
$a =$ the value of the limb divisions
$a_1 =$ the value of the vernier divisions.

Then $na = (n - 1)\, a$

And $a_1 = \frac{n - 1}{n}\, a$

And $a - a_1 = \frac{1}{n}\, a$

Thus if the vernier is divided into 60 parts and the limb to single degrees

$$\frac{1}{n}\, a = \frac{60}{60} = 1 = (60 - 59)$$

the expression $a - a_1$ is therefore the least count of the vernier and in that case is equal to 1 minute or in other words 1/60th of a degree.

To make a reading it is therefore only necessary to note first at which space the zero falls and then to look along the vernier and note which line on the vernier coincides with that on the limb. Let it coincide at p divisions from the zero, then the fraction of a limb space, viz., $a - a_1 \times p$ will be the value of the reading which must be added to the amount read opposite the zero of the vernier. For example, if the zero of the vernier was at 52° plus an amount x, and if the 15th line of the vernier coincided with a line on the limb, then the reading required would be $52^\circ. + x$.

and $x = (a - a_1)\, p = 15'$

or $x = \frac{p}{n}\, a = \frac{15}{60} \times 60 = 15'$

The reading would therefore be $52^\circ \cdot 15'$.

When it is required to construct a vernier for a given least count, then to find n, the number of spaces into which the vernier must be divided,

$$n = \frac{a}{a - a_1}$$

If, for example, a limb is divided into 5 minute spaces = 300 seconds and a least count of 5 seconds is required, then

$$n = \frac{300}{5} = 60$$

and the number of spaces on the limb covered by the vernier will be $n - 1 = 59$.

The verniers should be examined at various positions on the limb when, if all is correct, the first and last divisions of the vernier will coincide with the limb divisions. If, however, coincidence occurs short of or beyond the last division by an amount equal to $\pm\, y$ divisions the vernier is too long or too short by $y\,(a - a_1)$. Call this amount z,

$$\text{then} \quad (n - 1)\,a = na_1 + z$$

$$\text{and} \quad a - a_1 = \frac{1}{n}\,a + \frac{z}{n}$$

On a correct vernier the value of the reading $x = (a - a_1)\,p$

$$\text{becomes} \quad \frac{p}{n}\,a + \left(p\frac{z}{n}\right)$$

When the vernier is too short by the amount z the correction to the reading is $+\,p\dfrac{z}{n}$

and when it is too long by z is $-\,p\dfrac{z}{n}$

For example, take a limb which is divided into 10 minute spaces and having a vernier with a least count of 10 seconds. Then the number of divisions on the vernier will be 60 covering 59 on the limb. If it is found that the vernier is too short by $z = 5$ seconds then an addition to every reading of the amount

$$+\,p\,\frac{z}{n}$$

must be made. If $p = 24$ that is, if coincidence takes place at the 24th division of the vernier, then

$$24 \times \frac{5}{60} = \frac{120}{60} = 2 \text{ seconds.}$$

In other words in the above case every minute read on the vernier must be increased by ·5 second or every second by $\dfrac{\cdot 5}{60}$ second.

CHAPTER VI

THE TRANSIT THEODOLITE

THE transit theodolite is the king of surveying instruments and deservedly so, as it is from the user's point of view the most useful weapon at his command, and, moreover, is so easily adjusted and tested without auxiliary apparatus that its accuracy can always be relied upon. It may be termed a self-checking instrument and differs in this respect from most other industrial pieces of apparatus such as thermometers, weights, measures or sextants, all of which require to be checked periodically against standards of their own class if their readings are to be relied upon. The theodolite, on the other hand, contains within itself the means of checking and adjusting all its parts, and if in actual use any fault develops, it is generally shown up at once, so that the matter can be adjusted and no fear need be entertained of accumulating a mass of inaccurate data as would happen in the case of such an instrument as a thermometer or measure of length which had become incorrect.

Theodolites are made in various sizes, designated by the diameter of the graduated circles, these sizes ranging from 3 inches up to 12 inches, the latter being the largest now used for general surveying work. Tacheometers are merely theodolites, the telescopes of which are adapted for the measurement of distances as well as for the more ordinary purpose of laying out or measuring angles in altitude and azimuth, so that no special description need be made here as the only difference consists in the optical work of the telescope, mention of which has been made in a previous chapter. Tacheometers are, however, often divided centesimally instead of sexagesimally in order to simplify the subsequent calculations. The main feature of the transit theodolite is that it contains a telescope which can not only be turned through any angle in a horizontal plane, but can also be rotated through any angle in a vertical plane. The spindles upon which the instrument turns are known as the horizontal and vertical axes. Writers of textbooks generally refer to the axis upon which the horizontal circle turns as the vertical axis because it normally stands in a vertical position. Surveyors and instrument makers call this the **horizontal axis,** and the axis about which the telescope turns, and to which the vertical circle is fixed, the **vertical axis.** This is obviously the most correct nomenclature for these parts, and in order to avoid confusion when describing the instrument the horizontal axes are to be understood as those upon which the whole upper part turns in azimuth, and the vertical axis as that upon which the telescope revolves. The horizontal axis is mostly a double one, that upon which the alidade and plate turns being called the **inner centre** while that upon which the circle is fixed is known as the **outer centre.** The **socket** is the portion in or on which these axes turn. The **plate** is the horizontal table to which the verniers and the standard which carries the telescope is fixed and the divided circle is often referred to as the **limb.** As the ultimate accuracy of the theodolite depends on the perfection with which these centres or axes are designed and made, a description of the various forms existing at present is given herewith.

Horizontal Axis. Fig. 68 shows the usual type of axis fitted to theodolites up to 6 inches. The inner axis is made of phosphor bronze or bell metal and the outer axis and socket of gun-metal. These centres are first roughed out in an ordinary lathe or automatic and then very carefully finished on a dead centre lathe. The female portions are bored out and then finished with a taper reamer to exactly the same angle as the centres. After being allowed some time to season they are ground together with oil stone dust and then lapped up by hand until a perfect fit is secured. In recent years the perfection to which modern tools can be made allows these centres to be so machined that they can be fitted together perfectly without the use of any abrasive. This is an obvious advantage, as there is thus no fear of minute pieces of abrasive being left in the pores of the metal. Great skill is required in the manufacture of these axes and only workmen of exceptional ability are employed on this part of the construction.

With this type of construction nearly the whole of the weight is taken on the faces which must of course run true with the taper part, the taper merely acting as a steadying guide. If too much weight is carried by the taper part the turning motion will be stiff and liable to bind, on the other hand, unless the taper part fits its socket a certain amount of play would be introduced which would of course render the instrument useless for its purpose. It is in getting these points fitted to a nicety that so much skill is required, and manufacturers find that only about one man in a hundred is capable of being taught to perform this work satisfactorily. It is important also that the inner and outer surfaces of the outer axis carrying the limb be concentric, and to insure this, this part is turned on a truly ground arbour on the dead centre lathe in a very exact manner before the final finishing. When a compass is not required to be used with the theodolite the centres can be made of hardened steel. The use of this material renders the work much easier of accomplishment, as owing to the perfection of modern grinding

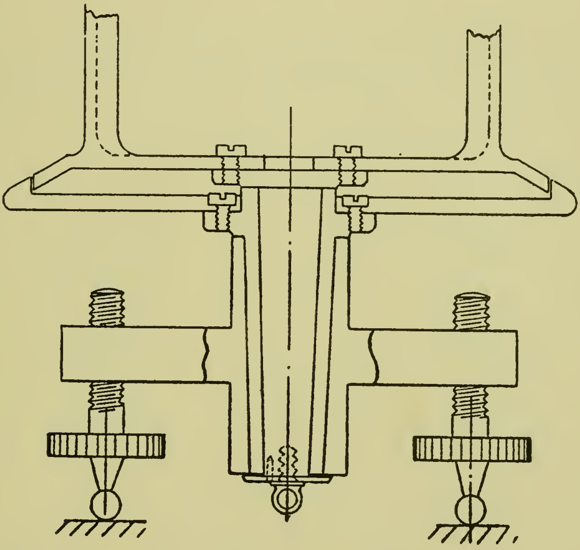


FIG. 68—Double taper axes

machines hardened steel can be formed and finished to a high degree of perfection. The steel can of course be polished to a much finer degree than any of the softer metals, and the fear of any wear taking place, even after many years of use, is negligible. With the design shown in Fig. 68 the whole of the pressure due to the weight of the upper part and the circle is carried between the outer centre and the socket. In large instruments, or indeed in those of 6 inches diameter where accurate setting is required this is objectionable as it is difficult to make the instrument wheel sweetly and the tangent screws are found to propel the circles in a series of jerks. The instrument also is liable to the defect known as "flexure," the cause of which is as follows :—When the centres are hard to move the first thing which happens when the tangent screw is turned in the direction to push the circle away from the clamp is the bending of this clamp. Then the circle starts to move following the motion of the screw, but as soon as the screwing ceases any slight vibration or in fact the act of removing the fingers from the tangent screw will cause the clamp to take up the normal position from which it was bent, thus pushing the circle a little further round. For ordinary theodolites reading to 20 or 30 seconds, this defect is not important, but with micrometer reading instruments, it must be avoided if accurate setting is expected. There are other similar defects due to the tangent screws and clamps themselves, but these will be dealt with later. In order to minimise this defect of flexure in the clamps it is obviously important in the first place to keep the weight of the moving parts as small as possible, and to this end the larger instruments are constructed where possible of aluminium or other light alloys, and even the circles themselves are often made in this metal with of course a band of silver inlaid in the usual way to take the dividing.

Independent Axes. For large instruments and the better class of smaller ones, the centres are constructed as shown in Fig. 69. This construction has the advantage that the weight of the limb is carried independently, thus allowing the lower tangent screw to be made to work as lightly as the upper one. It is true that the lower screw is not of so much importance as the upper one, as in modern work it is only used to alter the position of the circle, and not for the repetition of the reading, which was the method supposed to lead to increased accuracy in days gone by. In this figure it will also be seen that the end of the inner axis rests on a ball and spring. This spring can be adjusted vertically and is arranged to take about three-quarters of the weight of the whole of the upper part. This allows the alidade to move freely, and in consequence to follow the motion of the tangent screw exactly and smoothly. Sometimes in place of the spring an adjustable screw takes the weight directly. On large instruments this method seems to act very well, but most careful attention to the adjustment is required in order that there may be no possibility of the lifting of the centre from its face.

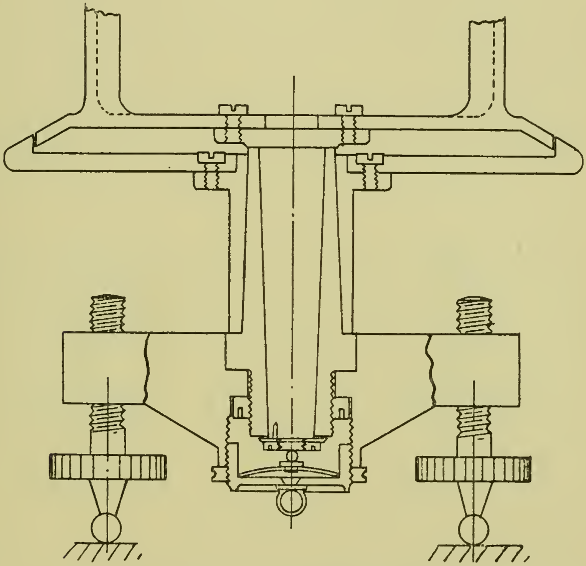


FIG. 69—Independent axis

Parallel Axes.—Another form of centre is shown in Fig. 70. In this it will be noticed that the axis is parallel in form instead of the usual taper. For instruments of small size, when the centres are made of steel, this type would appear to be satisfactory. It has the advantage that any rise and fall will not cause additional slackness, and it is of course much easier and cheaper to make, as it is capable of being produced by machinery in mass quantities. It has also the advantage, that there is no fear of want of concentricity between the outer and inner centres. Its main defects, however, are that it is not possible to ensure the necessary quality of fit between the parts, that the actual working surfaces are short, and that the inner axis is insufficiently supported in the tripod. Another type of centre sometimes employed in German instruments consists of a double cone, the

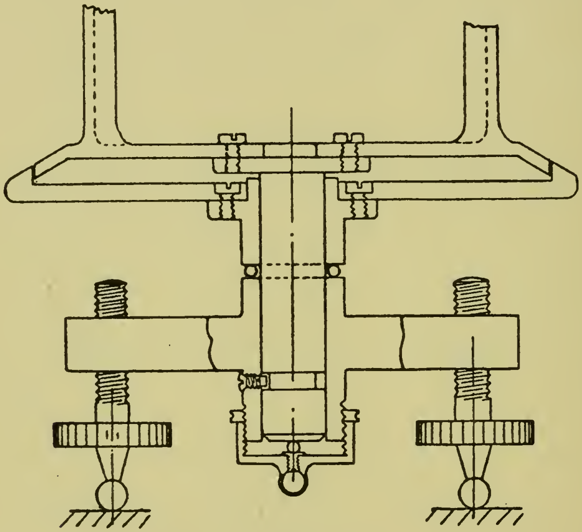


Fig. 70—Parallel axis

upper one to guide the axis and the lower one made flatter to take the weight. It is difficult to see how these two cones can work other than independently.

In certain instruments, e.g., those with eccentric telescopes, the upper part carries the hollow axis while the solid cone is fixed to the base. This construction gives long centres and enables the centre of gravity of the whole instrument to be kept very low.

It will be noticed that the limb on each of the examples shown is screwed to its axis and not made part of it. The reason for this is that it is impossible to place the circle when it is being graduated exactly in the centre of rotation of the dividing engine. The consequence is that when the limb is mounted upon its own centre and revolved, a slight amount of eccentricity is present. This is adjusted by scraping out the hole and bedding the limb down truly central with its own axis. This operation is carried out when the theodolite is finished, as it can then be easily tested and adjusted by its own verniers or micrometers in the exact position in which it has to remain. Centering error is not generally of great importance and it is difficult to eliminate it entirely, but instrument makers like to make it as small as possible, being usually content if it is equal to about half the amount which can be read by the verniers. As surveyors, save in exceptional cases, take the mean of opposite readings, the true value is not affected by any error of eccentricity. In the case of a sextant, however, eccentric error is all important and great pains must be taken to ensure the correctness and permanence of the setting of the limb on its axis.

On the end of the axis a small hook is fixed. This has a fine hole drilled vertically through it to take the plumb line, which thus hangs truly in line with the axis. It should be noticed that this is the only correct position for the plumb bob. If it is hung from the stand, as it is in many continental instruments, it will not indicate the true centre unless the top of the stand is also level. In town surveys and tunnelling work, the correct centering of the instrument is of great importance, and care should be taken to see that the hole from which the plumb bob is suspended revolves truly when the instrument is wheeled. This can be done on the type shown in Fig. 68 while the instrument is on its stand. In the examples shown in Figs. 69 and 70 it is necessary when testing for this, to turn the instrument upside down and to revolve the tribrach.

Vertical Axis.—When the horizontal axis has been adjusted to verticality by the foot screws it is necessary that the vertical axis be horizontal, and many instruments, especially those of larger size, are fitted with an adjustable part for the purpose of rendering it so. For small instruments reading to 30 seconds the maker can fit this axis permanently in its correct position, so that it need never be adjusted, and for practical purposes this construction has many advantages, the chief of which is that the whole instrument can be packed in its case in one piece, thus making a much more compact box and lessening the liability to accidental damage. The bearings can thus be made more secure and properly bedded down into the uprights. When, however, surveyors wish to take face left and right readings, it is necessary to make the axis so that it may be lifted out of the standards, and this constant removal each time the two readings are taken, and each time the instrument is packed away in its box, leads to wear, thus necessitating some form of adjustment for horizontality. Fig. 71 shows a usual method of effecting this. The standard is split on one side and pushing and pulling screws fitted as shown. By moving these screws, one side of the axis can be raised or lowered. In order to allow this to be done without putting a strain on the axis the actual bearing surfaces are made slightly segmental as shown. This means that the area of contact is extremely small so that in a very short time the axis starts to wear into a groove. The constant removal of the axis also tends to make a series of flats on the bearing, which soon impairs its accuracy. This wear is shown much exaggerated in Fig. 72, and the effect of using the adjustment screws is shown in Fig. 73. It is obvious that this adjustment

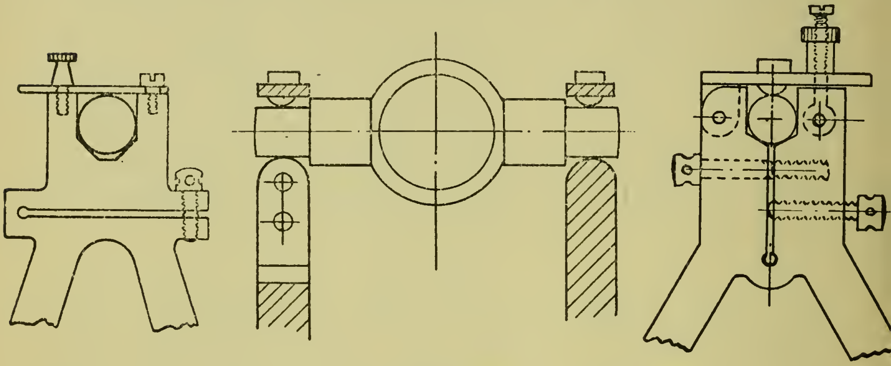


FIG. 71

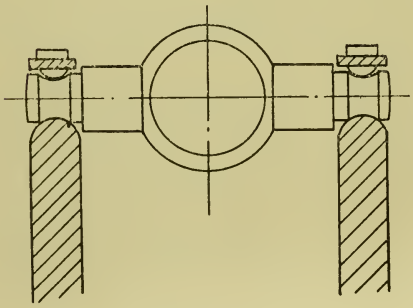


FIG. 72

is a very crude one, and one which should not be tolerated in instruments with any pretensions to accuracy. Sometimes an adjustment is fitted to those instruments in which the telescope is not removable. This is generally arranged as shown in Fig. 74, and Fig. 75 shows the effect which the adjustment has on the axis. Fig. 76 shows a design due to Messrs Casella which obviates these difficulties. In this example the axis is carried in two sockets which do not revolve in the standards. The axis is made taper and the bearing is long and not liable to become worn by the ingress of dirt and grit, and moreover, any adjustment for horizontality does not affect the actual bearing. The area of the wearing surfaces is in this design many times greater than in the old instruments which in most cases merely relied on point contacts, thus necessitating constant attention, and adjustment of this vital part. The horizontal circles of theodolites

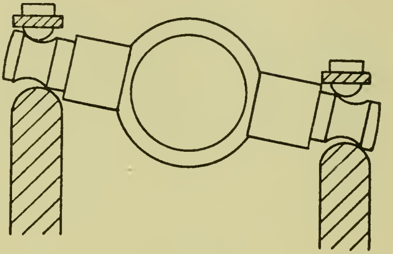


Fig. 73

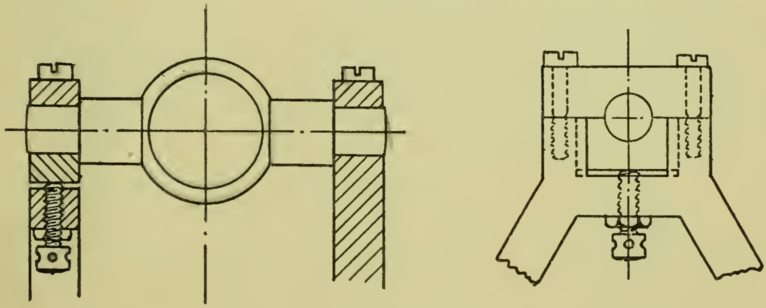


Fig. 74

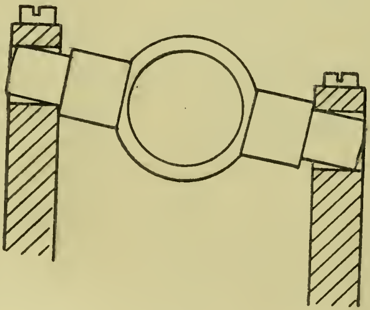


Fig. 75

have usually been generously designed in this respect, but the vertical circles, the readings of which are in many cases of more importance, have always suffered from a lack of stability and wearing qualities, not only in the actual axis bearings but also in the socket fitting of the vernier arm, the mechanical arrangement of which necessitated the cutting down of the bearing to, in most cases, less than half-inch. This figure also shows the method employed by this firm to adjust the focus of the telescope. The axis, as will clearly be seen, is pierced and carries a milled head and pinion which engages with a rack in the telescope tube. The milled head is therefore always in a convenient, and the same, position for use, no matter at what angle the telescope is tilted.

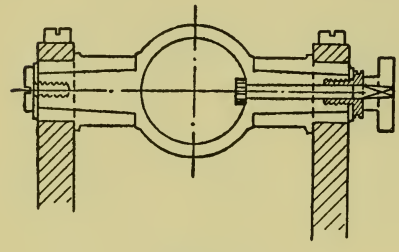


FIG. 76

Foot Screws.—Fig 77 is the usual form of foot screw. It is tapped directly into the tripod which is split at this point and fitted with a capstan headed screw for adjustment purposes. The ball end is fitted into a drilled hole, an adjustment screw being also fixed in the base. Owing to the fact that all screw threads are exposed, a good deal of wear takes place with this form and also, although it is easy to drill the three holes in the tripod accurately in line and truly spaced, it is not a simple matter to insure that the tapping is as exact. The result is that with this type a little binding takes place at certain points. Figs. 78, 79 and 80 show methods of adjustment by split taper bushes in which the tripod is not tapped. These bushes can be made weather and dust proof thus prolonging the life of the screw threads. They can also be easily replaced in case of wear or damage having taken place.

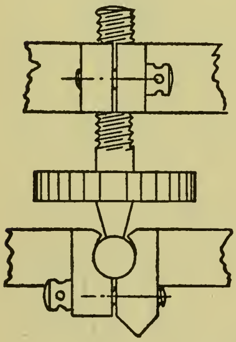


FIG. 77

The screw and its bush is made from drawn phosphor bronze or German silver and cut with a V thread of about 40 to the inch, this pitch being found to give sufficient sensitivity to the levelling. In large instruments, the foot screws are often placed in the reversed position as shown in Fig. 191, with the milled head above the tripod instead of below. This allows the centre of gravity of the instrument to be kept lower, and as the distance from the point of the screw upon which the instrument rests to the screwed bush in which it is held is much shorter, any slackness in the thread will not disturb the setting to the same extent. This arrangement is not used on the smaller sized instruments owing to the fact that it is not so compact and not quite so convenient to use. Many other forms of levelling devices have appeared from time to time, and for light simple survey instruments, such as compasses and builder's levels, a ball and socket arrangement gives quite good enough results. For accurate work, however, the three-screw design holds the field and so long as these screws are kept in good order they are, on the whole, very satisfactory. On many American instruments and in most of those used in Australia, four screws are employed, and many surveyors assert that that system is the most satisfactory for general use. The four-screw system has the great merit of being very compact, and those who employ it claim that the levelling can be done much more quickly. It is also claimed that wear on the screws does not affect the stability of the instrument, as they can be jammed tight between the base and quadripod no matter how slack the threads may be,

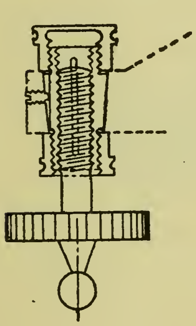


FIG. 78

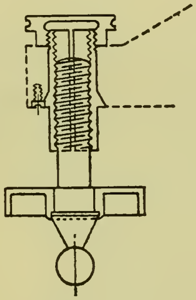


FIG. 79

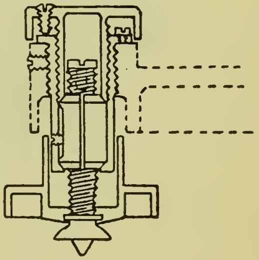


FIG. 80

and should they become bent they can still be used, whereas with three screws a bent screw makes it impossible to effect the levelling. Its chief disadvantage is that it is possible to distort the main socket of the centres by tightening the screws up too much, and numbers of instruments are damaged in this way every year. It is mainly a question of the system the surveyor has been accustomed to, and as a certain demand for four-screw instruments still exists, manufacturers are compelled to supply both kinds. **Two-screw Base.**—Figure 81 shows a small builder's level, in which only two screws are employed for the levelling. The centre of the tripod is continued down and a ball formed on its end; the whole instrument rests on this point and on two screws which are placed at right angles to each other from the centre. If the telescope is placed over and levelled by each of the two foot screws in turn, it will then be truly level in every direction, thus bringing the setting down to the simplicity of operation claimed for the 4-screw system.

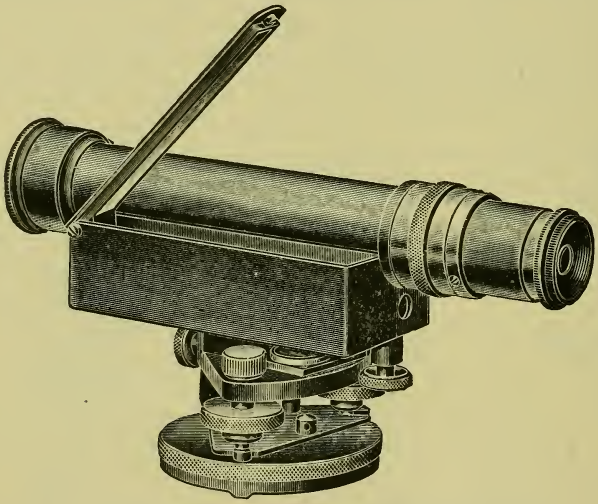


FIG. 81—Two-screw simple builders' level

Locking Plate.—The locking plate is the part used to fix the instrument to its stand, and many designs have been produced all having some advantages and disadvantages. Sometimes the locking plate is incorporated in a centering head, thus enabling the instrument to be centered exactly over any given point. Fig. 82 shows a form in fairly general use and

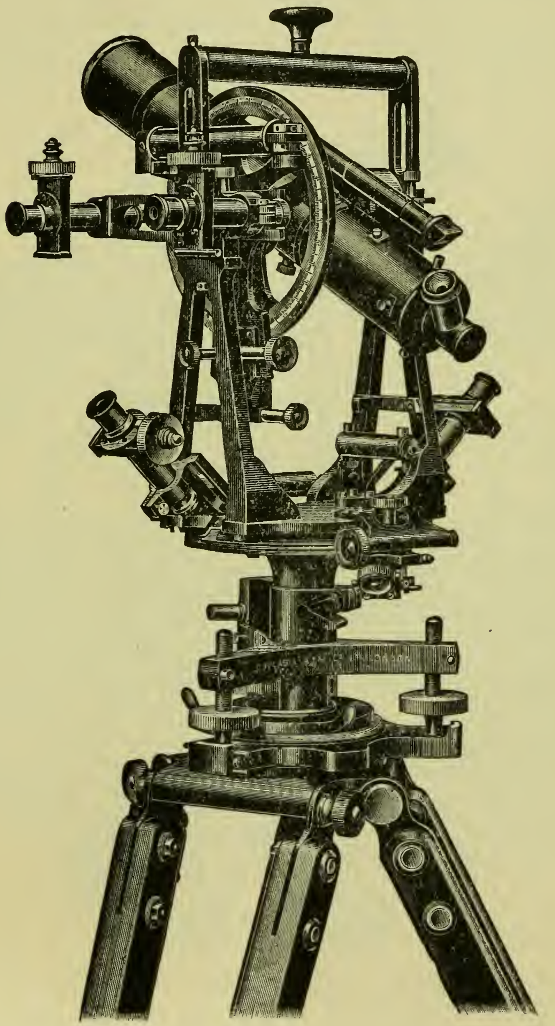


FIG. 82

Fig. 83 shows the same design but incorporating a centering head. The bottom part is made from a gun-metal casting and has a thin top plate which can revolve in an undercut groove.

This top plate has three keyhole slots which, when it is turned slightly sideways, release the ball feet so that the instrument can be removed from its stand. This form of plate is not very satisfactory, as it is easily bent, and when it is only very slightly worn the balls become loose and have no means of adjustment.

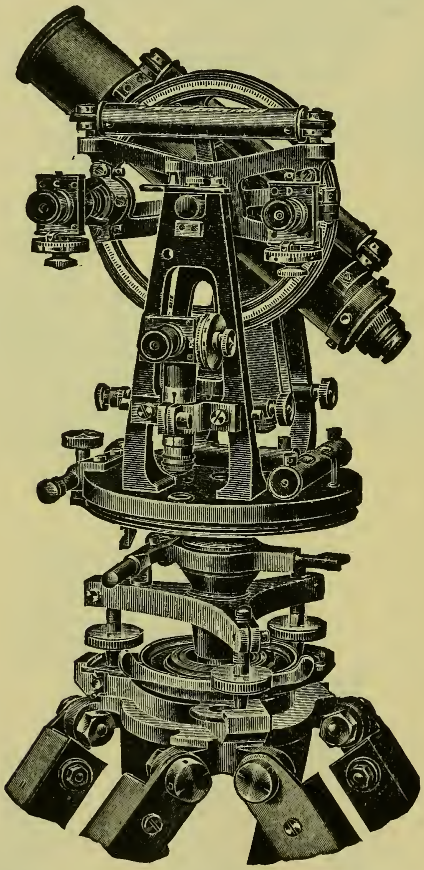


FIG. 83—6-inch Micrometer Theodolite

There is also this disadvantage, when the instrument is lifted out of its locking plate the three screws are exposed and unsupported, with the result that they are often bent. This is a most serious defect, as when bent it is impossible to use these screws for levelling, and the only way the work can be continued until the necessary repairs are effected is to level up the instrument by pushing the legs into the ground. This is, of course, most unsatisfactory. In Fig. 77 the ball ends of the screws are fixed permanently into the base, in which position they are much more securely held and cannot easily be damaged. The friction on the ball can also be adjusted to a nicety with this system, which accounts for its popularity. When, however, a centering device is required, a sub-base of some kind must be fitted, or the top of the stand must be arranged in such a way that it can be moved relatively to the legs. As both of these systems add a considerable amount of undesirable weight to be transported, the design shown in Fig. 84 has been evolved, which is a great improvement on those in former use. In this system the ball

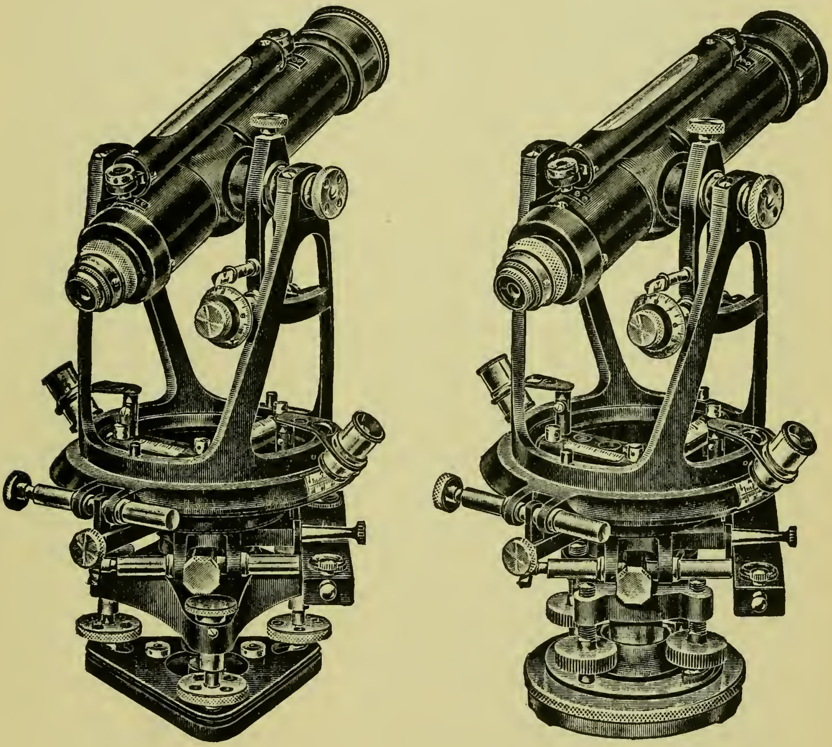


Fig. 84 Fig. 85

Railway Transit Theodolite, 3 and 4 levelling screws feet are held down on to a base having hole, slot and plane seats prepared to receive them. Between the two plates a triangular piece of metal, having a screwed hole in its centre, can slide about. The top of the stand, which has a large hole in its centre, is quite plain, so that the whole instrument can be placed on it in any position desired. A threaded tubular piece is then passed through the hole in the stand and screwed into the socket of the triangular plate, thus tightening the instrument down securely on to its stand. If this screw is slackened slightly, the whole instrument can slide in any direction over the top of the stand, and can thus be accurately centered over the mark on the ground. With this system, the screws can be adjusted for smoothness of working and to take up wear, and as they sit in a geometrical seat are free from any possible binding. There is also the incidental advantage that it is much easier to place the instrument directly on the stand and then fix it with the central screw, than to hold up the whole instrument and screw it on to the stand by revolving the lower part. The fact that the stand has merely a hole instead of an exposed screw thread is of manifest advantage. In practice the protecting cap for the stand head screw is often lost, with the result that this thread becomes damaged to such an extent that it is impossible to screw the base of the instrument on to it. As a rule, the stands are treated much more roughly than the instruments themselves, so that it is of advantage to keep them as simple as possible, and to arrange that all the working parts, such as the centering device, etc., should be part of the instrument itself, so that it can be packed away in the case where it is less liable to accidental damage.

Clamps and Tangent Screws.—In order to obtain the slow motion necessary for the fine settings required in theodolites, some form of clamp and tangent screw must be used, and many designs for these have appeared from time to time. In the older forms, it was usual to arrange that a pair of flat plates could be clamped by a screw on to the edge of the circle, this clamp being moved by a screw of fine pitch anchored to some fixed part of the instrument. This design had many unsatisfactory features, and is only now used in exceptional circumstances. In all modern designs the clamping takes place on the centres themselves or on concentric rings fixed to the circles.

Great care must be taken in the manufacture of the clamps, and a considerable amount of skill is required with certain designs to get smooth working. Unless the fitting is good, the act of clamping disturbs the setting of the instrument, and it is sometimes found that repeated clamping and unclamping will move the circle round a portion of a degree at each operation. Fig. 86 shows two forms of central clamps which were very popular some years ago, but which are not often fitted now. They suffered from the defect mentioned to a marked extent, which is probably the cause of their dropping out of favour. It is obviously impossible to determine just where the clamp will grip the centre and which side of the split portion will move first, so that the clamping and unclamping had the same effect on the circle as would be given by a fine toothed ratchet. Fig. 87 is the design now employed on modern instruments. This is known as a die clamp and when well-made gives excellent results. The small square or sometimes semi-circular die is fitted very carefully into the body of the clamp and soldered there before machining out the hole, so that the face is of the

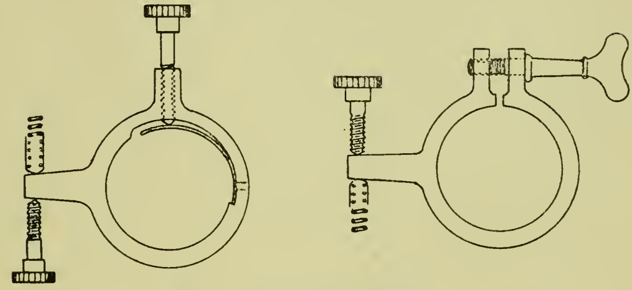


Fig. 86—Spring clamps

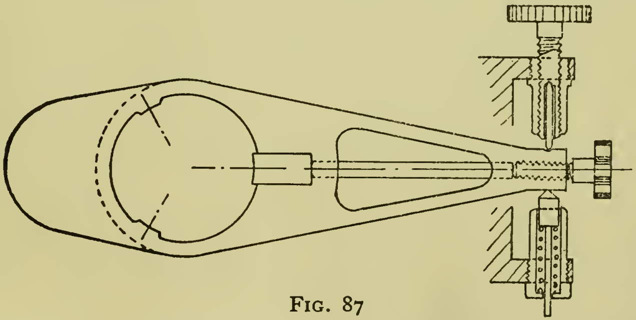


Fig. 87

same radius as the part upon which it is to clamp. It is then unsoldered and fitted to move out and in without any perceptible shake. If it does not engage with the centre truly, or if it has any side shake, not only will it fail to clamp the parts effectually together, but the act of clamping will cause the circle to move progressively. The first defect is fatal to good results, and the second annoying to the user unless he is working by the repetition method when, of course, the readings would be valueless. These defects are therefore to be avoided, and can only be minimised by accuracy in the workmanship. Another defect found in many clamps is shown up as an alteration of the reading when the clamping screw is tightened. This is due to the fact that the end of the clamp arm, where it engages with the tangent screw, is held fast between the point of the screw and its opposing spring. The tangent screw bracket is fixed to the part carrying the vernier so that when the die is tightened up it tends to push the centre to one side. If the bracket happens to be in line with the vernier no error is noticed, but when it is at right angles to it, the movement is at once seen. Again, if the point of the tangent screw does not revolve truly concentric with the screw thread itself, the turning of this screw will cause the circle to move with a periodic error. This is a serious defect and is especially noticeable in the vertical circle, as an inaccurate screw can lift the pivot off its bearing owing to the very slight control on this part in the orthodox design. A simple test for this condition is to open up the axis clips and set the central web on to a plumb line. When the tangent screw is rotated, it will be found that the intersection of the web wanders from side to side of the plumb line. A method of overcoming this defect is shown in Fig. 88 which illustrates a form of clamp arm used on large instruments. It will be seen from this illustration that the arm is hinged in such a way that the portion gripped between the tangent screw and its spring plunger may move either vertically or horizontally. There is thus no possibility of any lifting or cramping of the axis to which a clamp of this kind is fixed.

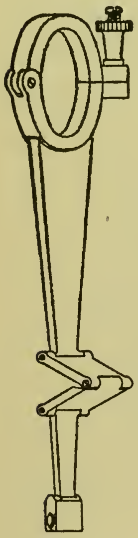


FIG. 88
Floating clamping arm

Floating Tangent Screw. In figure 87 it will be noticed that the screw is drilled up for about half its length and a small strut piece, pointed at both ends, and somewhat smaller in diameter than the hole, is inserted. The outer point of the strut fits into a conical hole in the clamping arm, thus keeping it in position. The spring plunger in the other side is made smaller than the hole in the spring box, so that it too can float. This form of tangent has then no control on the position of the clamp, and cannot therefore draw the circle out of its central position. It is well to see that the clamp is balanced about its centre and to insure this, a counterweight is sometimes cast on the side opposite to the screw as shown in Fig. 87. A better plan when it can be arranged is to bring the clamping screw out on the side opposite to the tangent screw. Fig. 89 is the end view of a form of clamp often employed. This is the same clamp as in Fig. 87, but the tangent screw, instead of bearing directly on the clamp casting, engages with a tail piece standing upwards or downwards at right angles to the main body. This is not a good design, as it introduces the fault known as flexure previously mentioned, and the tangent screw propels the circle in a series of jerks instead of smoothly, as it is obvious that its tendency is to bend or turn the clamp on a horizontal axis. Various forms of clamps employing conical friction members or split expanding sleeves have been employed, but as they have not come into general use they need not be illustrated here.

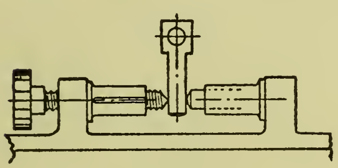


FIG. 89

Tripod Stands.—The stands used to support surveying apparatus vary according to the class of instruments with which they are to be used, and to the relative amount of stability required. Generally speaking, tripod stands of a portable nature are not satisfactory when an instrument such as an 8 in. theodolite has to be supported in such a way that the best results may be obtained. For such measurements, it is necessary either to build up a brick or concrete pier, or a heavy braced tripod made of timber, which can be firmly spiked or sunk into the ground.

On the other hand, a prismatic compass or small builder's level can be carried quite efficiently on a light folding stand of wood or metal, such as is used for a photographic camera. For a 5 or 6 in. theodolite, including those fitted with micrometer microscopes, the portable stand is quite efficient, provided it is so designed that it may be set up and rigidly clamped, and that the parts are sufficiently massive, to prevent any tendency to torsion when in use. Fig. 93 shows a good type of stand head which can be efficiently tightened up by means of a spanner. In this example it will be noticed that the metal head carries 6 lugs, which are well spread, thus giving great stability and freedom from twisting. The ends of the wooden legs are surrounded on three sides by metal channel pieces, so that there is not any liability of splitting, as there is in the pattern where the wood is bolted direct to the metal head, or where a tongue of metal is merely inserted in a slot in the wood and held there by means of screws. Figs. 91 and 107 show a very good pattern, in which the wooden legs are held in a metal casting at the upper end. This casting is bored at the top to receive a cylindrical metal pin, the ends of which are held in split bearings formed in the stand head. These bearings may be tightened up on the pins, thus rendering the joint stiff and free from shake. The lower ends of the legs are bolted securely into metal shoes (Fig. 92) with projecting spurs, so arranged that they may be pressed firmly into the ground with the foot. This stand is very efficient and rigid, and has this incidental advantage. The wooden parts are straight rectangular pieces of mahogany, so that in case of damage any semi-skilled person can easily replace a broken piece, it being only necessary to drill a few holes in the lath and bolt it into place, no forming

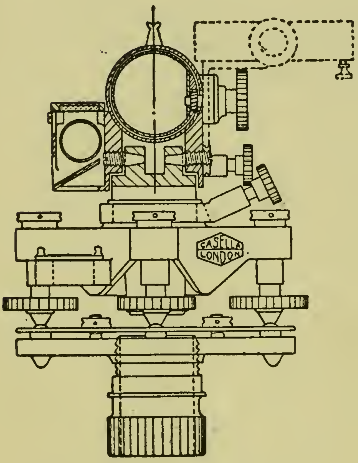


Fig. 90—End view of level

up or gluing being required. Fig. 198 shows a type of stand which is made of round mahogany rods hinged at the points, an expanding screw at the top of each leg serving to force the metal tops of the legs on to pins tapped into the stand head.

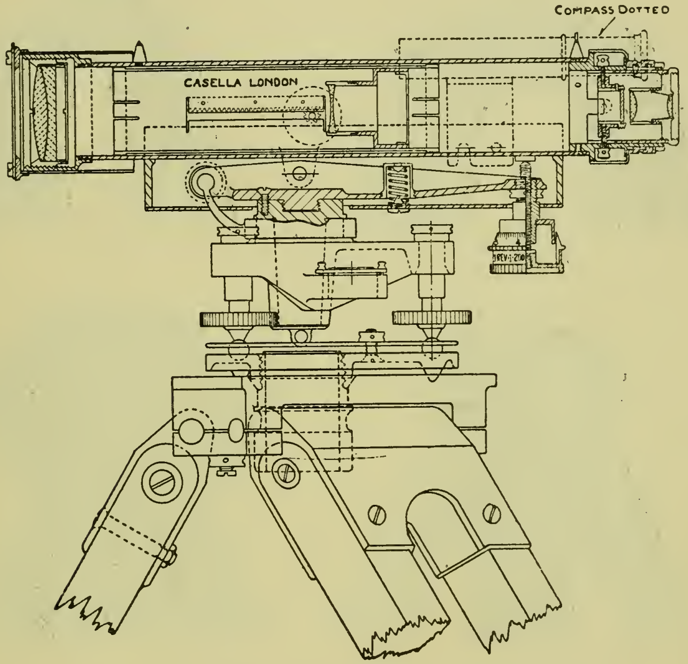


FIG. 91—Tilting dumpy level on framed stand

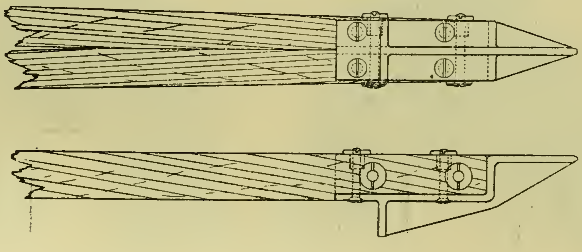


FIG. 92

This type of stand is portable and stable but takes rather longer o set up.

Fig. 96 shows a type of stand so arranged that all three legs may be tightened up by means of a single screw. This is carried out as follows. The cross bar at the top of each leg has spherical ends. These bed into hollow ended plungers which are carried

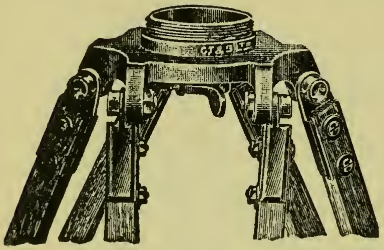


Fig. 93

Fig. 94

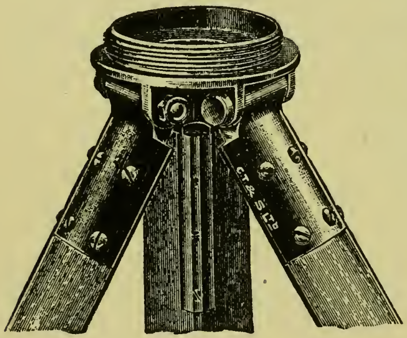


Fig. 95

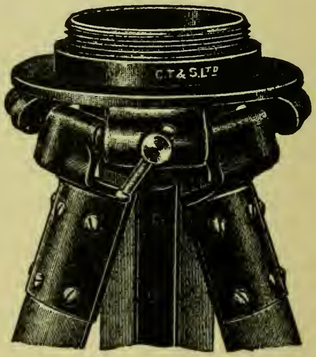


Fig. 96

Various forms of tripod heads

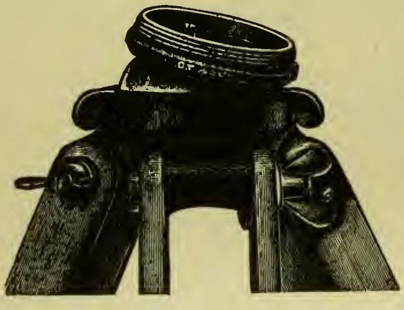


Fig. 97

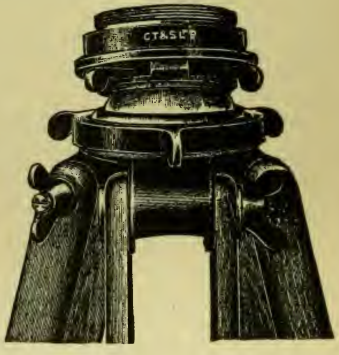


Fig. 98

in the metal head. One of these plungers is split in the centre so that when a pointed screw, shown on the front of the head, is screwed up, these plungers are forced apart, thus pushing their hollow ends tightly against the spherical heads on the legs. This is a very convenient style of stand, its main defect being that the wearing surfaces are so small that constant adjustment is necessary. Fig. 176 shows a folding stand extensively used for plane table work. These stands, when well made, are fairly stable and sufficiently good for such work as exploring, etc., where portability is of primary importance. As there are so many joints to work loose, and as there is no efficient means of taking up wear, this type cannot be used for first class work.

The stand head is sometimes fitted with a ball and socket device for quickly levelling the instrument, an example of which is shown in Fig. 97, while Fig. 98 shows a similar stand but with a sliding top for centering the theodolite. These ball and socket arrangements are very useful when it is necessary to set up the instrument on uneven ground or on the side of a hill. When much work is being done in precipitous country, surveyors often carry stands with one or more legs made to slide. These stands cannot be made quite so rigid as the more straightforward variety and should only be used in cases of necessity. The old style of round stand, Fig. 95, is now seldom made. It is not very rigid and is rather heavier than those of the framed kind. Another defect of that type of stand is that the spread of the lug which fastens the wood to the head cannot be made very wide, thus reducing the resistance to torsion.

Gradienter Screw

Figs. 84 and 85 show a 5 in. theodolite to the telescope of which is fitted a micrometer for measuring distances or determining grades, known as a gradienter screw. This device is much used in America and in the hands of careful operators is capable of giving good results. It is merely an ordinary tangent screw fitted with a large head divided into 50 parts and an index divided to read the number of turns and parts of a turn taken. The pitch of the screw and its distance from the axis is so arranged that the cross hair of the telescope moves over 1/100th foot space on a staff placed 100 feet distant from the centre of the instrument when the screw is moved over one division on the head. One complete revolution of the screw will therefore move the web over 0·5 foot in 100 feet. To set a grade for railway or drainage purposes it is only necessary, after levelling up carefully and setting the head to zero, to set the required grade up or down by turning the screw through the correct number of divisions. Any point cut by the line of collimation will then be on the grade required. It is only necessary to find the number of divisions which the web moves over the staff when the screw is turned through one or more revolutions to determine at once the distance. For example, if two revolutions of the screw moved the cross line over 2·326 feet on the staff, the distance would be 232·6 feet from the staff to the centre of the instrument. A pole with a target at each end, say 10 feet apart, is often used instead of a staff, as longer ranges can be taken by this means. The distance is therefore

$$\frac{\text{length of target}}{\frac{1}{2}\,(\text{revolutions})} \times 100$$

When the staff or target is at a different level from the instrument the readings will require to be reduced to horizontal distance, and tables may be obtained for this purpose. The same principle may also be applied to the horizontal circle ; in this case the target is, of course, supported horizontally. In either case, it is necessary to see that the staff or target is presented correctly to the instrument, and for this purpose a small telescope is sometimes fitted to the target, to enable the operator to set it at right angles to the line of collimation. For a vertically held staff it is usual to set it correct by a plumb bob or spirit level, but some operators prefer to have it held at right angles to the line of view. When working on slopes and holding the staff vertical the line of sight will be inclined to the staff so that if D = the distance and d = the intercept of the staff for one turn of the screw and a = the angle to the bottom reading from the horizontal, then for this line $D = d\,(100 \cos a - \sin a)$ and the horizontal distance between the instrument and the staff $= d\,(100 \cos^2 a - \frac{1}{2} \sin^2 a)$.

When using fixed targets the spacing of which is d if v =

the number of turns of the screw required to move the web from one target to the other then

$$D = \frac{100}{v} d$$

and the horizontal distance =

$$d \frac{100 \cos^2 \alpha}{v}$$

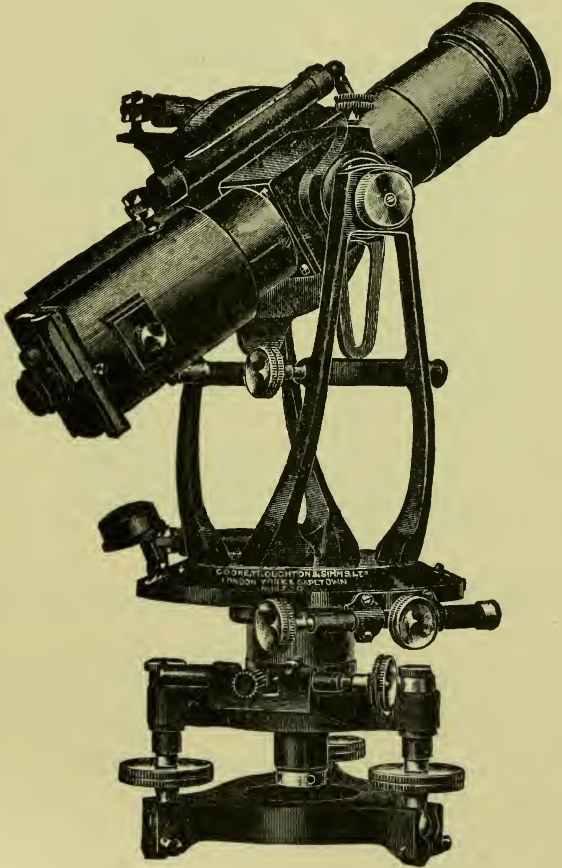


FIG. 101—Jeffcott's patent direct-reading tacheometer

In this instrument a pair of cams and levers move the webs as the telescope is tilted in altitude, thus simplifying the necessary calculations when working on inclined sights. For a full description see Professor Jeffcott's paper in vol. XLI. " Reports of Civil Engineers of Ireland."

The main disadvantage of the gradienter screw is that the instrument has to be handled between the two readings. This sometimes leads to errors which, unless the observations are repeated, are not easily discovered. For this reason, probably, the more direct stadia method is gaining in popularity for distance measurements, although it is not of course so convenient for laying out or finding gradients. As the methods of stadia measurement have been treated in many text books, no further mention of this system need be made, except to state that the old objection to the filming of the glass surface upon which the lines are ruled, is no longer valid, as in all modern instruments the diaphragm in its cell can be instantly removed from the telescope for cleaning purposes, and replaced without any fear of disturbing the line of collimation. The subtense bar method of measuring distance is much used by military engineers. In this system a bar about 10 feet long, having targets at each end, is supported horizontally, and its intercept measured either by repetition on the horizontal circle of a theodolite or by means of a micrometer in the eyepiece of the telescope, and where a large amount of this kind of work has to be carried out, special instruments are used. These instruments are made with very powerful telescopes as low as possible in centre of gravity, as great stability is desirable.

Casella's

Double Reading Micrometer Theodolite

This instrument has recently been designed for use by geodetic and exploration parties, where accuracy and speed of working is desired. One of the most serious faults in micrometer instruments hitherto produced, has been the delicacy of the mounting of the microscopes, and their consequent liability to damage or derangement, and although, as pointed out in a previous chapter, many improvements have been made to these details, still most designs leave much to be desired. The greatest drawback to the micrometer instrument is the number of times it has to be handled after the telescope has been set on the object, as it is necessary to read the four micrometers and to walk all round the instrument at each setting. As these operations have very often to be carried out in the dark, the danger of damage, or at least of putting the instrument out of adjustment, is a very real one. Also the length of time spent in taking a set of readings in these days of highly paid engineers, greatly increases the cost of a survey by micrometer theodolite.

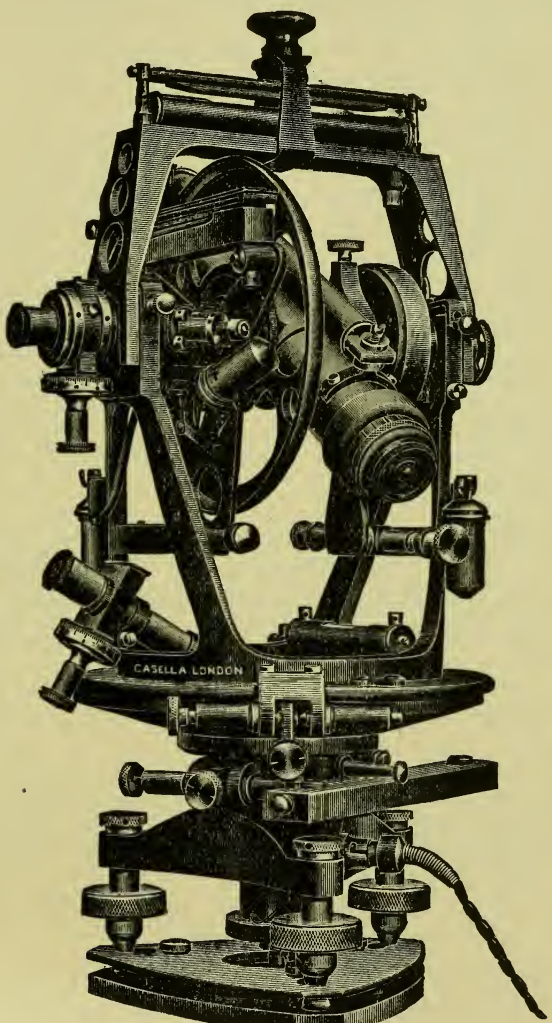


Fig. 102—Casella's patent double-reading micrometer theodolite

so that any improvement which will enable the speed of working to be accelerated, should be earnestly sought after. It is necessary in all theodolite settings to take the mean of each side of the circle, and if this can be done on one micrometer a considerable amount of time is saved and the possibility of errors creeping into the results is much reduced.

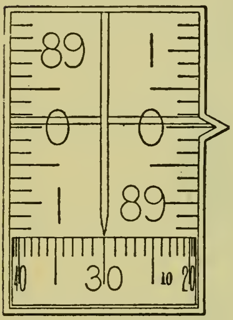


FIG. 103—Enlarged view of field

In this micrometer the diametrical points of the dividing have been brought into one field, together with the drum of the micrometer as shown in Fig. 103. It is therefore possible to take the mean of the opposite sides of the circle at one glance, and as the micrometer for the vertical circle, which is treated in a similar manner, is conveniently placed, all the four readings and also those of the bubbles, can be taken without the necessity of moving from the front of the instrument.

This improvement is noteworthy when it is realised that it has been effected by an actual reduction of the number of parts employed and that these parts are more robust and are so incorporated in the body

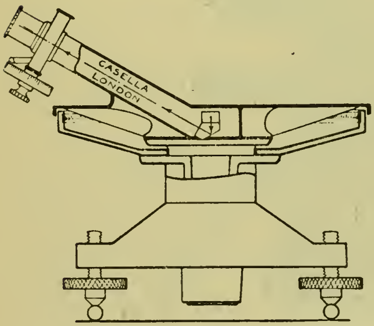


FIG. 104—Section through horizontal circle at A

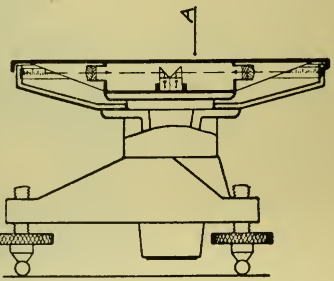


FIG. 105—Section through horizontal circle

of the instrument that it is impossible to put them out of adjustment in ordinary use. There is also incorporated as part of the design, and not as an extra attachment, a complete lighting installation for use at night. This is so arranged that the wire from the battery is attached by a plug to a stationary part of the instrument (viz., the tripod) and the current being carried up through the axis of the circle, there is no possibility of the wires getting entangled while the various settings in altitude and azimuth are being made.

Switches are fitted to each set of lamps, so that those not required may be cut out at will, and a variable resistance is provided for altering the intensity of the light so as to get the most suitable illumination.

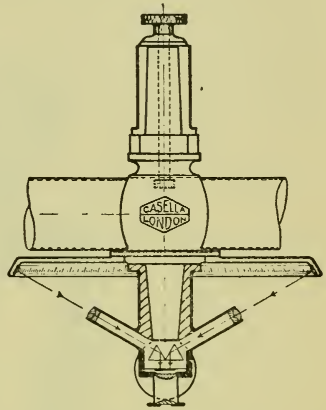


Fig. 106—Section through axis of vertical circle

Figs. 104 and 105 show the construction of the microscope details, and from Fig. 106 it will be seen that the vertical circle is carried in totally enclosed taper sockets and not revolving on the standards. Fig. 107 shows a similar theodolite designed for tunneling work but having no vertical circle. In this pattern the microscope is completely enclosed in the body of the instrument so that there is no possibility of damage to this part. The object glass of the microscope and the deflecting prisms are mounted directly on and turn with the inner centre. In this position they are of course very stable and well protected, and any strain on the plate, uprights or circles can have no effect on their position. The electric lamps to illuminate the dividing for night work will be seen mounted directly over the windows in the circle cover. They are supplied from a dry battery, accumulator or hand dynamo, the current being led up through the inner axis. Having the lamps thus fixed to illuminate the dividing radially along the lines is essential if consistent readings are required. When the dividing is illuminated by a lamp held in the hand it is difficult to arrive at this condition, as any side illumination, however slight the inclination, tends to render the reading ambiguous.

Fig. 109 shows this effect clearly. When the light falls on the surface from the direction A, all parts of the divisions are evenly illuminated, but when it comes from any direction such as B, part of it is in shadow, so that correct setting is impossible. On large fixed instruments the illumination is best made by transmitting the light through the microscope object glass itself

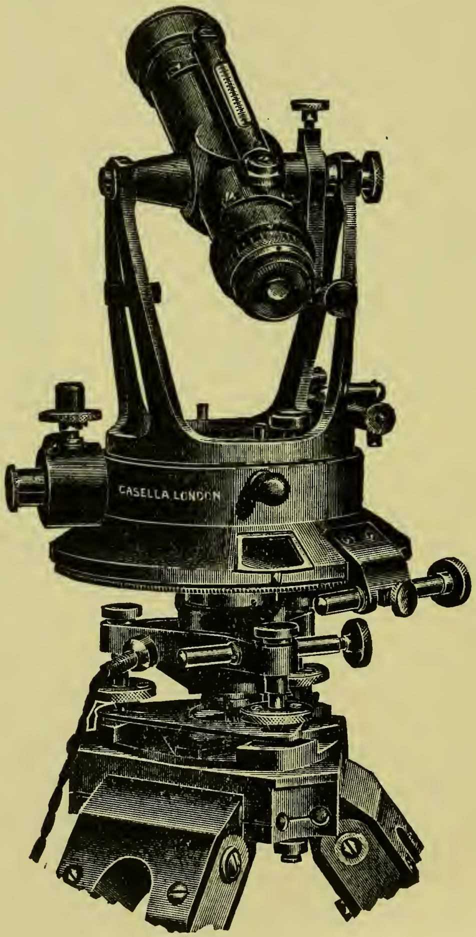


FIG. 107

as shown in Fig. 110, the light from a preferably distant source being reflected by a plain glass placed at an angle to the axis of the microscope. It is not practicable to fit this kind of illumination to the usual surveyor's theodolite, but so long as the light falls radially on the divisions sufficiently good results are obtained for all practical purposes.

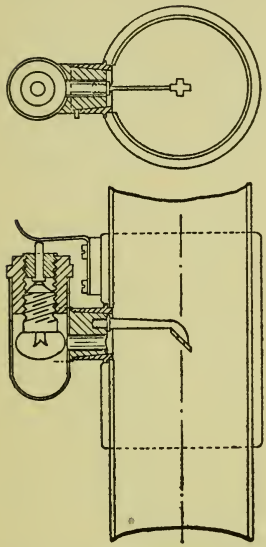


FIG. 108—Electrical illuminator for telescope

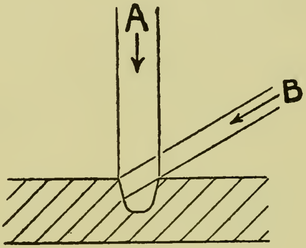


FIG. 109
Section of divided surface

It is to be noted that the same care should be taken when arranging the illumination of verniers, especially those which are divided to read down to 5 or 10 seconds, as considerable errors can result by inattention to this important detail.

There is another system of micrometer reading due to Heyde, a diagrammatic representation of which is shown in Fig. 111. As will be seen, the two microscopes which read the horizontal circle are carried on a separate centre passing through the ordinary inner axis, thus allowing them to be rotated slightly in relation to the upper part. The amount of this rotation, which need

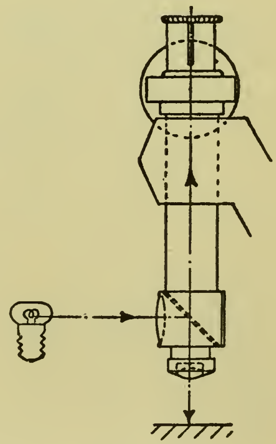


FIG. 110

only be very small, is equal to one division of the circle, and is measured by means of a micrometer screw with a divided head, which, when it is set to zero, holds the two microscopes at 90° from the line of collimation of the telescope. The microscopes each carry a single wire or a pair of wires close together which are focused on to the dividing of the horizontal circle at diametrically opposite graduations. To use the instrument the telescope is set on to the object in the usual way by means of the tangent screws, and the micrometer head, having been set to zero, the value of the nearest division is read by the microscopes. The left side of Fig. 112 shows the appearance of the field at this setting, in which the reading is $180° + 40' + x$. It is now only necessary to measure the amount of rotation of the microscopes which is required to bring the web back by the distance x, this being done by means of the micrometer screw shown, one whole revolution of which equals

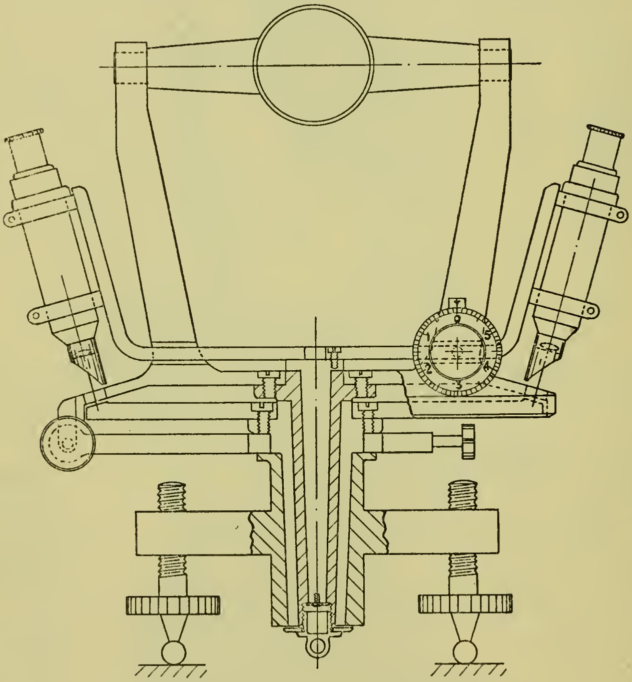


FIG. 111

one division of the circle, i.e., in the case shown 20 minutes. If this head is divided into 60 parts, each division will equal 20 seconds, or if other values are taken, the readings may be 5″ or single seconds as desired. It is well, however, to arrange so that only one revolution of the micrometer screw is required to traverse the microscopes over one space on the circle otherwise the screw, when it is extended further, does not work at the correct radius, thus leading to errors of run. When this system of reading is combined with the double reading arrangement as shown in Fig. 102, the operation of the instrument becomes very convenient, as the mean of both sides of the circle can be made at one setting, thus simplifying the operation very considerably and leading to greatly increased speed of working. The appearance of the field in this case is shown in Fig. 112, where the reading is

$$180^\circ + 40' + \left(\frac{x + y}{2}\right)$$

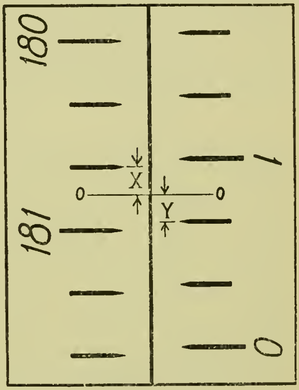


FIG. 112

It is now only necessary to measure x and y and, provided the centering of the circle is correct, one setting of the micrometer will bring the nearest two divisions between the webs so that the mean value of say 180° · 48′ · 15″ can be read at once. If, however, the centering is not correct, the amounts x and y must be set separately, the one requiring the smallest amount of movement being taken first and then the other. If, however, instead of using the webs as shown, an index is fitted to give only an approximate zero, and coincidence is brought about on the dividing itself, the mean of the two readings can be made without further calculation, as it is easily

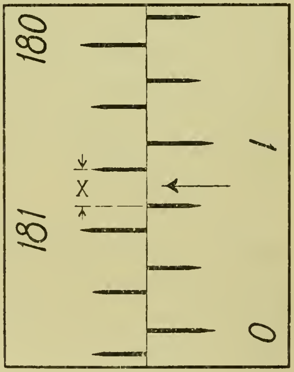


FIG. 113

seen that it is always possible to bring the actual graduations into coincidence, even if the centering is not absolutely correct. The field in this case would be as shown in Fig. 113, where the arrow merely serves to show the number of whole degrees and the 20 minute interval to be read. The first reading in this case is now

$$180^\circ + 40' + \left(\frac{x}{2}\right)$$

Now, as the micrometer screw causes the graduations to move apparently in opposite directions, it is only necessary to bring the division lines into coincidence with each other, the amount of rotation of the drum being at once equal to $\frac{x}{2}$ thus giving the mean of the two sides of the circle directly. The necessary relative shift of the parts can be made in three ways (a) by keeping the circle fixed and moving the whole of the upper part, (b) by fixing the upper part and moving the circle, or (c) by clamping both the circle and upper part and moving the optical elements only, which in this case would be carried in a separate centre as shown in Fig. 111, but modified to suit the double reading arrangement fitted as in Fig. 102.

On the Adjustment of Transit Theodolites

Instruments are carefully examined and tested before leaving the maker's hands, and under ordinary conditions of use will remain in adjustment. It is always well however, and essential on primary work, for the user before making any extensive survey to verify the various adjustments himself, as instruments are sometimes injured through accidents in the field, or in transit from place to place.

The following are those which he can make without any auxiliary apparatus. First of all a general examination of the instrument, its stand, packing, and accessories should be undertaken, and any necessary oiling or cleaning done. The foot screws, tangent screws and the tightening screws on the stand should be adjusted and all parts examined for slackness, etc. The actual adjustments should now be undertaken, and are best made in the following order :—

(1) **To Adjust the Levels on the Horizontal Vernier Plate.** Set up the instrument on solid ground with the legs firmly planted and all clamps tight. Release the lower clamping screw and set the long plate level parallel with a pair of the foot screws. Bring this bubble to the centre of its run and turn the instrument in azimuth 180 degrees. If the bubble does not keep in the centre of its run, adjust for half the error by the capstan head screws at the end of bubble tube and for the other half by means of the foot screws, repeating this operation, if necessary, until the bubble remains in the middle of its run while the instrument is revolved through 360 degrees.

(2) **To Adjust the Transit Axis to the Horizontal.** (a) If the instrument is provided with a stride level, erect this on top of the axis (reversing it in order to examine its own adjustment and correcting if necessary) and if the bubble does not come correctly to the centre of its run, raise or lower the axis by the opposing screws just under the Y of the standard. The bubble should now remain in the centre of its run when the instrument is revolved in azimuth through 360 degrees. (b) If no stride level is supplied with the instrument, focus the telescope (being careful to eliminate parallax) on a small well-defined point at a considerable elevation and some distance from the instrument, bringing the cross wires to cut the point exactly. Then depress the telescope as much as possible and place a mark exactly at the point of intersection of the cross wires. Turn the telescope 180 degrees in azimuth, transit it and bring the cross wires to bear on the first point. On again depressing the telescope, if the wires cut the lower mark the axis is horizontal, but if not, one side of the axis must be raised or lowered, as before, to correct half the error. Repeat these operations until the adjustment is correct.

(3) **To Adjust the Line of Collimation at Right Angles to the Transit Axis.** (a) If the theodolite is one in which the transit axis is not removable from the standards, it is necessary to proceed as follows:—The instrument being level and the horizontal verniers reading 180 degrees and 360 degrees, direct the intersection of the webs on any small, well-defined object by means of the lower tangent screw, unclamp the horizontal vernier plate and turn the instrument through exactly 180 degrees in azimuth

and clamp there. Now transit the telescope and if the vertical web does not cut the same point, correct for half the error by means of the small opposing screws just in front of the eyepiece and the other half by the lower tangent screw. Repeat until this adjustment is perfect. (b) If the transit axis is removable, direct the intersection of the telescope webs on any small, clearly defined object, by means of the lower tangent screw. Open back the clips of the Y's and reverse the transit axis in its bearings ; release the clamp of the vertical circle and transit the telescope. If the vertical web does not cut the same point as before, correct for half the error by means of the small opposing screws in front of the eyepiece, and for the other half by the lower tangent screw. Repeat the observation and divide the error again until the adjustment is correct.

(4) **To Adjust the Level on the Vernier Arm.** The instrument being still level, bring the bubble on the vernier arm to the middle of its run by means of the clip screws and then set the zero of the vertical circle exactly to zero on the verniers, and clamp. Take the reading of the horizontal web on a levelling staff at a considerable distance. Now revolve the instrument through 180 degrees in azimuth and transit the telescope. Adjust the verniers to read zero on the vertical circle and then take another reading of the staff. If it is not exactly the same as in the first observation, correct half the error by the clip screws, repeating if necessary until both readings are alike. The bubble on the vernier arm should now be brought to the middle of its run by means of its capstan headed screws. All bubbles should now remain in the middle of their runs when the instrument is turned through a complete revolution.

In the workshops of manufacturers the actual tests carried out are rather different from those required by the surveyor, and the adjustments are also made in a much more convenient and accurate manner by means of testing apparatus specially constructed for the purpose. In the first place, the maker must test all the pivots and bearing surfaces, adjusting screws, slides, etc., to see that they are correctly formed, and that they function accurately in the way it is intended they should, a rough indication of the work required being as follows :—

Telescope.—The pivots of the vertical axis are measured for equality of diameter, to see that they are truly circular in section and that they are concentric with each other. The distance from each shoulder to the centre of the telescope is then checked and after mounting into the uprights a test is made to see that the tubular body, when placed vertically, revolves truly concentric with the azimuthal axis of the instrument. The fit of the object glass cell, focusing slide and rack, the eyepiece and diaphragm fittings are all examined and adjusted where necessary. **The horizontal axes** are then examined and all the clamps tried to see that they function perfectly in order that any serious fault may be discovered before the final adjustment of the instrument is undertaken. When all the mechanical details have been examined, the instrument is oiled and set up ready for adjustment. These adjustments are similar in character to those which the surveyor would perform in the field, but instead of using distant marks in the open, use is made of the collimation method due to GAUSS. This method allows the work to be carried on indoors under ideal conditions and with properly illuminated objects upon which to set the telescope, so that the adjustments can be more accurately and expeditiously made than by the usual field methods. The **collimator** usually consists of a telescope of about 14 in. focus, the specially good object glass of which is set at solar focus from a spider web diaphragm carried in the usual position. These webs can be adjusted to be in the line of collimation of the object glass in the usual manner.

Where exact measurements of the errors of the instrument under test are required, a micrometer screw is fitted to measure the displacement of the webs in the focus of the collimator. The telescope part is similar in construction to that of an ordinary Y level but fitted with a striding spirit level which can be placed on the collars and reversed end for end to determine its own adjustment. The webs are illuminated by an electric lamp and reflector. As the telescope of the collimator has been set for infinity, parallel light received by the object glass will be brought to a focus on the webs, and also light received on the webs by the illuminating lamp will be projected, by the object glass as a parallel beam in the reverse direction. If then the instrument to be tested is set up in front of the collimator with the two object glasses fairly close together and approximately parallel, the webs of the collimator may be examined by the telescope under test, provided this latter is also set to solar focus. It should be noticed that owing to the fact that parallel light is being used, it is not necessary that the axes of the two telescopes should exactly coincide. Fig. 114 will show this clearly. Let us suppose that two collimators are set up at an angle of say 30° and it is required to test this angle with a theodolite. It will be evident that it is not necessary to place the theodolite exactly at the point of intersection A, as any other position such as B will still allow the angle to be measured correctly.

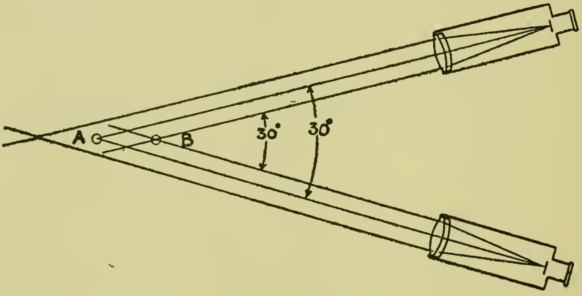


FIG. 114

It is due to this fact that the method of Gauss is so useful for the purposes of tests of this nature as very correct settings can be made without any great care having to be taken to place the instrument to be tested in any exact position in relation to the collimator. It is well, however, to place the two object glasses approximately in line with each other in order that the maximum amount of light may be received by the instrument being tested. The collimators are generally three in number, and are bolted to a ferro-concrete or water cooled cast-iron arch, Fig. 115.

Two of the collimators are adjusted to be exactly in line and level, and the third vertically over the centre of the pier which is arranged to carry the instrument to be tested. A similar apparatus, but arranged horizontally, is used for the testing of sextants. It will now be seen that the telescope to be tested may be set up on its stand and the equivalent readings to those given previously be made, and that when testing dumpy or Y levels the work may be done much more expeditiously. When it is required to test the graduations of the circles, two additional collimators are fitted to the arch, one about 15° in azimuth and the other 15° in altitude. A number of readings can then be taken at various parts of the circles and the errors of the graduations obtained by comparing the readings with the known angle between the collimators. The only other test necessary, except of course those for resolving power, magnification and other qualities of the optical parts of the telescope, is for concentricity of the inner and outer axes. This is done by unclamping the instrument, holding the upper part and revolving the circle. Any error will be shown by relative movements of the webs where they cut those of the collimator.

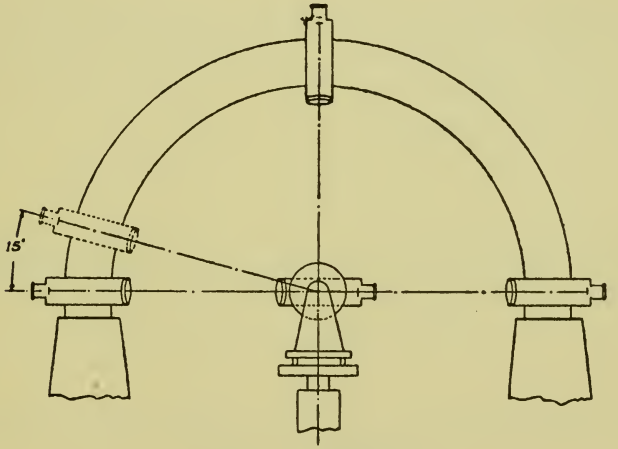


FIG. 115—Collimator

A test may be taken to determine any variation in the line of collimation when the telescope is set to short focus. This is done by first setting on to the collimator and then on to a mark on the wall as near as possible within the range of focus of the telescope rack. It is seldom with modern instruments that any appreciable error is found in this part, owing to the ease with which manufacturers can correct for this defect. The value of the stadia intervals can be tested on the same apparatus and also the run of an eyepiece micrometer or gradienter screw.

When it is desired to find the amount of collimation error by means of fixed collimators, it is convenient to have one of these fitted with a micrometer in its eyepiece. If the right hand collimator as shown in the illustration Fig. 115 is fitted in this way the procedure is as follows.

The instrument which is already in good adjustment is set up and levelled and the telescope webs directed to cut the webs of the left collimator exactly. It is then transited and the error (a) measured by means of the micrometer in the right hand collimator.

The plate is now unclamped, revolved through 180 degrees and the telescope clamped and set by means of the tangent screw on the left collimator. It is again transited and the error (b) measured as before.

The error of collimation will then be

$$\frac{b - a}{4}$$

If the telescope is now reversed in its Y's and a similar set of readings c and d made the error will be

$$\frac{d - c}{4}$$

If the micrometer web in the collimator is now set to

$$a + \frac{b - a}{4}$$

and the thread in the telescope brought into coincidence with it the instrument will be in perfect collimation adjustment.

This test also shows whether the pivots on which the telescope turns are in error. If they are perfect the corresponding readings in each set will be alike, i.e., a = c and b = d, and the mean of the pairs in each set will be zero.

In practice errors of collimation, provided they are not very large, are completely compensated by face right and left readings. An endeavour should, however, be made to keep them as small as possible. Likewise, small errors due to non-horizontality of the telescope pivots can be eliminated, but when taking azimuthal angles the error of a single setting becomes greater as the zenithal angle becomes less, so that it is necessary carefully to check this adjustment by means of a striding level, when working on steep sights. The taking of azimuths at small zenithal angles should therefore be avoided when possible, as it is extremely difficult to get good results in that position. On the other hand, for zenithal angles the errors due to non-verticality of the main axis are never of much importance, being at no time greater than its zenithal angle which can always be made extremely small by means of the principal levels.

If z is the angle of inclination of the main axis to the zenith and a the azimuth of the line of sight to this vertical, then the error at azimuthal angle A and the zenithal angle Z is

$$\text{Error of } A = z \sin (A - a) \cot Z$$
$$\text{Error of } Z = z \cos (A - a)$$

On the other hand, when the pivots of the telescope are inclined to the horizontal at an angle b

$$\text{then the error of } A = b (\cot Z)$$
$$\text{and the error of } Z = \text{zero}$$

It is therefore clear that as Z becomes small, the error of A, at a small inclination b becomes very great.

The general performance of the instrument for such points as stability and flexure of the parts and for the way in which the telescope follows the motion of the tangent screws are all made evident during the tests, as owing to the delicacy of the setting on to the collimator webs, any inaccuracies in the working of these parts are so noticeable that they must be rectified before the adjustments can be carried out satisfactorily. A rough but very good indication of the value of the instrument is to examine the position of the webs in relation to the body of the telescope. If when the eyepiece is removed they do not appear to be placed centrally in the tube, either the construction of the mechanical parts is at fault or the object glass is not properly centered. An instrument showing this defect should be rejected.

The angular field of view may be easily determined by setting up a staff at a small distance from the instrument and noting the number of divisions seen in the field. If then the angle subtended at this distance by the same number of divisions be measured by means of the circle of the theodolite, the angle of field will be given and from this angle the apparent field of view may be calculated. This apparent field is equal to half the tangent of the angular field multiplied by the magnification of the telescope.

Theodolites with Eccentric Telescopes

Fig. 116 shows a type of theodolite much used by continental surveyors in both large and small sizes. The advantages of this position of the telescope will be apparent when it is required to examine objects placed vertically above or below the instrument, and for certain surveying operations in mines instruments of this kind are invaluable. Apart from the convenient position of the telescope, another advantage which this design has over that of the more usual central type is that much larger optical units may be employed without the necessity of raising the standards to an undue height. When therefore a good deal of stadia work has to be carried out the eccentric type has manifest advantages, especially in cases where the determination of distances are of greater importance than the angular measures. The principal disadvantage under which this type of instrument labours, apart from the fact that it is not quite so easy to adjust, is that it is necessary to apply corrections to all the readings on account of the eccentricity of the telescope. Fig. 117 is a plan diagram of the setting of an instrument of this kind showing

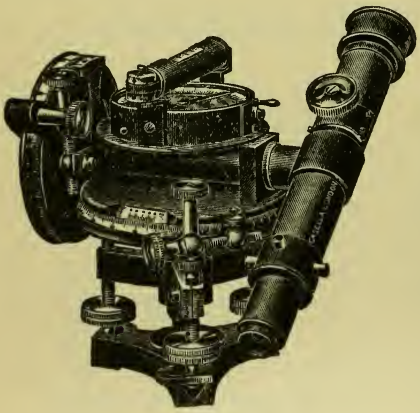


Fig. 116

how the azimuthal angles are affected by the position of the telescope. Let A be the axis about which the alidade turns; DH the telescope when set on point E and BG its position when set on C. Then the angle through which it turns is θ_1 But the angle which we require to measure is C A E = θ which is obviously a different angle from that shown on the limb, which is actually measuring θ_2 or the angle E J C. There is therefore an error due to parallax at each setting, the magnitude of which will depend on the length of the sights and the distance from the line of collimation to the axis of rotation. The true azimuths may be calculated for a single sight, but it is more usual, when using this form of instrument, to take face right and left readings and so eliminate the parallax error. Fig. 118 shows a method of effecting this. Let A as before be the axis of the instrument and E and G be the two points the azimuthal angle of which is to be measured. This angle will be EAG = θ. First measure angle θ_1 by turning the telescope from a to b. Then by transiting and revolving the plate take angle θ_2 with the telescope in position c and d. The required angle θ will then be

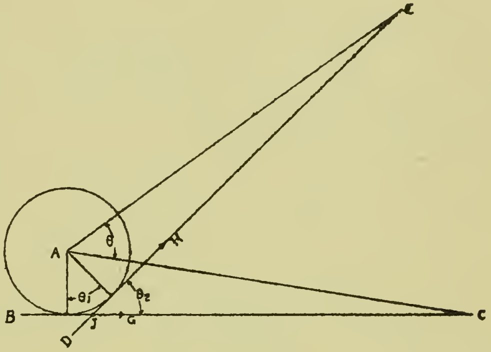


FIG. 117

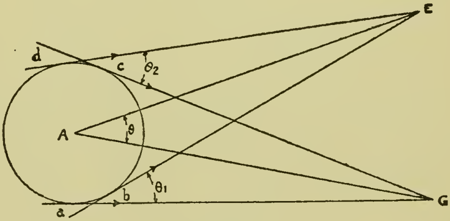


FIG. 118

$$\frac{\theta_1 + \theta_2}{2}$$

This may be proved as follows:—Let P, Q, R and S be the circle readings in positions a, b, c and d

And readings T and V those at AG and AE

$$\text{Then } \theta = V - T$$
$$\theta_1 = Q - P$$
$$\theta_2 = S - R$$

And since GA bisects cGa

And since EA bisects dEb

$$\text{Then } T = \frac{P + R}{2}$$

$$\text{And } V = \frac{Q + S}{2}$$

Therefore

$$\theta = \frac{Q + S}{2} - \frac{P + R}{2}$$

$$= \frac{Q - P}{2} + \frac{S - R}{2}$$

$$= \frac{\theta_1 + \theta_2}{2}$$

It will be obvious that modifications must be made in the usual procedure when adjusting the telescope on an instrument of this kind, and that the labour involved in taking the angles is much greater than that required with the more usual type having a central telescope. The extra work necessary when computing the angles is also a serious drawback to this system, which is probably the reason why it is not more extensively used. When being used, however, for astronomical work, the errors of parallax have less weight, and for quite small instruments such as is shown in Fig. 116 these errors are not important, as theodolites of this size are mostly used on compass surveys, the results being plotted in such a way that the errors are eliminated.

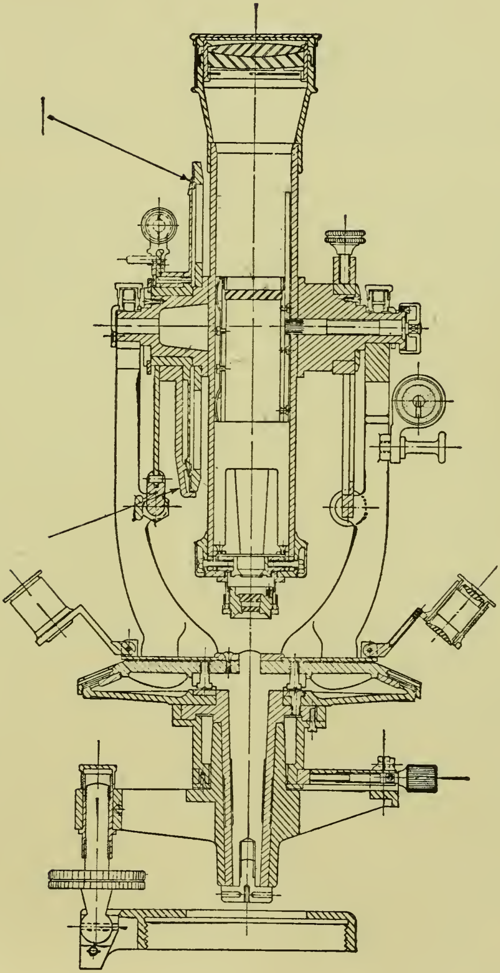


FIG. 119—Section of 6 in. transit theodolite

CHAPTER VII

LEVELLING INSTRUMENTS

LEVELLING operations are almost of as much importance as those carried out with the theodolite, and much thought has been given to the subject of the design of suitable instruments for this purpose. The surveyor's level has arrived at such perfection that it is only in minor details that it is likely to be modified in the near future. It performs its work so well that the ultimate accuracy depends on the stability of the bench marks, the positions of which may vary owing to the movements of the earth's crust, rather than on the instrument itself. Improvements will no doubt be introduced, and are, in fact, constantly being produced, to render the instrument more compact, quicker to set up and to read. Endeavours are being made to arrange matters so that the personal errors of the observers qualify the results to a less and less extent. In spite of what has been written above, the ideal instrument has, however, not yet been produced, and in fact those in use or contemplated at present, are far from ideal from the user's point of view. The present procedure is as follows :—An instrument is set up to read a distant staff. It is levelled by means of a spirit bubble which serves to set the line of collimation of the telescope at a true tangent to the earth's surface. The image of the staff is then examined in co-incidence with the webs marking this line of collimation, and the mean of several readings gives the true level. This means that the indication of the bubble upon which we are relying has to be transferred to another part of the apparatus before we can make use of it, with the result that errors are likely to be introduced during this operation.

The ideal instrument would be one which would project into the field of the telescope a picture of the two ends of the bubble superimposed on the image of the staff and in such a form that their relative positions could be accurately determined, thus enabling true level to be read at once on the graduations of the staff. Some instrument maker or man of science will no doubt produce a practical design of this nature, but at present no such instrument is available, so that we must be content in the meantime to improve the existing apparatus in such a way that errors in the transferring process are eliminated as far as possible, that the setting and reading of the bubble is rendered simple, and that the relative position of the bubble and the line of collimation shall be as invariable as it is possible to make it. There are two main types of levels in use at the present time—A, the **dumpy** and B, the **Y level.** Various modifications of each of these types are produced, but recent design has tended in the direction of improving the dumpy level in an endeavour to obtain the results which the Y level is intended to give, but in a simpler and more exact manner. For ordinary levelling operations when known bench marks are being connected up, the dumpy level is the most popular and deservedly so, as it is a very robust instrument which, if well-made and adjusted, may be relied upon to give consistently accurate results within its limits. Its adjustment in the workshop by means of a proper collimator is quickly and easily made, but for a surveyor in the field, the method which will be given later is rather laborious, and requires some skill and care to effect properly. For this reason many users now prefer other instruments which are either self-checking or which can be readily adjusted from a single station even for purposes for which the dumpy pattern was formerly considered the most satisfactory type. Up to about ten years ago, levelling was done by setting the instrument up to revolve truly level in azimuth about its axis and then taking the back and fore sights, thus relying on the accuracy of fit of this main axis. Since then levels having an elevating screw arranged to tilt the telescope and therefore the line of collimation through a small angle have been revived and bid fair to be universally used in the future. The reason for this revival seems to be that more attention has been given to the design of reading devices to facilitate the setting of the bubble at the moment of reading the levelling staff. This method has been found much quicker in use and more accurate in its final results than the older one of setting the axis truly vertical in which the time taken at each setting to arrive at perfection is very much greater than that required to place the instrument approximately level and then to make a final precise adjustment for each separate sight. The disadvantage of the former method is most noticeable when the work has to be done on soft ground where the setting is likely to be disturbed by the operator walking round the instrument. As the dumpy level is, however, likely to remain in use for certain purposes, a description of its main features and its method of adjustment is given herewith. Fig. 120 shows a modern type of dumpy in which the axis is cast integral with the telescope body and can thus be machined up truly at right angles to this body, and can be made so strong and solid that there is no likelihood of any deformation of these parts.

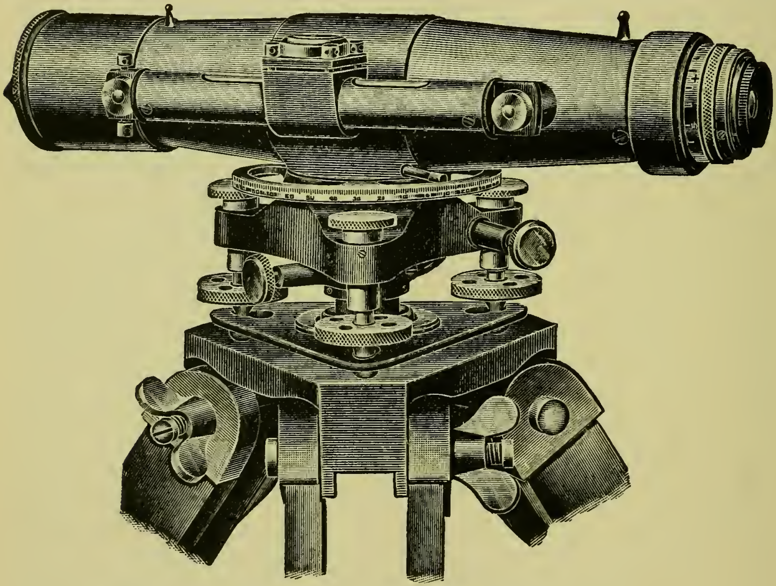


Fig. 120—Dumpy level with large divided ring

As the accuracy of the instrument as a level depends on the perfection of this part, great care is taken during manufacture to see that the fit is as good as it is possible to make it, and that the working faces are so generously designed that wear is not likely to affect the results to any appreciable extent. The centering of the object glass used in a dumpy level must be good as there is no means of adjusting it once it is fitted. This defect is shown in Fig. 121. Most makers therefore take great care that this detail is properly attended to and also that the line of collimation is not disturbed when the telescope is set to focus on different distances. As has been explained previously, **the internal lens** method of focusing has removed the likelihood of error in this part. As the only adjustments which the user can make are to the diaphragm and the level bubble, it will be seen that reliance must be placed on the perfection of the work done by the manufacturer during construction, which indicates that only instruments by first class makers and then only those of very solid construction should be purchased. The following gives the most convenient method of adjusting a modern dumpy level when the work has to be done in the field.

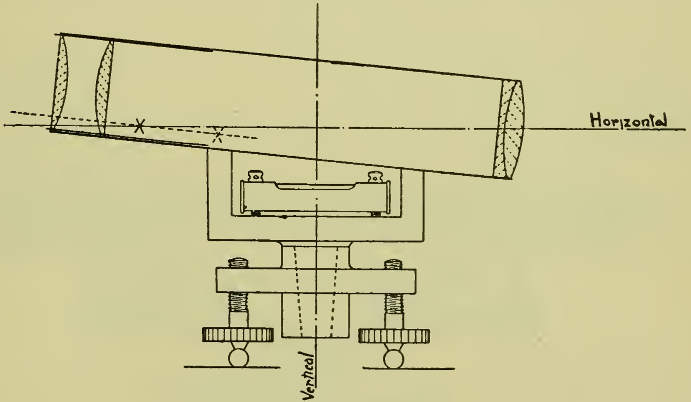


FIG. 121

Adjustment of Dumpy Level.

(1) Drive in three stakes in a straight line on a level piece of ground, at equal distances apart, say two chains.

(2) Set up the instrument firmly over the middle stake and bring the bubble to the centre of its run.

(3) Then turn the telescope through 180 degrees, and if the bubble does not remain in the middle, correct half the error by means of the foot screws and the other half by the capstan nuts of the bubble tube.

(4) Now place a levelling staff on one of the stakes and take an exact reading with the horizontal web.

(5) Remove the staff to the other end and drive the stake in until the reading is exactly the same as the first one.

(6) Set up the instrument and level carefully at a point about 30 feet from the stakes and in a straight line with them, and take an exact reading of the staff when set upon the near stake.

(7) Then take the reading of the staff when set upon the other stake, and if these readings do not agree correct by the antagonistic screws of the diaphragm and repeat until both readings are exactly equal.

Y Levels

The Y level differs from the dumpy in that it is completely adjustable from a single station and can be so arranged that by taking the mean of two or four readings the results are free from instrumental errors. This is evidently a most desirable quality and one that, if possible, every instrument should possess. It is not achieved, however, without the introduction of corresponding

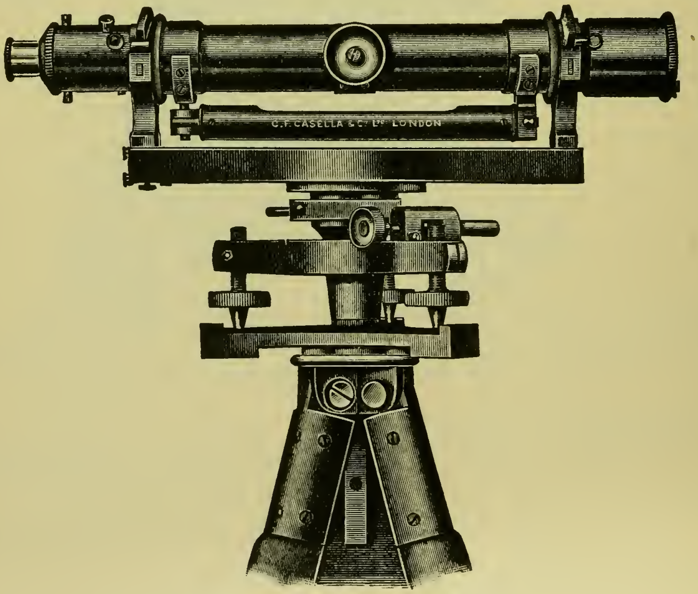


Fig. 122—Three-screw Y level

disadvantages and in consequence the Y level as originally made has fallen into disuse to a very large extent, except in America, where it is still the most popular levelling instrument among surveyors running lines of secondary importance. It has been the aim of designers to produce instruments having all the stability of the dumpy level and at the same time to incorporate the best features of the Y level, and a good deal of success has attended these efforts in recent years.

Fig. 122 shows the form in which the Y level was constructed about twenty years ago, from which it will be seen that it differs from the dumpy in that the telescope instead of being fixed permanently to the stage is merely held down in Y bearings at each end by clips which may be folded back, thus allowing it to be reversed end for end and also to be rotated about its line of collimation. One of the Y bearings is adjustable for height, allowing the line of collimation to be set perfectly at right angles to the main axis upon which the whole of the upper part rotates. The bubble is also attached to the telescope so that its indications may be checked by reversal. The method of adjustment used by surveyors is extremely simple and is as follows :—

Adjustment of Y Level.

(1) Focus the intersection of the webs carefully on any small well-defined point, and clamp the instrument firmly. Turn the telescope on its axis of collimation through 180 degrees, and if the horizontal web does not cut the same point exactly, correct half the error by means of the capstan screws of the diaphragm and the other half by the foot screws. The vertical web should be adjusted in a like manner. The intersection of the webs should then remain exactly on the point while the telescope is revolved on its axis of collimation.

(2) The bubble should now be brought to the centre of its run by means of the foot screws. Open the clips of the Y's and reverse the telescope end for end. If the bubble does not remain in the centre of its run, adjust for half the error by means of its capstan nuts and half by the foot screws.

(3) The bubble being in the centre of its run as in (2), turn the instrument 180 degrees in azimuth and observe if there is

any displacement of the level. If there is, correct half the error by means of the capstan nuts under the Y's and the other half by the foot screws. Repeat the operation with the telescope at right angles to the first position, when the bubble should remain in the centre while the instrument is revolved round its axis.

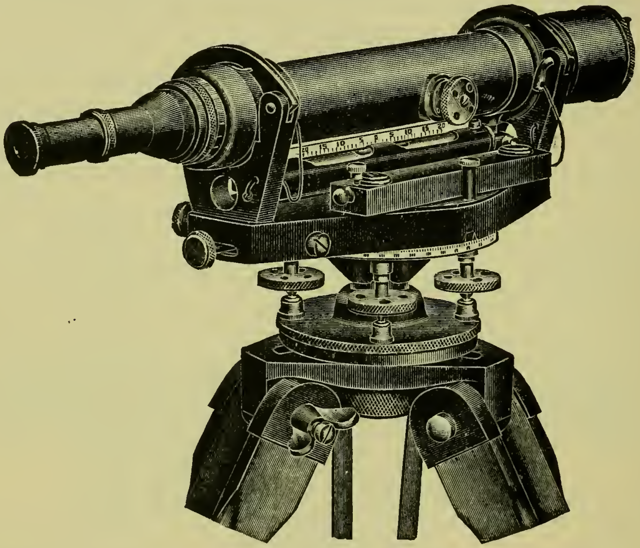


FIG. 123—Four-screw Y level shown with erecting eyepiece in place

When the instrument is adjusted periodically in this way, excellent work may be expected from it, but its accuracy will still depend on the perfection with which the parts have been constructed. It is obvious that accurate rotation upon its centre is still as necessary as with the dumpy level, as any slackness in this part will render the results unreliable. It is also to be noted that equality in the diameter of the collars of the telescope is essential, and although the maker can produce these collars concentric and accurately to size, in time a certain amount of wear is bound to take place, owing to the fact that they are completely exposed to the weather. Grit soon finds its way into the bearings, so that a certain amount of grooving is sure to take place. Flats also develop on the collars, especially in those instruments which with a view to economy of space are packed in their cases in one piece, so that it is easily seen that the supposed superiority of this form of level is largely illusory. In addition, the whole instrument is not very robust, is taller and therefore more affected by the wind, and has a number of loose parts which may easily become damaged or lost. Instances have been known where the telescope itself has disappeared from the case, so it is not to be wondered at that the Y level has decreased in popularity. In the form just mentioned the readings are not free from instrumental errors, as it is only possible to take readings in two positions, but if the bubble is fixed as shown in Fig. 122, and it is made of the reversible type, it is possible to take readings in four different ways, i.e.—

1st, with the bubble at the top.

2nd, with bubble at the bottom.

3rd, with bubble at the top and telescope reversed end for end.

4th, with bubble at the bottom and telescope reversed end for end.

The mean of these four readings will indicate true level and be free from instrumental errors. This alteration to the level adds nothing to its complication and it is therefore surprising that instruments have not been more generally constructed in this fashion. The value of this modification was first pointed out by Monsieur Simon about fifty years ago and many of the continental makers arrange their bubbles in this way. In actual practice it is more convenient to mount the bubble in the side of the telescope instead of underneath, as in Fig. 122. In America, however, where the Y level is almost exclusively used, very few makers have adopted this system in spite of its manifest advantages. Mr T. F. Connolly has revived the question and in a paper* recently read by him has given a very clear explanation of the matter. He has also pointed out that if the bubble tube is accurately calibrated, the mean of two readings taken by merely rotating the telescope on its axis of collimation will give true level. This will not of course be free from instrumental errors, but owing to the fact that the telescope can be arranged to rotate in a closed cylindrical well-lubricated bearing, and that modern bubbles can be so exactly formed and calibrated, these errors

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* *Journal of Scientific Instruments*, Vol. 1. No. 9

may be considered negligible, even for the most precise work. Any residual errors which there may be are in addition not of importance for precise work as when levelling of the greatest accuracy is required, the practice is to make the sights of equal length so that these errors tend to cancel out in the final results.

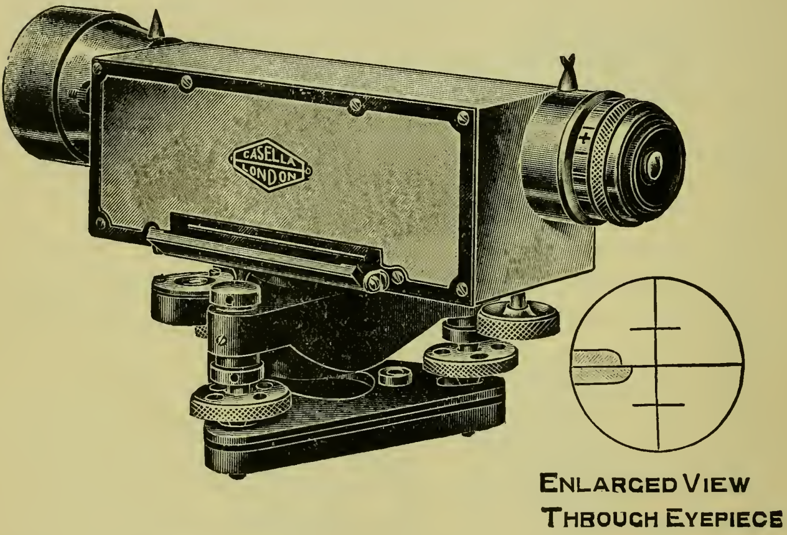


FIG. 124—Totally enclosed precise tilting level with prismatic bubble reading device which brings the image of the bubble into the field of the main telescope.

Levels with Tilting Screws

Fig. 124 shows a sectional elevation and Fig. 125 an outside view of Casella's precise level with micrometer screw which serves to tilt the whole telescope and its attached bubble about a horizontal axis carried near the centre of the telescope. This level is fitted with the prism reading device shown on page 58. All the optical work is enclosed and hermetically sealed in the body of the instrument, an optical device in the eyepiece allowing the image of the ends of the bubble to be examined and brought into co-incidence by means of the tilting screw. A good deal of thought has been expended on the improvements of instruments on this system with such satisfactory results that as a type the tilting level is likely to supersede all others for both ordinary and precise work, especially when as in the example shown the image of the bubble is brought into the field of the telescope. On the dumpy level shown the axis is only of minor importance, as its function is merely to allow the instrument to turn easily and to hold it steady. As the line of collimation can be fixed once and for all by the maker, the only adjustment necessary or provided is one to bring the bubble parallel to this line of collimation. This can be done by the method used when adjusting the dumpy level except that instead of moving the webs the whole telescope is raised or lowered by the tilting screw to read true level on the staff and then the bubble is adjusted to the centre of its run. This adjustment is carried out by sliding the whole of the prism system by means of a milled head screw placed near the object glass end. When using the level it is only necessary to bring it approximately level by the foot screws, to tilt the telescope to bring the bubble to the centre of its run and then take the reading of the staff. A practical trial of this type of level will at once convince a surveyor that at least one-third of the time taken with the usual level is saved, as most of the time required and most of the difficulty in setting up a level is due to the care which must be taken to see that the bubble

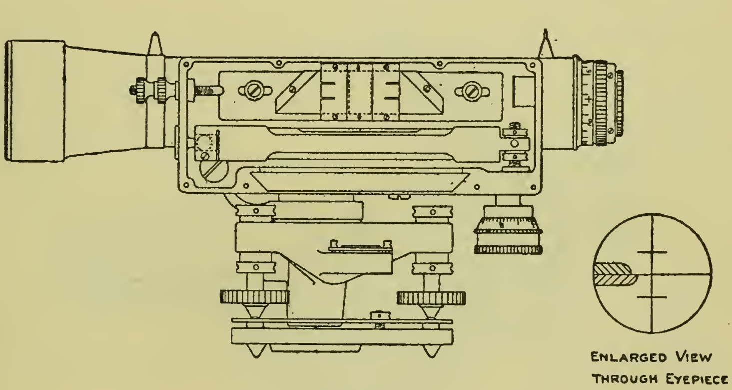


Fig. 125

Section of precise tilting level.

Appearance of the field of view in the telescope remains central when the telescope is revolved 360° in azimuth. The image of the bubble being magnified by the eyepiece allows very exact coincidence of the bubble ends being made.

Fig. 126 shows a simple type of **builder's level** constructed on this principle. The tilting screw will be seen directly under the eyepiece, and as a mirror is used to view the run of the bubble the setting can be done very expeditiously without moving from the front of the instrument. The telescope of this level is focused by means of an internal lens which is moved along the inside of the tube by the rotation of a spiral collar, the milled portion of which is seen just in front of the eyepiece.

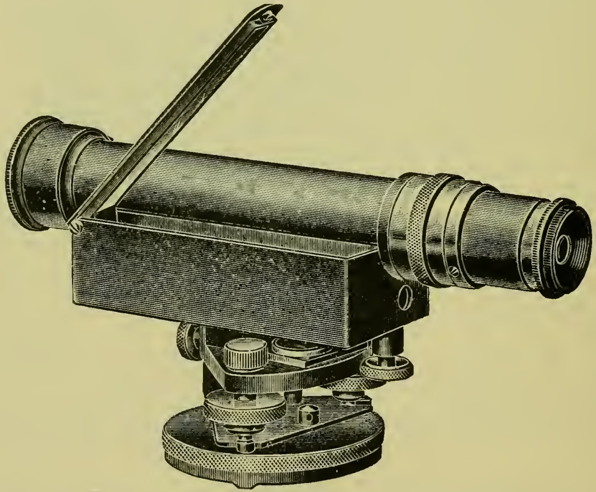


Fig. 126

A circular bubble is attached to the base to enable this part to be set approximately level, as unless this is done too many turns of the tilting screw would be required to bring the main bubble to the centre of its run at each fresh sight. An incidental advantage which the tilting level has over either the dumpy or the Y, is that if the tilting screw is arranged as a micrometer screw of proper pitch and if it carries a divided head, it can be used to set off grades or measure distances, and in fact most of the better class instruments are arranged in this way. In the example shown in Fig. 125 the micrometer screw is of such a pitch that one turn = 1 in 500 and with suitable pitch and leverage this figure may be 1 in 1000 or any other value required.

A description of the parallel plate method of reading the staff has been given on page 39 and the various devices for reading the bubble on page 56, to which the reader is referred for details. When adjusting this type of tilting level the bubble is brought to the centre of its run, by means of its opposing screws, thus bringing it parallel to the line of collimation of the telescope, or by moving the prism system. The head of the micrometer screw, which is only friction tight on its spindle, can then be set to zero, when the instrument will be in complete adjustment.

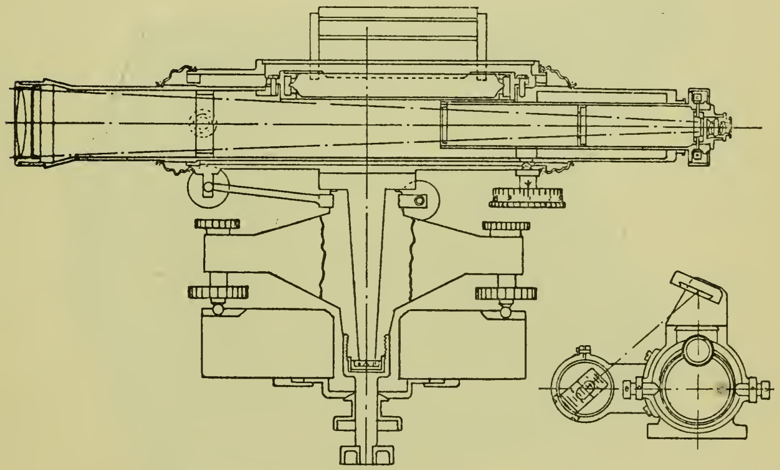


FIG. 127—American pattern precise dumpy level

On some instruments the diaphragm is so arranged that it may be rotated slightly when the adjusting screws are loosened. When of this form it is necessary to see that the wire is horizontal. This can easily be checked by directing the telescope after levelling on to a distant point and seeing that the wire follows this point when the instruments are turned in azimuth. On modern instruments the diaphragm is fixed permanently horizontal and in any case as the staff is always read in the centre of the field, this point is not of any great importance. Fig. 127 shows the type of precise level used exclusively by the United States Geodetic Survey. It has been designed by that Department for the very exact work demanded by the U.S.A. Government, and in use has been found to give most excellent results. It is a dumpy level arranged for the tilting screw method of use, this screw carrying a divided micrometer head for gradienter work. Its main features are the setting of the level tube inside the telescope as close to the line of collimation as possible, and the method of reading the bubble at the moment of setting on the staff. This is arranged by a mirror over the bubble, which reflects its image in a pair of prisms carried in a tube on the side of the tilting telescope. The general arrangement is similar to the French pattern shown in Fig. 57. The separation of the prisms can be adjusted by a milled head in such a way that the image of the ends of the bubble are always central in the field in spite of variations of length due to temperature. The bubble tube is also arranged with a chambered end to allow for adjustment of the actual length of the bubble under extreme temperatures. The tribrach is made of cast iron, the centre being of hardened steel. The telescope body and the mountings of the bubble have, in the latest instruments, been made from invar, it being claimed that the use of this material has somewhat improved the constancy of adjustment. Comparative trials with this method of

Fig. 128—Builder's levelling outfit in leather case

bubble reading and that shown in Fig. 58 have been made with the result that while equal accuracy was obtained, the latter form proved rather easier and quicker to set. It will be noticed that the central form of holding down screw has been used in this instrument. As this arrangement or some modification of it is undoubtedly the best method of fixing a surveying instrument to its stand, it is surprising that it is not more generally employed.

The method used for the adjustment of this level by the U.S. Coast and Geodetic Survey, is as follows :—

Two staves are placed about 100 metres apart and the level is set up about 10 metres from one of them. Sights are now taken first on to the far staff and then on to the near one and the figure booked. The instrument is now moved to within 10 metres of the far staff and another pair of sights taken. (The two instrument stations are between the two staff points). The staff readings must be taken with the bubble in the middle of its run. The required constant C to be determined, namely the ratio of the required correction to any staff reading to the corresponding subtended interval is

$$C = \frac{(\text{Sum of near staff readings}) - (\text{Sum of distant staff readings})}{(\text{Sum of distant staff intervals}) - (\text{Sum of near staff intervals})}$$

The total correction for curvature and refraction must be applied to the sum of the distant rod readings before using it in this formula. The level should only be adjusted if C exceeds ·010. This adjustment must be made by moving the level vial and not by moving the reticule.

The value of the stadia interval is found as follows :—

The object glass is first set to solar focus by pointing it on to a distant object and the distance from the centre of the object glass to the cross wires measured. This gives the focal length of the object glass F.

The distance from the object glass to the centre of the axis is then measured giving the figure C.

The instrument is now set up in accordance with the formula given (see page 42, Anallatic Telescopes) in the following way :— From a point directly under the axis of the instrument as shown by a plumb bob, an amount equal to F + C is measured and from this point distances of 100, 200 and 300 feet are laid off. Several readings of the stadia interval are made on a staff placed alternatively on the three distant points and the average reading at each point calculated. The average reading at 300 feet is divided by three and the average at 200 feet by two. These two numbers and the average reading at 100 feet are again averaged, thus giving a mean value for the interval of the webs. For example :—

If the average reading at 300 feet = $3'\cdot06$
,, ,, ,, ,, 200 feet = $2'\cdot04$
,, ,, ,, ,, 100 feet = $1'\cdot01$

Then

$$\frac{\frac{3\cdot06}{3} + \frac{2\cdot04}{2} + 1\cdot01}{3} = 1\cdot017$$

The distance from the staff to the centre of the instrument will then be :—

$$\text{staff reading} \times \frac{100}{1\cdot017} + (F + C)$$

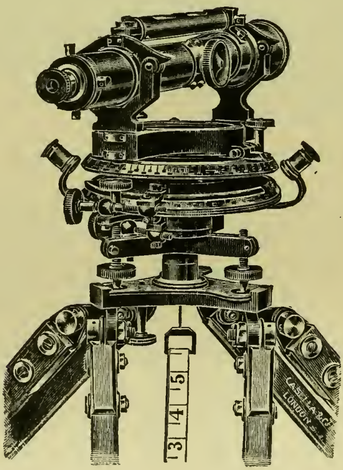


FIG. 128a—Special gradient telemeter level

CHAPTER VIII

SIMPLE SURVEYING INSTRUMENTS

Abney Levels, Clinometers, etc.

VARIOUS instruments for rough levelling are extensively used, many of them of excellent design, and in careful hands giving reliable results within their limits. The Abney level, designed by the late Sir W. de W. Abney is perhaps the most popular instrument of this class, as it gives slopes as well as levels and is sometimes combined with a compass, thus enabling magnetic bearings to be taken. Fig. 129 shows this level in its simplest form, and Fig. 130 shows an instrument fitted with a vernier and a lens to enable the reading to be made to 10 minutes of arc. As generally constructed, it consists of a square metal tube with an arc fixed at one end reading degrees of slope, over which an index arm having a spirit level attached moves in a vertical plane. To take the angle of depression or elevation of any object, the line of sight is directed towards it through the tube, a milled-edge wheel being turned by the left hand till the bubble of the spirit level is seen (through a slot cut in the upper side of the tube), to coincide

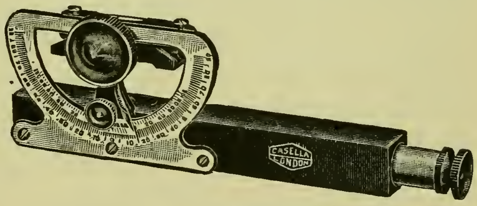


FIG. 129—Simple Abney level

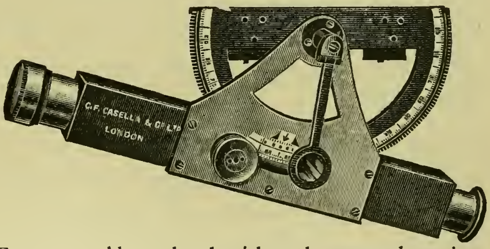


FIG. 130—Abney level with rack-actuated setting

by reflection in a silvered plate with the object. The required angle is read off on the scale by means of the vernier on the index arm.

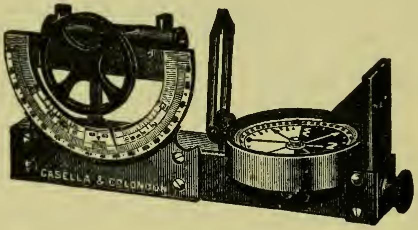


FIG. 131—Abney level and prismatic compass

To find the height of an object, the instrument is raised to the eye and the index-line is aligned on the object. By turning the milled-head wheel, the bubble is then brought into the centre of its run, so that it cuts the index line. The line on the gradient scale that coincides with the upper sharp edge of the index arm is then noted. The distance from the observer's position to the base of the objective is now measured and the distance divided by the figure noted on the gradient scale. The result will be the height required. For instance, supposing the edge of the index arm cuts line 3, and the distance is 150 feet, then 150 ÷ 3 = 50 feet = the height of the object. **To find small heights** at close range, the following method can be used :—Set the edge of the index arm to line 1 on the gradient scale (= 45° by arrow-point of vernier), then look through the instrument, holding it so that the bubble cuts the index-line on the mirror. Move steadily backwards or forward until the object the index-line and the bubble coincide. The distance measured from the observer to the object, plus the height of the observer, will be the required height.

For setting-out slopes, fall for drainage, etc., the index is first set to the desired angle of slope and the instrument placed on a straight-edge, the ends of which are resting on stout wooden pegs driven in the ground. The bubble is brought to the centre of its run by driving one of the pegs further into the ground. This process is continued throughout the length of the work.

The arrow-point in the centre of the vernier scale is used as an index in conjunction with the degree scale, the vernier reading usually to 10 minutes of arc.

The following tables will be found useful. Table A gives certain angles of elevation or depression, which give unity of rise per amount of run. Thus 18° of elevation gives 1 vertical to 3·0 horizontal. Table B gives for certain angles up to 85° the amount of rise or fall per 100 of run, measured horizontally. Heights can therefore be found as follows :—Thus, for 4° of elevation the rise would be 7·0 per 100 horizontal, and an object 300 feet from the observer subtending an angle of 4° would be 7·0 × 3 = 21 feet in vertical height.

TABLE A

Degrees	One in	Degrees	One in	Degrees	One in	Degrees	One in
1	57·0	8	7·1	18	3·0	30	1·73
2	28·6	9	6·3	20	2·7	32	1·60
3	19·0	10	5·6	22	2·4	34	1·43
4	14·3	12	4·7	24	2·2	36	1·37
5	11·4	14	4·0	26	2·0	38	1·23
6	9·5	16	3·4	28	1·88	45	1·0

TABLE B

Horizontal Distance = 100		Horizontal Distance = 100		Horizontal Distance = 100	
Angle	Rise or Fall	Angle	Rise or Fall	Angle	Rise or Fall
1	1.7	12	21·4	35	70.5
2	3·5	13	23·2	40	84·2
3	5·3	14	25·2	45	100·0
4	7·0	15	26·9	50	110
5	8·8	16	28·7	55	143
6	10·6	17	30·7	60	174
7	11·3	18	31·8	65	214
8	14·1	19	34·5	70	275
9	16·0	20	36·6	75	303
10	17·7	25	46·9	80	575
11	19·5	30	58·0	85	1143

Optical Square

This optical square is a new invention. With it straight lines or right angles can be laid off from any point with great facility and accuracy.

In laying off a straight line the instrument is held vertically over the spot through which the straight line is to pass, with the forefinger cover-the slot at the back of the prism case. The position of one end of the line being located, either by a pole or some other defined object, the position of the other end of the line can be determined by placing a pole, or stick, in such a position that when the two objects are observed through the top and bottom prisms respectively, they will be superimposed, or in coincidence.

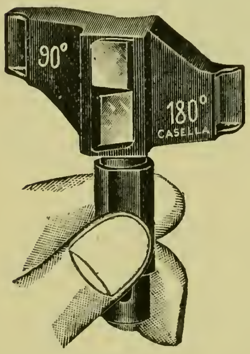


FIG. 132

For laying off a right angle, the instrument is held vertically over the spot which is to be the apex of the right angle and one sight is taken direct through the instrument, and the right angle is laid off either by the top or bottom prism according as it may be required, to the left or to the right.

For greater accuracy a plummet may be attached to the lower part of the handle for locating more exactly on the ground the position from which the sights are taken, or if desired the instrument can be supported on the end of a light stick.

The special advantages of this optical square are: It cannot easily get out of adjustment, owing to its strong and simple construction; the prisms being unsilvered are not liable to damage by damp; it is handy and compact and light, and its weight complete with case does not exceed 5 ozs.

Brunton & Pearse's Mine Transit

The Brunton & Pearse's mine transit is a compact instrument measuring 2¾ ins. × 1 in. and weighing about 8 ozs. It consists of a stout aluminium box, containing an engraved compass dial, silvered graduated ring and a bar needle with jewelled cap fitted with a lever for raising this needle off its pivot when not in use. An arm, having a spirit level fixed at its upper end and at its lower end a vernier, moves over a divided arc, thus allowing vertical angles to be read. At the back of the box is a small knob for moving the spirit level and arm. The east and west points are transposed to facilitate the direct reading of compass bearings. In the cover a mirror is fitted, having a fine hair-line cut diametrically across it, and near the hinge a small aperture is made for sighting. Opposite the cover a hinged arm is fitted, having a pinhole sight at its extremity. Two flat faces are cut on the box for placing the instrument on a surface when finding or setting-out angles of elevation or depression.

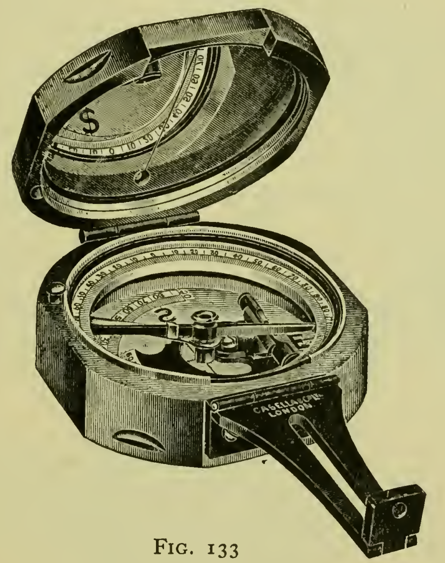


FIG. 133

It is also fitted with a pinion for setting-off the magnetic variation when in use as a " true-north " compass.

Instructions for use. To take **horizontal angles** open the cover to an angle of about 150° and place the long sight at an angle of 90°. Stand facing the object and hold the instrument in both hands as shown in Fig. 134. The object and front sight will be reflected in the mirror and, together with the fine hair-line, can be brought into alignment. Allow the needle to settle, and then read off the magnetic bearing on the compass dial.

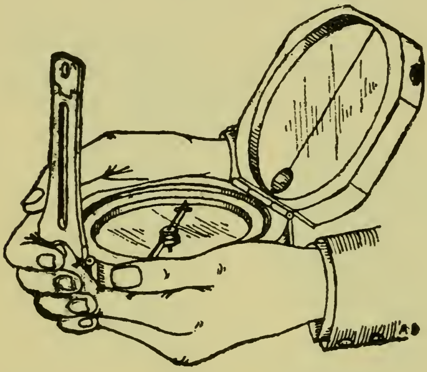


FIG. 134

To take vertical angles, open the cover to an angle of about 45° and the long sight as far back as it will go, then turn up the small pinhole portion to an angle of 90°. Hold the instrument in the left hand, as shown in Fig. 135, and, looking through the pinhole sight and through the aperture in the mirror, align the instrument on to the object. Bring the bubble, which can be seen by reflection in the mirror, into the centre of its run by moving the small arm at the back of the box with the thumb and finger of the right hand. The angle can then be read on the graduated circle shown.

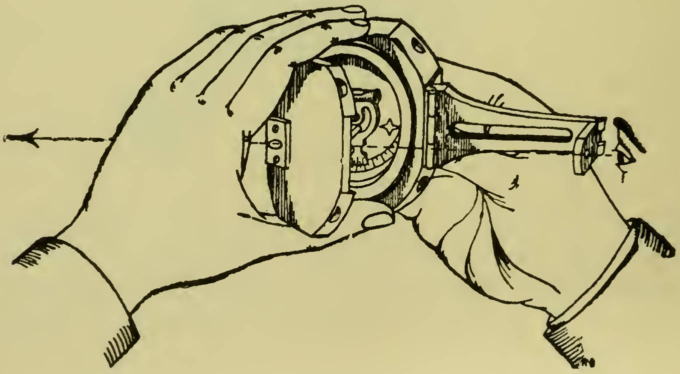


FIG. 135

Fig. 136 is another type of clinometer level which is very useful, as the bubble can be made longer and therefore more sensitive. This instrument can hardly be used in the hand, and is therefore not quite so convenient for rough work as the Abney. On the other hand, being fitted with a sensitive bubble it is good enough for accurate work, which probably accounts for its popularity.

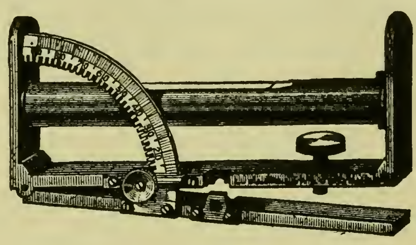


FIG. 136—Bubble clinometer

The **Verschoyle Pocket Transit** (Fig. 137), combines the functions of an Abney level, prismatic compass and clinometer. Only one observation is necessary to obtain the magnetic bearing and the vertical angle of any point. For rapid topographical work and for use in difficult positions this instrument is invaluable.

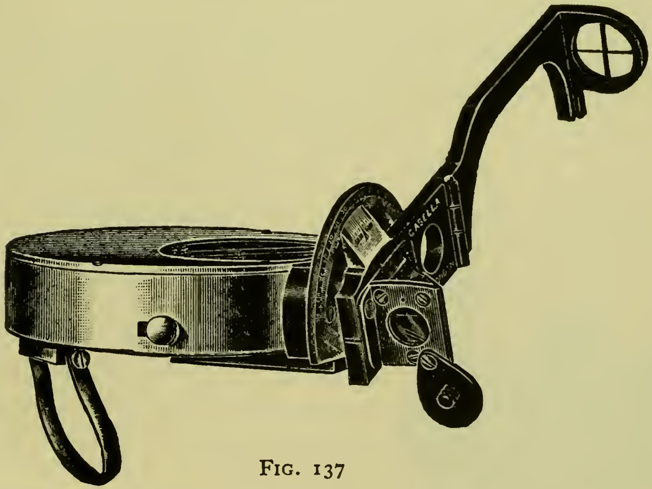


FIG. 137

The Hanging Level.—A very convenient instrument for use about buildings is the hanging level shown in Fig. 138. This consists of an ordinary spirit level fitted with two hooks adjusted to be parallel to the run of the bubble. When hung at the centre of a fine fishing line, one end of which is fixed to a stake, pegs may be set up level in the ground very quickly by quite inexperienced labour, or by the use of a levelling staff or graduated rod grades for drainage purposes may be easily laid out. For such work as the foundations of a house or the levelling up of a tennis lawn, the pegs may be set without difficulty to within 10 minutes of arc, which is a considerably better result than that ordinarily obtained with the usual straight edge and mason's spirit level. On a calm day and in skilful hands results to double this accuracy may be expected.

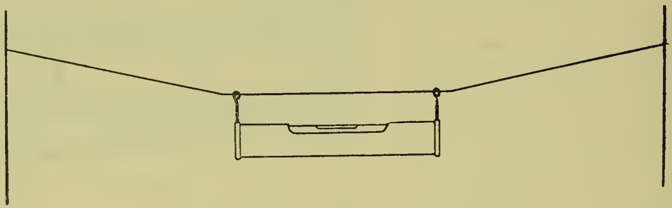


FIG. 138—Hanging level

Prismatic Compass

The prismatic compass is universally popular for preliminary surveying and exploring. The most usual size has a divided ring of $3\frac{1}{2}$ inches in diameter divided into half degrees. Fig. 139 shows the ordinary form taken by this instrument, from which it will be seen that it consists of a flat circular box to contain the divided circle. Across the diameter of this ring a flat permanent magnet is fixed, having its centre pierced to take a jewel. The ring is accurately balanced about this centre, and a small sliding weight is fitted to the magnet to adjust for dip. In front of the box a magnifying right-angle prism is fitted and held in a small dovetailed slide which allows this prism to be raised or lowered in order to bring the divided circle accurately into focus. The prism box is hinged so that it may be folded back when replacing the cover used to

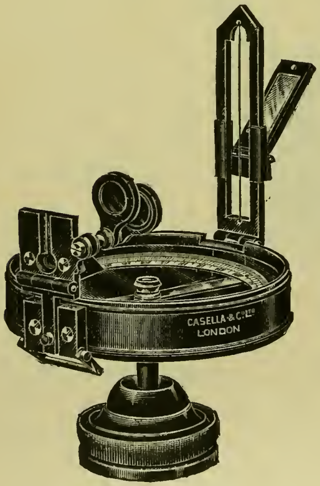


FIG. 139

protect the glass during transport. Above the peep hole of the prism a slit is cut so that the surveyor can bring the vertical wire shown at the back into line with the target and the prism, and at the same time read the divided circle. The vane at the back carrying the wire can be folded down on to the glass before replacing the cover, thus rendering the whole instrument quite portable and free from any danger of accidental damage. A hinged sliding mirror is fitted to the vane as shown and a pair of dark glasses may be swung in front of the prism slit. This enables the user to take sights on to the sun at any altitude and thus the bearing of any object in relation to the sun may be determined with the greatest ease. When the vane is folded down for packing, it engages with a small vertical pin, which, acting on a lever, lifts the magnet off its pivot and locks the ring against the glass cover. A small finger piece is fitted in the side of the case, which operates a friction brake, thus allowing the user to stop and steady the oscillations of the ring when about to take his readings. A screwed socket is fixed to the outside of the bottom of the box, so that the instrument can be used on a tripod stand. The tripod head shown is fitted with a ball and socket joint for levelling purposes, the centre of the ball portion being pierced to take a small taper axis, thus allowing the whole instrument to be rotated in azimuth.

As the compass leaves the hands of the maker it is generally in good adjustment, and the user is seldom, if ever, called upon to make any alterations to the original settings. In fact there is hardly anything he can do to correct any apparent errors, and the whole instrument is so simple that the only adjustments likely to be required are those due to serious damage which would necessitate its return to the maker for repair. There are only two tests which the surveyor need make (a) to determine the index error and (b) the accuracy with which the needle comes to rest. The index error (a) can easily be obtained by a few settings on known marks, and (b) by repetition on the same mark. If the needle does not always take up the same position it shows that either the pivot point has become blunt or that the jewel has been damaged. The blunting of the point is the only damage which is likely to occur, and care should therefore be taken that the sighting vane is folded down and the needle lifted off its point whenever the instrument is being carried from place to place. The prismatic compass is sometimes combined with a clinometer, an example of this type being shown in Fig. 140. The cheaper instruments have cardboard dials instead of aluminium.

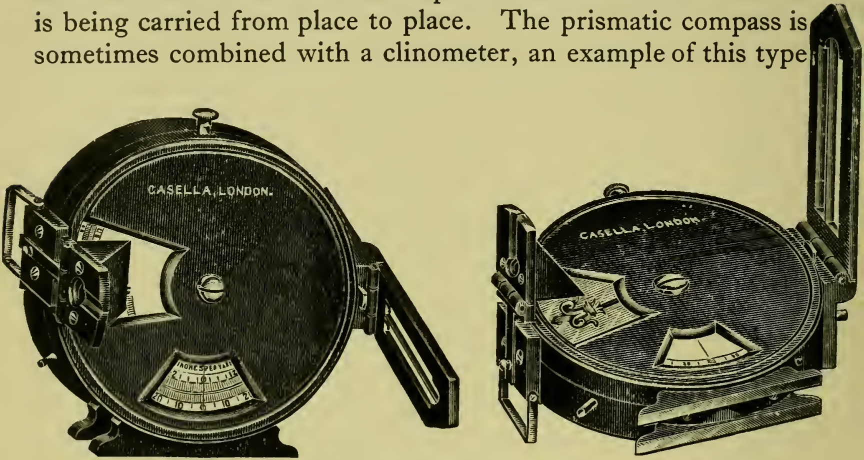


Fig. 140—Prismatic compass and clinometer

Fig. 141 shows the type of prismatic compass used by the military services. It is similar to that already described, except that the sighting line is ruled on a glass disc fastened in the lid and an outer divided ring is fitted to enable bearings to the magnetic meridian to be laid off. The instrument illustrated is of the type in which the card floats in liquid. This is a much better form than the usual pattern, but is of course rather more expensive. Its main advantages are that it is rather more sensitive owing to the reduced weight on the pivot, and that, as it is practically dead beat, the readings may be taken in much less time. Most of

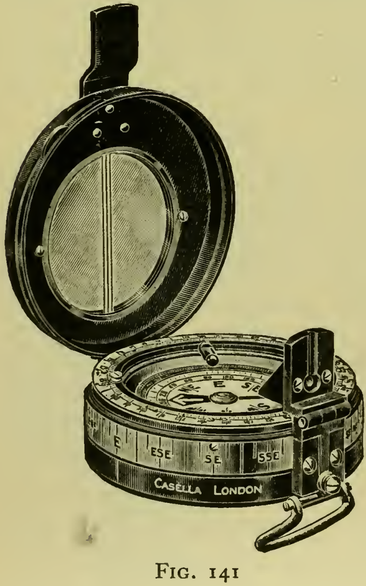


Fig. 141

these liquid compasses can have their dials painted with radium compound to enable readings to be taken at night, without the necessity of other illumination—an obvious advantage for military purposes.

Pocket Altazimuth

This useful pocket instrument shown in Fig. 142 consists of compass and clinometer rings pivoted in a case so arranged that the divisions of these rings can be seen in the ocular at the same time as the distant mark. The telescope can be focused for distant objects in the ordinary way and the oscillations of the circles damped by finger pieces. The small buttons shown on the top of the case serve to lock the two pivoted rings when they are not in use. The instrument can be screwed to a stand when required, and owing to the help of the telescope, rather closer settings can be made with it than with the ordinary compass or clinometer. By the use of the ball and socket head of the stand, rough determination of altitude may be made;

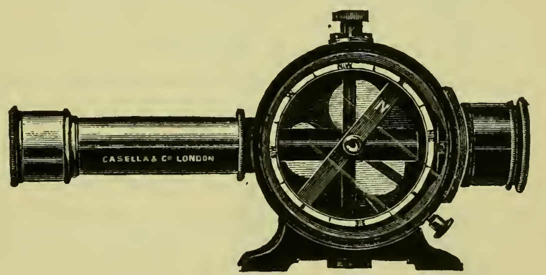


FIG. 142—Casella's altazimuth and clinometer

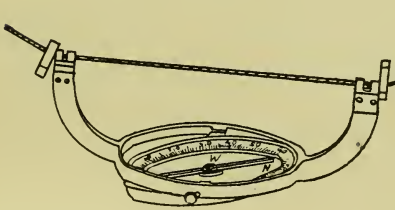


FIG. 143

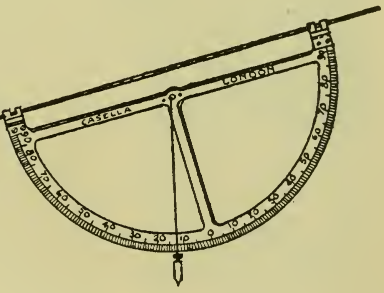


FIG. 144

Hanging compass and clinometer

azimuth can, of course, be determined by means of the compass, and levels or grades by the clinometer.

Fig. 143 shows a type of compass largely used on the Continent on mining work. Its method of use will be evident from the illustration and is similar to that given for the hanging level.

Fig. 144 is a clinometer which may be used in the same way for measuring grades and is extensively employed for this purpose, especially in underground work, as it can be operated quite successfully by the foreman in charge of the working gangs.

Trocheameter.—When it is required to measure distances in an approximate manner along a road or over ground which can be traversed by a vehicle, an instrument to count the revolutions of the wheels is found to give sufficiently good results for many purposes. Fig. 145 shows a useful form of counter of this nature. The rectangular metal frame is fixed to the wheel spokes by means of leather straps or cords, and thus revolves with it. A heavy weight, having a pair of worm wheels pivoted at its centre, is carried on a fixed central spindle. As the metal frame and spindle revolve, this weight hangs down and does not take part in the revolutions of the wheel. The spindle has a worm formed at its centre which gears into the two worm wheels shown. As the metal frame revolves, the worm wheels carrying the graduations are turned round their axes, the number of revolutions being read on the divided circle engraved on the front wheel, against an index fixed to the weight. These two worm wheels run on the same spindle and both gear into the same worm, but as the front one has 100 teeth and the back one 101, the back one will lag behind the front by one tooth in every 100 revolutions, the relative movement of the wheels being shown on a circle of 100 parts

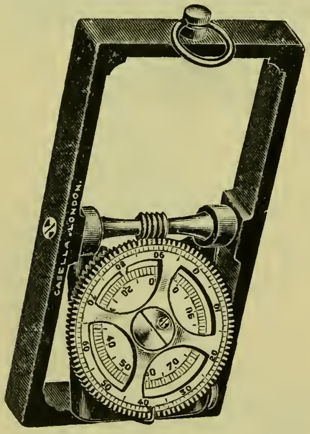


Fig. 145—Trocheameter

engraved on the back wheel and read against an index fixed to the front one. This very simple and ingenious mechanism is, as will be seen, capable of recording every revolution up to 10,000 and then repeating. Another device operating on the same principle is the **perambulator** shown in Fig. 146, the wheel of which is generally made 6 feet in circumference and registering up to 100,000 yards or a corresponding amount in metres or links.

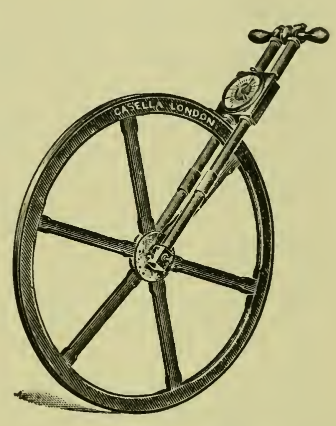


FIG. 146

Another instrument used for a very rough approximation of distances is the watch form of **pedometer** shown in Fig. 147. Inside the case is a heavy weight pivoted at the end of a short arm and held slightly above the horizontal by means of a light spring. At each step which the pedestrian makes, the weight descends and moves forward a small ratchet wheel by means of a click attached to the arm of the weight. These oscillations are totalised on the dial which is engraved to read to 100 miles or kilometres. It is necessary of course, for each user to check the pedometer over a measured distance and to find the correction which he should apply to convert his paces into miles. Some instruments have an adjusting screw which allows the weight to take up more or fewer teeth, thus enabling the user to set the pedometer to agree approximately with the length of his step. It is better, however, simply to count the number of oscillations made, as the means of adjustment are generally not sufficiently fine for the purpose of direct conversion into distance.

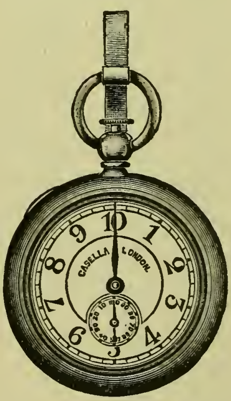


FIG. 147—Pedometer

CHAPTER IX.

LEVELLING STAVES

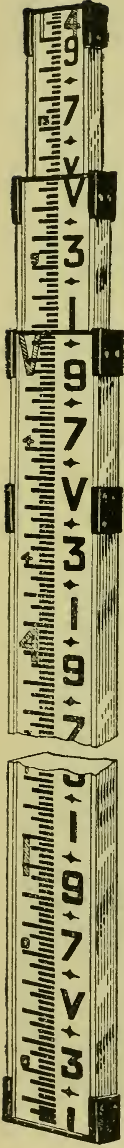


Fig. 148

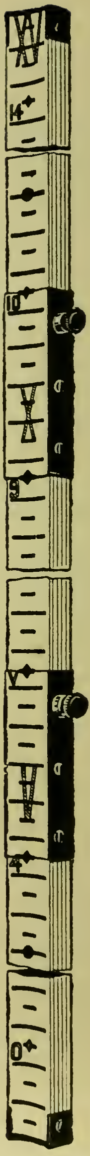
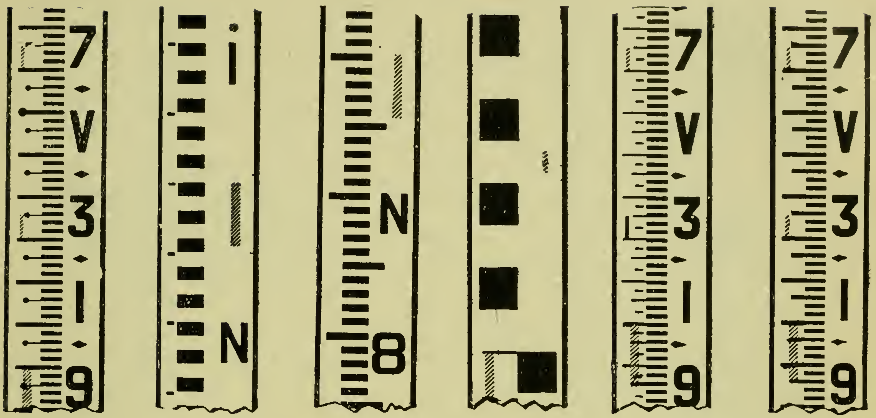


Fig. 149
Folding
levelling
staff

THE levelling staves or graduated rods used by surveyors are of two kinds, viz., the self-reading and the target rod. Fig. 148 shows the usual pattern of self-reading staff employed to-day. It is made of mahogany in the form of a hollow rectangular box for the two bottom sections and a solid slide for the top part. When the three sections are closed the length is usually about 5 feet and when extended about 14 feet. They may be obtained with a total length of from 6 to 16 feet. Each section, when extended, is held in its proper position by a spring clip, and care should be taken to see that these are placed accurately and fit without shake as otherwise errors, difficult to trace afterwards, will be introduced into the readings. A great many designs for the divisions and figures have been produced, but there is very little difference in the actual accuracy of setting obtained by any of them. It is largely a question of taste and a surveyor after a few hours' practice with a new form of marking becomes quite at home with it. Sometimes the figures are inverted in order that they may appear the right way up in the field of an inverting telescope. An example of this is shown in F.I., Fig. 150.

Sometimes the staff is made in two pieces of solid rectangular section arranged to fold in the centre (Fig. 149). This is a very good form but it is not quite so well balanced nor so stiff, and when made longer than 14 feet is rather unwieldy. Its main advantages are that it is not so expensive and that when folded for transport the painted graduations are protected from accidental damage.



A
Feet, Tenths, & Hundredths.

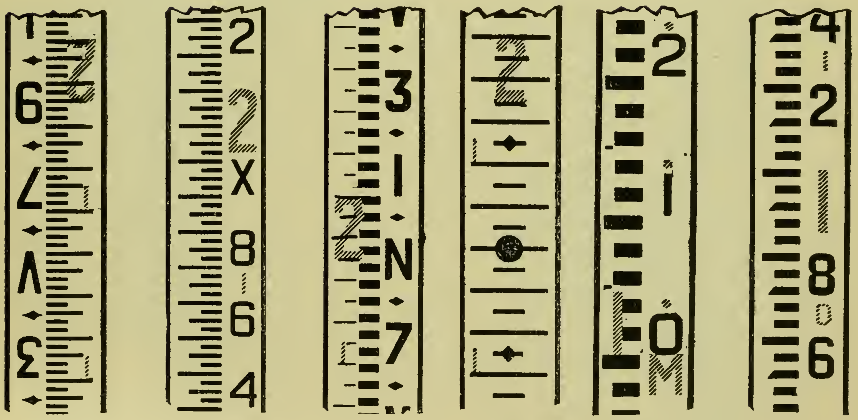
B
Standard Metres, Decimetres & Centimetres.

C
Metres & Half Centimetres.

D
Feet & Tenths.

E
Feet, Tenths & Hundreths

F
Standard Upright Sopwith, Feet, Tenths, & Hundredths.



F. I
Standard Inverted Sopwith, Feet, Tenths, & Hundredths

G
Feet, Inches, & Eighths.

H
Feet, Tenths, & Fiftieths.

K
Scotch Reading, Feet, Tenths, & Twentieths

M
Metres & Centimetres

P
Stadia Reading, 1 in 100, Feet, Tenths, & Fiftieths.

FIG. 150—Levelling Staves, specimens of various staff readings.

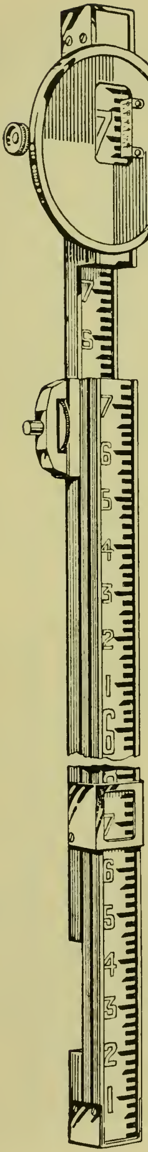


FIG. 151

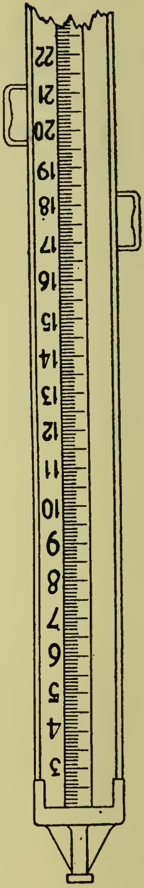


FIG. 152—Precise levelling staff

In America the target levelling staff is very extensively employed, Fig. 151 showing one pattern known as the Philadelphia rod. This rod as generally made is 13 feet long when extended, the upper portion carrying a coloured target which may be accurately set to the graduations by means of a vernier. These rods are very neat and light and settings on the target may be made with great accuracy even at distances where the graduations on the self-reading staff would be indistinguishable. For long sights they are indispensable, but it of course requires two expert operators to run a level on this system and it is now generally considered better to take a number of short sights rather than one longer one, owing to the errors introduced by atmospheric refraction. Fig. 153 shows a triangular metal plate which is placed on the ground to serve as a turning point for the staff. For precise levelling the staves already described are not sufficiently accurate, and the pattern shown in Fig. 152 is the one usually employed. This is fitted either with a circular level bubble or a plumb line to enable the rod man to hold it exactly upright. It is usually made 10 feet long from well-seasoned and varnished mahogany either solid or made up of three separate pieces, glued and screwed together. A groove is made on the front face in which a strip of invar about 1 inch wide is stretched. This strip is fixed only to the metal shoe at the bottom, thus allowing for expansion of the staff. The face of the invar is engraved with lines either 1 cm. or 1/100 foot apart, with the corresponding figures painted on the wooden face. The bottom of the metal shoe is fitted with a hardened steel disc about 1 inch in diameter. The turning point on which it is used is either a round headed metal peg driven in to the ground or, when the levelling is being done along a railway line, the rail spikes or chair bolts are used for this purpose. In the U.S.A. and Canada, all precise levelling is, whenever possible, carried out along the railway track, owing to the convenience of transport for the surveying parties and the ease with which the work can be carried out on these comparatively level lines. Precise levelling is always repeated from the opposite direction, and unless the results agree within the prescribed limits, the whole of the work is done over again. Two staves are always employed with the level set up midway between them, and comparatively short sights are the rule, never in any case exceeding 450 feet. Particulars of

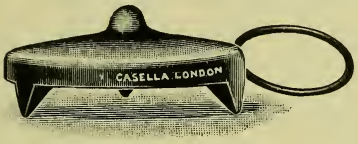


FIG. 153—Foot plate for levelling staff

FIG. 154—Circular spirit level for levelling staff

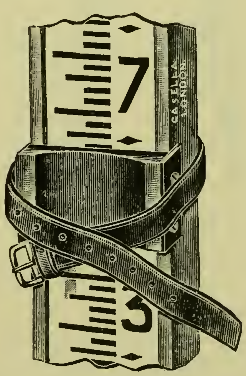


FIG. 155—Staff protector.

the accuracy aimed at are given in the chapter on geodetic work, in which reference is also made to the theodolite method of taking levels.

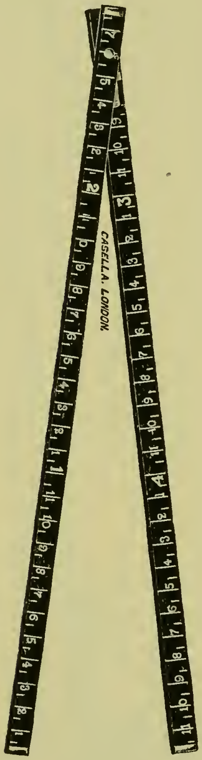


Fig. 156a—Surveyor's 5 ft. folding rod.

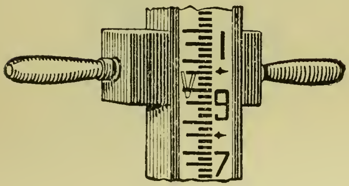


Fig. 156—Holder for levelling staff.

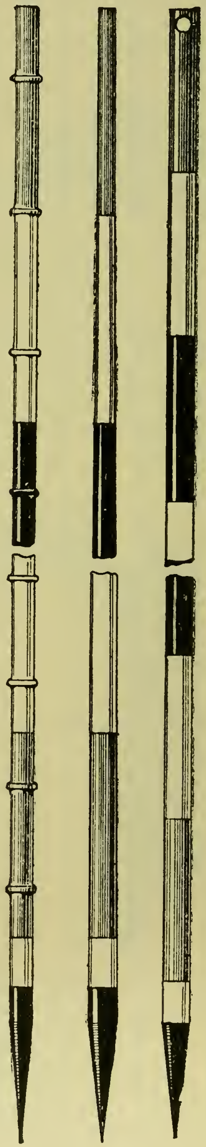


Fig. 156b—Ranging poles.

CHAPTER X.

PHOTOGRAPHIC SURVEYING

PHOTOGRAMMETRY may be defined as that branch of technical applied science which is concerned with the determination of the forms and dimensions of objects from photographic pictures of those objects. A photograph which is free from optical or mechanical distortion is in truth a perspective pure and simple, and all the laws and principles of perspective are applicable to the interpretation of such photographs.

For the correct interpretation and use of perspectives for measuring purposes it is necessary not only that they should be true geometrically, but we must know or ascertain by some means a number of particulars concerning each perspective. Especially is it necessary to know :—

(1) The position of the spot from which the perspective was obtained (station).
(2) The picture plane.
(3) The orientation of the view.
(4) The trace of the principal plane.
(5) The trace of the horizon plane.
(6) The principal point (intersection of) (3) and (4).
(7) The length of the distance line, which in the case of a photograph is the working focal length of the lens.

Various instruments have been specially designed to give true photographic perspectives always in a vertical plane and at constant distances and furnished with specially designed mechanism inside the camera for recording on the negative all or nearly all the information necessary for interpreting the picture.

The practical advantages which result from having the necessary data for interpretation recorded on the face of the picture instead of in separate note-books, are very great. Risks of error and confusion are very much reduced. Much time is saved both in the field and in the office. Plotting operations are rendered more easy, certain, and accurate, and the pictures will be more valuable as permanent records for future reference.

The theory and the methods of photogrammetric measurement are not at all new. They were fully expounded more than forty years ago by Col. Laussedat, *Directeur du Conservatoire des Arts et Métiers*, Paris. Also from time to time there have been many photographic surveys made in many different countries over limited areas and with excellent results, but it has been reserved for the Canadian surveyors under the guidance of the late Mr E. Deville, Surveyor-General, to demonstrate on a very large scale, and finally and conclusively that for hilly and mountainous districts the photographic method is superior to all others. It has been proved to be very much quicker and cheaper than any other known method and more convenient and at least as accurate.*

Some of the special advantages of the photographic method may be epitomised as follows :—

(1) It is often possible to obtain photographic pictures of places for surveying purposes which it would be quite impossible to survey by any more ordinary means, e.g.:—(a) In many exposed mountainous regions where the weather is generally unsettled and uncertain with only occasional fine periods ; or when so much time is of necessity consumed in travelling to and returning from a surveying station that it is impossible to spend much time at the station. (b) For military purposes in an enemy country. (c) When a traveller is compelled by circumstances to traverse unknown country at a rapid pace ; and speaking generally wherever and whenever it is possible to obtain occasional clear views from spots visited, but not possible to stay for any length of time at those spots or to revisit them. In all such cases the photographic method is the best because it is the only effective one.

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* Deville has shown that in Canada the cost of a photographic survey by methods heretofore in use is considerably less than one-third of the cost of a plane table survey.

(2) Photographs contain an amount of detailed information concerning the country photographed, which it is quite impossible to gather from notes of observations and sketches alone, so that in all cases they may be of great practical service ; not only for checking observations made and noted in the field, but also for supplementing those observations and filling in details which had escaped notice.

(3) Frequently it happens that preliminary experimental surveys are required for irrigation purposes or for ascertaining the best routes for roads or railways. In such cases it is often excessively difficult, if not impossible, to decide at the outset how much plotting will be necessary for the purposes immediately in view. If a series of observations taken and noted turn out to be insufficient, it may be necessary to revisit the stations for further observations. If, to be on the safe side, a tolerably exhaustive detailed survey is made in the first instance, it may turn out afterwards that the whole of the labour has been wasted, so far as the particular purpose in view is concerned, because the ground surveyed has ultimately proved to be unsuitable. In either case there will be waste of valuable time, and in every case where a complete detailed survey has not been carried through in the first instance, it will always be necessary to make such a survey after a general plan of construction has been decided upon.

With photographic surveys there need be little or no waste of time from such causes. A fairly complete series of photographs can be taken in the first instance in less time and at less cost than would be required for the most cursory preliminary survey, and these photographs will afterwards serve all purposes, not only for plotting preliminary surveys, but also for filling in details whenever and wherever a precise knowledge of detail is required.

The main elements of difficulty which affect the subject of phototopography may all be conveniently ranged under two heads :—

(1) The difficulty of obtaining sufficiently good photographs suitable for mapping purposes.

(2) The difficulty of constructing maps from these photographs.

The difficulties under the first head may be further subdivided under two heads as follows :—

(a) Those of a purely photographic nature.

(b) Those incidental to the choice of suitable stations.

The purely technical difficulties under (a) may be conquered by a preliminary training on the part of the persons who are concerned in producing the photographic pictures. Clear, well-defined pictures and, therefore, properly exposed plates, are essential to success, so that great care must be taken in the actual manipulation of the camera at the stations, as otherwise much valuable time may be lost if any of them have to be reoccupied. The difficulties under (b) can only be conquered by experience on the part of the surveyor in charge of the operations, and the choice of stations, and the proper orientation of the camera must be skilfully carried out if the actual work of constructing the map in the office is to be done expeditiously. The actual number of pictures which should be taken from each station will vary with the character of the country being surveyed, and from the point of view of economy, this number must be reduced to the utmost. When known triangulation points can be included in the picture, the stations must be so chosen that as many of these points as possible may be observed from each station and that the same points may be photographed from at least two, or better still, three stations. The problems met with are similar to those which the surveyor encounters in any other form of topographic work, but more forethought is generally required owing to the fact that the results are not immediately obtainable as they are, for example, in plane tabling, and that mistakes are therefore not easily rectified. The greatest difficulties, however, are those under (2). The construction of the maps from the photographs entails a great amount of labour and requires considerable practice, and those charged with this work, being office men and not generally familiar with the country being mapped, have to rely on the pictures for all their information. This is a great handicap, and unless the photographs are technically perfect and properly identified by records of their orientation, etc., the construction of the map becomes extremely difficult, if not impossible. The various methods used in the plotting of the maps are very fully dealt with in E. Deville's book on "Photographic Surveying" and by Flemer in "Phototopographic Methods and Instruments" to which the reader is referred.

Bridges Lee Photo-Theodolite

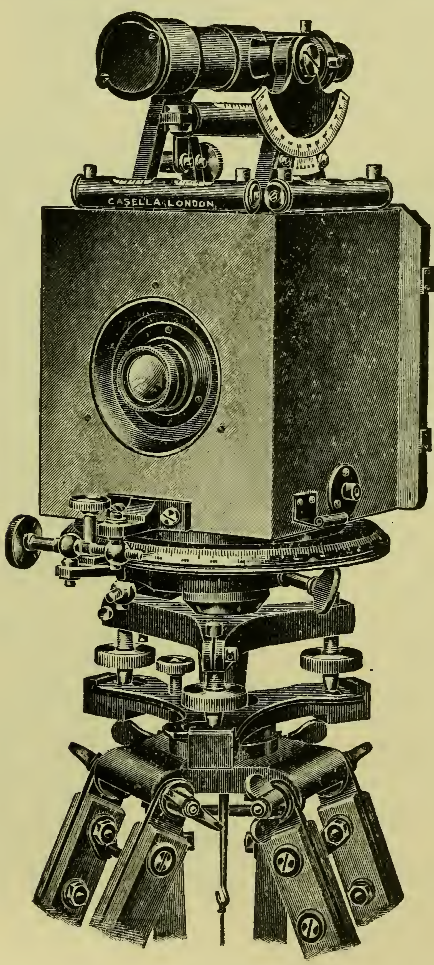

FIG. 157—Photo-theodolite

Figs. 157 and 158 show the Bridges Lee photo-theodolite, a very popular and compact instrument, which has been used with great success in many parts of the world. It consists of a rectangular box made of aluminium, to the front of which is fixed the lens, the back portion having a frame arranged to take dark slides of the usual form. The ground glass screen shown may be used to examine the field of view, but no focusing arrangement is fitted, it being necessary of course to take all the pictures at a fixed focus. Inside the camera box a rectangular frame carrying a pair of cross wires is fitted on a horizontal slide and

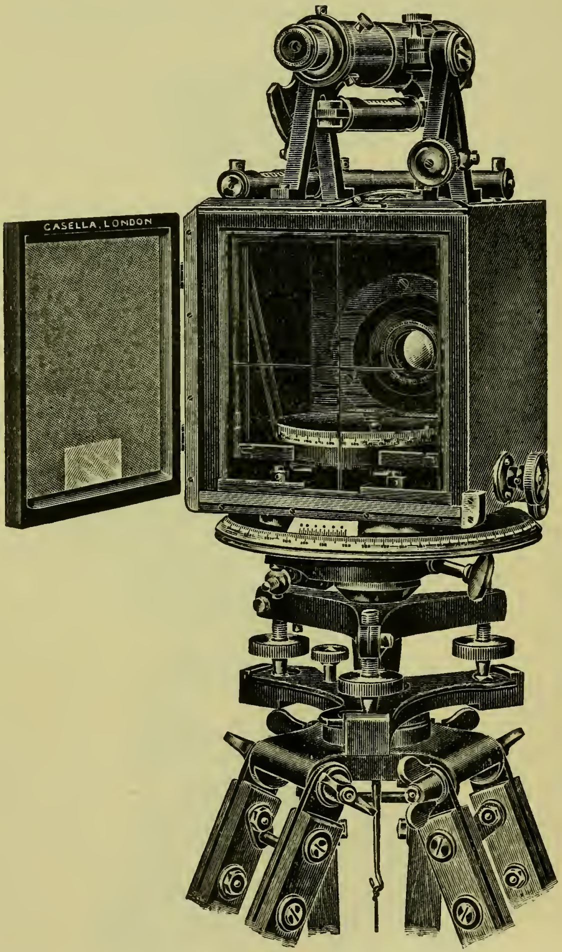

Fig. 158—Photo-theodolite

geared to a pinion, the milled head of which may be seen on the right in Fig. 158. This frame may be moved out or in, in a direction parallel to the axis of the lens. When the dark slide is placed in the camera and its shutter withdrawn, this frame may be racked back until the cross hairs touch the photographic plate. When the exposure is made, a trace of the position of these hairs is made on the plate, thus defining the median vertical plane and the horizon of the instrument. A circular compass having a transparent scale is pivoted on the base of the moving frame in such a position that its graduations are also traced on the plate. There are also two small recesses in the back of the frame into which slips of celluloid may be inserted. On these may be written any information the operator may desire to record on the picture. A telescope is fitted to the top of the instrument, and the whole apparatus being mounted on an axis may be revolved in azimuth under the control of the divided horizontal circle and vernier shown. The instrument may therefore be used as an ordinary theodolite for taking angles in altitude and azimuth. The stand, which is made very strong and well-braced, is generally only about 3 feet high, and, as great stability and freedom from vibration are essential, it is usual to hang a net or sheet from the three legs. A quantity of earth or stones may be placed into this net, thus holding the whole apparatus down very firmly. The adjustments of this instrument are simple, it being only necessary to arrange that the line of collimation of the telescope is truly placed with relation to the axis of the instrument, that the plate stands truly vertical and that the intersection of the cross hairs on the back frame is truly in the axis of the photographic lens. These latter points are fixed by the maker, and owing to the solidity of the box and the mounting of the lens, should never need adjustment.

Spirit levels are fitted in the usual way to allow of exact levelling of the instrument.

Canadian Surveying Camera

Figs. 159 and 160 show the type of surveying camera due to Deville and largely used by the Canadian Government for survey work in the Rocky Mountains. This instrument is very similar to the Bridges Lee photo-theodolite, but carries no telescope or compass. The azimuth and compass bearings are taken at the camera station by a separate theodolite, which may be fitted on the camera stand, and no arrangement is made for recording this information on the photographic plate itself. The camera proper consists of a rectangular metal box closed at the front in which is affixed the lens. This lens is adjusted to be at its correct focal distance from the back edge of the box. An outer sheath made of mahogany carries the dark slide. When this slide is inserted in the slot shown at the top of the camera and its shutter removed, the back portion of the mahogany sheath may be screwed forward by means of the thumb screw shown at the back of the camera. In this way the photographic plate may be pushed forward until it comes in contact with the back of the metal part of the camera, and is thus in the exact focal plane of the lens. The opening against which the plate presses is slightly smaller than the plate, and carries four notches, one on each of its sides. These notches are placed exactly on the horizon and vertical lines and show up clearly on the negative when it is developed. In cameras of this type it is important that the photographic plate should stand truly vertical when making the exposure. This is insured by bringing the spirit levels exactly to the centre of their runs just before exposing the plate. The method of adjusting the level is as follows :—

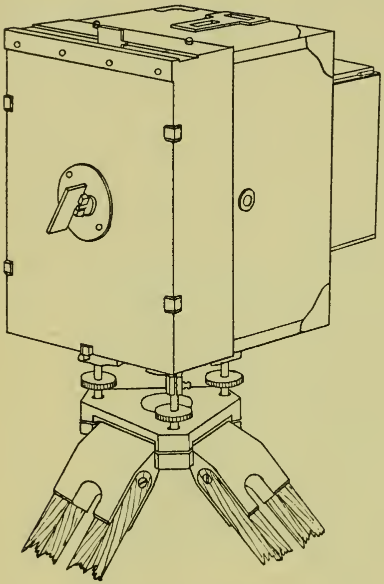

FIG. 159—Canadian pattern photo-theodolite

A sheet of glass blackened on one surface is clamped against the notched frame at the back of the camera in the exact position which the photographic plate is to occupy. A theodolite is then set up in front of this glass and the image of a distant point brought into coincidence with the telescope diaphragm. The theodolite is then turned in azimuth and set on to the image of the same point as seen reflected from the sheet of glass. If the webs do not now coincide with the point, the camera is tilted by means of its foot screws until perfect contact is made. The glass plate and therefore the back of the camera will now be vertical. It is then only necessary to adjust the bubble to the centre of its run so that it can then at any time be used to control the verticality of the photographic plate.

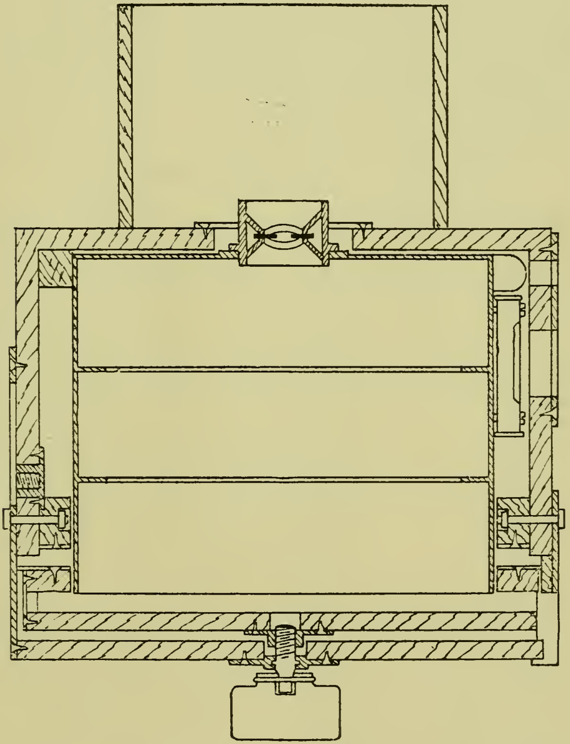

FIG. 160—Section of Canadian surveying camera

The transverse bubble which serves to control the horizontality of the horizon line is usually adjusted by the maker, but its truth may be checked by taking photographs of a natural horizon line or of points the levels of which have been determined by means of a theodolite.

Various types of photo-theodolites have been made, and are in use, and in some of these the arrangements are such that the pictures may be taken at any angle to the horizon. This has many advantages in certain territory, but the labour and the mathematical computations involved in the production of the maps are very much greater in this case than when all the pictures are taken with the plate vertical.

Stereo-photographic System

Another method which has come into use to a considerable extent in recent years is the stereo-photographic system. Fig. 161 is a diagram which will serve to show the principle upon which this method is based. L and L_1 are the positions of the camera lens, when the instrument is placed for the purpose of taking the photographs at the ends of a measured distance B. The two photographic plates are shown by thick lines at the distance f, from the lens, f being the focus of this lens. The camera positions are such that the plates stand vertical and in the same plane. A line drawn from a point P at infinite distance, through the lens, will therefore meet the two plates at their centres, viz., at P_1 and P_2. On the other hand, a point d at some shorter distance will still meet the left hand plate at P_1, but will meet the right hand plate at d_1, instead of at P_2. If, therefore, we measure the distance P_2 d_1 we can calculate the required distance D from the similar triangles d P_1d_1 and $L_1P_2d_1$, the values of f and B being known. The height of the point d above the camera horizon

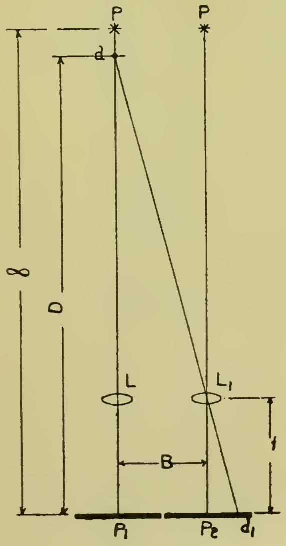

FIG. 161

may be obtained in a similar way. This method was first suggested by Deville for use in Canada where a large amount of very successful photographic surveying work has been carried out.

In practice when using this scheme, pairs of photographs are taken at the ends of a measured base line in parallel directions and with the plates vertical. These photographs can then be measured by means of a special instrument known as a stereo-comparator or plotted directly from the plates by the use of a stereo plotter. It is obvious that great accuracy in the setting of the camera is essential when using this method, as want of parallelism of the plates when they are being exposed leads to large errors in the measurements. The dry plates usually employed are those of the orthochromatic variety and when these plates are used in conjunction with suitable dense orange screens the amount of detail and clearness of the various distant points is remarkable. When transparencies are made from these negatives, the contrast is very striking, and very fine settings may be made under the microscopes used during the plotting operations. When the Bridges Lee instrument is to be used in this way the telescope is mounted at a right angle to the position shown in Fig. 157. It is arranged to transit and is so adjusted that its line of collimation is accurately parallel to the plate and therefore to the picture plane of the camera. Two tripod stands are employed and are set up at the ends of the measured base line, as shown in Fig. 162. The camera is erected on one of the stands and levelled up in the usual way. A

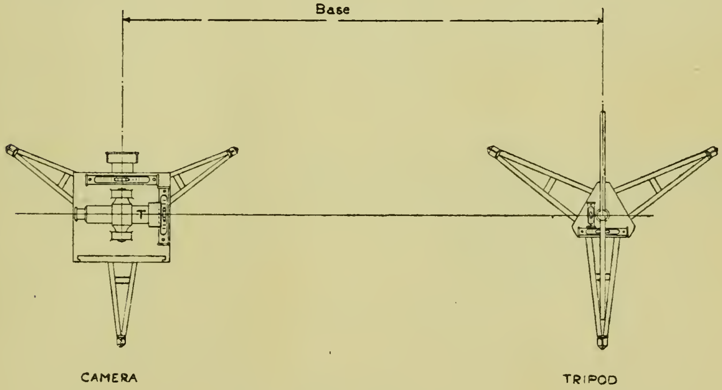

Fig. 162

target, consisting of a small vertical pointed rod is fixed to the other stand and the telescope wires are brought to cut this target exactly. If the camera is in adjustment the plate will now stand vertical and will be parallel to a line joining the centres of the two stands. After the plate has been exposed, the camera and the target are interchanged on the stands and a similar setting made. Another plate is now exposed so that we then have two pictures taken at a measured distance apart and in parallel directions. The measurement of the base line is usually made by means of stadia or subtense readings on the telescope, as in mountainous country it is not often possible to measure these bases directly by means of a tape or chain. For the purpose of making these measurements, a short target or divided rod is supported horizontally on the distant stand so that the base length can be measured just before taking the first picture, see Fig. 163. When the camera is transferred to the opposite end, a check measurement may be made when desired by transferring the stadia rod to the stand first occupied by the camera. The time required to take the pictures by this method is very much greater than in the older system, owing to the time consumed in setting up the camera and measuring the base lines, and some difficulty is experienced in certain cases in finding suitable stations. It is often only possible to take one photograph per station and it is rare that suitable bases can be laid out to enable more than three pictures to be obtained from any one point. When more than one picture is to be taken at a station, it is necessary to have additional tripod stands; one at the end of each base which has to be laid out.

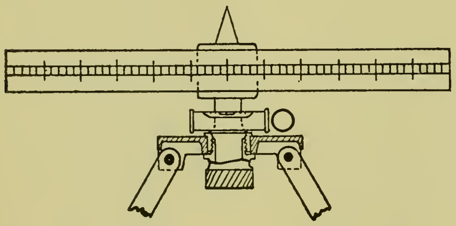

FIG. 163

There are two chief methods used when constructing a map from the stereoscopic negative (1) by means of a stereo-comparator and (2) by the use of that instrument in conjunction with a special plotting attachment.

The Stereo-comparator

This instrument, which is the invention of Dr Pulfrich, makes use of the effect of stereoscopic accommodation to combine the images of the two views in the well-known manner, so that instead of separately setting pointers on to the same feature on each picture, a single setting can be made, thus reducing the time necessary to carry out the work and at the same time increasing the accuracy of the results. Fig. 164 is a diagrammatic view of the stereo-comparator. A is the main base carrying the whole apparatus. A slide B, which is fitted into this base can be moved along it by means of the hand wheel and screw C, the amount of its movement being measured on scale S_1. Another slide, D, is fitted into B and can be moved by the screw and hand wheel F, its position in relation to B being read off on scale S_2. A casting supported on the base A, carries the slide S to which the binocular microscope shown is fixed. The whole microscope may be moved at right angles to the plane of the paper on the slide S ; a and b are the two photographic plates carried as shown, a being fixed to and therefore moving with slide B, while b is fixed to slide D. It is evident therefore that screw C will move the plates a and b together while screw F will alter the distance between a and b. The interocular distance of the microscope eyepieces may be adjusted and the focus of the object glasses may also be adjusted to the proper distance from the plates a and b. A pair

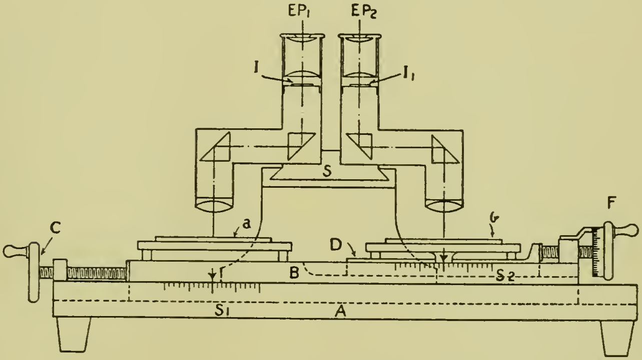

FIG. 164—Stereo-comparator

of indices I and I_1 are placed in the mutual focus of the object glasses and the eyepieces, the appearance of these in the field when viewed together being shown in Fig. 165. The scale S_1 is called the azimuth scale ; S_2 the parallax scale and a scale attached to slide S, the height scale. The method of using the apparatus is as follows :—

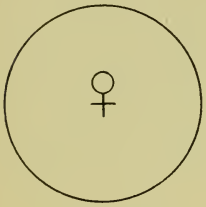

Fig. 165

The object glasses are first set by the operator to correct focus and each eyepiece adjusted to its index in order to eliminate parallax in the usual way. The eyepieces are then set at the interocular distance of the observer thus combining the indices I and I_1, stereoscopically to form a single image. The screw C is now moved until when using the left eye only the principal line impressed on the left picture coincides with the index I. A similar adjustment is made on the right picture using the right eye only. On looking through the microscope the indices will be combined and will appear to be suspended over an object at infinite distance. If the plate b is now moved by means of the screw F, it will be possible to bring the index gradually nearer until it appears to be suspended over any object desired. The amount of movement necessary to effect this will be shown on the scale, S_2, and is evidently equal to the parallax of the point ranged upon. As the focal length of the camera lens is fixed, and as the length of the stereo base between the two camera positions is known, the graduations of the scale can be converted directly into terms of horizontal distance by the application of a suitable constant. The objects as seen by the microscope will stand out in sharp relief, owing to the exaggerated effect given by the long stereoscopic base which was used when taking the pictures, so that the index may be set very easily and accurately on to the selected points. Any number of points may be measured in this way, and points of equal height may also be determined, thus allowing contour lines to be readily obtained. When a sufficient number of points have been tabulated, the map may be constructed with much greater ease and accuracy than in the older method of intersections, where at least three measurements must be made to fix any one point as against one pointing only in the stereo-comparator. A special drawing board is used for the actual plotting of the points, but it has been found best to have two operators, one to use the microscope and the other to do the plotting. The work even then is rather trying and laborious and mistakes are liable to occur in the transference of the data from the observer to the draughtsman. To obviate this latter difficulty, Capt. Vivian Thompson of the School of Military Engineers at Chatham, devised an instrument which he calls a stereo-plotter, a description of which may be found in the Journal of the Royal Geographical Society, for May, 1908. In this instrument the slides B and S are connected by gearing to two arms which are pivoted at one end to a special drawing board placed alongside and in line with the comparator. These arms therefore move over the board through angles depending on the distance over which the slides are moved. Another slide can be moved by hand at right angles to control the position of these arms, i.e., vertically, and may be set at any point on a scale graduated to suit the stereoscopic base. When the reading of any point given by the scale S_2 is set on this drawing board scale the position of that point may be plotted on the paper without further calculations. An instrument of this description reduces the time required to plot the map very considerably and also reduces the possibility of mistakes in the identification of the points in the different pictures.

Stereo Plotter.—Captain Thompson has suggested an improved form of his apparatus in which all the plotting is done automatically without reference to any scales, but up to the present an actual apparatus does not appear to have been constructed by him. In 1911, however, Lieut Ritter Von Orel, who was in charge of the photogrammetric department of the Military Geographical Institute at Vienna, invented a completely automatic plotter for use in conjunction with the stereo-comparator. In this instrument the three slides of the comparator are connected up by linkage motions to suitable arms which move over the drawing paper which is placed at the back of the instrument. It is only necessary to set the comparator index on any point of the picture when the arms indicate its true position on the drawing paper. Contours may very readily be drawn by this instrument, as it is only necessary to set the index to any height above or below the horizontal and to follow this height across the various points at the same altitude on the picture.

A full description of **Von Orel's stereo-autograph** has been published in *Mitterlingen A. u G.* 1911, to which the reader is referred for further details.

The main advantage which the stereo-plotter has over the method of plotting by intersection is the greater speed with which the work can be done. By Deville's method of intersections, the plotting of 100 points takes about a week, whereas with the stereo-plotter it is claimed that this number can easily be accomplished in an hour, and by the Stereo-autograph in probably half that time.

Another advantage which the stereoscopic method has over that used formerly is that the identification of similar points in the various pictures is rendered much easier owing to the fact that exaggerated relief effects are obtained and that the points are examined under magnification and can therefore be set very exactly by means of the micrometer screws. There is no doubt however, that the plotting part of the apparatus is the weakest link in the chain and that full advantage cannot be taken of the exactness of the setting which may be made under the microscope.

All these photogrammetric schemes fail when the country to be surveyed is flat and wooded, but when the region to be mapped is rugged or mountainous the stereo method in conjunction with a suitable plotter is undoubtedly superior to all others, both in accuracy and speed. Since the advent of the aeroplane and airship great strides have been made in aerial photography, and a number of surveys have been made with excellent results by means of photographs taken in this way. The chief difficulty to be encountered is the determination of the angle which the plate made to the horizontal at the time the photograph was taken. When the plate is parallel to the ground, the resulting photograph is rather mosaic-like, and can only serve as a rough guide for such purposes as military operations. Owing also to the height of the camera and the consequent fore-shortening, it is impossible to arrive at the altitude of the various points above the general level, and therefore contours cannot be determined.

Photographs on Inclined Plates.—To obviate this difficulty, proposals have been made to take the pictures on plates inclined at an angle to the horizon. If some method could be devised to measure and record this angle at the time the photograph is being taken, the subsequent work in plotting would become easier and more exact. Up to the present no design has been produced which is altogether satisfactory, but no doubt some scheme will shortly be evolved, as the subject is one which is receiving a good deal of attention at the present time. When the photographs are taken on inclined plates, the carrying out of the necessary computations is very laborious and various methods have been proposed, all having for their object the simplification of this work. One scheme is to set up the picture in a camera in front of a special theodolite which is used in the same manner as if it were placed on the camera station. Another is to re-photograph the picture in such a way that it is brought back to the vertical. Hugershoft & Cranz have recently constructed an apparatus on which plotting may be done directly from the actual stereoscopic negatives taken from an airship. It must be confessed that the subject is one which bristles with difficulties, both mechanical and mathematical, but its fascination and its possibilities are so great that developments in the direction of the simplification and precision of the apparatus are sure to take place in the near future.

The best books on the subject to which those requiring fuller details are referred are :—

"Photographic Surveying," Deville.
"Phototopographic Methods," Flemer.
"Mapping from Air Photographs," McLeod.
"Applications de la Photographie Aerienne," Roussilhe.

CHAPTER XI

Apparatus for the INVESTIGATION OF THE UPPER ATMOSPHERE

DURING the last few years great attention has been paid to the study of the upper air and to the conditions of wind, temperature and humidity which are found there. The remarkable extension of aviation has made it more than ever necessary to pay close attention to the air currents over the surface of the earth, and modern military requirements include, even on the battlefield, a meteorological staff and apparatus for assisting them in predicting wind and weather conditions for various purposes.

The meteorological conditions of the upper air are studied either by means of rubber balloons filled with hydrogen or by means of kites. The balloon may be comparatively large, about one metre in diameter, in which case it will carry small instruments recording the temperature and barometric pressure at various heights, or a smaller balloon may be used, not carrying any instruments, whose path in the air is followed by a theodolite self-recording or otherwise. The former are usually called "**pilot balloons**" and the latter "**ballons-sondes.**" The recording instruments carried on the balloons have to be made extremely small and light, for the balloon ascends until the air becomes so rarefied that it bursts, and the skeleton, with the instruments, fall to the ground. As the records have to be obtained from the instruments, after they have fallen, it is very important that these should not be damaged. Owing to the extremely ingenious design of Mr W. H. Dines, F.R.S., these instruments are made so light that they fall comparatively slowly to the ground, the burst balloon acting as a parachute, Balloon meteorographs, as they are called, record only the pressure and the temperature, the trace being made on a light metal plate about the size of a postage stamp. This is first coated with copper, electrically deposited, and then with silver, the object of this being to produce a surface completely free from polishing marks. On such a surface, the scratches made by the hard steel points of the recorders are unmistakable. They are observed and measured by means of a low-power microscope with a micrometer eye-piece and a special mechanical stage.

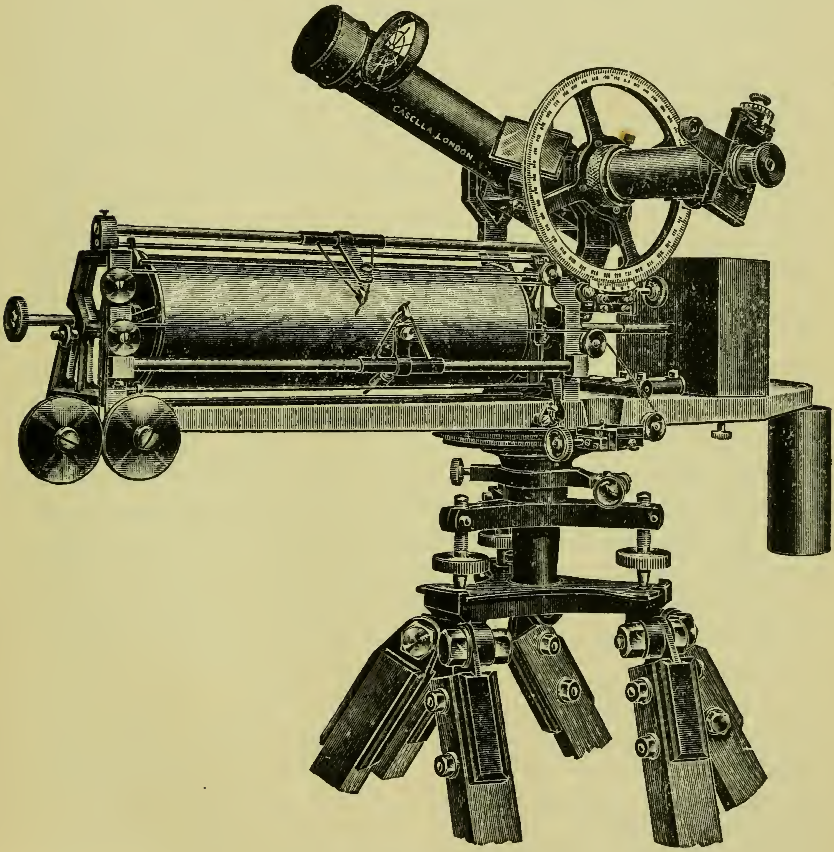

FIG. 166—Recording theodolite

Where kites and kite balloons are used, the recording instruments can be rather heavier and more elaborate, and Mr Dines's and other patterns of meteorograph in such cases record not only pressure and temperature, but also humidity and wind velocity. **The kite meteorograph** is very much larger than the one for balloons, and the records are made not on small metal plates, but on circular paper charts.

The chief method of studying the movements of the air at various altitudes is that of observing the path of a small balloon (filled with hydrogen) which is released from the ground and is followed in its movements by means of a theodolite. Two forms of theodolite are made for this purpose, one being more or less an ordinary theodolite as used by surveyors, and the other being fitted with a clock and drum so that the movements of the telescope in altitude and azimuth are recorded automatically on a chart.

Self-Recording Theodolite.

The appearance and construction of the self-recording theodolite are clearly shown in Fig. 166. The clock is placed at one side of the upright pillar carrying the telescope and vertical circle and drives the horizontal drum on the other side. The telescope is of the right-angle type, the rays from the objective being reflected by a prism so that the observer always looks in a horizontal direction whatever may be the height of the pilot balloon. The aperture of the objective is $1\frac{7}{8}$ inches the overall length of the instrument is 35 inches. The vertical and horizontal circles are $7\frac{1}{4}$ inches in diameter, and carry verniers reading to 0·1 degree. The movements of the telescope in altitude and azimuth are conveyed by fine chains to two pen carriages travelling over German silver guide rods in front of the drum. Each chain is attached to a groove cut in the periphery of the divided circle and the amount of the travel of the pen is directly proportional to the angular movement of the telescope. Spring-boxes are fitted to maintain the tension of the chains. The telescope is provided with a micrometer eyepiece which is made use of, in observations with a single theodolite, to determine the distance of the balloon by measuring the angle subtended by a tail of known length hanging from it.

There is also a **cloud attachment,** shown in the illustration, consisting of an etched glass disc, a mirror and a sun-glass. This is used not only to observe the movements of clouds but also as a " finder " for picking up the position of the balloon and placing its image in the centre of the field of view.

The clock rotates the drum once in an hour and there is an attachment for lifting both pens simultaneously from the chart so as to make time marks. These are usually made once a minute. Plain sheets of paper are commonly employed as charts, the edges being held together by a strip of gummed paper. Base lines, from which measurements can be made, are ruled while the chart is in position on the drum, after the curve has been traced. To do this the telescope is clamped at each even 10 degrees of altitude and azimuth and the drum is rotated by hand so as to cause the pens to rule the lines. Glass scales divided into half degrees over a range of 10 degrees are supplied for the tabulations.

Self-recording theodolites for pilot-balloon observations are used either in pairs erected at the ends of a measured base or singly. When a single instrument is used it is assumed that the balloon rises at a constant and known rate, so this method is not suitable for obtaining information as to the structure and movements of the lower layers of the atmosphere.

Method of Observing with a Pair of Theodolites

The theodolites are placed one at each end of a measured base line, which should be, if possible, not less than a mile and a half, or 1,700 metres, in length, and in a direction at right angles to that in which the balloon may be expected to travel.

Two observers are required, one at each theodolite. The balloon is released by one of the two observers at a pre-arranged signal, and at the moment of release the observer at the other theodolite starts a stop watch.

Readings of the altitude and azimuth angles of both theodolites are taken at each minute from the start, and the resulting observations are tabulated and worked out by the ordinary trigonometrical methods.

Method of Observing with a Single Theodolite

The advantage of the one-theodolite method is that it can be used at very short notice, as when the sky clears for a short time only. The rate of ascent of the balloon with this method must be assumed, and in the case of moderate heights may be taken as uniform.

It does not give such accurate results as the two theodolites with a long base line, but the working out of the results is much less laborious, and more sets of observations can be taken in the same time.

One minute readings of the altitude and azimuth angles are taken as in the previous method, giving a series of positions from which the horizontal trajectory of the balloon is obtained. The lengths of the minute runs give the wind velocity during each minute and the height is obtained from the time that has elapsed since the release of the balloon.

CHAPTER XII

GEODETIC SURVEYING

THE dictionary definition of the word "geodetic" is "The science of measuring the earth or any portion of it, from the Greek *ge* the earth and *dias*, to divide." The term is now used to denote surveys on a large scale which take into account the shape of the earth as distinct from small surveys where the earth is supposed to be a plane surface. The subject may conveniently be divided up into a number of sections, each having its own special problems, and each using instruments designed specially for their own particular work. A useful division into sections may be as follows :—

(1) Base line measurement.
(2) Triangulation.
(3) Levelling.
(4) Topography.
(5) Astronomical work.
(6) Traverses.
(7) Hydrography.
(8) Tide measurements.
(9) Terrestrial magnetism.
(10) Geodesy, or the measurement of the shape of the earth.

The principal object of a geodetic survey is to furnish the necessary data and to fix the control points for all minor surveys. These minor surveys can then be carried out quite independently and to any degree of accuracy required, and can afterwards be connected up to the main control points of the precise survey, in such a manner that each detail will fit perfectly into the whole scheme. It will be evident that on surveys of this magnitude, the utmost precision in the details must be rigorously maintained if a serious accumulation of errors is to be avoided. The instruments must be equal to the best obtainable, and they must be adjusted, and kept in adjustment, in the most precise manner, and finally, it is essential that the control points laid down by this survey must be permanently fixed and carefully guarded, if they are to be of any service to those connecting their minor surveys up to them. In order that these control points may be situated in suitable positions it is usual to send out a preliminary survey party to reconnoitre the ground and fix stations from which the necessary sights may be made. These stations may not always be suitable for the location of the control points, as for example, the middle of a marsh may be an excellent position in which to build a tower to support a theodolite from which good sights may be obtained, but be quite unsuitable for the sinking of a permanent reference mark. In this case, subsidiary lines would be run by the main party to points where marks could be fixed in the rock or in stable ground. It will be seen that the preliminary work must be carried out by particularly expert and skilful men if serious expense and delay are to be avoided, especially in country which is mountainous or covered by dense forest or undergrowth. Not only must the surveyor in charge of the party be a man of great experience in surveying in order to choose stations from which good sights and triangles of the proper shape may be obtained, but he must choose points for base stations where transport facilities and supplies may be secured. The party usually carries small light instruments, just enough to make a rough map of the district traversed, and to give sufficient details to the main party following, to enable them to pick up the locations. As the main triangulation is built up on a measured base line, a description of the methods of setting out and determining the length of these bases and the apparatus used will serve as a starting point for the whole subject.

Base Line Measurements

Until about fifteen years ago the measurements of base lines for precise trigonometrical work was an expensive and laborious undertaking, and even when the very greatest care was taken the results were not always above suspicion. A number of systems were in use, but all were modifications of either the end-to-end or line-to-line rigid bar method, the principal differences being in the refinements introduced in the search for accuracy. Glass, wood and metal rods were in general use, and sometimes the rods were made compound, in an attempt to keep the length constant under varying conditions of temperature. Many ingenious devices were employed to adjust the contact between the end abutments or to bring the engraved lines into coincidence but in spite of the most elaborate precautions, the final results were not up to the standard demanded and easily obtainable in other portions of the survey. In America, apparatus was used in which the bars were immersed in melting ice, but the cost of these elaborations proved prohibitive, although the results were certainly of a very high order of accuracy. The introduction of invar has changed all this, and to-day base lines are measured with the greatest ease and at a comparatively small expense by either a small expert party or else by the ordinary surveying party as a part of their routine work. Indeed, so simple has the operation become that, accurate lines quite up to geodetic standard are regularly measured by traverse parties, and on city surveys, where modern conditions demand results of a very high class, owing to the high value of the land and the complications of the network system of sewers and other underground work. Invar, which is an alloy of iron and 36% nickel, has a coefficient of expansion of about ·00000023 per degree Fahr., the figure for steel being ·0000064 per degree Fahr. Invar can be obtained either in the form of wire or rolled out flat into tape. The latter form is the more generally used for the reason that it takes up less space, is easier to wind on to the reel and is not so easily kinked. Should it become kinked, the fault is more readily discovered than in the wire. On the other hand, the wire is not so susceptible to disturbance by the wind, but as in any case it is not desirable to measure a base line in the presence of wind, the latter defect is not of importance. Recent redeterminations of bases by means of invar tapes, the original measurements of which had been made by rigid bars, have shown differences of as much as 1 in 60,000. As the probable error aimed at and usually obtained by means of the invar tape is one part in a million,* it is not likely that the rigid bar will be used in the future for any base measurement. In fact, ordinary steel

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* In the measurement of the Stanton base by the U.S. Government the probable error on a length of over 13,000 metres was ± 5·15 mm., which works out at 1 part in 2,560,000.

tapes had been used quite successfully for base measurement before the discovery of invar, and provided the work was carried out at night or on cloudy days, under stable temperature conditions, the results as to accuracy compared very favourably with those obtained by the ordinary bar method with of course an enormous saving in the cost of the operation. The tapes are generally 50 metres in length, although sometimes those of 100 metres are employed. The 50 metre tape is easier and quicker to handle, and experience has proved that on the whole this length is the most economical, especially when the work has to be carried out on rough or sloping ground. It is usual for each party to carry two or three tapes which are used to check each other and each mile section is measured twice, once with each working tape, the third being kept as a standard. The two results must agree to less than

$$\frac{\sqrt{d}}{50{,}000} \quad \text{where } d = \text{the distance}$$

Sometimes all three tapes are used in combination, each tape for one-third of the distance.

Many designs of supporting and stretching apparatus are in use, some of them being quite elaborate. The best type to employ largely depends on the nature of the terrain over which the measurement is being made, but as suitable country can usually be chosen, the apparatus need not be very elaborate. When it is necessary to work over rocky ground, short tripod stands are useful, as they may be quickly set up and are easily transported, but if the work is to be done quickly, and this is generally essential, a large number of stands will be required, owing to the desirability of placing them in position ahead of the measuring party. In the U.S.A. the method always employed is as shown in Fig. 167. A number of stakes of 4″×4″ timber are driven firmly into the ground at 50 metre intervals, with one intermediate supporting stake. These are set and their levels taken by a gang ahead of the measuring party, or if the weather is windy or unfavourable, the stakes are first set and then the measurements carried out on calm days. On the top of each terminal stake a piece of zinc or copper is nailed, on to which the graduations of the tape are transferred. The intermediate stake has a nail driven into it on which the tape is supported, the tape being calibrated, supported in this way both before and after the measurement. A pair of simple wooden levers, hinged to a plank on which the tape men can stand, serve to give the necessary tension, usually 30 lbs., or whatever tension was used when the tape was standardised, the amount being read by a spring balance at one end. The corrections for level and temperature are then applied and the horizontal distances computed from the mean of the various measurements. This method of using the tape is extremely simple and straightforward, and providing the ground is suitable for the firm setting of the stakes, is very expeditious and can be carried out by a party of five or six people at the rate of two miles per day.

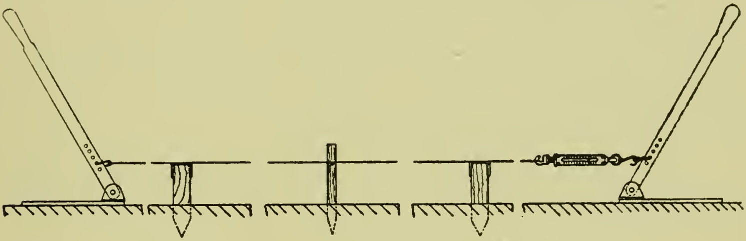


FIG. 167

When a tape used in this fashion has been standardised while supported in the same way, the only corrections required are

(a) For difference from standard.
(b) For height above sea.
(c) For inclination.
(d) For temperature.

The correction to be applied for (a) is obvious, while those for (d) are not generally of great importance when using invar of the first quality—

(b) Height above Sea Level.

If H = height above sea-level in feet
R = radius of the earth in feet
B = length of base in feet

Then the required correction will be

$$-\frac{H}{R} \times B$$

(c) For Inclination.

Let l = length of that part of the base which is inclined

a = angle of inclination

Then the correction required will be $-l(1 - \cos a)$

Or approximately

If l = the measured length in feet

h = the difference in level in feet between the two ends of l

Then the reduced length

$$L = l - \frac{h^2}{2l}$$

Thus if the distance l, measured on the slope is 25 feet and the difference in height is 2 feet, then the horizontal distance

$$= 25 - \frac{4}{50} = 25 - \cdot 08 = 24\cdot 92 \text{ feet.}$$

When long tapes are being used and no intermediate supports are possible, it is necessary to apply a correction for sag unless the tape has been standardised while hanging in a natural catenary. This correction for sag is approximately found as follows:

if l = length of tape in feet

t = the applied tension in lbs.

w = the weight of the tape in lbs.

then the correction to be applied is

$$l\frac{w^2}{24t^2}$$

and on an incline a the sag will vary as $\cos^2 a$.

(d) **Temperature Correction.** If

T_0 is the temperature at which the tape is standard
T_1 the observed temperature of the tape at which the measurement was made
e the co-efficient of expansion of the tape
l the length of the tape

Then the correction to be applied will be given by

$$(T_1 - T_0) \times e \times l$$

Formulæ have been devised to give a more exact correction for sag, but it must be remembered that the accuracy to which a base may be measured with an invar tape using the simple method already described is really higher than is actually required, owing to the fact that the probable errors introduced in the expansion of the triangles and in the astronomic determination are very much greater. If, however, the tape has been standardised while lying on a flat surface, the corrections for sag become important. The introduction of **invar** is due to the researches made by Dr Ch. Ed. Guillaume at the International Bureau of Weights and Measures at Sèvres. It may be procured in three qualities as follows :—

(a) With a coefficient of expansion less than 0·8 microns per metre per degree Centigrade.
(b) With a coefficient between ·8 and 1·6 microns.
(c) With a coefficient between 1·6 and 2·5 microns.

Invar of quality (b) is the kind usually employed for base line tapes and wires.

It has been found that slight molecular changes take place in invar with the result that a gradual growth is shown after a few years. An alloy containing 42% of nickel has been found to be free from this defect, but its coefficient of expansion is greater, being about 8 microns per metre per degree centigrade.

Invar is superior to steel from the point of view of freedom from liability to oxidation but it is, of course, much softer and more easily bent. It is, however, quite strong enough for the purpose under consideration, as it will seldom be subjected to a greater pull than 30 lbs. Invar is easily corroded by acid, so that care must be taken that the tapes are not exposed to this substance, and that the oil used on them is free from acid or any other corrosive substance. The tapes are generally made about 6 mm. wide by $\frac{1}{2}$ mm. thick, a 50 metre tape weighing about 1,200 gms., and are wound on an aluminium reel about 18 inches in diameter it being necessary to use one of this size in order to avoid giving a permanent set to the material of the tape. The graduations on the tape are either ruled direct on the surface of the invar, in which case a portion at each end of about 6 inches is divided into millimetres or 20ths of an inch. In other cases lines are ruled on silver or nickel sleeves surrounding and fastened to the tape. Some tapes have a division line ruled at every metre or yard, but the most popular form seems to be those in which the millimetre divisions are ruled at the ends only, as when made in this way set ups and set backs may be measured at once without the use of an additional rule.

When wires are used the general plan is to fix to each end of the wire a piece of invar tape about 8 inches long, these being divided into millimetres in the usual way. The ends of the tape are folded over and riveted to form a small eye into which a shackle bolt may be fitted, thus allowing the tape to be attached to the stretchers. Fig. 168 is a drawing of the type of reel used to carry the tapes. It is made of aluminium, its slot being only sufficiently wide to accommodate the tape easily. Fig. 169 shows a type of stretcher used in America. In this instrument the spring balance is carried on gimbals and counter-weighted, the point of the rod being shod with iron to allow it to be pressed into the ground at any convenient point.

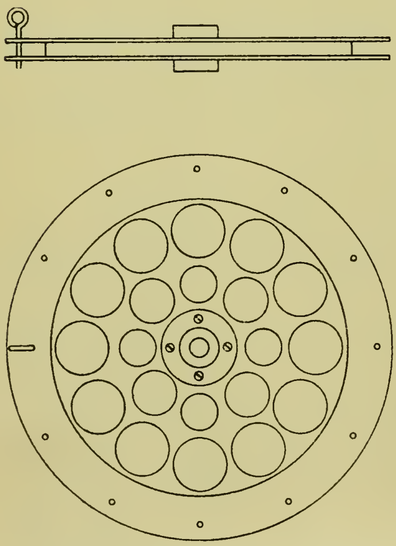


Fig. 168—Reel for invar tape

When the terrain is unsuitable for this method of working, special tripod stands must be employed, and great care must be taken that those at the terminals do not move during the transference of the measurement ahead. With this method, greater care and skill are required, and consequently greater cost is incurred, so that the matter must be carefully considered before the work is undertaken. When measurements must be made along a rail or the curb of a footpath, good results cannot be obtained owing to friction, especially in wet weather, if the tape is allowed to make contact with the ground along its length. As, however, it is seldom that an accurate base is required under these conditions, special arrangements can easily be made in case of need. The invar from which the tapes are made must be carefully annealed, and aged before graduating and standardising, and a record of its history must be kept when the highest class of work is expected. No difficulties have so far been found in this part of the work, and indeed the accuracy obtained in actual practice is more than sufficient for the requirements of the most precise geodetic survey.

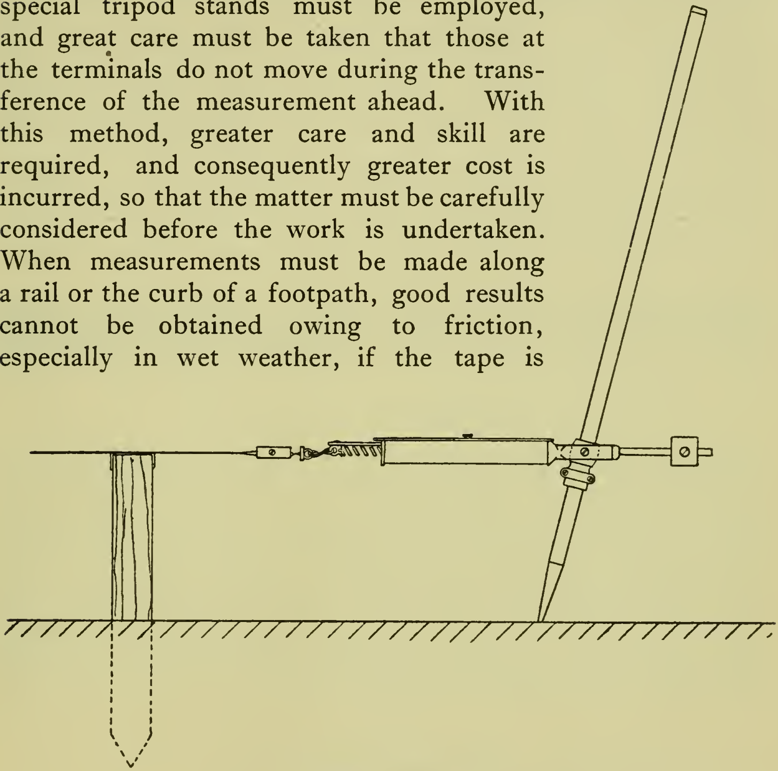


FIG. 169 Tape stretcher, American pattern

Fig. 170 shows the type of thermometer generally employed to take the temperature of the tape or chain. Two small clips are fitted to the back of the frame, thus allowing it to be fastened to the tape at any position required. The bulb is made small and sensitive and arranged so that it may lie close to or touching the metal tape, and thus take up nearly the same temperature as the metal. If the air temperature is rising or falling rapidly, the temperature shown by the thermometer will not necessarily be that of the tape so that care must be taken when such conditions obtain to see that sufficient time is allowed for the tape to take up the same temperature as the surrounding air. In laboratories electrical methods of determining the temperature of the metal have been used with success during the standardisation of accurate tapes. This method is based on the fact that the ohmic resistance of the wire increases with its temperature, but these refinements are not necessary in the field, and are too elaborate for general use. The matter is mentioned here because it has been shown that large errors may occur when an attempt is made to measure the temperature of the tape directly by means of an attached thermometer.

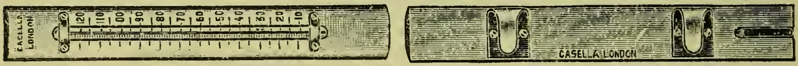


Fig. 170—Tape thermometer

Triangulation

Triangulation is based on the proposition that if one side and the angles of a triangle are known, the other sides may be calculated. In the last section, the method of measuring the base was shown. When this has been done, a theodolite is set up over each end of the base line in turn, and the angles to a target marking the apex of the triangle is measured. This measurement of angles is then carried on from point to point, and the length of the sides calculated and plotted on the map. Reference marks are fixed in the ground at these triangulation points, and these are the controls for all future surveys, such as the secondary or tertiary triangulation, or for the topographic surveys or levelling lines. The triangulations are classified according to their accuracy, those of the primary or precise triangulations being so arranged that the closing errors of the angles shall not exceed an average of about 1 second of arc. That is to say, the sum of the three angles shall not differ from two right angles by more than ± 1 second of arc after due allowance has been made to the observed angles on account of the curvature of the earth.

The length of the sides of the triangles will vary according to the territory over which they are being sighted, distances of as much as 150 miles having been obtained between mountain tops. The usual length of side is about 30 miles, as longer sights generally involve the building of excessively high and expensive towers on which to place the theodolite and the target. Fig. 193 shows a tower 80 feet high of the pattern used in the U.S.A. It consists of two separate framework towers, the outer on four legs to act as a platform for the observer, and the inner one on three legs, to support the theodolite. When the theodolite is moved to another location, the tower shown is used to support the sighting target. As most of the observing is done at night, a motor car head light lit by electricity is employed as the target, but in daylight a heliotrope, Fig. 191, which is a small mirror capable of being set by means of a telescope so that it reflects the rays of the sun on to the observing instrument, is used with good results.

Fig. 171 shows the type of theodolite used for primary triangulation. These instruments do not differ essentially from those already described, except as to the size of the circles. The circles are also not generally arranged for repetition. They usually have horizontal circles of 10 or 12 inches diameter, graduated into 5 minute spaces and read by two or three micrometers to single seconds directly and to 1/10th second by estimation. The instrument shown has a circle of 12 inches diameter, and is read by three equally spaced micrometers with a pointer microscope to read the degree divisions. It is arranged for reversal of pivots and the telescope carries a micrometer in the eyepiece to enable distances to be estimated and to allow for the taking of azimuth by astronomical means. The centre on which the alidade turns is made of hardened steel and the whole of the upper part is made principally of aluminium, in order to reduce the weight to be carried on the pivot, thus allowing the setting to be made without undue strain on the instrument. In recent years, owing to the improvements in the manufacture of instruments

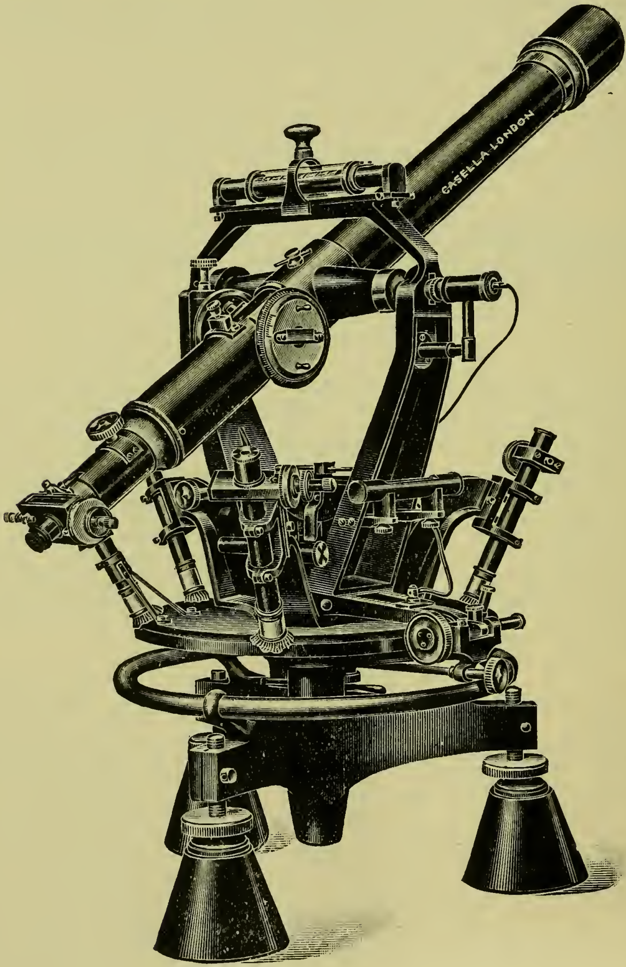


FIG. 171

and in their graduated circles, the 12 in. theodolite has been discarded in favour of those having circles of 8 in. and 10 in. diameter, as it has been found that quite as good work is to be obtained from the smaller instrument at considerably less expense and

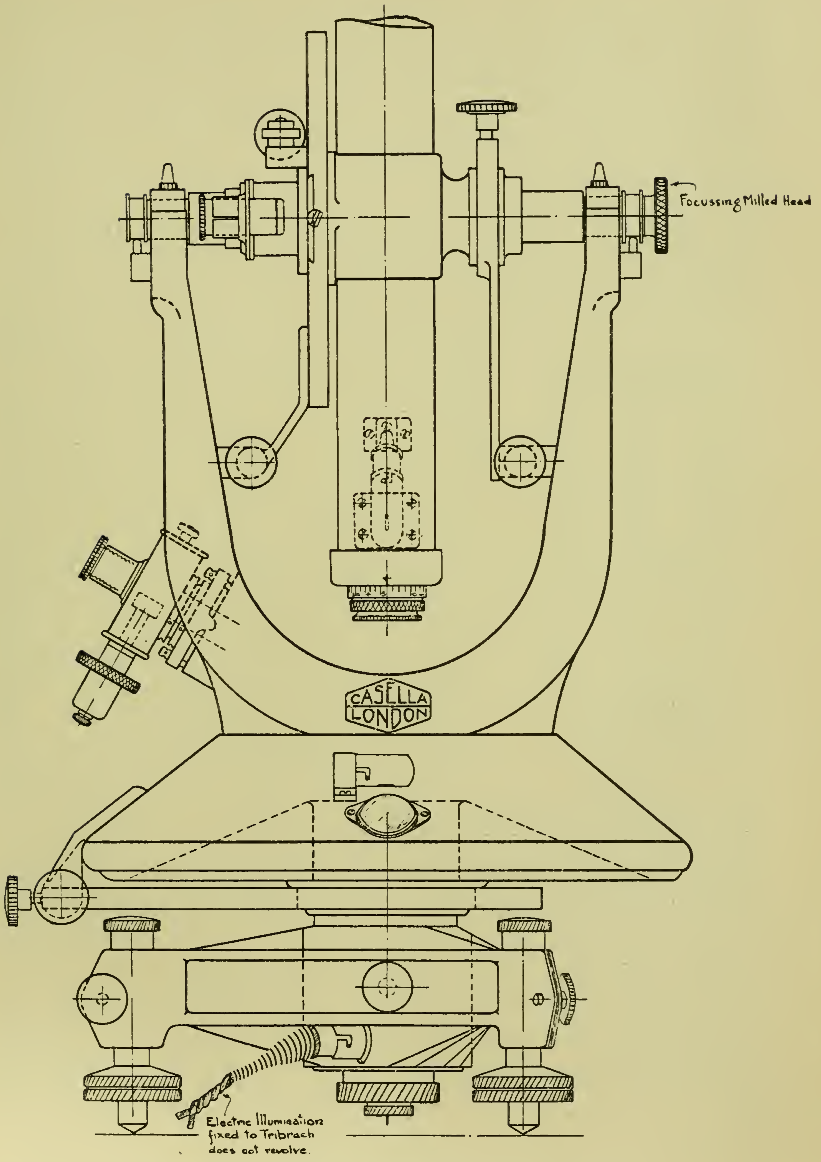
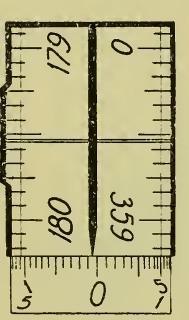


FIG. 172—10-inch double reading micrometer theodolite

at greater speed. The reason why the smaller instrument is more desirable has been given in a previous chapter, and there is no reason why even smaller instruments than 8 in. should not be employed on primary work, except that a comparatively large telescope is required, owing to the long sights which economy has dictated should be taken. Each triangulation station is generally marked by a block of concrete set in the ground, in which a brass disc is cemented. There are usually one or two additional reference marks which are located by distance and angle measurements from the main mark. These enable the positions to be found even if the original mark has been destroyed. Astronomical observation for time, latitude and longitude are made when possible at each triangulation station when the angles are being measured, but as different instruments are often used for this purpose, it is not always convenient to make the measurements at the same time. If not done at the same time, the geographic position is determined at some other place and referred back to the triangulation station. The primary triangles are subsequently extended and filled in by a **secondary triangulation** the closing error of which is kept within ± 3 seconds of arc. This is again connected up by a **tertiary triangulation,** the allowable error of which is about ± 5 seconds, and it is this latter network which is the basis upon which the topographic and ordinary land surveyor's work is established, and on which, therefore, our detail maps are founded. When, however, the nearest point on the triangulation network is some considerable distance from a point where a detailed survey is to be made, it is usual to connect up by means of a precise traverse survey, a short description of which is given in Section 6.



Enlarged View of field of Casella's Patent Double reading micrometer

FIG. 172a

Levelling

The instruments employed on precise levelling have already been treated fully in chapter VII, and the methods used in geodetic work are very similar to those made use of in ordinary levelling, except that more care and a larger number of readings are taken at each station in order to keep the results within the prescribed limits of accuracy. The heights are often expressed in metres, and are always referred to the mean level of the sea.

Whenever possible, the level lines are run along the railways or roads, owing to the ease of transport, and the suitable nature of the ground generally traversed by these highways, and to the fact that the bench marks, when fixed, are usually in positions unlikely to be disturbed, and easily identified. The procedure when the ground is fairly level, is simply to set up the instrument midway between two staves about 800 feet apart, first sighting on one staff and then on the other, the difference in reading being the difference in height between the two points. The instruments now used are those having a tilting screw and bubble reading device and having an object glass of about $1\frac{3}{4}$ in. diameter, with a magnifying power of 30. Care is taken to see that the level bubble does not become unevenly heated and that its position is read at the instant of taking the staff value. Stable turning points on which to set the staff are employed as previously mentioned. The line is split up into sections, one mile in length, and the figures are checked by going over the work a second time from the opposite end. The maximum difference allowed is about ·2 inch in the mile section. The average error is, of course, much smaller than this, and the accuracy obtained on large circuits of 1,000 miles or so being of the order of $\frac{1}{8}$ inch per mile as a maximum with an average for several circuits of less than ·025 inch per mile. In recent years the U.S.A. geodetic engineers have run lines having a circumference of 3,000 miles, showing average closing errors no greater than ·2 millimetre per kilometre. This is a remarkable performance, and a wonderful testimony to the officers carrying out the work and to the stability and perfection of their instruments.

The rate at which the work has been done is also remarkable, as much as 150 miles having been completed in a month, this including double levelling for each mile. When the triangulation of an area is in progress it is usual to compute the levels between the stations from vertical angles read by the theodolite after the length of the sight has been calculated. The angles are of course read from each end and the mean of the two averaged. This method is only useful as a rough check as, owing to the variable conditions of the atmosphere, corrections for refraction have to be applied and as these corrections are based on very unreliable data, the results are very poor compared with those obtained by precise levelling. When possible, the lines are adjusted to those made by precise levelling, checks of this kind showing that the theodolite levelling cannot be relied upon closer than ± 2 inches per mile.

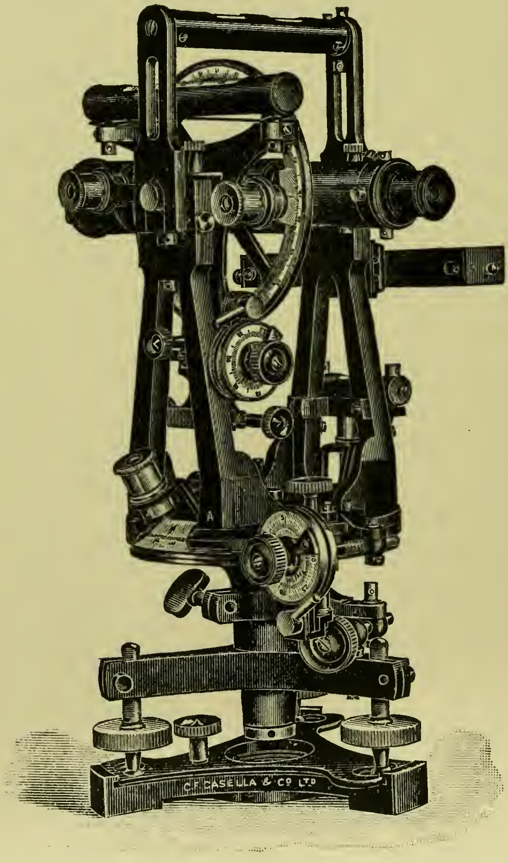


Fig. 172b—4-inch transit theodolite fitted with Reeves's patent tangent micrometers

CHAPTER XIII

TOPOGRAPHY

TOPOGRAPHY has for its object the collection of data which can be used for the production of detail maps showing all the natural and artificial features of the surface of the country to a scale suitable for the purpose to which the map is to be put.

The method used for producing any particular map must therefore be studied in relation to the scale decided upon, and the accuracy required in the detail. Apart from dimensional data, probably the most important feature required in a map used for general purposes is the undulations of the surface. Formerly these were shown by colouring or hachuring, but as this method was not sufficiently exact for modern requirements, the use of contour lines has now become universal on maps with any pretensions to accuracy. Contour lines are lines of equal altitude above sea level and the ground bounded by any contour line is that which would remain above the suface of the sea should it rise to that particular line. The contour lines are drawn at equal intervals of altitude the magnitude of these intervals depending on the scale of the map and the characteristics of the ground levels. Maps, as everyone knows, also show the general characteristics of the surface, such as rivers, lakes, forests, bogs, etc., and special maps are often subsequently made to exhibit the geological formation and such information as the trend of the flow of water, as would be required by those considering the establishment of waterworks or engineering projects. When the country mapped is near the sea, particulars of inlets, tides and soundings are given, this work being carried out in such detail as may be required from time to time. As many different problems have to be dealt with, many different methods of carrying out the work have been devised, the principal of which are as follows :—

1st. For rough preliminary work in a new country, the prismatic compass is used to take the bearings of selected points and the distances are estimated either by the time taken to travel over them by horse, on foot or by motor car. Sometimes a perambulator, as shown in Fig. 146 is used, and often the pedometer Fig. 147 is all that is required. Military authorities employ various simple range finders which give distances with sufficient accuracy for preliminary purposes and such methods as the distance carried by a rifle bullet, or the time taken for sound to travel, have been used from the earliest times for estimating distances.

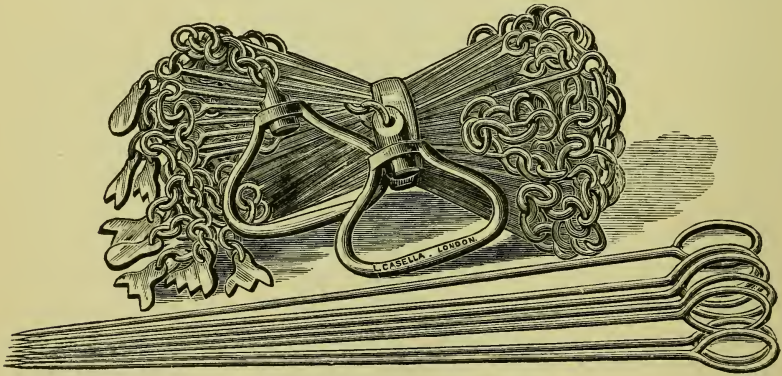


Fig. 173—Land chain and arrows.

2nd. When greater accuracy is required, a favourite method is to find the distances by means of stadia measurements, using a transit theodolite and stadia rods. At the same time, the angles of elevation of the different points are read on the vertical circle of the instrument, so that the horizontal distances and levels can be computed from these readings. The lines are tied up with known triangulation marks already placed so that with a sufficient number of stations and copious sketches, very accurate maps may afterwards be made in the office.

3rd. By chain and level survey. When the ground is suitable, or in populous neighbourhoods, the most accurate method is to lay the area out into rectangles and measure the sides by means of chain or tape, Figs. 173 to 175, and to

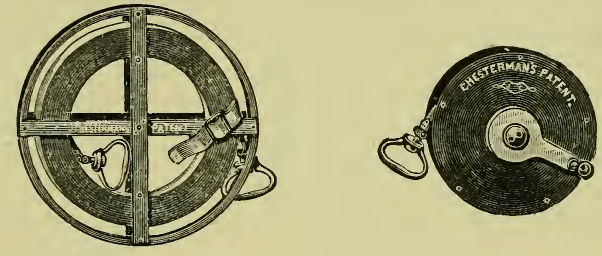


FIG. 174—Steel band tape on metal reels

take the elevation of each point with a dumpy or precise level. Offsets are measured and plans of buildings and other features are sketched in. When sufficient details are taken and careful notes kept, very accurate maps may afterwards be drawn in the office, and the contour lines can be filled in from the level records. The survey is, of course, connected up with all known triangulation and bench marks in the area. This is the most straightforward and simplest method of all, but as it is also the most expensive, is only suitable for small areas, and in places where accuracy is of primary importance.

FIG. 175—Steel band tape in leather case

4th. By plane table. The method of plane tabling is perhaps the most expeditious, and where the country is difficult, certainly the most satisfactory from most points of view. The reason for its popularity is that the work is completed in the field, and very little office work is afterwards required to finish the map. This has the great advantage that mistakes in interpreting notes, which may have been made some time previously, and often by another surveyor, are avoided, and the necessity for making laborious sketches and directions to guide the map makers abolished. Another advantage is that the surveyor has all the features of the country in front of him when he is actually drawing his map, and can plot in at once all the salient features in their exact positions much more easily than he can give sufficiently accurate data to enable a draughtsman who has no knowledge of the country to do this work. It is true that the map making is carried out under better conditions in the office, and that those made in the field can only be considered as a rough draft; at the same time the final accuracy obtained by plane tabling, especially in difficult country, is much higher than that generally arrived at by any other means, except chain and level. Fig. 176 shows a form of plane table often employed. It consists of a drawing board fixed to a light tripod and so arranged that it may be brought level by means of foot screws and spirit level. It can also be rotated in azimuth in order to bring the alidade to bear on the different points. Sometimes the foot screws for levelling are omitted, the necessary adjustment being made by pushing the points of the legs into the ground. On the other hand the stands and levelling devices are sometimes more elaborate, and a slow motion screw is fitted to enable exact azimuth settings to be made. The main requirement is that the stand should be as rigid as possible in order

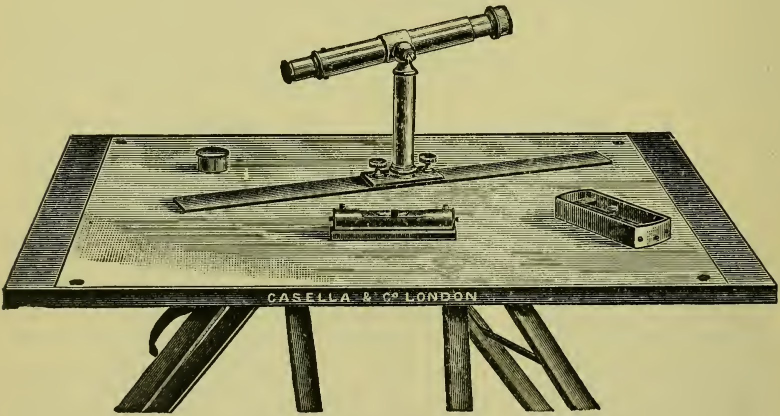


Fig. 176—Simple telescopic alidade

that the drawing board may be relied upon to keep accurately in position. The sighting rule or alidade varies according to the accuracy desired, some forms being quite elaborate. Fig. 177 shows a simple metal and a boxwood rule, the former having folding peep sights at each end mounted with the line of collimation directly over the bevelled edge of the rule and fitted with a simple circular bubble at its centre. It is obvious that if the alidade is set on any object, a line drawn

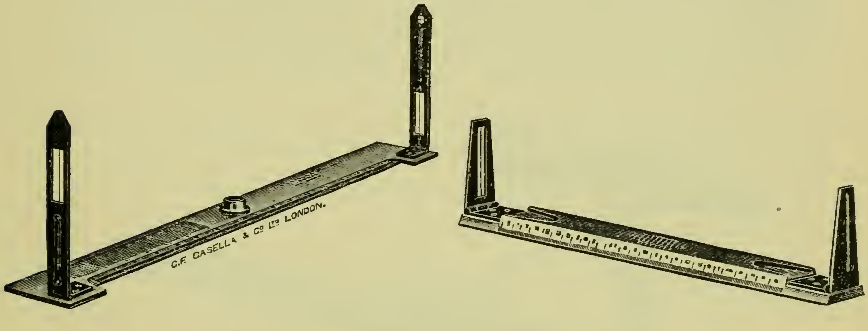


FIG. 177—Simple sighting alidades

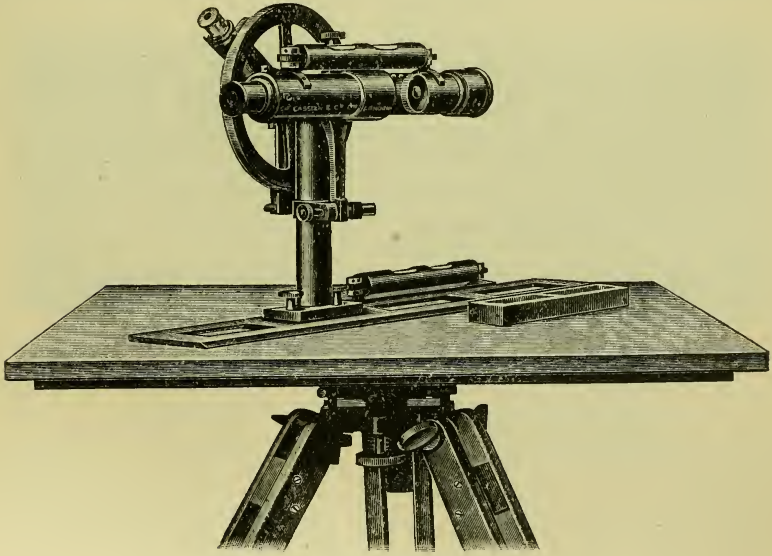


FIG. 178—Telescopic alidade

along the bevelled edge would, if produced, reach that object. Similarly, when the same object is sighted from another known point, the intersection of the two lines will fix its position and its distance can be determined when the work is done to scale. The graphic solution thus afforded is invaluable, especially when inaccessible points are being dealt with, and when an alidade such as that shown in Fig. 178 is used, the stadia distances and elevations of the points may be determined at the same time, thus giving all the data necessary to make a most complete and perfect map. The work checks itself as it proceeds, and the surveyor can take a large number of observations and plot them at once, being relieved of the necessity of making elaborate notes. Fig. 179 shows a very portable form of alidade used by exploring parties. The telescope, which is fitted with stadia lines, is so arranged

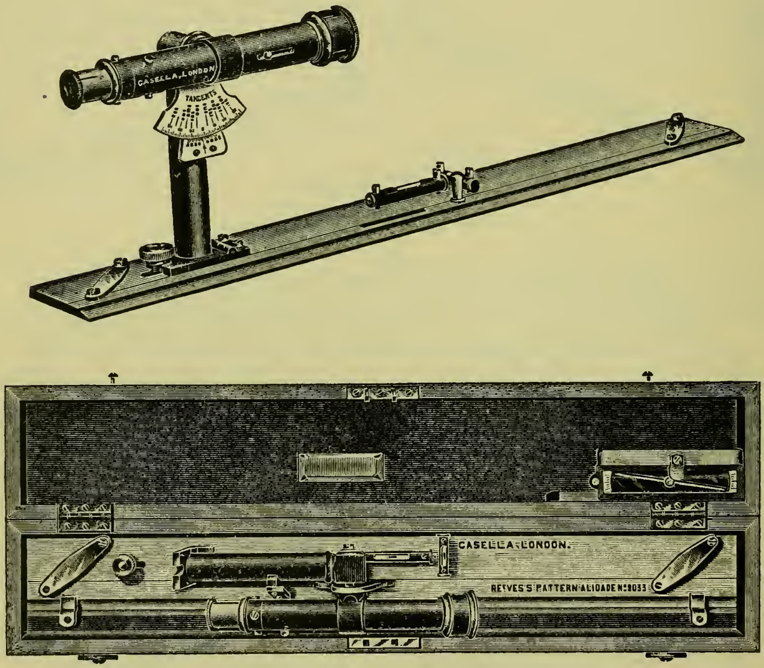


FIG. 179—Reeves's folding telescopic alidade

that the angles of elevation and depression can be read from the scale seen under the axis. This quadrant also carries a scale of tangents and the bevelled base plate is fitted with a parallel rule attachment. The bevelled edge is often graduated with a scale corresponding to the scale of the map being produced, but more often an ordinary boxwood scale is used to plot the distances on the paper.

Plane tables are sometimes made with rollers at each end, arranged to take a long piece of paper so that a continuous map may be made. This has some advantages in theory, but is not a very practical scheme for an instrument which has to be used in the open under varying climatic conditions.

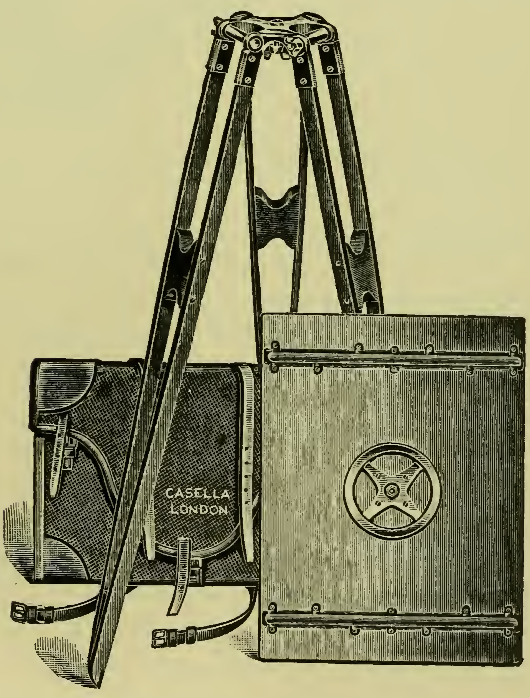


FIG. 180—Plane table, stand and canvas carrying case

Potter's Alidade

Fig. 181 shows a form of alidade devised by the Rev A. J. Potter, which makes use of a simple optical principle which does not appear to have been used in this connexion hitherto.

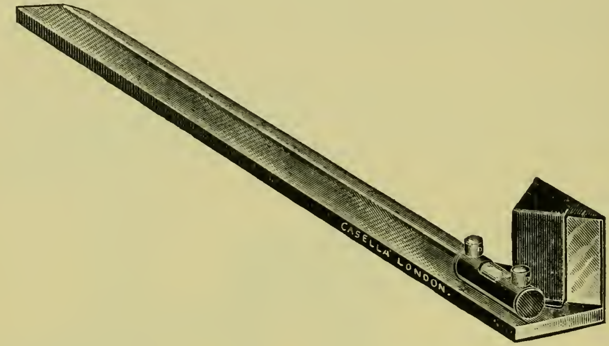


FIG. 181—Potter's patent prismatic alidade

If ABC (Fig. 182) be an isosceles glass prism, a ray of light RO, etc., parallel to the hypotenuse BC, falling upon AC, will be refracted towards BC, and after total internal reflection from BC, will re-emerge from AB parallel to the original direction.

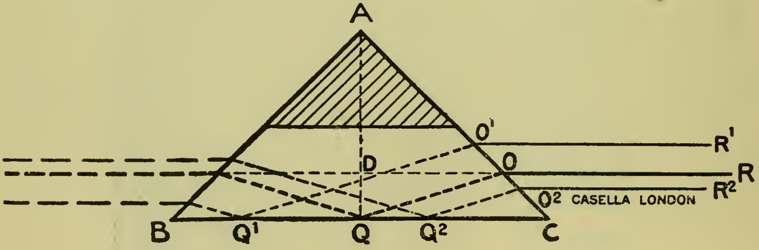


FIG. 182

One such ray, viz., that whose mean line is reflected at Q, the middle point of BC, will re-emerge in the same straight line as the original ray.

The most convenient form of isosceles prism for the purpose is one which is right-angled at A.

The position of the ray RO, whose refracted mean line OQ falls upon BC at Q, depends on the refractive index of the glass. Assuming this to be 1·58 the perpendicular distance of RO from BC works out as .25 of the length AQ, and may be given as roughly a quarter, for an average flint glass.

It will be clear that a ray falling on the shaded portion of the prism, roughly half the width from A to Q, will not re-emerge from AB, since the mean refracted ray will not fall on the internal reflecting surface BC.

It will also be clear that the emergent image will be inverted left for right, or where the sighting arrangement is used in a vertical plane as a clinometer, the image will be upside down.

If then the prism be attached to a rule with BC parallel to the edge and overlapping it by the given proportion, the coincidence, in a vertical (or horizontal) plane, of the image seen through the prism with the direct view as seen above will bring the fiducial edge of the rule into line with the object sighted.

The advantages claimed for an alidade made on this principle over the ordinary non-telescopic pattern are as follows :—

(1) Simplicity and strength. Since it consists of one solid part attached to the rule, with no screws or hinges to work loose, the adjustment, once determined by the makers, may be considered exact and permanent. It may readily be tested by sighting on some object, and then reversing end for end.

(2) Clear illumination and absence of parallax. With the ordinary pattern, parallax can only be avoided by making the slit in the rear-vane so narrow as seriously to limit and interfere with visibility. Moreover the wire in the front vane, to be serviceably strong, must have a measurable width, usually subtending an angle of several minutes at the eye end. With the prismatic pattern, a slight parallax of a different character is theoretically possible, but is entirely negligible in practice. There is no obstruction either to the direct view or the inverted image, the latter re-emerging with practically no loss of light.

(3) Sighting above or below the level of the plane table. The unsatisfactory procedure of stretching a thread between the

tops of the sight-vanes is obviated, sights being readily made to any required elevation with the instrument as it stands. By reversing, so that the prism end is near or overhanging the farther edge of the board, objects considerably below the horizontal can be sighted with only a little less ease.

(4) Accuracy of alignment. The most important feature of the prismatic alidade is that a displacement of the rule involves, through the laws of reflection, an apparent displacement twice as great, as between the direct view and the image given by the prism. A movement of less than one minute of arc can thus be appreciated by the observer. This is considerably less than could be distinguished by the finest pencil marks which could be made in ordinary practice by a skilled observer.

In the form of plane table and alidade employed by the Indian Government the board is made of aluminium ribbed underneath for strength and measuring 22 × 24 inches. It is carried on a levelling tribrach fitted with a tangent screw for azimuth setting. The alidade carries a telescope with a magnification of 25 and is supported on a large base arranged as a parallel rule.

The telescope is fitted with a sensitive level bubble, and an arc, reading to minutes by vernier, is pivoted on the upright, and so arranged that it may be brought level by means of an attached spirit bubble.

A centering arm carrying a plummet is supplied to enable any point on the map to be brought over the ground mark.

The general construction of an alidade of this kind follows that of a transit theodolite of a similar size, about 5 in. and no further details need be given here.

The plane table, no matter how elaborately arranged, cannot in itself be considered an instrument of precision and if tested in a laboratory in the way one would test a theodolite or level, one feels that little reliance should be placed on its indications.

In the field, however, it shows up in a very different light. It is soon apparent that the sights may be taken much more accurately than they can be plotted on the map, and when it is realised that the data necessary to construct the map need not be of greater precision than that which may afterwards be scaled from it when made, the desire for laboratory methods of working and adjustments disappears. Given reasonable stability in the instrument and its stand, the plane table, in the hands of competent surveyors, cannot be equalled for speed and convenience, and the resultant accuracy of the map is all that can be desired owing to the simplicity with which the three-point problem can be resolved and to the fact that cumulative errors are not likely to arise as the work proceeds. It is this simplicity which gives to the instrument its value and it is often found that the simpler the apparatus the more exact the result, as may be seen under the heading of Base Line Work, where the apparently crude method of tape measurements over fixed pegs is far ahead both in point of accuracy and speed of all the more elaborate methods of rods or complicated tape and tripod installations. The principal points which must be accurately attended to are as follows :—The base line should be as long as possible, the intersections should be made at fairly large angles, and the orientation should be carefully done and checked in order to see that the table has not moved between the taking of the sights. The actual plumbing of the table over station

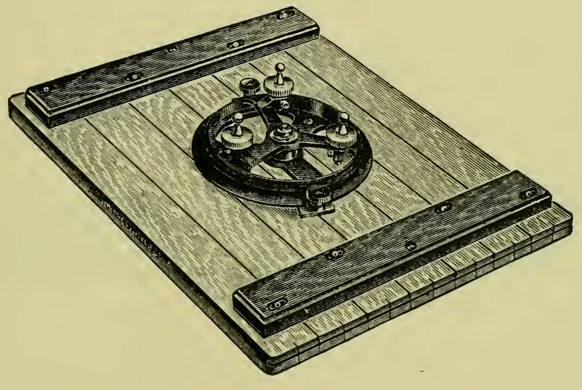


FIG. 183—Levelling base for plane table

marks is, except for very short sights, not of great importance, as a large error in placement would not be discernible on the actual map. The levelling of the board is carried out to sufficient accuracy with a small circular level, as any sights which are being made by the alidade telescope are separately controlled by the bubble attached to the vernier arm. The alidade telescope is sometimes fitted with a filar micrometer in the eyepiece for the measurement of distances, a description of the method of using this fitting being given on pp. 47 & 48.

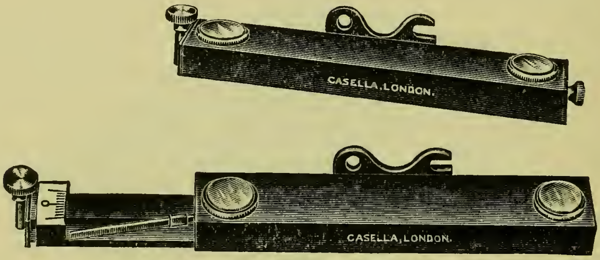


FIG. 184—Casella's enclosed trough compass

It is usual to employ a trough compass to determine the magnetic bearing of the various points being plotted. Fig. 184 shows the form taken by the instrument supplied by Messrs. Casella for this purpose. It is placed against the edge of the alidade, thus allowing a line in the magnetic meridian to be drawn on the map.

CHAPTER XIV

ASTRONOMICAL WORK

IN order that the triangulation network of a country may be definitely located on the globe, it is necessary to carry out a certain number of astronomical observations of a comparatively simple nature. In a small country, the necessary points are furnished by the fixed observatories, but when the area to be dealt with is large, or where no suitable fixed points are in existence, the geodetist must either establish permanent observatories to carry out the work, or make observations by means of portable instruments as the survey proceeds. The determinations generally required are those for time, latitude, longitude and azimuth, and the portable instruments used for these observations are described herewith.

For the less important points all the observations required may be made by means of a transit theodolite, which in fact in reconnaissance and exploring is the only instrument usually carried. As, however, special instruments have been devised for more accurate determinations, the various types in use for each of the four classes of work will be described in the order given above.

Time

When the time is required at a station to within about half a second, the **sextant** is suitable; it is capable of giving results within this limit, and owing to its portability and the speed with which the observations can be taken, it has become a very popular instrument with land surveyors doing this class of work. The ordinary mariner's sextant shown in Fig. 207 is the type usually employed, and although more complicated forms have been designed and produced, the instrument as invented by Hadley in the form of a quadrant has, with a few minor improvements, held the premier place. The optical principles on which the instrument is founded, and the methods by which it is adjusted have been treated fully in another

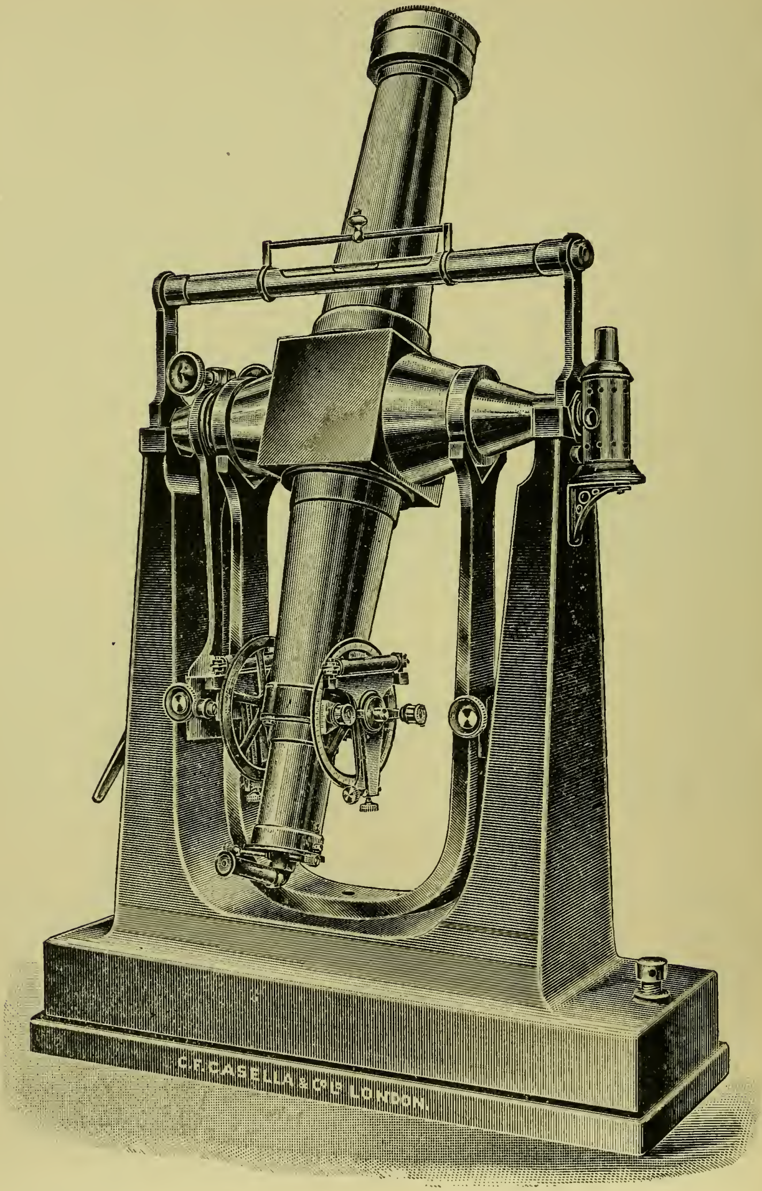


FIG. 185—Large transit instrument

chapter. It may be mentioned here, however, that as there is no means of easily checking the accuracy of the divisions on the sextant limb, only those instruments which have been examined and certified at any well-known testing institution should be purchased. When the more refined determinations required in geodetic work have to be carried out at temporary observatories, the **astronomical transit instrument** is employed. Fig. 185 shows a large instrument of this type, and Fig. 186 is a similar instrument but smaller and arranged with an elbow telescope. These instruments are adjusted in the same manner as an ordinary transit theodolite, except that there is no horizontal circle for azimuth setting, but merely a pair of adjusting screws for setting the line of collimation in the meridian after the apparatus has been placed in an approximately correct position on its supporting pillar. This pillar is usually built up of concrete on a solid foundation as great stability is necessary if good results are to be obtained. Before any observations are taken the instrument is adjusted so that the line of collimation coincides with the plane of the meridian when the telescope is rotated on its axis. In order

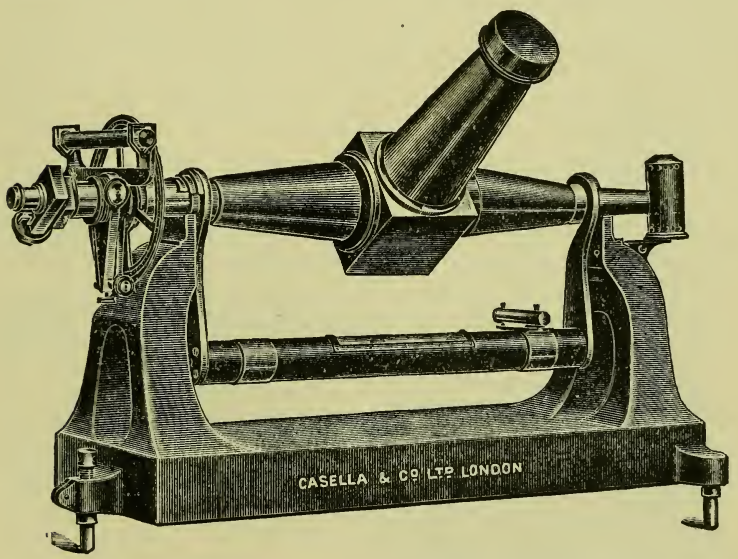


Fig. 186—Transit instrument with elbow telescope

that this may be so the telescope itself must be in collimation and the axis must be horizontal. So that these adjustments may be carried out and to allow for face right and left readings, the axis is fitted with a sensitive striding level, and with a special gear which by the operation of a small lever seen on the left hand standard lifts the pivots out of their bearings, swings the whole of the upper part round on a vertical axis and then lowers the telescope down on the opposite face. In the instruments shown in Figs 186 and 187, the reversal of the telescope is done by hand, which serves well enough for those having object glasses up to about 2 inches diameter. In the broken telescope type the line of collimation is turned at right angles by a pentagonal prism contained in the square portion of the axis which also contains a counterweight to balance the object glass end. As previously mentioned, the introduction of anything in the line of collimation which is likely to cause it to deviate from its correct position through relative movement of the mechanical parts is not good practice, and for this reason instruments having elbow telescopes are not very favourably received by those who seek the finest results, in spite of the obvious degree of comfort which this type affords to the observer. It is true that the actual observations as carried out in practice, are so arranged that instrumental errors are eliminated or very much reduced, but it is generally assumed that in order that this elimination may be effective, the parts must be stable between observations. This condition is difficult to obtain where the line of collimation has to traverse prisms or be reflected

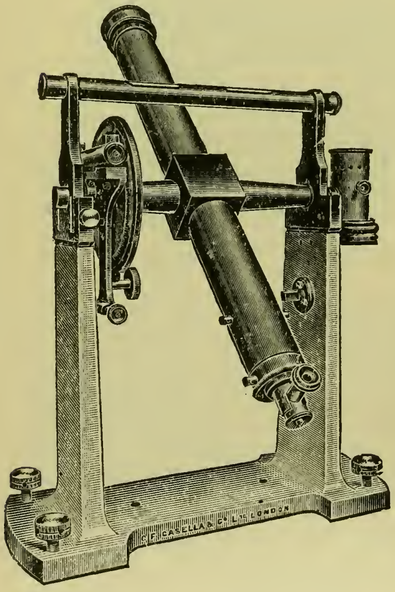


FIG. 187—Small transit instrument

by mirrors so that simplicity in the elements of an instrument of this sort is generally looked upon as a *sine qua non.* The graticule in the telescope is usually fitted with a number of vertical wires, generally five, but in some instruments as many as seventeen, and the method of observing is to note the time by a chronometer when the star cuts each wire in succession. This is done by counting the beats of the chronometer and noting the beat number as the star passes the wire, and when expert observers are employed on this work, the results are quite as accurate as those obtained by other and more refined methods

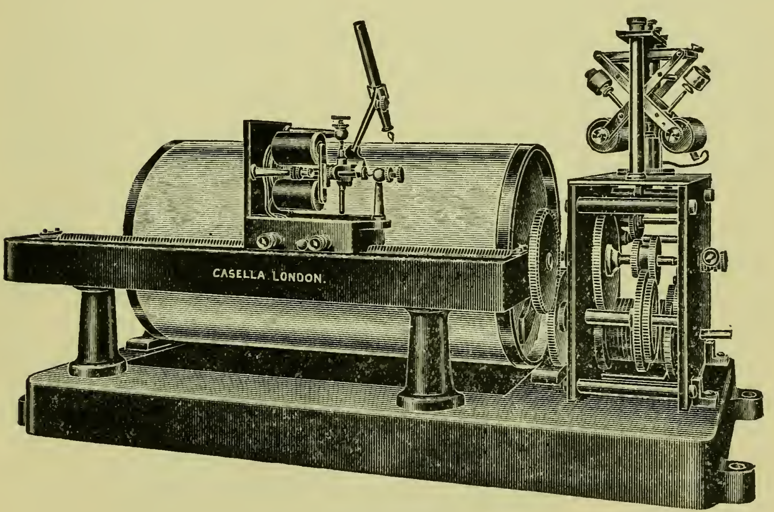


FIG. 188

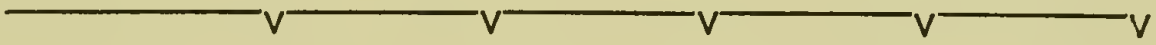
It is difficult, however, to allow for personal errors of observation, the magnitude of which varies greatly in individuals, and even alters from day to day in the same person. Various devices have therefore been produced to eliminate these errors or to reduce them to reasonable amounts. One method is to have a chronograph, such as that shown in Fig. 188, to produce on a chart a record of the beats of the chronometer or of a seconds pendulum.

Chronograph.—The instrument, as usually constructed, consists of a drum about 8 inches in diameter by 12 inches long, driven by a falling weight through a train of gears and controlled by a centrifugal governor. The weight and the advantage of the train can be altered so as to give either one revolution per minute or double that speed, or when electrically driven, or rather, when the weight is wound up by an electric motor, as much as one revolution per second. Spring driven gears are not satisfactory for this purpose so that the less portable weight drive must be used. The governor must be very carefully adjusted so that a uniform speed may be maintained, the success of this method of recording depending on the constancy of the speed of rotation of the drum.

Governors of various kinds have been tried, but the simplest and most successful hitherto have been those depending on friction as the controlling force. This is usually arranged either by fitting a collar to a revolving sleeve which rises and touches a light spring when the weights are thrown out by centrifugal force, or as shown in the illustration, which is a photograph of the type of instrument used by the U.S. Geodetic Survey, by means of a hook piece, which is attached to and revolves with a weight concentric with the spindle, engaging with a pin on one of the weights. When the weight rises, the pin engages with the point of the hook and drags it round with it. The added friction slows the clock down and when in consequence the weight falls, the hook is disengaged thus allowing the clock to speed up again. If the adjustments are carefully made, the speed can be regulated so that there is no appreciable difference in the distance apart of the second marks, right through the chart, but these adjustments must be checked before any observations are taken. In this connexion, it is interesting to note that the time taken at any station in setting up and adjusting the instruments is very considerably greater than that required for the actual observations.

The gearing also drives the pen carriage by means of a screw, thus tracing a spiral line on the chart from end to end of the drum of about 1/10th inch pitch. The pen may be an ordinary fountain or stylograph pen which is quite satisfactory for ordinary use. When, however, the highest accuracy is desired, the pen and its electrical parts must be made very light and an apparatus such as the siphon recorder used for telegraphic cable work is employed.

An electric current is fed to the magnet operating the recording pen and returns via a contact on the chronometer and through a hand operated key to the battery. The current flows continuously through this circuit and thus holds the pen arm up against a stop. When the circuit is broken either by the chronometer or by the key, a spring pulls the pen to one side, thus making a V-shaped depression in the otherwise continuous line.



The chronometer contact is so arranged that a break is made every second except at the 59th second in every minute, thus allowing for identification. The method of procedure is simply this.—As the star cuts each wire the observer presses his key, thus super-imposing on the chronograph chart a record of the times of transit. The exact times can then be measured to

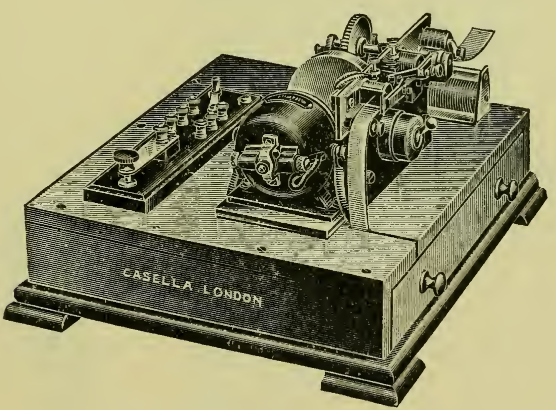


FIG. 189—Electrically driven tape chronograph

1/10th second by scaling to the nearest even second, as recorded by the chronometer. The exact peripheral speed of the chronograph drum, usually set at one revolution per minute, is not very important, but it is of course necessary that it should be uniform in order that the intermediate measurements for the parts of a second may be correctly estimated. The exact time shown by the chronometer hands is written on the record paper, and also the correction to be applied to its readings.

In order to reduce still further the personal errors of observation, large instruments are often fitted with a screw micrometer in the eyepiece the divided drum of which carries a number of contacts which automatically break the circuit as the drum is revolved.

Impersonal Micrometer. A device of this kind is illustrated in Fig. 190, which shows clearly the electrical contact strips fastened to the micrometer head. The number of these contacts may be from 5 to 20, depending on the pitch of the screw used and the speed of the chronograph drum, and they are usually unequally spaced in order that they may fall into groups, thus facilitating their identification on the chart. For example, if a series of 5 contacts are fitted they might be placed at 0 — 12·5 — 37·5 — 62·5 and 75 divisions of the drum, thus giving a trace easily interpreted.

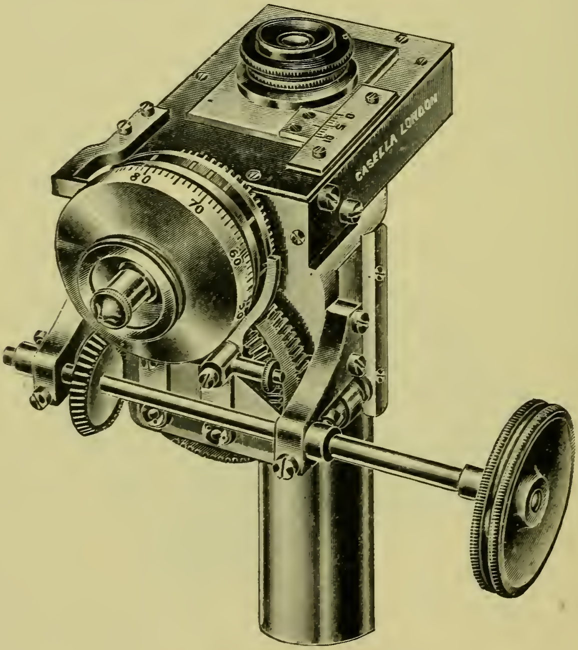


Fig. 190

A large number of contacts is not advisable, owing to the fact that there will then be more likelihood of interference between the contact marks and those of the chronograph, as when the breaks come together or nearly together they are difficult to interpret. It is necessary to arrange to relay the current through suitable apparatus, so that the delicate contacts on the chronometer and micrometer head are not compelled to carry the heavy current necessary to operate the pen of the chronograph. It is thus possible to transform a closing of the circuit at the micrometer head into an opening of it at the chronograph, this arrangement having been found the most certain in actual use. The method of using this device is very simple and no great amount of practice is necessary to get good results. All the observer has to do is to revolve the micrometer head so as to keep the star continuously bisected by the vertical wire, and as the record is made automatically on the chronograph, he can thus give his whole attention to the bisection. Much more elaborate instruments are employed in fixed observatories, some of them so arranged that the actual times of transit are recorded on a paper tape in printed characters or the currents are fed to the controlling apparatus of the standard clocks, or transmitted to distant stations by means of wireless. The chronographs are sometimes driven by electrical motors, the drums revolving as quickly as once per second, but apparatus of such refinement is confined to the largest institutions and is under the control of astronomers rather than surveyors. When determining longitude, the surveyor now makes use of the accurate time signals sent out by wireless from the large observatories, and a description of the method of receiving these signals is given in the chapter on wireless.

If the transit instrument is in perfect adjustment, the right ascension of a star would at the instant it cuts the line of collimation be the same as the local sidereal time, and the difference in the chronometer time would be the error of the chronometer. As, however, the instrumental errors can never be wholly eliminated, certain corrections must be applied to the observed results before the error of the chronometer can be determined. The actual adjustments required on a transit instrument are exactly the same as those already given for a transit theodolite, i.e. the following points should be examined. First set the micrometer wires vertical and adjust the line of collimation by reversing the axis on its pivots while ranging an object at least one mile distant. Setting on a near terrestrial object is not advisable, and in many instruments not possible, as no large amount of focusing adjustment is fitted or desirable. The telescope axis would of course already have been set up truly horizontal by means of the stride level, the adjustment of which must also be checked. The bubble of the finder circle should then be adjusted to the mean of two readings taken on opposite faces in order to eliminate its index error. When two finder circles are fitted, they should both be set to the same angle by means of their verniers, and the bubbles should then come to the centre of their runs when the telescope is set at the appropriate angle. The instrument will already have been set up approximately on the meridian, but its exact adjustment cannot be made accurately until after dusk. All the other adjustments should be made in daylight ready for the night observations. To set the instrument in the meridian first of all set the telescope on a star a few degrees from the zenith and note the time of transit on the chronometer. From this observation the chronometer error can be obtained, as slight error in the azimuth setting of the telescope will not affect the time of transit of a star so close to the zenith. Now set the telescope ready to observe on a star of large declination which is about to transit. A little before the time it is due to transit as shown by the corrected chronometer, set the middle wire of the telescope to bisect the star. Keep the star on the centre wire by means of the azimuth screw until it is on the meridian as shown by the chronometer time. The instrument will now be very nearly in the meridian, but the whole process may be repeated and the setting improved if time permits.

Latitude

As the latitude of any point on the earth's surface is the meridional zenith distance of any celestial object, the determination may be made in an approximate way by simply measuring the altitude of the sun or Polaris as it crosses the meridian. This may easily be done with the ordinary surveyor's transit theodolite or, as is usual at sea, by the sextant. This method is, however; not sufficiently accurate for the finest geodetic work, owing to the fact that large corrections must be applied to the observed figures in order to eliminate the effect of refraction and instrumental errors. The programme of observations may be designed to eliminate these latter errors, but the errors due to differences in refraction which vary with the altitude and which may also vary from day to day, are not easily allowed for, so that more refined methods of observation are necessary and have been in use for many years. As the refraction is least at the observer's zenith, this fact has been taken advantage of in the HORREBOW-TALCOTT scheme, which is the most popular method to-day of making latitude determinations. The new method employing the astrolabe of CLAUDE & DRIENCOURT has made great strides in recent years however, and a description of an instrument adapted for this work is given later.

Horrebow-Talcott Method. In the Talcott method, instead of taking absolute measurements of the altitudes, a differential determination is employed on stars very close to the zenith, so that errors of refraction are definitely eliminated, thus allowing of a much greater accuracy being obtained. This method has also the added advantage that it is not necessary to make accurate readings on a divided circle, thus eliminating another probable source of error. It is necessary to know the approximate latitude of the point of observation and to calculate the local time of pairs of suitable stars, but tables are now obtainable from which these pairs may be picked, and from which their declination may be extracted.

The method of using the instrument is as follows :—

A pair of stars which cross the meridian within five minutes of each other is selected, one to the north and one to the south, the difference in the zenith distances of which is within a few minutes. The instrument having been adjusted and set up truly on the meridian, the telescope is set by means of its finder circles about midway between the two stars to be observed. The micrometer web is now set to bisect one of the stars as it crosses the meridian. This micrometer reading and also a reading of the level is carefully made and booked. The telescope is now swung 180° in azimuth, i.e. against the other stop and similar readings are made at the moment this second star crosses the meridian. These readings, together with the declinations of the stars extracted from a specially compiled list, enables the latitude of the place to be calculated, thus :—

$$Z = \phi - \delta$$

and $$Z_1 = \delta_1 - \phi$$

then $$\phi = \tfrac{1}{2}(Z - Z_1) + \tfrac{1}{2}(\delta + \delta_1)$$

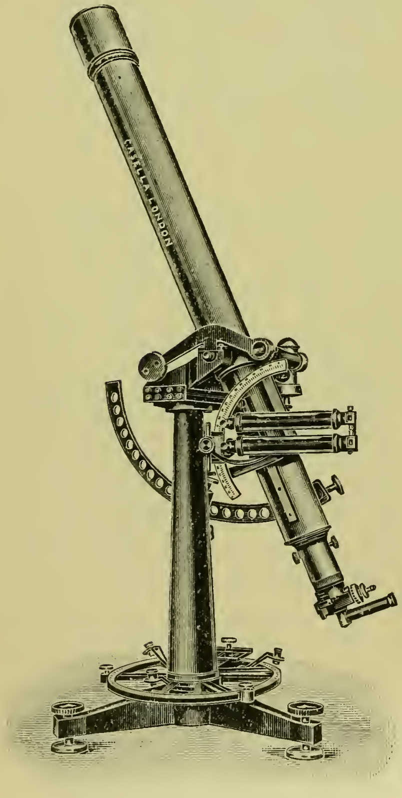


FIG. 191—Zenith telescope

A number of corrections must be applied to eliminate errors due to the small differences of refraction and any known instrumental errors. None of these latter errors are likely to be large in a well-constructed and adjusted instrument, and it is usually found that the largest discrepancies are due to careless handling of the instrument and temperature effects on the bubbles.

Fig. 190 shows a **zenith telescope** specially constructed for this work, but some transit theodolites are fitted in such a way that they may be employed for the Talcott method. The instrument shown is fitted with a telescope of about 36 in. focus and having an object glass of 3 in. aperture. At the eye end a micrometer is fitted which is read by a diagonal eyepiece giving a total magnification for the telescope of about 90 to 100 diameters. A delicate striding level is used to set the telescope axis truly horizontal, and a pair of sensitive latitude levels are attached to the telescope. The whole instrument may be rotated in azimuth on a long axis, and its position read on a divided circle attached to the tripod. There are two adjustable stops fitted to the base which allow the instrument to be swung exactly 180° in azimuth between the readings of the pairs of stars. Great stability in the mounting of the instrument is necessary and two observers are generally employed, one to bisect the star and the other to read the levels, and great care must be taken that no relative movement of the parts takes place during the time the readings are being made. As the micrometer value depends on the constancy of focus of the telescope, precautions must be taken to keep the instrument sheltered and free from temperature differences, and it is only by attention to such details as these that correct results may be obtained. Before any observations are made the instrument must be adjusted and the values of the level divisions and the pitch of the micrometer screw determined, if these are not already known. These latter values are usually obtained in the laboratory, but the micrometer values can afterwards be checked from the figures furnished on actual latitude determinations. The actual adjustments for collimation error, horizontality and verticality of the axes are made in the manner already given for theodolites and transit instruments, and need not be repeated here. It is especially important, however, to see that the micrometer wires are truly horizontal, as otherwise an error of considerable weight will be introduced into the calculations, the readings being too great on one pointing and too small on the corresponding reading, or vice versa. Zenith telescopes having the line of collimation eccentric to the vertical axis are much employed on the continent of Europe, but when they are made in this way, the adjustments are much more difficult to make, as the effect of parallax on the point sighted, due to the eccentricity of the axis, must be allowed for, and the accuracy of the divided circle must be assumed when rotating the whole instrument 180° in azimuth when pointing on the back sight. These instruments are often also arranged in such a way that the micrometer is placed on the side of the telescope tube, in order to give a more convenient position for the eyepiece. This means that a prism must be interposed in the line of collimation which as already pointed out previously is not good practice. The stops limiting the rotation in azimuth to 180° must be accurately set, so that the telescope is exactly in the meridian north and south, and this adjustment is made exactly as given for the setting up a transit instrument. The finder circles must be set to read true zenith distances, this being accomplished as follows :—

Set the telescope on some well-defined distant point, adjusting the bubble to the centre of its run, and take the reading of the circle. Now set on the same object with the telescope reversed, when the mean of the two circle readings will be the zenith distance. If the circle is now set to the mean reading and the telescope pointed again on the object, the level bubble may be adjusted by means of its opposing screws. This adjustment may easily be checked by pointing on to a star of known zenith distance. It is usual to go through all the adjustments to check them immediately before the actual observations for latitude are to be made.

As the Talcott method is capable of giving results of the highest order of accuracy, it is necessary when making the observations to see that instrumental errors are eliminated wherever possible. This is taken care of by careful adjustments of the various motions, by accurate calibration of the micrometer and the levels, and then by taking great precautions to insure that no relative displacement of the parts takes place during the time between the observations of the star pairs. For this reason the instrument should be carefully guarded against changes of temperature and against wind pressure, and the bubbles especially should be protected against the heat of the observer's body or the lamps used to illuminate them while they are being read. As any undue pressure placed on the instrument by the observer when turning the micrometer head will lead to large errors in the readings, a minimum amount of handling of this part is essential. Of course the skilful choice of stars and the programme to be observed in the observations will play a most important part in securing accurate results, but as these points are more in the province of the astronomer than the instrument designer, they need not be enlarged upon here. Finally, the accuracy to be expected and generally obtained from a well-adjusted zenith telescope taking the mean of 10 or 15 pairs of stars, is of the order of 1/10th of a second in the astronomic latitude.

Value of Micrometer Divisions. The method of obtaining the value of the micrometer divisions is, as mentioned before, best performed in the laboratory, but when it is to be determined in the field the following is a good procedure to adopt :—

The telescope is focused on some close circumpolar star near elongation and the time of its transit across the movable wire is taken at several settings. For this purpose, the wire is set one whole turn ahead of the star, the exact moment of its transit read and at the same time the position of the latitude level. The readings may also be taken at culmination, but in this case the results are not so accurate, owing to the fact that variations in the setting in azimuth are not eliminated, as the corresponding variations can be in the former method by taking into account in the calculation the readings of the latitude level. This level must of course also have its value determined very accurately, but this work is best done in the laboratory by means of the level trier. The best method of finding the micrometer values has been found to be by means of calculations made on the observed readings obtained when making latitude determinations. A large number of accurate observations are generally made at each station, the figures obtained being available for this purpose, and it is generally found that the mean results calculated in this way are more concordant than those obtained from special observations on the circumpolar stars.

Zenith Tube. A most accurate method of determining latitude, which, however, is only used at important fixed observatories, is by means of the **zenith tube.** This in essence is a large tubular casting bolted down on a concrete foundation and set to point to the zenith. At the top an object glass of large aperture is fixed in a cell which may be rotated in azimuth. At half the focal distance below the object glass a mercury trough is placed in such a position that the light from a star, after passing through the object glass is reflected back and focused on to a photographic plate or a micrometer fixed to rotate with the object glass. If the object glass is rotated 360 degrees, the image of the star will trace a circle on the photographic plate the radius of which will be the zenith distance of the star. As it is the zenith distance of the star when on the meridian which is required to be known, the method of using the instrument to get this result is as follows :—

The star on approaching makes a trail on the photographic plate. As soon as it reaches the meridian, the lens and plate are quickly turned 180° in azimuth so that the star will now make a trail on the plate parallel to the first one. The distance between these two trails when corrected for curvature, will then be twice the zenith distance of the star. Various corrections must be applied owing to the impossibility of instant reversal and to the fact that a reversal of 180° cannot be exactly made. The photographic plates are afterwards measured by means of a special travelling microscope in the manner familiar to astronomers. The idea upon which the zenith tube was based was due to Airy, and an instrument of this description was constructed and in use for fifty years at Greenwich Observatory. From the data obtained by its use Chandler first discovered the phenomenon of latitude variation.

This latitude variation is extremely minute, being only about ·5 second of arc so that the observations made for the purpose of measuring its magnitude must be very carefully carried out by means of the very finest instrumental aids. The actual variations are not yet definitely known, as their periods which are very complex have not been fully determined, nor are they likely to be until the observations taken over some years have been classified and the results computed. When it is realised that the total variation at the pole is probably less than 100 feet the delicacy of the determinations will be manifest.

Longitude

The longitude of a place is its angular distance to the east or west of the meridian at Greenwich and up until the advent of wireless telegraphy was undoubtedly the most difficult and troublesome determination which surveyors were called upon to make. The measurements are not in any way absolute, but merely consist in the comparison of the local time with the time at Greenwich or at some other point referred to Greenwich. At sea, mariners carry carefully regulated chronometers, the rates of which are known, and thus are able to compare their local time with that to which the chronometer has been adjusted. Should the chronometer fail or its rate become uncertain, the value of the determinations is lost and recourse has to be made to observations on the moon or the planets, an operation rather beyond the skill of the average navigator, and one giving inferior results. When the place at which the longitude is to be obtained can be connected with the overland telegraph wires, the operation becomes comparatively simple, as it is then only necessary to fit up a receiving apparatus and to compare the beats of the local chronometer with those of the observatory at the other end of the wire. This apparatus may consist of a telephone receiver so connected that the beats from the main observatory are super-imposed on those of the local chronometer, these latter being introduced into the circuit by means of a microphone. When more refined records are required, use is made of recording chronographs of the type shown on page 213 at both the sending observatory and the local station. These chronographs, in addition to recording the beats of the chronometers or standard pendulums alongside those made by the key or by the automatic contacts on the micrometer eyepiece, record also a number of special breaks on both chronographs simultaneously, the distances of which may be accurately measured off from those made by the chronometers. A comparison of the break made at both stations allows the difference in time between the two places to be calculated to a high degree of precision. The whole operation, the instruments used and the precautions to be taken are similar to those already given under the heading of time determinations, the only difference being that the times found at the two stations when compared with each other serve to give the longitude of the new station in relation to the main observatory, the position of which is already accurately known. The use of the telegraph wires introduces certain errors which must be allowed for. These errors are due to the time lag in the line, in the relays and in the magnets used to operate the chronographs. Whenever possible, the lines should be simple and run as directly as possible between the stations without having to go through local relays or other circuits at the telegraph offices. This cannot always be arranged of course, so that it is necessary to take special precautions to eliminate any errors due to this cause. The simplest method of ensuring good results is to make the set of special breaks from each end in turn, the times of which can be compared with those of the chronometers, as in this way the mean of the two sets of breaks should give an exact result. This will not be so unless the relays, etc., at each end are similar in lag and general character and there will also be the usual errors due to the personal equation of the observers. When therefore the determinations are required to be of the highest precision, it becomes necessary to make a change of observers from end to end and when any doubt is felt as to the similarity of lag in the apparatus each observer should instal his own instruments at the opposite station. It is usual to observe each night on 12 stars, the special breaks being made after the sixth set has been completed. When the work is carried out in this way and all the usual precautions have been taken, the probable error is something of the order of 0·015 second of time.

Photographic methods of obtaining longitude have been put forward from time to time, but have not come into general use on geodetic work, owing probably to the somewhat laborious calculations required and to the necessity of using rather expensive subsidiary apparatus to measure the photographic plates. The method is roughly as follows :—

A very stable camera is set up and pointed so that the image of the moon comes on the centre of the plate. A number of instantaneous exposures are then made at such intervals of time that the images do not overlap. Without disturbing the camera a set of time exposures are made on three or four bright stars of about the same declination, each such exposure leaving a trail on the plate. If then the local times of all these exposures are known the measurement of their positions will give the data necessary for the computer.

Azimuth

In order that the triangulation points may be correctly placed on the map, it is necessary to know the true north at a number of points and as the determinations act as a check on the triangulation angles, it is usual to take astronomical azimuth sights at each important point of the triangulation net-work. When the azimuth is only approximately required an observation on the sun is usually made with a transit theodolite the procedure being simply to point first on to the sun, noting the time, and then on to a fixed terrestrial mark. It is necessary to know the latitude, longitude and the local time, thus allowing the true bearing of the azimuth mark to be calculated. When more refined results such as those used in primary triangulation are required, it is usual to make the observations on Polaris or on the close circumpolar stars and these observations are made at the same time as are those of the triangulation angles and using the same targets. The most skilful observers and the very finest instrumental aid are necessary for this work, and surveyors generally consider the taking of astronomical azimuths as the most exacting operation they are called upon to perform. Owing to the large differences in the inclinations of the telescopes, which must be first pointed on to a star and then on to a terrestrial object, the stability of the instrument and the control of the horizontality of its pivots must be most carefully attended to. Otherwise the operation is very similar to taking ordinary terrestrial azimuth and all the usual adjustments must be carried out in the way already indicated, and with the most scrupulous care. The observations are always made in such a way that the instrumental errors are eliminated so far as possible, and for this reason the theodolite must be arranged for change of pivots so that face right and left readings may be made. The procedure is as follows :—

The telescope is first set on to the terrestrial mark, which is usually a signal tower carrying a powerful source of light if the work is being done at night, and a reading of the horizontal micrometers taken. It is then pointed on to Polaris, the time by the chronometer taken, and then the reading of the circle booked. The telescope is now reversed on its pivots and a pair of similar settings and readings are taken. Immediately after each pointing is made the striding level is read in order to find the inclination to the horizontal of the telescope pivots. The calculations are made later in the office and consist in first finding the bearing of Polaris to the meridian at the time of each pointing. The various corrections are then applied and the bearing of the line joining the instrument to the target or triangulation mark from the meridian is obtained. With this method the error in the final results of say ten complete sets of four observations is somewhere in the neighbourhood of ·3 to ·4 second, while the usual degree of accuracy expected from observations on the sun is about half-a-minute. For work of the highest accuracy the time determinations are of very great importance and the error of the chronometer should be known

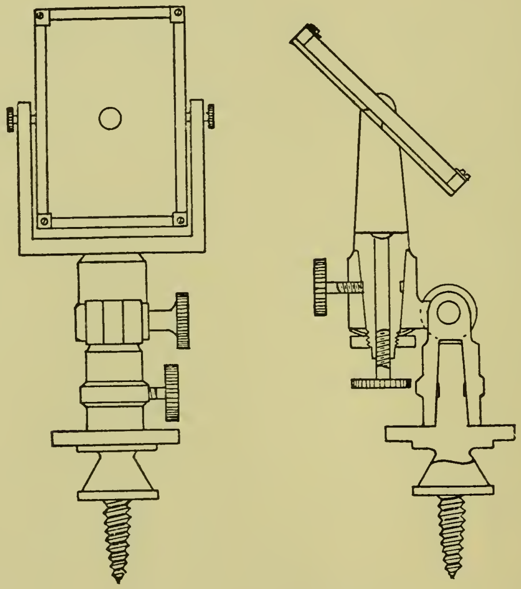


FIG. 192—Heliotrope

to well within half-a-second. The value of the level divisions must also be known and a correction applied to the figures. Thus :—

if D = value of one division

L = reading of left side of bubble

R = reading of right side of bubble

L_1 and R_1 similar readings with bubble reversed.

Then the correction to be applied is equal to

$$D \times \frac{(L + L_1) - (R + R_1)}{4} \times \tan a$$

It is therefore easily seen that when the altitude A is great, the horizontal setting of the axis is important.

Eyepiece Micrometer.—Another method of taking azimuth readings is by means of a micrometer in the eyepiece of the theodolite. The procedure is as follows :—

The telescope is first pointed on the star and the micrometer read. It is then lowered in altitude on to a fixed target, and the difference in turns and parts of a turn between these two settings noted. In order to do this it is necessary that the target should be almost under the star when at elongation, as only small differences in azimuth can be read in the micrometer eyepiece. It is of course understood that during the observations the horizontal part of the instrument is securely clamped in azimuth, as the readings of the circle are not used in this method. If, as sometimes happens, the readings must be made on stars at large hour angles very few observations can be taken as the star passes out of the field of the telescope too quickly. When the observations are made at elongation, there is the added advantage that errors in time will not have much weight in the calculations. It is usual to take a number of readings on the micrometer both of the star and of the target, and the order in which these are best taken is as follows :—

First, the micrometer is placed at about the centre of its run and the web is set on the target by turning the instrument about its azimuthal axis. The horizontal circle and the upper part are then securely clamped in azimuth. Four or five settings are now made on the target using the micrometer screw only and the readings booked. The telescope is then tilted in altitude on to the star and the striding level read. Three or four bisections of the star are then made with the micrometer and the chronometer times booked, together with the settings. The striding level is then read and the amount of tilt booked. This level is then reversed and read and three more pointings are made on the star, the figures being booked together with the times by the chronometer. The telescope is now reversed on its pivots, and the above star readings, etc., repeated in the new position. The telescope is then lowered on to the target and four or five settings are made and booked. Such a set of readings will take about fifteen minutes and on a suitable night two or three such settings may be made leaving plenty of time to read the bubbles and to set the micrometers, if the operations are thus carefully mapped out and rehearsed beforehand. Just before the telescope is reversed on its pivots it is usual to read the zenith distance of the star, as it is necessary to know this when making the calculations. When accuracy such as that expected from a main observatory is required, it may be necessary to make a number of determinations of the zenith distance, owing to the fact that the value is continually changing. The value of the micrometer turns must be accurately known for work of this nature, and as explained before, this value is usually determined in the laboratory. The surveyor generally likes to check its value or its constancy for himself however, and the simplest method of making this test is to measure a small angle between two fixed terrestrial targets or two plumb bobs by means of the horizontal circle of the instrument, the mean of a number of readings being taken in order to eliminate errors of circle dividing and eccentricity. The same angle is then measured with the micrometer, and, providing a sufficient number of settings are made and the targets are of such a nature that they may be accurately pointed upon, the results obtained by this method are better than those to be expected from pointings on the close circumpolar stars. This latter operation is carried out in the following way :—

The telescope is pointed on to one of the close circumpolar stars just before elongation, and clamped securely in altitude and azimuth. The micrometer is set a few turns from its mean position towards the side from which the star is apparently travelling. When the star transits across the web the chronometer time is taken and then the screw is moved one whole turn, thus putting it ahead of the star ready for the next transit. A number of transit turns are thus taken, covering the whole of the screw. From these figures the micrometer value may be calculated, but it is necessary to know the level values and the chronometer times very accurately. The calculations required before exact values can be obtained by this method are very laborious and it is doubtful if the results achieved repay the labour involved in taking the observations and making the computation. When determinations of azimuth have to be made in very high latitudes, the above methods are not altogether satisfactory because of the high altitude of the slow moving stars. It is possible to calculate the azimuths from data furnished by the observations made for time if when these observations are made a pointing is also made on a terrestrial mark and its position determined by the micrometer. For this purpose, the mark must be nearly in the meridian in order that it may be covered by the screw of the micrometer. The procedure otherwise is similar to the micrometer method given above. The close meridian mark must of course be connected up to the usual triangulation marks by the direction method already given.

The targets used for azimuth work vary according to the nature of the ground over which the sights must be made, and it is often necessary to raise them to a considerable elevation above the surrounding country in order to get the sights clear of trees, buildings and other obstructions. see Fig. 193. The best mark is undoubtedly an electric head light such as those used on motor cars and for short distances such a lamp may be placed in a wooden box the front of which is covered by tracing cloth having a piece of black tape stretched vertically across its centre. Very good settings may be made on such a target at fair distances, but no target should be placed closer to the instrument than about a mile, as otherwise the telescope focus must be changed when pointing on to the star, thus leading to the possibility of errors owing to the likelihood of displacement of the line of collimation. Care should also be taken that the line of sight does not pass close to any tall buildings or even along the side of a hill, as when this is done errors due to lateral refraction are likely to be introduced. This precaution is especially to be observed when taking terrestrial azimuths and it is always noticed that when sights are being taken in a populous neighbourhood where the lines must necessarily run close to such objects, the results are not so good as those made in open country. It is therefore much better in such cases to take a number of angles on successive days and nights, rather than to rely on the mean of a large number of observations made at one setting.

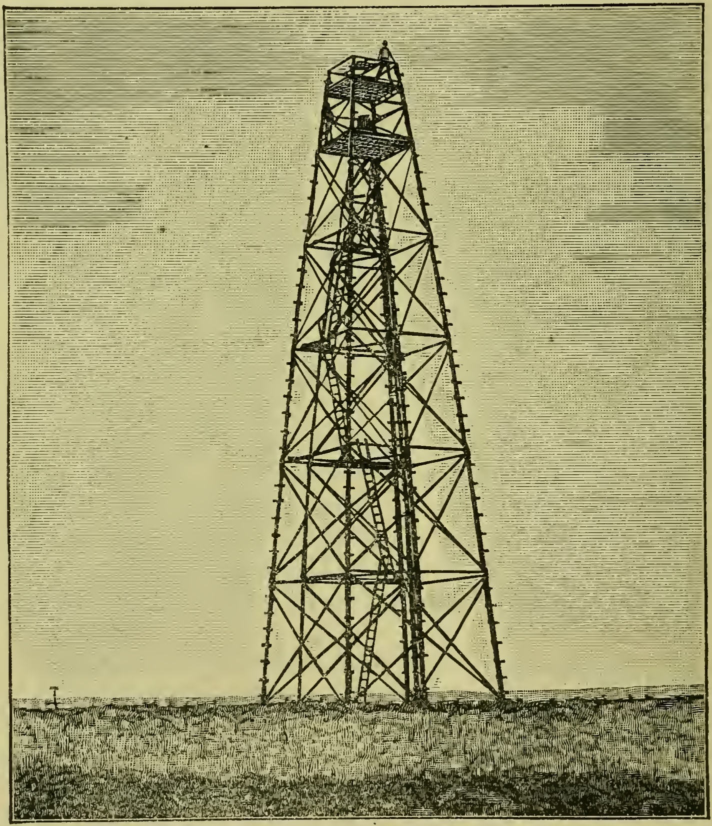


FIG. 193—Double tower used on primary triangulation. The inner tower supports the instrument, the outer one carrying a platform for the observer

CHAPTER XV

PRISMATIC ASTROLABE

THE works of Claude & Driencourt have drawn attention to a method of latitude determination by means of an instrument of their invention which they have named "L'Astrolabe à Prisme." The results obtained from this instrument are extremely good, and the portability of the apparatus and the ease with which the determinations can be made, will no doubt lead to the extensive use of their method.

The greatest difficulty which is encountered in the accurate determination of latitude, is the want of stability of the instruments, and the care which must be taken in their adjustment. In the astrolabe, on the other hand, the instrumental errors are practically negligible, as it relies for its accuracy on the permanence of shape of a glass prism having angles of 60° about. This prism is comparatively small and can be polished to a very high degree of accuracy, and provided that no great fluctuations of temperature take place during the observations, its shape may be deemed constant for the purpose of the measurements under discussion. Fig. 194 shows the elements of the instrument which is simply a fairly powerful telescope placed horizontal and fixed to an axis allowing it

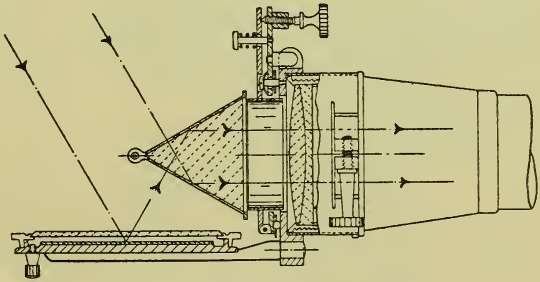


FIG. 194

to be turned in azimuth. The 60° prism is fixed in front of the object glass on a frame so made that it may be adjusted accurately to the line of collimation of the telescope. Below and just in front of the prism a shallow trough containing a film of mercury is supported in such a position that the image of a star is reflected by the mercury surface into the prism and thus along the telescope where it is brought to focus on the reticule.

When the telescope is levelled, the image of a star at 60° altitude is reflected from the mercury surface and at the same time another beam from the same star passes through the top face of the prism and is similarly reflected and passes down the telescope. These two images will move one up and one down the field of view, the apparent motion being at double the rate at which a single star image would move when viewed directly as in other instruments. When the instrument has been set up and adjusted it is only necessary to note the time at which the two images cross each other, this giving the time at which the star was at 60° of altitude or if the prism differs by a few seconds from the correct figure of 60° at some other constant angle depending on the angle of the prism and the refractive index of the glass. As these figures may be obtained very exactly in the laboratory, the necessary correction can be applied when making the computation. For example, if the angle of the prism differs from 60° by an amount d, and if r is the refractive index of the glass, then when contact is made on the two images, the constant to be applied will be

$$\pm d \left(\frac{3r - 1}{2} \right)$$

The accuracy to which the latitude may be found with a well-constructed instrument having an object glass of about 2 inches diameter and a magnification of about 120 is ± ·2 second, and the time to

$$\frac{\cdot 03}{\sin \lambda}$$

where λ is the co-latitude. This is a wonderfully good result when the comparative simplicity of the apparatus and the speed with which the observations may be carried out are considered.

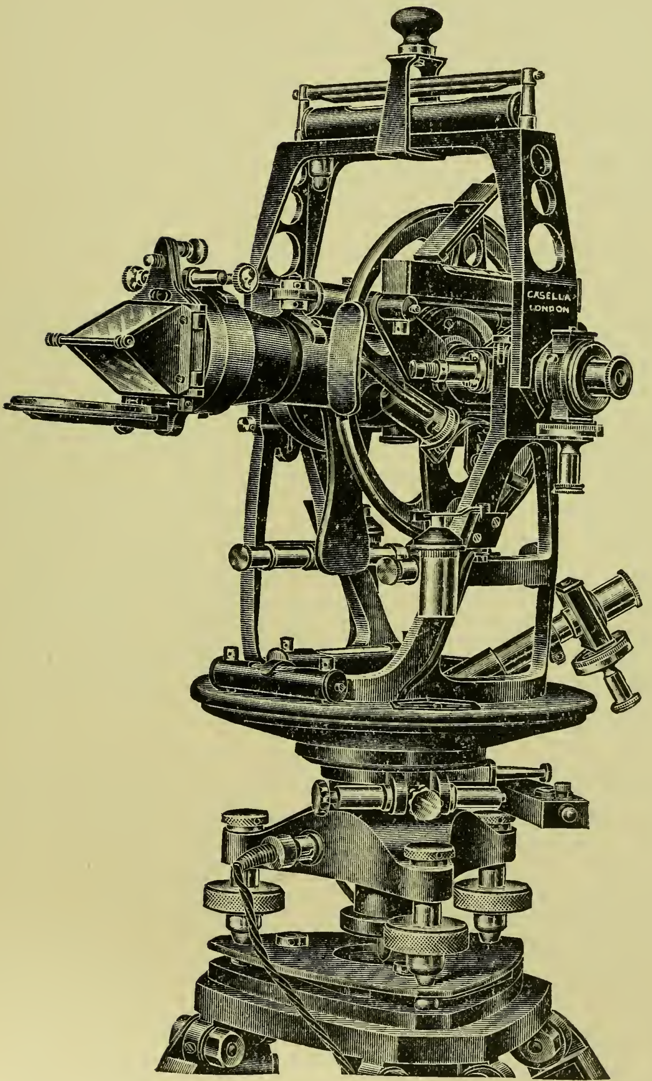


FIG. 195—Prismatic astrolabe attachment on a micrometer theodolite

The weight of the apparatus is small compared with other instruments giving an equivalent result, and there is no necessity to construct special supporting piers or stands, as the ordinary portable tripod gives sufficient stability. In addition a complete determination including the setting up and the adjusting of the instrument may be made in about two hours, so that there is no doubt that this method is destined to become very largely used. It is true that the instrument is a special one of use for this purpose alone, but as it is so portable, this is no great disadvantage when it is considered how perfect are the results and at what a comparatively small cost the determinations can be made.

For making similar determinations, Mr Reeves of the Royal Geographical Society, has designed a **prism attachment** which may be fitted to an ordinary transit theodolite, a photograph of this being shown in Fig. 195. As may be seen, this attachment is arranged to be clamped on to the object glass cell, and is so fitted that slight adjustments may be made to the prism in two directions at right angles to each other. The whole apparatus may also be rotated slightly about the axis of collimation of the telescope. Below the prism a detachable arm carries a small boxwood or aluminium tray containing a copper plate amalgamated with mercury on its upper surface. The whole attachment only weighs a few ounces, so that although it is desirable, it is not absolutely necessary to fit a counterbalance weight to the other end of the telescope.

Adjustment of the Prism Attachment. The theodolite having been set up and adjusted in the usual manner, the telescope is directed to and accurately set on some well-defined distant point. The attachment is then slipped on to the object glass cell and clamped so that the leading edge of the prism is about level. The telescope should now be depressed 60°, when the point ranged upon should be in the field of the telescope. By means of the two adjusting screws, the point should be brought accurately to the intersection of the webs. When the telescope is moved in altitude, the point should follow the vertical web, but if it does not do so, it may be brought to the correct position by manipulating the small screw at the top of the cell. The readings should be repeated, when, if all is in order, the telescope may be levelled and the mercury trough placed in position. A small quantity of clean mercury is now placed in the trough, any surplus being removed by means of a glass rod which is drawn across the rim, this rim being slightly higher than the amalgamated surface. If the glass rod is rotated counter clockwise and at the same time pushed across the trough, any dirt which may be on the surface of the mercury will be removed, attention to this detail being important, in order that the two star images may be approximately of the same brightness.

For the method of carrying out the observations, reference may be made to the works of Ball & Knox Shaw, who have compiled excellent star lists and devised a simple graphic method of computation. These authors state that under good conditions the time may be determined to within 1/10th second and the latitude within 1 second by means of a small instrument, and at the expenditure of only two hours of observations. Weld Arnold states that with a prism attachment fitted to a 6-inch theodolite, the latitude of New York has been determined by him to within ± 1 second.

A number of theoretical objections have been raised against the prismatic astrolabe, but there is no doubt that the actual results obtained in practice leave little to be desired, and the other advantages of the instrument are so manifest that this method is bound to become very largely used in the future. Good workmanship is required if the best results are desired, and the prism and object glass must be of the very highest quality, as otherwise the images of the stars will be imperfect and the settings in consequence ambiguous.

It is to be noted, that as the relative speed of the star across the field is double that of a direct image, the accuracy of making coincidence is equal to that obtained by the direct method when using an ordinary telescope of double the magnification.

Another advantage which this method has is that stars 30° from the zenith are the best upon which to make observations on an average night, and that errors due to asymmetrical refraction are not introduced into the results. In the instrument used by Claude and Driencourt, the adjustments are similar to those given except that the prism may be set to correct position in relation to the line of collimation by the method of autocollimation. In order that this may be carried out conveniently, the reticule which consists of two vertical and two horizontal lines forming a rectangle in the centre of the field is strongly illuminated by means of an electric lamp fitted to the telescope thus showing up the spider lines black against a bright background. The image of these lines is therefore reflected from the back face of the prism and superimposed on the wires themselves, a pair of adjusting screws being furnished to bring the images into coincidence.

In an instrument recently designed by T. Y. Baker, various improvements have been incorporated which appear to render the apparatus capable of greater accuracy. In this design the prism, instead of being fixed in one position, is arranged so that it may be rotated about a horizontal axis, thus bringing each edge to the front in turn. The three angles of the prism have purposely been made slightly different from each other, one being as nearly 60° as it is possible to make it. The other two angles differ from 60° by about + 7 minutes and — 7 minutes. It is thus possible to take three readings of each star by rotating the prism 120° between each observation. It is obvious that the prism must be very accurately mounted to rotate so that the adjustments remain correct for all three positions. It would seem that the advantages of the three readings on this instrument as against one on the original type must be great to justify a departure from the simplicity of the Claude and Driencourt design, especially when it is considered that the main virtue of the astrolabe lies in its extreme simplicity and freedom from instrumental errors, and that, with a fairly large object glass, capable of working on small magnitude stars, plenty of opportunities are offered for observations on any reasonably clear night. Another improvement incorporated in Baker's instrument is the provision of a small auxiliary prism to split the direct image of the star, so that two images appear in the field separated horizontally by a small amount. These two images move downwards while the indirect image moves upwards in between them. It has been found that a closer approximation of the time of coincidence can be made on this system than on the usual scheme having two star images only.

When the instrument must be used in windy weather, it is necessary to shield the mercury surface by means of a glass cover and care must be taken that the reflections from the glass are not mistaken for those from the mercury surface, and that the glass is so arranged that no constant error is introduced. The cleanliness of the amalgamated surface of the tray is of importance, as otherwise a flat clear mirror-like reflector cannot be obtained. It is necessary to clean the copper surface with strong nitric acid occasionally, and to take care that no grease comes in contact with it. The old amalgam when it becomes thick and tarnished should be scraped off with a safety razor blade, and when all is kept in proper order a film of less than 1 mm. thick is quite sufficient to give a good reflecting surface if care is taken to see that the tray is accurately level when the instrument is wheeled in azimuth. The thinner the surface, the less likely is it to be disturbed by wind and the cleaner it is the clearer will be the image in the telescope. Care must be taken in packing away the trough and the spare bottle of mercury and it would be best to pack these parts in a separate case as small globules of mercury coming in contact with the working surfaces of the instrument will very quickly cause damage to them. When an instrument is fitted with divided circles on silver, the divisions can be effaced in a few hours by coming in contact with the merest trace of mercury.

A list of stars for use with the astrolabe has been compiled and published by Ball & Knox Shaw, and Weld Arnold, of the American Geographical Society, has completed a very extensive list, which will no doubt be available shortly in printed form.

CHAPTER XVI

GRAVITY

A BODY on the earth's surface is acted on by two opposing forces, one tending to repel it, due to centriufgal action, the other tending to attract it owing to the mass of the earth. The force due to the latter is the greater of the two with the result that bodies tend to fall towards the earth. The resultant of these two forces is known as gravity. It was discovered in the 16th century that a pendulum had a different rate in different latitudes. At a later date this variation was found to be due to the fact that the earth is not truly spherical. Later on, delicate measurements showed that the variations in the density of the earth's crust could be determined and in recent years instruments have been devised which enable mining engineers to locate reefs and oil bearing beds by means of such measurements. As it is necessary to know the shape of the earth in order that the great triangulation lines may be assigned their proper values all large continents have been or are being surveyed for gravity. The apparatus used for this purpose is comparatively simple in its elements, but as the forces to be measured are so small, or rather, as they differ so slightly from each other, very many precautions have to be taken if the results are to be of any use. The apparatus in modern form consists of a rectangular case made of bronze, so arranged that it may be exhausted of air by means of an air pump. Inside the case, a pendulum is hung on an agate plane and knife edge. Its period of oscillation may be one second nearly or half a second nearly, the latter length of pendulum being now the more usual size for comparative work, owing to its greater portability, and also to the fact that it is not so difficult to keep the much smaller case free from vibration. The swing of the bob is about $\frac{1}{4}$ inch at the commencement of the determination and once started it will continue to oscillate for about 10 hours in the vacuum chamber. Invar is the material now used for these pendulums, as with the bronze or steel ones formerly used the temperature control was too much of a problem except at a fixed station. On the side of the case a glass window is fixed to enable the swing of the pendulum to be examined through a telescope. The method of use is simply to compare the oscillations of the pendulum with the beats of a chronometer or clock. The period of the pendulum is so arranged that it makes one oscillation less in about every 5 minutes than the chronometer, and in this way its rate may be determined with great accuracy. Sometimes the beats of both the pendulum and chronometer are recorded simultaneously by photography, but this is a refinement only used in special cases. The determinations by an apparatus of this kind are only comparative, and must be referred to some place where absolute values have been obtained over a series of years. The error of the rate of the chronometer for this work must be very accurately known, and in this direction the matter has been very much simplified in recent years owing to the advent of the wireless time signals sent out from all our great observatories. The reception of these signals is fully dealt with in another chapter, and need not be further referred to here. The greatest errors introduced into these determinations of gravity are those due to the vibration of the whole apparatus, which, although very heavy and supported on a concrete base, is very susceptible to earth tremors. The rocking of the case due to the oscillation of the pendulum itself is another cause of error. This rocking of the case is in certain stations measured either by the variations in capacity produced between fixed and movable condenser plates coupled to an oscillating triode valve or by means of a specially constructed interferometer, such as those designed by Michelson. These measurements may, with suitable apparatus, be carried to any degree of refinement required, until we come to the point that what we are really measuring is the actual variation in the length of the pendulum itself.

The figures obtained from these gravity determinations are used to calculate the shape of the earth and a recent computation made in the U.S.A. from a very large mass of data obtained there and in Europe and India, gives the value of the flattening as 1/297·4. These determinations are necessary for geodetic work which of course must take into account the departure of the earth from an exact spherical form. The radius of the sphere has been measured periodically since the Christian era. The method of making this measurement is as follows:—When a long arc on the meridian has been measured, the difference in the altitudes of the sun or a star, as measured at each end of the arc, gives the data necessary to compute the circumference of the earth. As an enormous amount of data is now available from the measurements made on triangulation work, these figures have been used in recent computations rather than those from special measurements, but the actual values obtained do not differ greatly from those computed by Bessel in 1841 and by Clarke in 1866. The latter gives the following values :—

$$R = \text{Radius at the equator} = 6{,}378{,}206 \text{ metres}$$

$$P = \tfrac{1}{2} \text{ Polar axis} = 6{,}356{,}584 \quad \text{,,}$$

$$\frac{R - P}{R} \quad \text{compression} = \frac{1}{295}$$

This figure of the Clarke ellipsoid is in good agreement with the value given the U.S.A. of

$$\frac{1}{297{\cdot}4}$$

arrived at from gravity measurements only. The accuracy of the determinations of gravity by means of the pendulum is about 20 parts in a million. Professor Michelson of the University of Chicago, so well-known for his work on interferometry, has designed a new apparatus by means of which much more accurate and much quicker results are hoped to be obtained. An accuracy of 1 part in 1,000,000 is being aimed at and will probably be realised. The apparatus in contemplation is to consist of a long quartz rod supported at one end. The depression of the free end of the beam, due to different values of gravity, will be measured by means of an interferometer of a specially sensitive kind.

A new method for the determination of gravity at sea has recently been tried by Dr Vening Meinesz. This apparatus was set up on a submarine belonging to the Dutch navy and used on a voyage to the East Indies. Full particulars of this voyage will be found in the Geographical Journal, vol. LXV, No. 6, for June, 1925.

Every schoolboy has been taught that the earth has the form of an "oblate spheroid" the impression left on his mind being that if he could see it from a sufficient distance it would look something like a very flattened orange or a Rugby football. In point of fact the actual flattening is relatively so minute that it would be quite impossible for the eye to appreciate it at any scale. If a model of the earth were made about the size of an orange and exactly to scale the actual difference between the equatorial and polar diameters would only be about 1/100th inch, an amount which the eye could not of course appreciate. This simple illustration will serve to show the amount of care required in the handling of the instruments used on the work of making these measurements and the precision with which the apparatus must be constructed and adjusted.

CHAPTER XVII

TERRESTRIAL MAGNETISM

A STUDY of terrestrial magnetism is not now of such great interest to land surveyors as formerly, but in those countries having a sea coast, the publication of data showing the variation of the compass is of the utmost importance to mariners.

A short description of the principal instruments used may therefore be included here. The determinations to be made are: (a) magnetic declination; (b) horizontal intensity; (c) dip. The instruments used in fixed observatories are generally made to record continuously by photographic means, but as their principles are the same as those used at temporary stations, it will be sufficient if a description of the portable apparatus in general use is here given. Fig 196 shows the usual form taken by the instrument employed for measuring the dip. This is known as the **Kew Dip Circle.** It consists, as may be seen from the illustration, of an accurately balanced needle, having highly polished steel pivots about

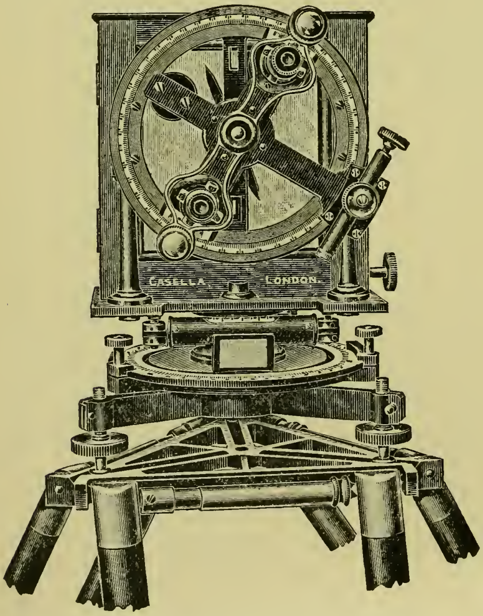


FIG. 196—Kew pattern dip circle

which it may turn or rather roll. These pivots are supported on two accurately levelled agate knife edges, on which they may roll with very little friction. Two microscopes are fixed, one over each point of the needle, thus allowing the exact coincidence of the points with a spider line in the eyepiece to be read. The needle may be lifted off the knife edges by a lever arrangement similar to that used in chemical balances. The whole of the upper part may be turned round an axis and so set in the meridian or at any other azimuth, a pair of stops serving to limit the movement to 180° from any setting. The microscopes may be turned round an axis at the centre of the vertical circle shown and their position read by means of the attached verniers. The instrument is set up on a brick or concrete pier in a hut which is free from any magnetic material.

The adjustment of the dip circle will be evident from a study of the methods given for other instruments of a similar nature and is easily carried out. The testing of the needles, however, is a matter beyond the average surveyor, as the determination of their accuracy can only be made by comparison with other needles, the constants of which have become known through many years of careful use. It is usual and almost essential to send the needles and preferably the whole of the apparatus to a testing observatory, such as Kew, and to obtain a certificate for their performance. Very great care is necessary in the manufacture of the needles, as they must be most carefully balanced about their pivots and the pivots themselves must be truly in line, very highly polished, circular in section, equal in diameter, and accurately parallel. Very highly skilled men are required to carry out this work, with the result that a good set of needles will often cost as much as the remainder of the instrument. The needles are magnetized by stroking them with a pair of bar magnets, and for this purpose they are held in a wooden fitting with a cap which screws down over the pivots and protects them from accidental contact with the bar magnets.

All the parts of the instrument must be made of material free from any magnetic substance, and the observer using the apparatus must see that no steel articles likely to affect the needles are on his person during the tests.

The mode of using the instrument is as follows :—

The agate edges and the pivots are carefully cleaned with pith and needle No. 1 is placed on the fork of the lifter. The glass window is then closed and the needle carefully lowered on to its pivots. The microscopes are set to 90°, i.e., with the line joining them vertical, and the whole instrument turned in azimuth until, when the needle is vertical, the instrument is approximately in the magnetic meridian. The needle is now lifted off its pivots and gently lowered again, thus giving it a slight oscillation. The azimuth circle is now adjusted until the upper microscope web bisects the swing and a reading is taken of the horizontal circle. A similar reading and setting is made with the lower microscope. Another pair of readings is then made with the instrument turned 180° in azimuth. The means of these four readings allows the direction of the magnetic meridian to be determined. The limiting stops are now set, so that when the observations for dip commence, the reversals may be quickly made without the necessity of reading the azimuth circle. No great accuracy is required in this setting as the errors due to a setting slightly away from the meridian are generally negligible. The needles, usually two in number, are marked No. 1 and No. 2, the ends of each being engraved A and B for identification purposes. The two needles are first magnetized so that the A ends are dipping. No. 1 needle is then placed in the instrument and with circle right the upper microscope is set to bisect the swing and the verniers read. A similar setting and reading is then made with the lower microscope. The whole instrument is then turned 180° in azimuth and a similar pair of readings taken. The needle is now reversed on its pivots, thus bringing the engraving to the back and a further set of readings taken. This makes four instrument settings and eight vernier readings and constitutes a quarter set. No. 2 needle is now inserted in the instrument and a similar quarter set of readings taken. The needles are now magnetized in the opposite directions, so that the B ends are dipping and a half set of readings taken with needles 1 and 2. This completes one determination, there being thus sixteen instrument and thirty-two microscope settings. Sometimes a double setting of the microscopes is made at each needle position, this method involving sixteen instrument and sixty-four microscope settings for one complete set. The mean of all these readings gives the true dip free from any instrumental errors. When observations are to be made near the pole, a different style of support for the needles is used, in order that a clear space may be left for viewing their ends at the nearly vertical position. It is difficult to set the instrument truly in the magnetic meridian near the pole by the method given, so that other arrangements have to be made or else determinations each side of the meridian are made and the true dip calculated from the observed dips.

Observations at Sea. When observations for dip have to be made at sea the instrument is constructed rather differently, as it would be impossible to use needles rolling on agate edges. The needles are therefore supported on end pivots similar to those used in watches, the whole instrument being swung in gimbals supported on a massive bronze pillar. The dip circle is sometimes fitted with an attachment which allows observations for **total force** to be made. This attachment consists of a small frame fixed at right angles to the line joining the two microscopes and in front of them and so arranged that a special needle, No. 4, may be clamped to it. Another special needle, No. 3, is placed in the instrument and observations on the inter-action of the two needles are made. From these observations the total force may be calculated. The dip shown by No. 4 is taken separately with a small weight added to one end of it, but as these determinations are only of academic interest, the reader is referred to special publications on this subject for fuller details.

Sometimes a detachable trough compass is fitted to the top of the instrument case, which, in conjunction with peep sights or a small telescope, allows the instrument to be used to obtain a rough indication of the magnetic declination. Recently, instruments known as **dip inductors,** have been used with great success. These give rather more accurate results, but owing to their nature, cannot be easily transported. The first apparatus of this kind, due to a suggestion made by Professor

Schuster, was used at the Greenwich Observatory, at which place there is a very fine equipment of magnetic instruments, the records being made photographically.

Goolden's Portable Dip Circle. This instrument Fig. 197 is intended to meet the want of a dip circle, of moderate cost, which will not only indicate the magnetic dip, but also be capable of some exactitude in measurement.

A 3½ inch needle, provided with adjustable counterpoises ingeniously contrived so as to bring the centre of gravity accurately into the axis of support, is carried in jewelled centres on a horizontal axis. The inclination of the needle to the horizon is read upon a metal circle, graduated on both sides, and the whole is enclosed in an air-tight box with glass faces, revolving about a vertical axis. In order to facilitate the adjustment of the needle to the magnetic meridian, the vertical axis of the instrument is furnished with a spring arm which can be clamped to it, and there are four metal studs on the stand at right angles to each other into which the head of the spring arm fits when pressed down with the finger. The stand is provided with levelling screws, and a small level is carried in the mahogany box, into which the instrument is fitted for transport.

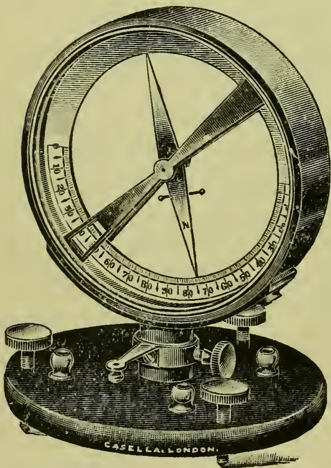


Fig. 197—Goolden's portable dip circle

Magnetometers

The two other elements necessary to define the magnetic field, viz.: the horizontal component of force **h** and the declination **d** or the angle between the true meridian and the magnetic meridian, are usually measured in the field by means of the unifilar magnetometer, a picture of which is given in Fig. 198, showing the instrument as arranged for the determination of **h**

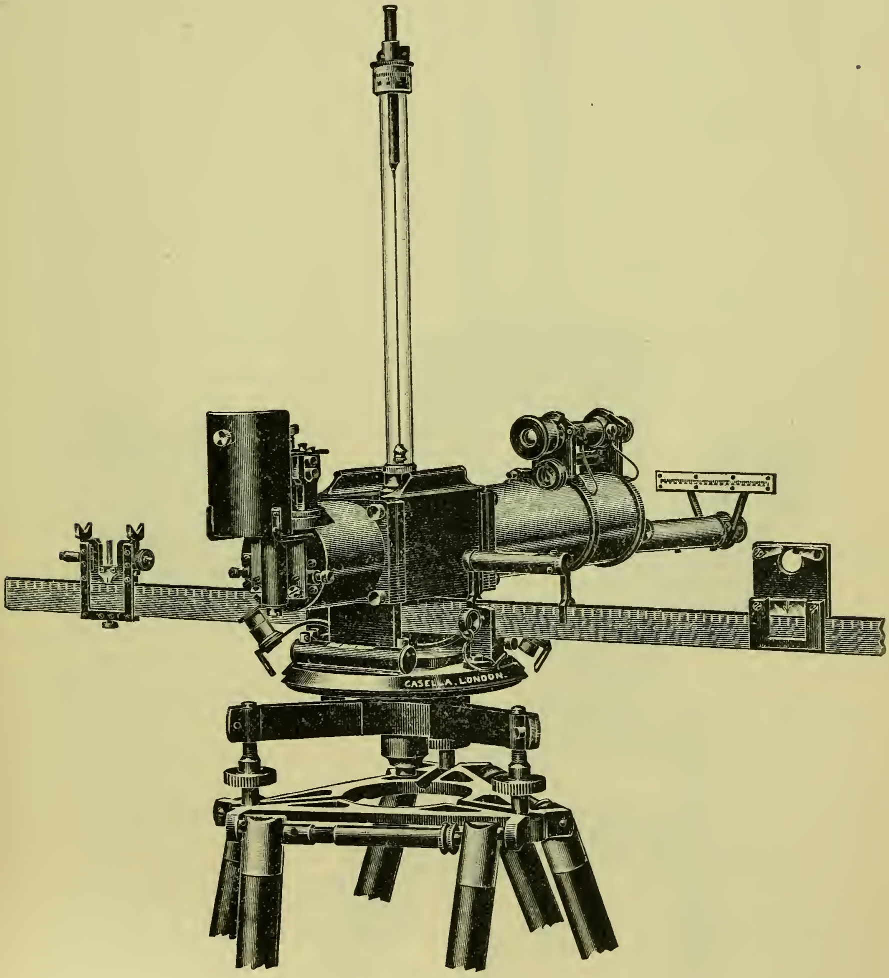


FIG. 198—Kew magnetometer arranged for the determination of the horizontal component of force

by what is known as the vibration method. When arranged as shown in Fig. 199, the instrument can be used for the

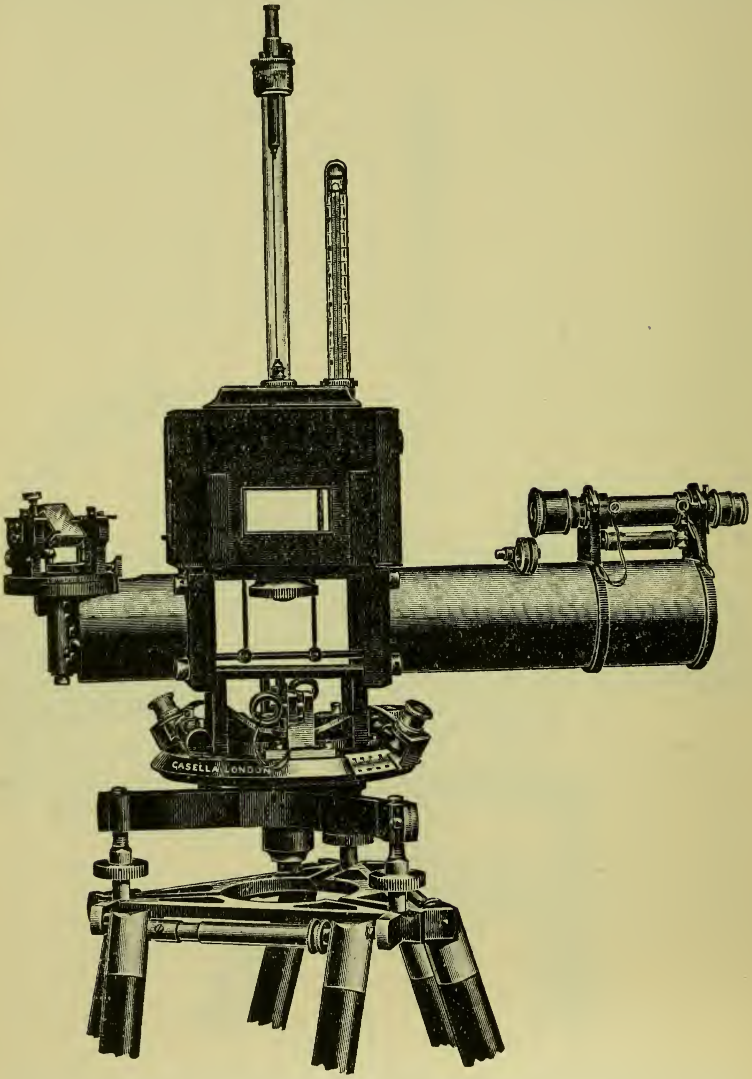


FIG. 199—Kew magnetometer, arranged for the determination of the declination

measurement of declination. It consists of a tripod with three levelling screws supporting a divided circle, which may be read by means of a pair of verniers in the usual way. Attached to the vernier plate and capable of being rotated with it in azimuth about a central socket, is a metal super-structure in the form of a cubical box to each side of which a metal tube is attached. One end of this tube carries a small speculum mirror, which may be independently rotated in azimuth and tilted in altitude, the other end of the tube carrying a telescope in Y bearings. This telescope, when set to solar focus, may be used to direct the instrument to read the sun's position by reflection in the mirror, a pair of dark glasses just in front of the object glass, serving to cut down the intensity of the sun's rays. By observing on the sun in this way, in conjunction with the time as given by a chronometer, the meridian may be laid down and a suitable azimuth mark fixed upon which subsequent settings may be made. A wooden box is supported as shown above the central axis of the instrument. In this box the magnets may be suspended. These are hung by a strand of unspun silk from a torsion head supported by the glass tube shown. A thermometer is fitted so that the temperature of the air in the case may be determined at the time of taking the observations.

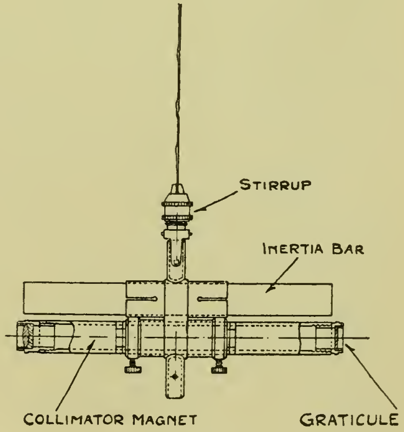


FIG. 200

Magnetic Declination

The simplest determination to make is that of **d** and for this purpose a magnet similar to that shown in Fig. 200 is inserted in the instrument. At one end of this magnet which is tubular and 10 cm. in length by 1 cm. in outside diameter is a graticule, Fig. 201, and at the other a lens, the focal length of which is such that parallel light passing through it is brought to focus on the graticule. If the instrument is placed in about the magnetic meridian, and light directed from the mirror on to the magnet, this light will pass through the graticule and the lens and emerge as parallel rays. The image of the graticule may therefore be brought to focus on the webs of the telescope when this latter is also set to solar focus. It is now only necessary to rotate the instrument slowly in azimuth by means of the tangent screw to bring the central web of the collimator magnet into coincidence with the vertical web of the telescope, or rather, to let the telescope web bisect the swing of the web in the magnet. The magnet is now suspended by the opposite shank, and a similar setting made, the position in azimuth being read on the horizontal circle in each case. If the magnet is now removed, the angle between the position just found and that of the fixed azimuth mark already established may be measured on the horizontal circle by setting the telescope on the latter mark. It should be noted that it is desirable to have the azimuth mark at least a mile distant in order to avoid the necessity of re-focusing the telescope between the two readings. Several readings are taken in both positions of the magnet and the mean of all the readings gives the angle between the magnetic meridian and the azimuth mark. If the bearing of the mark to the true north is now added the result is the magnetic declination.

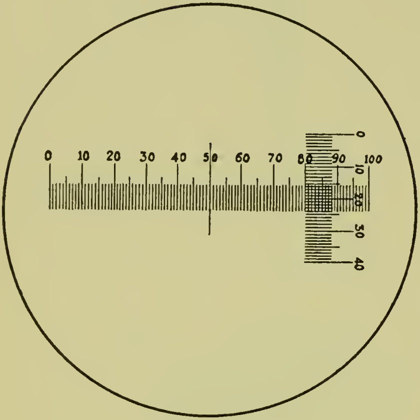


FIG. 201

Horizontal Component. The observations and the necessary computations for **h** are rather more difficult and great precautions must be taken if the results are to be at all good.

Two independent observations are made :—(a) To determine the period of vibration of the magnet ; (b) To determine the angle through which the magnet when placed at given distances from the centre of the instrument can deflect a similar magnet suspended from the torsion head.

Vibration Experiment. The instrument is used for (a) fitted up in exactly the same manner as when **d** is being determined. It is set so that the magnet web coincides with that in the telescope. The magnet is then given a slight swing and the time taken to make say 100 vibrations is noted by means of a chronometer. It is usual to note the time at every 5th or 10th vibration, the mean of all these times being the accepted figure. It is desirable to keep the arc of vibration very small, as otherwise it is difficult to determine the exact time of transit of the two wires.

A number of corrections must be applied to the readings, such as temperature, error of chronometer, etc., but the largest correction is due to the torsion of the suspension. This must always be determined separately just after the **h** or **d** experiments. The method of doing so is to hang from the suspension a brass plummet, having the same weight as the magnet. This plummet is generally made as shown in Fig. 202, the knife edge at the bottom serving to determine its position. If the torsion head is rotated, this knife edge may be brought into line with a mark placed on the bottom of the box. The suspension is then supposed to have no torsion. After the experiment with the magnet the plumb bob is again inserted and if it does not now read zero the amount of rotation of the head necessary to bring it back again to zero is noted. On some instruments the plumb bob carries a divided circle on its periphery. This circle may be examined by means of the telescope, an auxiliary lens being fastened to the side of the box to allow the image to be brought to the proper focus. The mean of these two positions is assumed to be the torsion during the time of the experiment.

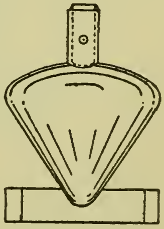


FIG. 202

In order to determine the effect that this amount of torsion would have on the readings the magnet is again inserted and the number of divisions of the graticule of the collimator magnet which pass over that of the telescope for certain amounts of rotation of the torsion head are noted and in this way the necessary corrections may be calculated and added to the original readings.

Deflection Readings. When making deflection readings (b) the instrument is arranged as shown in Fig. 198. The top wooden box is removed, the deflection bar is inserted and a subsidiary telescope and scale is fixed to the tubular portion of the apparatus. The deflection bar is made of brass graduated on one edge and is clipped by pegs on to the vernier plate, thus rotating with it. Mounted so as to slide along this bar is a clip having two Y bearings arranged to hold the magnet which has been used in the previous experiments. A similar clip is mounted at the other side to carry a thermometer and to act as a counterbalance. A striding level is usually supplied and is shown on the bar to the right of the magnet box. A special magnet carrying a small mirror, see Fig. 203, is suspended in the box after the torsion has been removed from the suspension. An image of the ivory scale seen just above the lower telescope is reflected, by the mirror of the magnet, down the telescope so that the amount of swing of this magnet may be determined in terms of the divided scale. When the instrument is set on the magnetic meridian, the zero of the ivory scale will coincide with the vertical wire on the telescope. The magnet which was used is now placed on the bar at various distances, usually three, and on both sides and the consequent deflection of the mirror magnet noted. From these observations the value of **h** may be calculated.

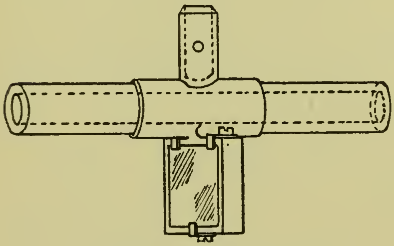


FIG. 203—Deflection magnet

In Fig. 200, above the magnet will be seen a tubular socket. This is to contain a cylinder of brass called the **inertia bar,** which is used to determine the moment of inertia of the magnet, its own moment of inertia being calculated from its dimensions. In order that this figure may be accurately determined, the brass bar must be truly parallel and its ends must be plane, but as these determinations are made once and for all at some testing laboratory, such as Kew, or the National Physical Laboratory, no further mention need be made of this subject. The only adjustments which the observer can carry out on this instrument are those for the collimation of the telescope and the reflecting mirror and its mounts. All the other elements are fixed and must have had their constants obtained at a main magnetic station by comparison with other instruments and with the result obtained through years of observations.

The Schuster dip inductor consists essentially of a coil of copper wire which can be rotated about an axis in its plane of symmetry. The ends of the coil are respectively joined to the segments of a two-part commutator upon which rest two pairs of brushes. The coil can be rotated from a distance by an endless cord which passes over a pair of pulleys, so that in general a resulting E.M.F. will be found at either pair of brushes. The E.M.F. arising from such rotation only vanishes at both

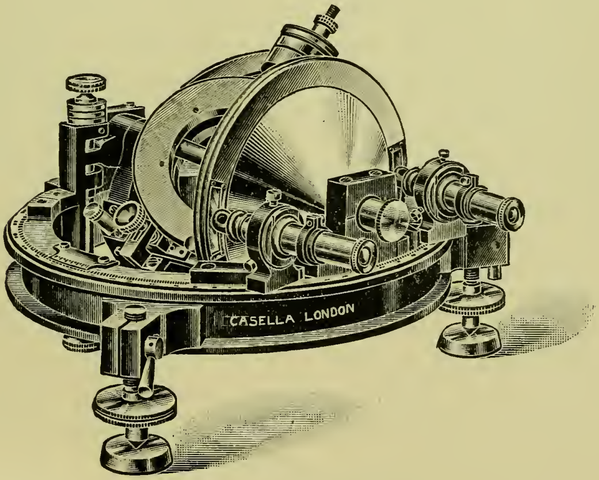


Fig. 204—Dip inductor

pairs of brushes when the axis of rotation is parallel to the direction of the magnetic field in which the instrument is situated. A ring in which the spindle of the coil is journalled has quick and slow motions in azimuth and in altitude so that the necessary adjustments are readily made. The settings where zero E.M.F. is obtained are indicated by a sensitive galvanometer connected by means of a switch to either pair of brushes as desired. Four independent readings of dip may be made thus allowing instrumental errors to be eliminated.

Inductor Magnetometer. Recently, J. H. Shaxby has designed and used a portable magnetometer of the inductor type which is arranged to measure the vertical intensity and dip, the first by neutralising the earth's vertical component by the field due to a horizontal coil supplied with an adjustable current from a small secondary cell, the second by tilting the instrument through an angle θ until the component field normal to the base of the instrument in the tilted position is again neutralised. The dip is then given by the complement of $\frac{1}{2}\theta$. The two elements are thus measured with a minimum of manipulation by (1) setting on the meridian; (2) levelling; (3) adjusting a resistance; (4) measuring an angle. For further particulars of this instrument the reader is referred to the "Journal of Scientific Instruments," Vol. I, No. 8.

CHAPTER XVIII

THE SEXTANT

THE modern sextant in its elements and in the general disposition of its parts remains almost exactly as it was first invented by Hadley in 1731, although both Hooke and Newton had proposed similar schemes prior to that time.

The instrument received notable improvements by Ramsden and other makers of the late 18th century and except in minor details has remained unchanged for about 120 years. This seems most remarkable in view of the fact that it is not particularly comfortable to handle and that all the parts are so exposed to the weather and so liable to damage. In a laboratory drawbacks of this kind may not be of great importance, but at sea where the sextant is principally used, these defects would at the first glance appear fatal to its continued use. The fact remains, however, that no other instrument has yet been produced which can do the work so conveniently or so well on board ship, with the result that its use is quite universal. Apart from the unsatisfactory nature of the design of the details in so far as they are unprotected and fragile, the fact that the readings cannot be checked in any way makes the design one which would be considered crude in any other piece of precision apparatus. Not only must reliance be placed on a divided arc, the accuracy of the graduations of which are always open to suspicion and can only be checked by comparison with a standard, but the correctness of the centering of the axis on which the vernier moves must be taken for granted, as no facilities are provided for taking the mean of the opposites as in most other instruments having graduated circles. In addition to this, the fineness of setting of the vernier is only half that which can be made on such an instrument as a theodolite of equal limb diameter owing to the effect of the mirrors in halving the value of the circle spaces. To set a sextant to read 100° of altitude, the vernier is only moved over 50 actual degrees on the limb so that to read 10 seconds by the vernier on this instrument is equivalent to a reading of 5 seconds on any other divided circle. It is for this reason that sextants must usually be made with limbs of 7 or 8 inch radius to enable 10 seconds to be read on the vernier. On a theodolite of equivalent size, i.e., one with a 14 or 16 inch diameter circle, single seconds could easily be estimated so that it is readily seen what a poor show the sextant makes when compared with other angle measurers. The great merit of the sextant, however, lies in the fact that it can be used without the necessity of fixing it down on to a stand, and that no levelling is required. It is therefore invaluable for use on board a ship, being in fact the only instrument hitherto produced which can be successfully operated in such a situation. The optical principle on which the sextant is based is a very simple one, and may be readily followed by means of the diagram shown at Fig. 204. Let us suppose a pair of mirrors M_1 and M_2 fixed to a circular vertical disc B, which may be turned about a horizontal axis A. If the two mirrors are parallel to each other, light from a distant source S striking M_1, will, when it is placed at any angle, say 60° to the horizontal be reflected on to M_2, and then continue its path parallel to the incident beam so that the image may be

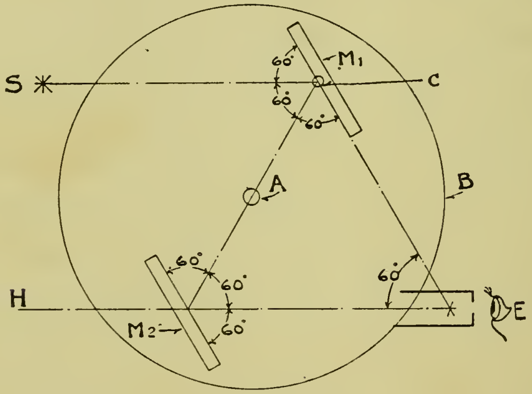


FIG. 204

picked up by the eye or a telescope placed at E. If now the disc is rotated about its axis A so that the beam S strikes M_1 at any other angle, say 80°, it will be readily seen (Fig. 205) that the emergent beam M_2E is still parallel to the beam S M_1, and may therefore be viewed as before. It is thus clearly seen that rotation of the whole instrument in altitude about any axis such as A will not affect the image, as seen by the eye, and it is just for this reason that the sextant is so useful for the purpose of measuring angles on board ship and that it may be used without the necessity of fixing it to a tripod or levelling it up in any way. If the mirror M_2 is divided vertically into two parts, one half being silvered and the other plain, it will be possible to see the distant source of light both directly through the plain part from the direction H E and by reflection along the path $SM_1 M_2 E$. If the mirrors are parallel to each other, the two images will appear in contact, but if there is a slight angle between them then they will be separated by a distance depending on the amount of the deviation from parallelism. If now one of the mirrors M_1 (Fig. 204) is pivoted so that it may be rotated about a point C, by known amounts, images of two distant objects such as a pair of stars or the sun and the horizon which subtend any angle up to about 120° at the eye may be brought into coincidence by turning this mirror a suitable amount, and the angle may be measured by noting the amount of rotation required to bring about this coincidence. It will be found that the mirror must be rotated through half the angle which the two objects make with each other, the reason for this being as follows :—

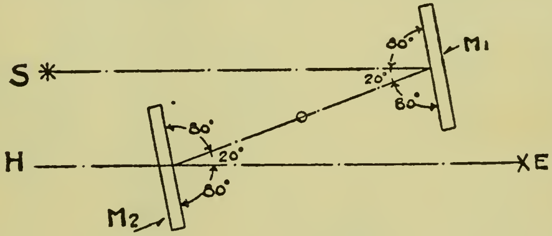


FIG. 205

In Fig. 204 the mirror M_1 is shown at an angle of 60° to the horizontal H E. If it is now turned as shown in Fig. 206 until it is at right angles to H E, that is through an angle of 30°, and if a ray is traced back from E, it will be reflected from M_2 at an angle of 60° as before, but will now strike M_1 at 30° instead of 60° and will be reflected to S. The angle S M_1 M_2 will now be 120° and S E H = 60° which is the actual angular measurement required. It is seen, however, that it was only necessary to turn M through half this angle, i.e., 30° so that the graduated limb on which the angular movement of M_1 is measured must be figured to show double the actual angle, the accuracy of reading being therefore halved. This, as mentioned before, is a serious drawback, and if some design could be evolved to enable the reading of the graduations to be doubled, instead of halved, the instrument could be made much more compact and much easier to handle. Up to the present, no useful suggestions have been made in this direction, so we must be content with the design as imagined by Hadley until something better has been evolved. Fig. 207 shows a modern sextant, known as the Britannia Cadet pattern, having a divided limb of 7 inches

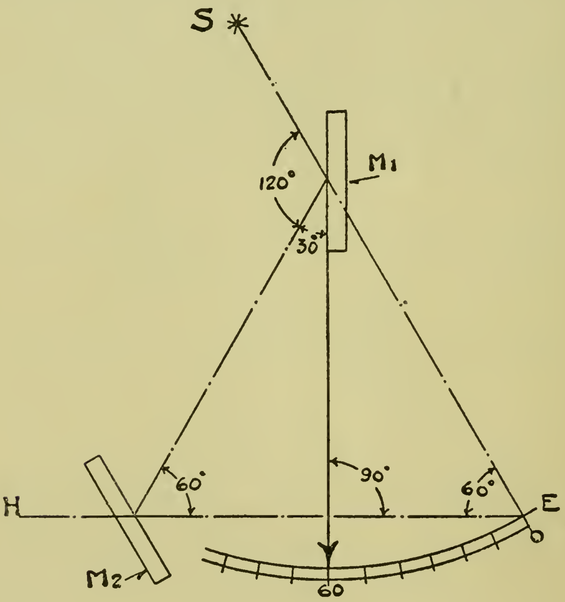


FIG. 206

radius read by means of a vernier and attached magnifier to 10 seconds of arc, and graduated up to 140 degrees. This instrument weighs about 3 lbs., which is quite as heavy as a sextant should be, when it is considered that it must be held up when in use by one hand. The main frame is made of a light casting of bell or gun-metal, the divided arc being an inlaid band of silver or platinum. The upper corner of the casting is pierced to take the socket into which the axis fits and on the front face brackets are screwed to carry the horizon glass and shades and also the index shades and the rising piece into which the various telescopes may be fitted by means of the interrupted screw threads shown. The back of the frame carries the handle and three short legs on which the instrument is supported when it is laid down on a table. Attached to the head of the axis is the vernier arm, to the lower end of which a clamp and tangent screw are fitted, and directly above the axis a frame in which the index mirror is held is screwed down on this arm. This mirror must be so fitted that its reflecting surface is accurately in line with the centre of the axis of rotation and the axis itself must of course be exactly at the centre of the graduated limb. The instrument, when in use for taking the altitude of the sun above the horizon is held with the front face

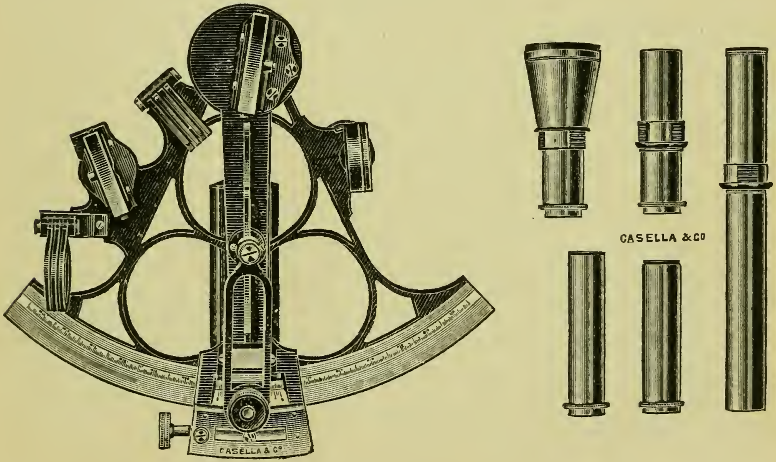


FIG. 207

vertical and the telescope horizontal. A suitable dark glass or any combination of the four supplied is turned up in front of the index glass, which is the one attached to the vernier arm. After unclamping the vernier it is set approximately to the altitude required. On looking through the tube the sextant is directed towards the sun and turned in altitude until the horizon is seen by direct vision to cut across about the middle of the horizon mirror, then the tangent screw is turned so that the image of the sun is brought down until it can be seen in the silvered portion of this mirror. When exact contact has been secured by the tangent screw the reading of the divided limb will give the altitude of the sun above the horizon at the time contact was made. There are dark glasses which may, when necessary, be turned up in front of the horizon mirror to reduce the glare from the surface of the sea, and dark shades may also be fitted to the telescopes when required. Although there are a number of adjustments which the user may, and indeed must make from time to time, the quality of a sextant mainly depends on the accuracy of the parts, and the way in which they have been built into the instrument, and as defects are not readily detected or rectified, only those instruments made by first class firms should be purchased, and even then only after they have been subjected to an independent test by some recognized authority, such as the National Physical Laboratory at Teddington. The principal points which must be attended to if the instrument is to pass the rigorous tests of the National Physical Laboratory are as follows :—The graduations must be accurately spaced and clearly cut and figured, and the vernier should match the limb truly at every part. The axis must be placed exactly at the centre from which the limb was graduated and it must fit its socket accurately and move smoothly without shake. The mirrors should be perfectly plano-parallel and held in their mounts without strain. The dark shades should individually and in combination be free from any tendency to distort the image, which means that they should also be plano parallel. These shades must be burnished into their mounts in such a way therefore that they are not strained in the process. The rising piece carrying the telescopes must work smoothly and be free from any perceptible shake, and must be accurately placed in relation to the mirrors. All these points are of fundamental importance and must be attended to by the maker as no adjustment by the user can compensate for them in any degree. The main axis of a sextant is similar in construction to that of a theodolite and must be most accurately fitted if good results are to be obtained. It is better to fit this axis before dividing

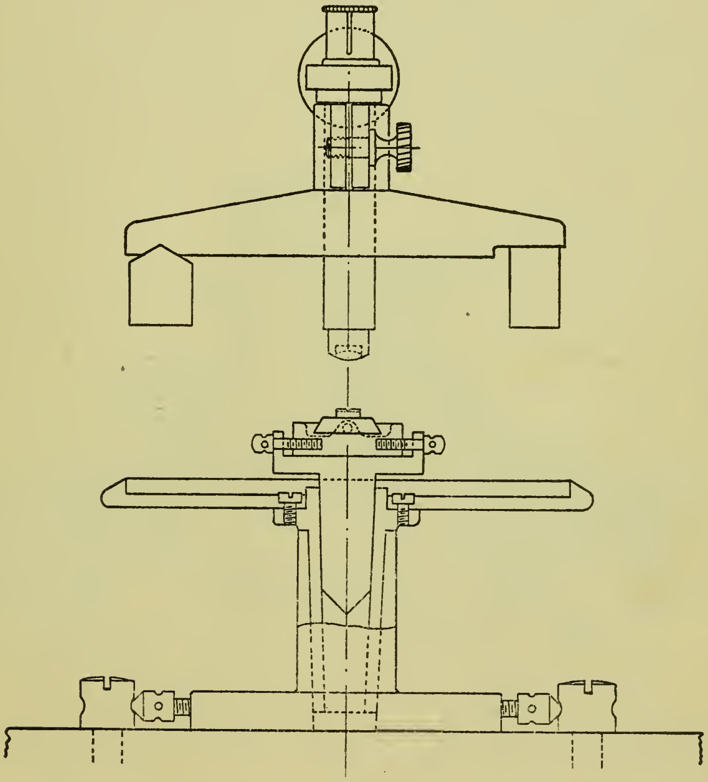


Fig. 207a.—Device for centering circles or arcs on the dividing engine.

the limb instead of endeavouring to correct the centering afterwards. When the work is done in this way, the centre of rotation of the axis must be exactly in the centre of the dividing engine, and to ensure this, a fitting shown in Fig. 207a is used. This, as will be seen, is a frame which may be attached to the axis by a socket at the bottom, the upper part of which carries two dovetailed slides at right angles to each other. The top slide carries a finely divided cross which may be brought by means of the adjusting screws accurately to the centre of rotation of the axis when this axis is revolved in its own socket. This adjustment is made under a microscope, attention to the fineness and clearness of the lines and their proper illumination being of great importance. This operation having been carried out it only remains to place the limb on the dividing engine and adjust it so that the intersection of the cross lines remains stationary when the engine centre only is revolved. It is obvious that when the limb is thus fixed down on the engine plate, the centre of the circle will coincide with the axis carrying the vernier. Very great care is needed in this operation ; the socket must of course be firmly fixed and the axis have had its final finishing before the dividing is carried out. In fact it is usual to finish the whole instrument, the marking of the graduations being the last job of all before the final assembly and adjustment. Various methods of holding the index and horizon mirrors in their frames and arranging for their adjustment have been tried and are in use, each maker's design differing slightly in detail. The principle is the same in most cases, and simply consists in holding the glass down by spring pressure against the points of three screws, each of which may be adjusted in order to rock the mirrors in any direction. In Fig. 208 these parts may be identified and also the flange pieces which serve to screw the frames down to the limb casting and to the vernier arm. The index frame is made solid at the back, somewhat in the form of a tray; but the horizon frame has half of the back portion cut away in order that the horizon may be viewed through the clear part of the glass. Sometimes the horizon glass is only half the usual width and completely silvered, but with this form it is not possible to get such a clean line of separation as in the usual type, where the silver, owing to its extreme thinness, may be very sharply divided, thus giving no shadow such as would be obtained from the thick edge of the narrower mirror. The shades which are made from neutral tinted glass, are circular in shape and burnished into brass frames, square for the index glass and round for the horizon. They must not be fitted too tightly, owing to the possibility of introducing strain, and it is best so to arrange that while there is no shake, the glasses may be turned in their cells by holding them between the finger and thumb and rotating the brass frame. These shades are pivoted on a taper pin fixed in a frame which is screwed down on the limb, a collet being interposed between each shade. These parts must be very nicely fitted, so that when any one frame is turned up in front of its mirror, it has no tendency to drag the others with it. The clamp is generally arranged to grip the edge of the limb just beyond the divided portion, a split die being used for this purpose, and a tangent screw of the usual form is fitted to give the necessary slow motion when following the sun. In Fig. 208 an endless type of tangent screw is shown. This is a very convenient type, and has come into use a good deal in recent years. It consists of a fine pitch worm attached to the milled head shown and carried in a small frame which is pivoted to the end of the vernier arm in such a way that it may be thrown out of or into gear with worm teeth cut the entire length of the arc. The two small thumb pieces when pressed together serve to disengage this worm from its wheel. To use this form of clamp and tangent, it is only necessary to press these two thumb pieces together, and push the arm to the portion of the arc required. When they are

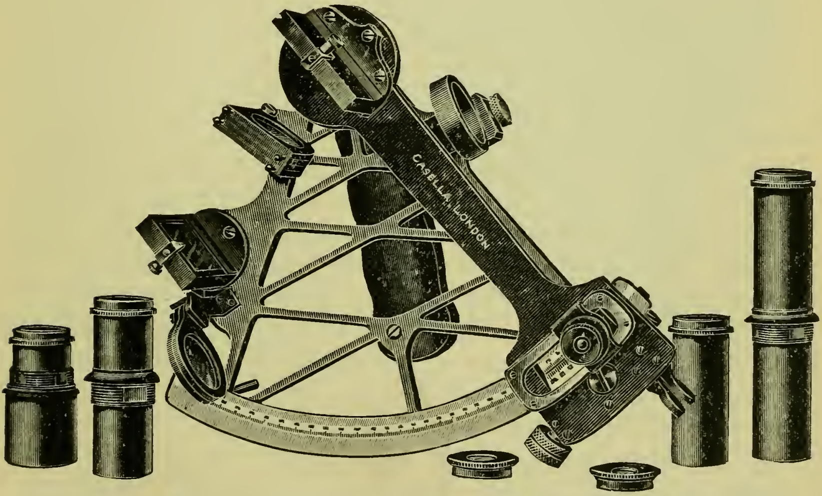


FIG. 208—Sextant with quick acting clamp and continuous tangent screw

released, the worm drops into its wheel, thus locking the arm. The slow motion may then be carried on continuously by rotating the milled head attached to the worm. A Ramsden reader is pivoted or arranged to slide above the vernier to facilitate the reading. The handle at the back is generally made of ebony or vulcanite, and various methods of fixing it to the frame are in use. In the example shown, it is fixed at one end by means of a metal screw passing through the main frame, the other end being held in a sliding fitting which allows the handle to expand or contract without putting any strain on to the limb. Sometimes a single central screw is used and on many instruments three screws are used, two of them being at the ends of a bridge piece which being made weak laterally allows for expansion in a longitudinal direction. Three or four telescopes or sighting tubes are generally supplied with the sextant, the one principally used being an ordinary Gallilean glass. A special telescope with high and low powers is used for star work, and an ordinary plain tube with pin hole sight is also supplied for use when necessary. In addition, a special telescope having four cross wires in the mutual focus of the object glass and eyepiece is used for the purpose of adjusting the instrument. Each of these telescopes can be held in the ring shown on the right, just under the index glass. This ring is supported on a square or triangular stem which is screwed at its end and fitted with a milled nut, the turning of which raises or lowers the telescope, thus allowing it to be brought central with the horizon glass. The telescopes do not screw directly into this ring, but into a subsidiary flanged piece fastened inside the ring. This flange is held by two screws against two points at right angles to them, which allows it to be rocked, and thus enables the adjuster to bring the telescope truly parallel to the limb.

Fig. 209 shows a new type of simple sextant designed by Appleyard for quickly taking sights such as terrestrial azimuths, where extreme accuracy is not required. This instrument is on exactly the same principle as the ordinary marine sextant except that the index glass is moved by means of a micrometer screw instead of the usual vernier arm, the angles being read on the micrometer head instead of on the vernier. The turns are counted by means of gearing and read through two small windows seen alongside the divided head, the figures of the latter being read by means of a prism just below the eyepiece. An electric bulb is used to illuminate the instrument at night, the battery being carried in the hollow handle shown. A different type of adjustment for the mirror from that already described is clearly shown in this illustration. The accuracy of a micrometer screw of this type is of course not so great as that of a divided circle which, once it has been properly graduated, always remains the same. The micrometer screw is subject to wear, and therefore to change in value, so that instruments of this type can only be used for very approximate settings. For such work, however, this sextant is an excellent type, as it is very much smaller and lighter than the usual instrument of 7 inch radius, and the readings can be made with greater ease and with less liability to error, and as the observer can read his angle at the moment of observation, a greater number of sights can be taken in the same time. Fig. 210 shows a type of sextant which has been developed by Mr Booth for use on aircraft, but which can be employed on land instead of the usual sextant where approximate results only are required. Fig. 211 is a diagram showing the principle on which this instrument works. Instead of viewing the horizon, which is seldom visible in satisfactory form from aircraft, use is made of a circular spirit bubble the image of which is brought by optical means into coincidence with the sun or other object the altitude of which is to be measured.

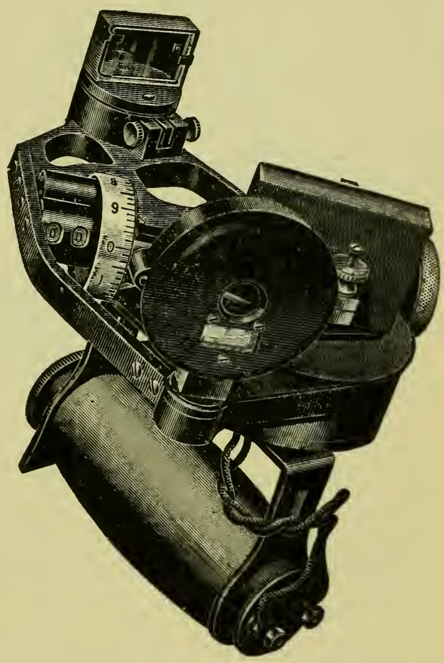


FIG. 209—Micrometer sextant with electrical illumination

M_1 is an unsilvered plane glass mirror and is the equivalent of the index glass in the Hadley sextant. M_2 M_3 M_4 are silvered mirrors. A is the circular bubble, and M_5 is a plain glass used to reflect light from an electric bulb B, when the instrument is being used at night. The circular bubble is mounted in a cell, the bottom of which is made of plane glass, so that the light is transmitted through it on to the mirror M_4 — M_3 through lens L, then reflected from M_2 and finally passes through the index glass M_1 where it meets the eye. The focal length of the lens is made equal to the radius of the concave surface of the level and is placed in such a position that the bubble is in its principal focus. The result is that the

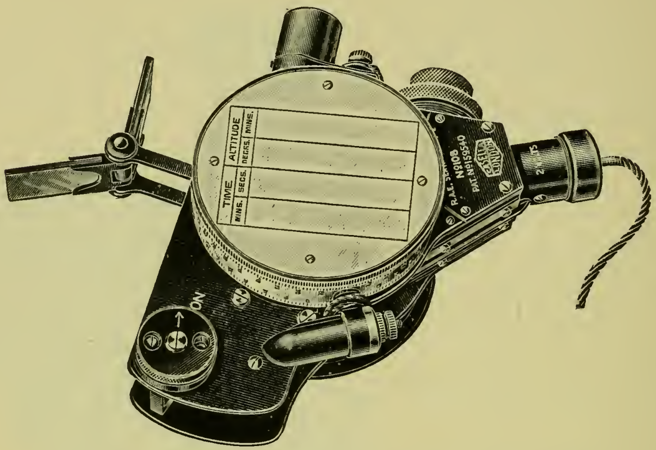


Fig. 210—Booth bubble sextant, with artificial horizon

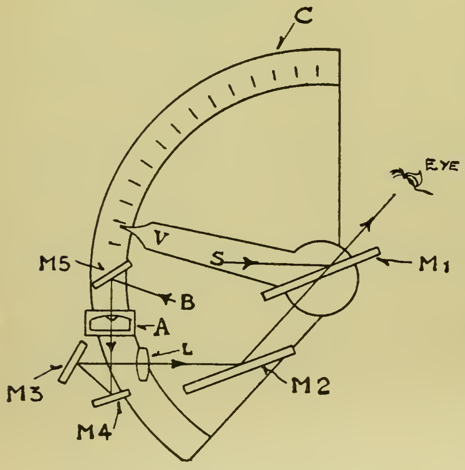


Fig. 211—Booth bubble sextant

bubble will appear to be on the horizon when viewed through the lens, and any motion of the instrument as a whole will not disturb its apparent position within the limits of its run. The instrument can therefore be used just as an ordinary sextant, the bubble serving instead of the usual horizon. If the mirror M_1 is now rotated, the sun's image received from the direction S may be brought into coincidence with the image of the bubble, and the altitude read in the usual way from the arc C. Should the natural horizon be visible, the whole of the bubble apparatus may be swung out of the way, and the horizon viewed in the usual way on M_2.

When viewing stars, the electrical illumination is used, but the observer looks up through the index glass instead of as shown, and sees the image of the bubble reflected from the underside of this glass. The two images may be brought into co-incidence in the usual way, and the brightness of the bubble image may be suitably adjusted by means of a rheostat fixed to the instrument frame. Dark glasses are interposed in the path of the sun's rays, and so mounted that by altering their inclination, the amount of light transmitted can be suitably regulated. The size of the bubble can also be regulated by means of a flexible diaphragm in the liquid container, and an electric bulb is fitted to illuminate the index of the reading scale.

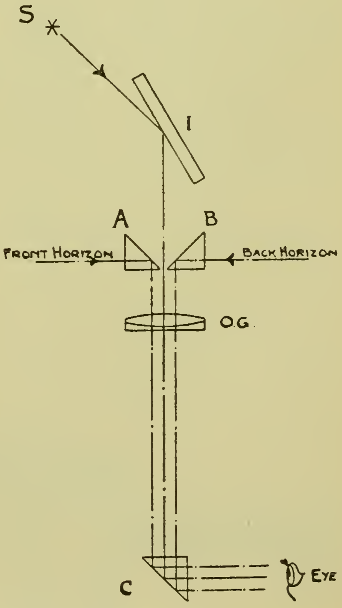


FIG. 212—Baker air sextant

Baker Air Sextant

Another interesting sextant designed by Commander Baker for use on aircraft, is shown in Fig. 212, which is a diagram of the optical principle. The main upright body of the instrument carries a telescope, the details of which have been omitted from the diagram for the sake of clearness. Its line of collimation is bent by the prism C and brought out horizontally through the eyepiece. Above the object glass a pair of right angle prisms A and B are placed, A being directly under the index glass I and B 180° in azimuth from it. These prisms bring the image of the back and front horizons down to the eye, a space being left in between them as shown, through which the image of the sun is also received by the eye, the appearance of the field of view being as shown in Fig. 213. It will be seen that no matter what the dip may be the true horizontal will be midway between the two horizons. Attached to the index mirror, which is of prismatic form in the actual instrument as constructed, is a worm and wheel which serves to rotate it in the usual manner, so that it is only necessary to bring the image of the sun down between the two horizons when its altitude may be read from the indices shown. The gearing and dividing is such that one division on the micrometer head is equal to 10 minutes of actual altitude, and as the divisions are comparatively coarse, the angle may easily be estimated to 2 or 3 minutes.

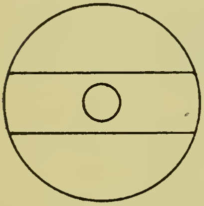


FIG. 213

Box Sextant

Fig. 214 shows the box sextant which is much used by land surveyors and explorers and for coastal sounding purposes. It is an instrument of very excellent and neat design, the optical principle on which it is based being exactly the same as the marine sextant already described. Its main advantage lies in the fact that all the parts are very well protected from accidental injury and that in the smaller sizes it is very compact and portable. The usual size in which it is made is 3 inches on which angles may conveniently be read to within $\pm$ 1 minute of arc this being sufficient for all ordinary

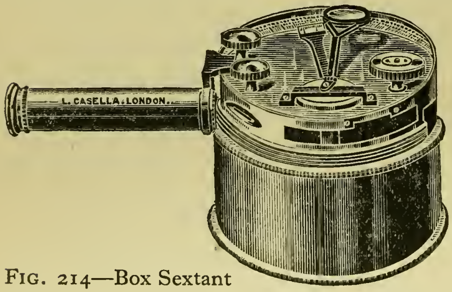


FIG. 214—Box Sextant

surveying purposes on which it can be used. The index glass, instead of being turned by a tangent screw as in the ordinary sextant, is operated by means of a toothed quadrant into which a pinion attached to a milled head gears. This has a reduction of gearing of about 10 to 1 and gives a sufficiently sensitive motion for the purpose. Two, and sometimes three dark shades are fitted and may be brought into the line of vision when required. For most purposes the eye is placed opposite a small pinhole in line with the horizon glass, but a small telescope is generally supplied either arranged to be attached to the face of the box by means of a milled head screw or else so fitted that it may slide into the body of the case. The lid of the box may be screwed down to cover the limb and vernier and when the instrument is in use, this lid may be screwed to the back of the case, thus acting as a handle by which it may be held either vertically or horizontally as required. The instrument, when in use, is held in the left hand and the index glass turned by rotating the milled head by means of the right thumb and forefinger. As generally constructed, the box sextant is only capable of taking angles up to 120° and when larger angles have to be measured, it is necessary to range on an intermediate mark and to combine the two angles found. Some sextants, however, are made with an additional index glass by means of which angles up to about 200° can easily be taken. As this type of sextant has not come into general use, no further description need be given of it here.

The Adjustment of Sextants

The maker of a sextant has to perform a number of tests and make certain permanent adjustments; the care with which these have been carried out determines the value of the instrument for accurate work. The adjustments left to the user, or necessary for him to make, are few and simple, and unless the sextant is subjected to rough usage, are seldom required. It is well, however, to check the adjustments occasionally, and this may be conveniently done in the following way :—

(1) **To set the Index Glass Perpendicular to the Limb.** Hold the instrument horizontal with the axis close to the eye,

and look into the index glass at such an angle that the edge of the arc may be seen both directly and by reflection. The vernier should be clamped at about the middle of the arc while making this adjustment. If the arc and its reflection do not appear to be in a straight line, they should be brought so by turning the adjusting screw at the top of the mirror, this being the only adjustment on this mirror possible or necessary. The index glass will now be perpendicular.

(2) **To set the Horizon Glass Perpendicular.** Set the vernier exactly to zero and point the telescope to the sun. If the glass is correctly placed, the sun will be seen as a single disc. If it does not appear so, the horizon glass should be rocked by means of its two adjusting screws until the image is perfect. It is well to verify this adjustment when holding the instrument horizontal, or at an intermediate angle, using any suitable well-illuminated object. When at sea, this adjustment may be made on the horizon, in this case the instrument should be held horizontal.

(3) **To Adjust Approximately for Index Error.** This adjustment is made by looking at the horizon when the vernier is placed at zero. If there is no index error the reflected and direct images will appear in a straight line. If they are not so a slight adjustment of the lower screw will be necessary.

(4) **To Determine the Index Error.** Set the vernier to zero and then with the tangent screw bring the two images of the sun to touch each other on one diameter and read the vernier. Then bring them into contact on the other side and again read the vernier. If there is no index error the two readings will be alike and if the error is small, it is usual simply to allow for its amount in the calculations. If the error is large, it may be reduced by adjusting the horizon mirror as already shown. For the purpose of making this determination, the sextant limb is divided to five degrees beyond the zero, these extra graduations being known as the arc of excess, and are used only to measure the sun's diameter for the above purpose.

(5) The only other adjustment which the user can make, and one which is very seldom required, is **to bring the line of collimation of the telescope parallel to the plane of the instrument.** As the lenses are generally properly centered, it

is usually sufficient to see that the body of the telescope lies parallel to the divided limb, but an exact adjustment may be made by the use of the inverting telescope, in the eyepiece of which the graticule having the parallel wires is placed. If the telescope is now directed to a pair of stars subtending a fairly large angle, the direct and reflected images may be brought into contact between the wires. On moving the instrument, if the images separate on one side and overlap on the other, the line of collimation is not correctly placed, and may be brought to its proper position by means of the two adjusting screws whch fix the screwed bush into the ring of the rising piece. The rising piece screw is only used to bring the centre of the telescope in line with the silvered edge of the horizon glass, and unless it is necessary to re-silver this glass, no adjustment is ever required after it has once been set to the proper height. If this adjustment is not correct, the direct and reflected images will not be of equal brightness.

Artificial Horizons

For measuring altitudes of stars or the sun up to about 60° the artificial horizon is employed when it is impossible to see the actual horizon, and Fig. 215 shows a very usual form taken by this instrument. The wooden or cast iron tray is set on the ground or on a stand in an approximately level position and filled with the mercury which is kept, when the instrument is not in use, in the steel bottle shown. A small funnel may be screwed into the neck of this bottle to allow the mercury to be

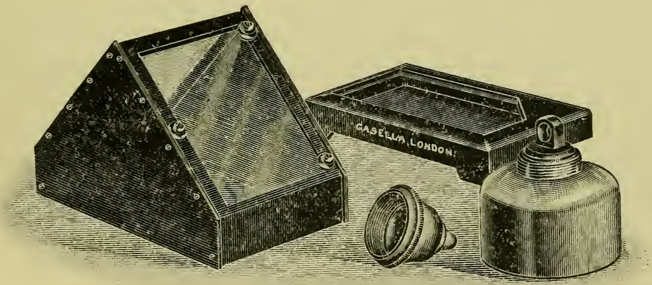


FIG. 215—Roof pattern artificial horizon and mercury bottle

returned to it at the end of the observation. The corner of the tray has a small hole and pocket so that the mercury may be poured back without any danger of spilling it. A gun-metal roof covers the tray during the observations, in order to prevent rippling, by wind striking the mercury surface, and on each side of it a piece of plano parallel glass is lightly held down by screws and washers, care being taken that no strain is placed on them by the fixing. This form of horizon gives very good results within its limits, its main disadvantage being that it is rather bulky and heavy, which is a serious drawback, especially as it is more used in exploration work than in ordinary surveying operations. Another form is shown in Fig. 216, which is much lighter and more compact. This consists of a circular steel box divided horizontally into two parts, the lower of which contains the mercury. The upper part which is covered by a plano parallel glass plate may be turned slightly on a central spigot in relation to the lower mercury container. When the upper section is revolved anti-clockwise, a pair of holes, one in the top half and one in the bottom, are brought together, thus allowing the mercury to be transferred to the upper portion. If the lid is now turned in the opposite direction the holes no longer coincide, so that the mercury remains in the upper half. It is now only necessary to place the instrument on a fairly level surface when it is ready for use. At the end of the observations, the mercury is again allowed to flow into the lower chamber where it is securely held when the lid is rotated as far as it will go in a clockwise direction.

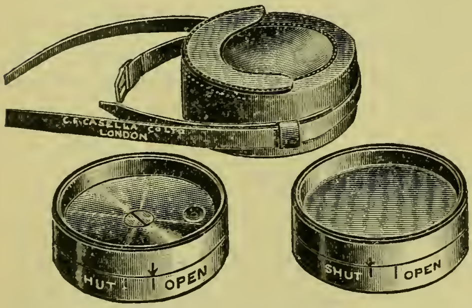


Fig. 216—Casella's portable artificial horizon

Another form of horizon consists of a polished black glass plate supported on three levelling screws. This is brought up level by means of a sensitive spirit bubble placed on its surface, this surface being either circular, square or oblong in different makes.

CHAPTER XIX

WIRELESS TIME SIGNALS

IN recent years the improvements in the transmission and reception of wireless time signals has led to their adoption for the determination of longitudes instead of the older method of line telegraphy, or where this was impossible, by the use of accurately timed chronometers carried between the stations. There is no doubt that in a few years' time, the wireless method will be universal, as the apparatus which must be carried is very simple and robust, and very little training is necessary in reception even for the most accurate work. Nearly every nation now transmits regular time signals from its high power stations and there are very few places on the globe where reception cannot be obtained with certainty. It is true that in some parts of the tropics interference from atmospherics may prove very troublesome and be so severe as to blot out the whole of the signals at times. The greater the distance the receiving set is from the transmitting station the more trouble is experienced from these atmospherics, and it is unfortunately useless to magnify up the strength of the signals as the strength of the atmospherics is multiplied in like degree. The distance at which signals may be picked up is only limited by the relative strength of the atmospherics to the signals. For this reason, it is well when signals must be received with certainty to tune in to the nearest transmitting station rather than to a more distant one, even though it may be thought that the signals from the former are not quite so accurate. As a matter of fact, the dots sent out by even the less important stations are remarkably consistent, and as all these stations compare their own signals with those from other sources, it is possible afterwards to obtain the actual error in time of any signal sent out, if the matter is of sufficient importance. There are two main types of signals radiated at the present time :—

(a) Ordinary time signals.

(b) Rhythmic signals.

Signals of type (a) are sent out in many different codes and are either automatically or semi-automatically transmitted. For ordinary time keeping purposes, the semi-automatic signals are sufficiently good and very simple to read, but for accurate work they should never be used for reasons which will be explained later.

The first station to emit regular time signals was the Eiffel Tower in Paris, the work being carried out by the French War Office, under the control of General Ferrie. These signals were sent out in the code shown in Fig. 217 and are now known as the ordinary or semi-automatic time signals. They are still sent out twice in 24 hours from that station, starting at 10·44 a.m. and p.m. At 10·44 after a warning call has been given, a series of nineteen dashes are sent, each lasting one second with a period of two seconds in between, except after the 19th dash, when there is a silence of five seconds followed by a single dot. This dot is the actual signal and takes place at exactly 10–45. There is now, as will be seen on referring to the chart, a silence of one minute duration, after which, at 10·46 another series of warning signals are sent, each signal consisting of a

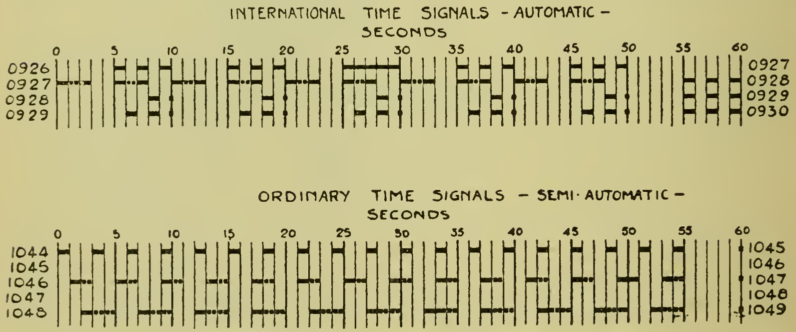


FIG. 217

dash and two dots. There is a silence of five seconds after the fourteenth signal and then a dot at exactly 10·47. Another series consisting of 11 signals each having a dash and four dots is now sent, a final dot at 10·49 completing the series. All these signals, except the four final dots, are sent out by hand, and cannot therefore be used for timing purposes. The four time dots are, however, sent out by contacts on the mean time clock at the Paris Observatory, and are said to be accurate to about 1/10th of a second, so that provided they can be received with certainty, they can be used, and are sufficient for most purposes. If, however, the receiver is at some distance from a station transmitting this type of signal, it may happen that atmospherics may blot out the whole four dots, whereas when the signals are all sent automatically, and therefore all of equal accuracy, there is not much likelihood of failure to receive at least some of them, from which the time may easily be deduced. In view of this difficulty, a new code was brought into operation and called the "International Automatic Time Code." All the signals are sent out by contacts on the mean time clock and a number of European and other stations now use this system, the transmissions being under the control of the *Bureau International de l'Heure.* The Eiffel Tower transmits this type of signal at from 9·26 to 9·30 a.m. and a list is given later of several high power stations, together with the wave lengths of their emissions. Fig. 217 shows also a chart of the international automatic signals from which the code can easily be learned. The beginning of the last dash, which is given after a silence of ten seconds is the actual hour signal and certain stations transmit a little later the exact time to ± 1/100th second at which this signal was actually sent. Most of the American stations transmit on a rather different system, which consists simply of a series of dots of about $\frac{1}{4}$ second duration at intervals of one second, the 30th, 56th, 57th 58th, 59th and 60th dots in each minute being suppressed in order to facilitate counting. The total duration of these signals is 5 minutes or 300 seconds, the dots corresponding to 35 of these seconds being suppressed. These signals are transmitted automatically and are therefore all of equal value. They are not quite so easy to distinguish as the European type, but are equally efficient if proper counting means are supplied at the receiving end.

There is another system of time signals of totally different type, which is sent out from most of the European stations. These are known as the Rhythmic or Vernier Signals, and are sent in units of sidereal time. Those from the Eiffel Tower consist of a series of dots each of about ·2 second duration. At the 60th, 120th, 180th, and 240th the dot is replaced by a dash of ·9 second duration, thus enabling the counting to be carried out very easily. The time interval between the dots is equal to $\frac{49}{50}$ of a sidereal second and the method of using them is similar to that of a vernier on ordinary linear scales. The beats are made to sound in a pair of telephones at the same time as those from a regulator clock, the pendulum of which beats sidereal seconds. It is then possible to compare the beats by noting at which seconds they coincide, and the accuracy which a trained observer can obtain is somewhere in the neighbourhood of $\pm$ 1/100th second. At large observatories, the wireless signals and the beats of the local clock are recorded on the revolving chart of a chronograph, similar to that shown in Fig. 188. At less important stations it is usual to fix a microphone and small dry battery in the clock case and lead the wires to the telephones which are also connected to the wireless receiving apparatus. Many of the time signal stations transmit by means of the spark system, so that it is possible to receive their signals on a simple crystal set when within reasonable distance. For accurate work, where of course reliability of reception is important, it is necessary to use an oscillating valve receiver and any good make of instrument which is arranged to tune to the proper wave length will be found quite suitable for ordinary purposes. When it is required to record the signals 3 or 4 amplifying valves in addition to the necessary relay and chronograph must be used, but as each station works under different conditions, and has special problems to contend with, details of equipment need not be given here.

Fig. 218 shows a diagrammatic circuit, such as is used at some stations, which will be sufficient to indicate the general trend of design.

The aerial circuit is tuned by means of a plug-in coil and condenser to the wave length required. This coil may either be direct or preferably loose coupled to the valve, in the plate circuit of which a reactance coil is coupled back direct to the aerial, thus setting up oscillations and enabling continuous wave signals to be received in the usual autodyne manner. The rectified currents are carried to an amplifier A which is so arranged that a suitable number of valves may be brought into circuit as required. The strengthened signals from A are then taken to coil B of the relay which, when energised, draws the armature up, thus switching battery F on to coil D of the pen magnet of the chronograph. Each incoming signal will therefore draw the pen to the left, thus making a slight U–shaped depression in the usual way. The coil C of the relay is connected to the seconds pendulum of the local clock. Coil E will therefore be energised once per second, thus making a U depression by drawing the marking pen to the right. It will thus be seen that the coincidences of the beats are easily recognised and the exact time determined in relation to the local clock. The form of trace given by a device of this nature is shown in Fig. 219 coincidence being shown at the 5th second. In practice, the simple form of relay shown would not function well, owing to the fact that the incoming signals vary in strength, whereas

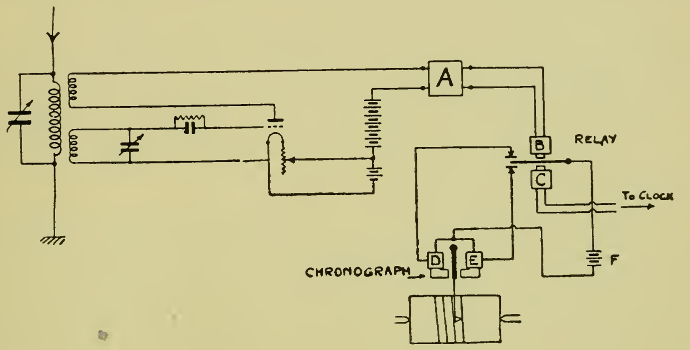


FIG. 218

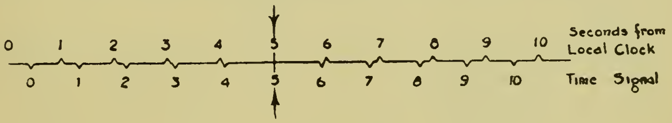


FIG. 219

those from the clock would be constant, so that special instruments such as the Marconi or Creed undulator must be employed, the variations in the trace being obtained by alteration of the wave length, by means of the insertion of additional capacity into the tuned circuit. The principal difficulty encountered with an apparatus of this kind is that in certain places the trace given by the atmospherics may make it difficult to read the record so that a selective receiving circuit should be employed, and in specially troublesome situations it is preferable to make use of some form of frame aerial the directive properties of which help to cut out not only atmospherics but unwanted signals from other stations.

Generally speaking it is found that only the bare minimum number of valves necessary to get good results should be employed, as the difficulty of control and the disturbances due to atmospherics are increased when the amplification is too great. Rapid strides are being made at the present time in the design of wireless apparatus, so that anyone contemplating the installation of a receiving set should consult the makers for up-to-date details.

The names of a few of the more important high power stations at present transmitting time signals are given herewith, together with particulars of their wave lengths and call signs.

G.M.T.		Stations	Call Sign	Wave length Metres	System	Wave
a.m.	p.m.					
3 0	5 0	Annapolis, U.S.A.	NSS	17145	American	Continuous
9 27	—	Eiffel Tower, France	F L	2600	Automatic	Spark
10 45	10 45	Eiffel Tower, France	F L	2600	Semi-automatic	Spark
10 0	10 0	Eiffel Tower, France	F L	2600	Rhythmic	Spark
8 0	—	Lyons, France	Y N	15500	Rhythmic	Continuous
9 0	—	Lyons, France	Y N	15500	Semi-automatic	Continuous
10 0	6 0	Balboa, U.S.A.	NBA	7000	American	Continuous
11 57	11 57	Nauen, Germany	POZ	3100	Automatic	Spark
—	8 0	Bordeaux, France	L Y	18940	Rhythmic	Continuous

These times and wave lengths may be altered from time to time, so that those contemplating the reception of signals should obtain the latest information from the Year Book of Wireless Telegraphy.

When the equipment has to be carried by an exploring party, specially compact receiving sets are desirable and the problem of suitable battery power must be studied. There are on the market now a number of low consumption valves which have made the equipment much lighter than formerly, and some months of good service can be obtained from the ordinary commercial dry battery, when using these valves. Special inert cells can now be obtained which do not deteriorate in the tropics, so that there is now no reason why any important exploring party should not be able to carry a set which would not only enable them to get the time signals but also to receive the news from the nearest broadcasting station. Some of the latest exploring parties have even been equipped with very efficient transmitters with which they have been able to keep in touch with civilisation during the whole of the time they have been away in the interior.

CHAPTER XX

MINE SURVEYING

THE methods and the instruments used on underground work are, in recent years, very similar to those employed on the surface, most of the specially designed apparatus such as dials and compasses having been replaced by theodolites and levels of the usual patterns. Some makers supply instruments with enclosed circles which are useful in wet mines and in positions where they are likely to be exposed to dust and grit, but unless the conditions are especially bad, the ordinary type of instrument is generally preferred, owing to the ease with which it can be taken apart for cleaning and oiling, an operation, by the way, seldom performed at sufficiently frequent intervals. When a considerable amount of plumbing has to be done, instruments with eccentric telescopes are often employed, such as those shown in Fig. 116. Or else a small auxiliary telescope is used so designed that it may be fitted either on the end of the axis or attached to and parallel with the main telescope. Fig 221 shows an instrument of this description. These instruments are both considerably used, but the latter type, owing to the necessarily rather flimsy nature

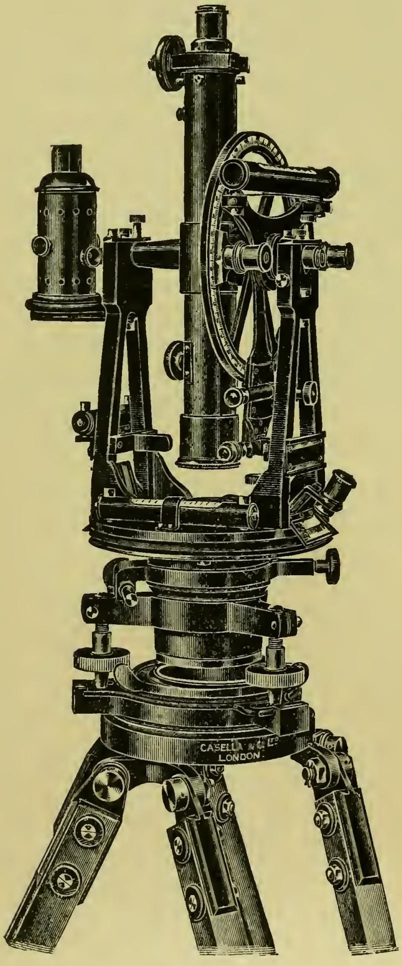


FIG. 220—Mining transit theodolite, hollow centre, enabling the telescope to be used for viewing the nadir

of the small telescope and its attachments is for the best work not to be recommended, as unless in the hands of very expert and careful surveyors, errors due to instability and mal-adjustment are very frequent. Errors in mining and tunnelling work lead to very serious troubles, especially when they are cumulative. It is often not convenient to recheck the work owing to the fact that the tunnels are not usually available for the surveyors, and if the tunnelling work has to be specially stopped and the lines cleared for them, the expense and delay is likely to be serious. This is especially the case in such work as driving a tunnel for a London tube railway. On these jobs the work is carried on night and day, and as the tubes are generally started from various shafts errors in alignment and level must be rigorously guarded against, so that the very greatest care is necessary in the setting out.

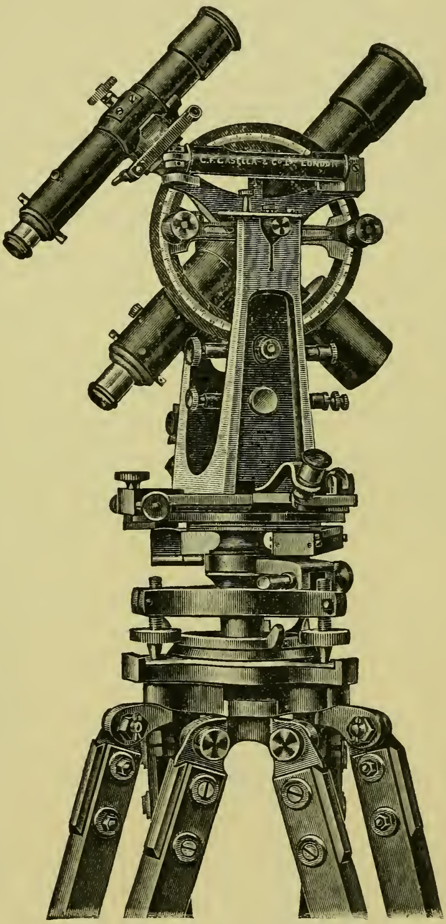


FIG. 221—Mining transit

As these tubes must be accurately connected up to the surface survey, very precise plumbing is necessary and this is carried out either by means of heavy plumb bobs or by optical plumbing. There is apparently very little difference in the final accuracy of these two methods, the plumb bob being mostly employed probably because of its simplicity. All the lines are also run along the tubes by means of plumb bobs, Fig. 222, suspended from the roof, the string being illuminated by means of an electric lamp fixed in a rough wooden box the front of which is covered with tracing paper. This, when placed behind the plumb line, gives an excellent mark on which to set the theodolite, and as the lines of the plumb bobs are suspended from dogs fastened to the iron lining of the tunnel, they can easily be re-hung when required, and quickly removed when the tunnel has to be cleared for the working gangs.

Sometimes an optical plumbing telescope is used for determining the vertical. This instrument takes the place of the theodolite on its stand and serves to transfer the surface sights to the bottom of the shaft, two settings being necessary to determine azimuth and position. When this method is employed, it is usual to have a number of interchangeable tripod stands upon which all the instruments can be mounted in turn, and on which the targets can also be fitted. The expense of an outfit of this description is considerable, and the setting up takes a long time. It is also a much more laborious undertaking to re-set and re-check the lines, with the result that the alternative method of plumb bob sighting has now become almost universal. Fig. 226 show one form of plumbing apparatus used to transfer the surface plan to the bottom of the shaft. The drum shown carries suitable lengths of piano wire. At the end of each wire a heavy plum bob is fixed and is immersed in a bucket of water or oil. The screw threads and nuts serve to position the wires in line with the theodolite on

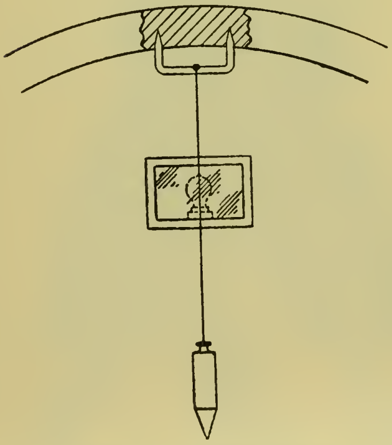


FIG. 222—Mining plumb bob

the surface. It is then only necessary to sight on to these wires below and thus continue the line in any direction required. The positions of the lines are measured by means of a steel tape, reference marks being placed on the iron lining of the tunnel for this purpose. It is desirable to place the points of suspension of the plumb bobs in such an azimuth that they may be in a line with the line which has to be run underground, as otherwise slight errors in the measurements of the distance between the instrument and the wires and the angle subtended by the wires at the instrument would have a large effect in the line of the tunnel. When it is not possible to do this conveniently, another method, making use of three plumb lines, is employed in such a way that no measurements are required except the distance which the wires are apart. As this can be very accurately and conveniently done at their points of suspension, this method leads to more accurate results than that which can be obtained with the two-wire scheme. Fig. 224 shows how the three plumb lines A, B and C are arranged. A wooden or iron bar placed on a staging over the shaft has three fine holes drilled in it so that (a) and (b) are exactly equal.

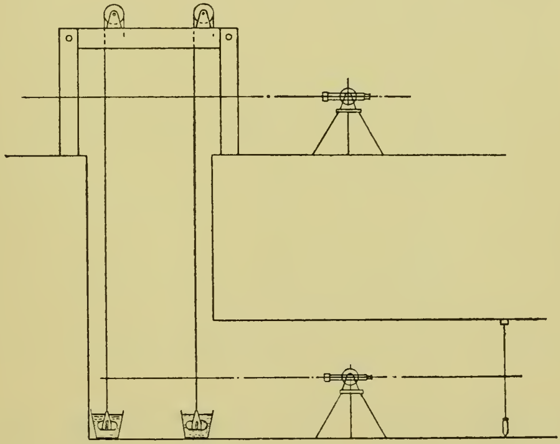


Fig. 223—Two-wire plumbing apparatus

This measurement, as mentioned, can be very accurately made, and the wires at the bottom of the shaft may be taken to be also

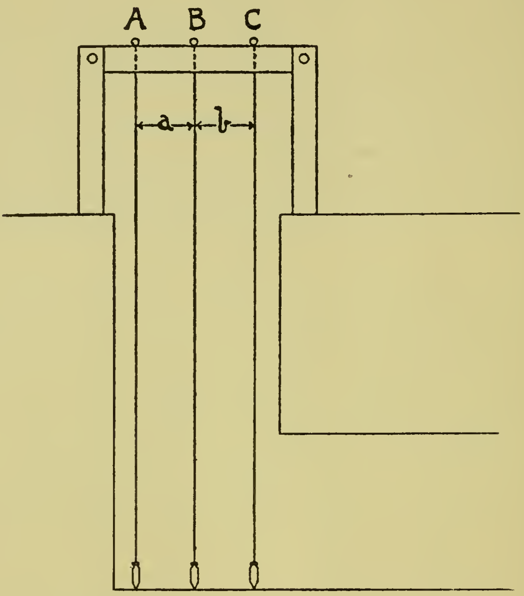


FIG. 224—Three wire plumbing

the same distance apart. The theodolite is then set up down below as shown in plan in Fig. 225 where P_1 P_2 P_3 are the three

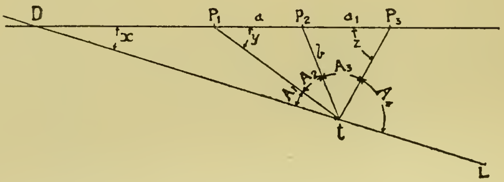


FIG. 225

wires, t the theodolite and D L the direction of the tunnel. It is now only necessary to measure the three angles A_1 A_2 and

A_3. Thus allowing the angles y and z to be calculated as follows :—

$$\sin y = \frac{b}{a} \sin A_1$$

$$\sin z = \frac{b}{a} \sin A_2$$

$$\therefore \quad \frac{\sin y}{\sin z} = \frac{\sin A_1}{\sin A_2} \quad \cdots\cdots\cdots \quad (1)$$

$$\text{Also} \quad x = A_3 - z$$

$$\text{and} \quad x = y - A_4$$

$$\text{and} \quad y = (A_3 + A_4) - z \quad \cdots\cdots\cdots \quad (2)$$

Substituting from (2) in (1)

$$\frac{\sin (A_3 + A_4) - z}{\sin 2} = \frac{\sin A_1}{\sin A_2}$$

$$= \frac{\sin (A_3 + A_4) \cos z - \cos (A_3 + A_4) \sin z}{\sin z}$$

$$= \sin (A_3 + A_4) \cot z - \cos (A_3 + A_4)$$

$$\therefore \quad \sin (A_3 + A_4) \cot z = \frac{\sin A_1}{\sin A_2} - \cos (A_3 + A_4)$$

$$\text{and} \quad \cot z = \frac{\dfrac{\sin A_1}{\sin A_2} - \cos (A_3 + A_4)}{\sin A_3 + A_4}$$

When the shafts are deep, difficulties arise owing to the movements of the wires, which are, in effect, long pendulums. It is necessary in this case to set the telescope webs to the centre of the swing. This can be done quite satisfactorily, but some surveyors prefer to fix the plumb bob and use for this purpose an apparatus similar to that shown in Fig. 226. This consists of a cast iron base plate having a large hole in its centre and carrying two divided scales at right angles to each other. The base is securely bolted down to a baulk of timber in such a position that the plumb wire hangs approximately in the centre of the hole. A theodolite is now set up at right angles to one of the scales and focused so that the wire and scale may be seen at the same time. The amount of swing is then read on the scale and the mean point noted. A similar determination is then made at right angles to the previous position. The bush shown, which has a small hole just fitting the wire at its summit is now placed on the wire, a saw cut being made at one side to allow this to be done without detaching the plumb bob. The four screws shown can then be adjusted to bring the wire over the mean divisions on the two scales, and thus it may be fixed in the exact position which it would assume when hanging freely. As the working shafts are generally only about 10 feet in diameter, the distance between the wires cannot be much greater than about 8 feet. It is obvious, therefore, that great care must be taken in their alignment, as otherwise

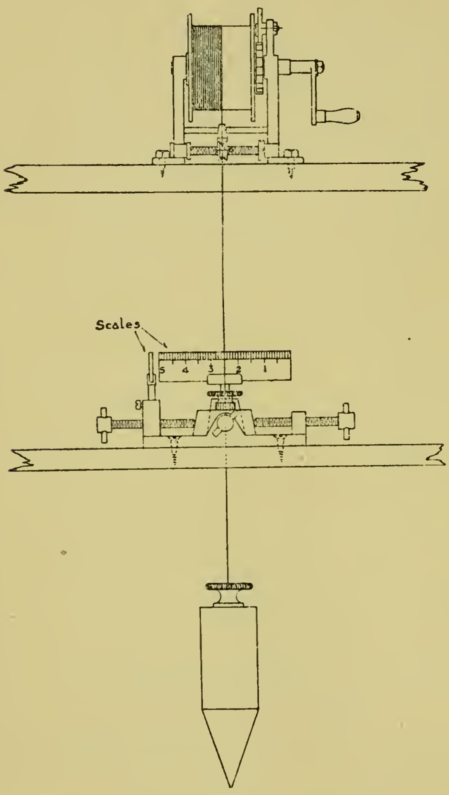


Fig. 226—Mine plumbing device

serious difficulties arise when the two sections of the tunnel which have been driven from opposite directions come to be connected up.

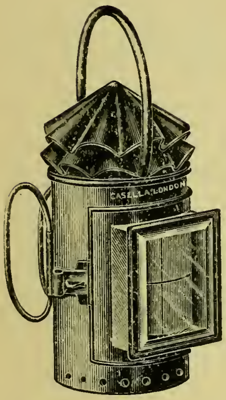


FIG. 227—Mining target lamp

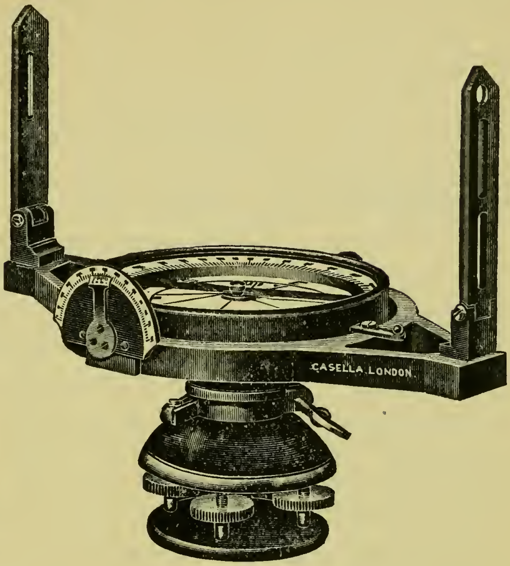


FIG. 228—Mining dial with four screws and quick levelling ball and socket head

CHAPTER XXI

ERRORS IN THE MEASUREMENTS OF ANGLES

THE errors introduced into these measurements are of two kinds :—(a) Instrumental errors ; (b) Observer's errors. Of these the instrumental errors are, with modern instruments, the least important, and most of them may be eliminated by careful attention to an observational programme which is designed in such a way that the errors tend to cancel out in the final results.

The principal instrumental errors are :—

(1) Collimation.

(2) Unequal height of Y's.

(3) Inequality of pivots of telescope.

(4) Graduation errors and errors in micrometers.

Errors due to 1, 2 and 3 may be eliminated as previously described, and certain of those due to 4 may also be eliminated. The errors of centering are eliminated by taking the mean of opposite readings. Those due to actual errors in the spacing of the graduations are not easily disposed of, but may be rendered very small by a suitable programme of observations. In order to do this, the pointings on any particular pair of targets should be made on different parts of the circle, it being usual on accurate work to take separate readings at six or eight equidistant portions. This procedure tends to eliminate any accidental errors of graduation as well as any periodic errors which the circle may have. Errors due to variations in the run of the micrometers can only be guarded against by making careful check readings before starting on the main observations, and it is often desirable to make an additional check at the finish of the work. Care should always be taken to see that all measurements are made by moving the micrometer and tangent screws in a positive direction only. The opposing springs in micrometers or tangent screws are only for the purpose of keeping the point of the screw in contact with the abutment, and no reliance must be placed on the movements due to them. This is a most important point, and one not always given sufficient consideration. It must be remembered that every instrument is defective to a certain extent, and that all its parts are more or less elastic, so that changes in its adjustments are bound to occur from time to time. It is therefore essential to verify the adjustment and working of the instrument before any important work is undertaken, and to adhere strictly to the programme of observations which has been laid down in such a way that any residual errors may be eliminated.

Errors of Eccentricity

In Fig. 229 let A be the centre of the circle from which the divisions were made; if the telescope is mounted so that it revolves truly on this centre and if it is pointed on B and C the angle θ will be of correct value when read by a single vernier. If, however, the axis of rotation is displaced to A_1 by an amount x the arc B_1 C_1 over which the vernier moves will not measure the angle C_1 A_1 B_1 which has been turned, owing to the fact that the graduations on this arc were struck from A and not from the centre of rotation A_1. The error introduced will be :—

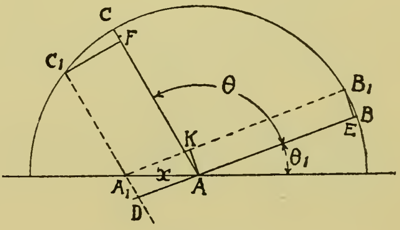


Fig. 229

$$B_1\,C_1 - B\,C = C\,C_1 - B\,B_1$$

As the arcs B B_1 and C C_1 are small we can substitute the perpendiculars B_1 E and C_1 F which, as the lines of sight are parallel, will equal A K and A D.

Now $AK = x \sin \theta_1$

and $AD = x \sin (\theta + \theta_1)$

$\therefore \quad C\,C_1 - B\,B_1 = x \sin (\theta + \theta_1) - x \sin \theta_1$

which equals $B_1\,C_1 - B\,C$

and therefore gives the error due to an eccentricity of the amount x. The maximum error is introduced when the displacement is at 90° from the zero of the verniers, the actual shortening of the arc being then equal to 2x. If, therefore, d = the diameter of the circle the error in minutes of arc

$$= \frac{2x}{\left(\frac{d}{2}\right)} 6875$$

In practice the means of the two or more verniers are always read, thus eliminating any error due to eccentricity. In sextants, however, only one vernier is available, so that the very greatest care must be taken to see that the axis is placed truly at the point about which the circle turned during graduation. Fig. 230 shows very clearly the condition which obtains when the telescope axis is out of the centre at right angles to the zero of the verniers. If A is the centre of the graduations and B is the centre about which the telescope turns, then to set the telescope on to points X and Y which subtend an angle of say 90° at the centre A it is necessary to turn it through the angle θ which is obviously greater than 90°, although the arc as measured on the circle is less than 90°.

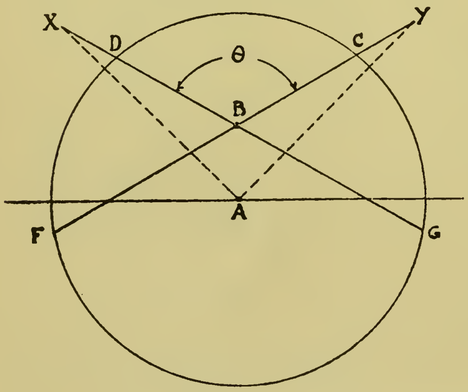


FIG. 230

In practice the graduations are read at C F and D G, the arcs

$$\frac{CD + FG}{2}$$

thus giving the correct angle, no matter how much B is displaced from the true centre A.

In addition to the elimination of the centering error the use of more than one microscope or vernier reduces the probable error of the readings as follows :—

Let (e) be the probable error of reading one micrometer or vernier and E the mean of n micrometers.

Then from the method of least squares the probable error

$$E = \frac{1}{n}\sqrt{\text{nee}}$$

$$= \frac{e}{\sqrt{n}}$$

If, for example, the probable error (e) for one micrometer is one second then

When using two micrometers $E = \frac{1}{\sqrt{2}} = \cdot 7$ second

When using six micrometers $E = \frac{1}{\sqrt{6}} = \cdot 4$ second

It will be seen that increasing the number of micrometers will decrease the probable error slowly and that nine micrometers would be required to reduce it in the above case to one-third of a second.

It is to be noted that two micrometers are sufficient for the elimination of the centering error, so that from that point of view there is no advantage in having more than two.

For the purpose of reducing the probable error it is unusual to employ more than four micrometers this number reducing the error to half that obtained from a single reading. When a greater number is fitted the theoretical advantages can hardly be realised owing to the probability of relative movements of the mountings, etc.

Observer's Errors

Are due to a great number of causes, some of which are at times very elusive and difficult to trace, and very difficult to cure. Marked differences exist between observers and it is only by practice and experience that efficiency and speed of working and accuracy in the final results may be obtained. Some of the principal errors under this head are due to readings of the verniers or micrometers or the telescope webs, which are inconsistent. This form of error in properly trained observers is unusual, due perhaps to the fact that those inclined to make errors of this kind cease to be surveyors. Errors due to readings which are consistently either too large or too small are more common, but not of course so serious. The largest errors, apart from mistakes in the actual booking of the angles read are generally due to poor setting up of the instrument and to failure to ensure that all the parts are properly secured and free from shake or instability. When the tripod is set up, it must be firmly pressed into the ground, and then, when the instrument has been placed in position and approximately levelled, all twist should be eliminated by slackening the thumb screws thus allowing the whole apparatus to take up an unstrained position before finally tightening up all the elements. Especial care should be taken to see that there is no slackness at the foot screws, neglect of this simple detail being undoubtedly the cause of some of the largest errors. Wooden stands usually twist when placed in the sun, and as the rate of twist is variable, it is important that the observations should be taken as quickly as possible, as delay between the settings on a pair of azimuth marks may lead to large errors when the direction of twist is such that the measures of the angles would be too great or too small. If twist of the support is suspected, it is well to measure the angles first from one side and then from the opposite side, the mean of these two readings being correct provided the rate of twist is uniform. On precise work it is of course important that the instrument be placed accurately over the station mark and on tunnelling work, especially, this detail must be attended to with the greatest care possible.

An idea of the accuracy of placement required is shown by the fact that an error in centering of 1/10th inch will give an error of three seconds at a distance of one mile. When, therefore, a plumb bob is used for the centering, care should be taken that it revolves truly when the instrument is wheeled in azimuth. Another source of serious error is that due to the state of the atmosphere, which is nearly always in a ferment, so that discretion is required on the part of the observer as to when he should make his observations, and how many he should take when the conditions are unfavourable.

Errors in the reading of the bubbles are not very common, but in levelling operations, inconsistent settings are to be avoided in view of the fact that the precision depends directly on this setting. Correct setting of the bubbles can only be obtained when the illumination is good and when it is properly arranged, and as explained under the section dealing with bubbles this is best done by transmitting the light through the bubble tube from below.

CHAPTER XXII

BAROMETERS & HYPSOMETERS

IN mountainous regions there are two other methods of finding levels or approximate heights, viz.: by the use of barometers and by determination of the temperature of the boiling points of water at various altitudes.

The barometers used are of two classes—A the **mercury** and B the **aneroid.** The mercury barometers always employed are of the Fortin type, as this pattern can easily be rendered portable by screwing up the mercury until it fills the tube. Fig. 231 shows an instrument of this kind fixed to its tripod and Fig. 232 shows the leather case in which it can be packed for transport. The scale is graduated down to about 12 or 14 inches, which is equivalent to an altitude of about 20,000 feet, and provided care be taken in the transport and reading, fair results can be obtained. The apparatus is, however, very cumbersome to carry, and the delicate mercury tube is easily damaged or rendered useless by the ingress of air to the vacuum space, so that the method is seldom used except by large well-equipped parties.

The aneroid barometer, on the other hand, when well made and compensated, is a very reliable and portable instrument and is capable of giving excellent results in careful hands. It is small, portable and easily read, and not liable to damage, provided reasonable care be taken during transport. Figs. 233 and 234 shows the type of instrument usually carried. It is about 4 or 5 inches in diameter and may be obtained with scales marked for descent to 2,000 feet and ascent up to as much as 20,000 feet when required. For readings up to 10,000 feet, the scale is divided to read to 2 feet intervals and for 20,000 feet the reading is generally to 5 feet. Instruments of 2 or 3 inches diameter can be obtained, but the scales are rather too

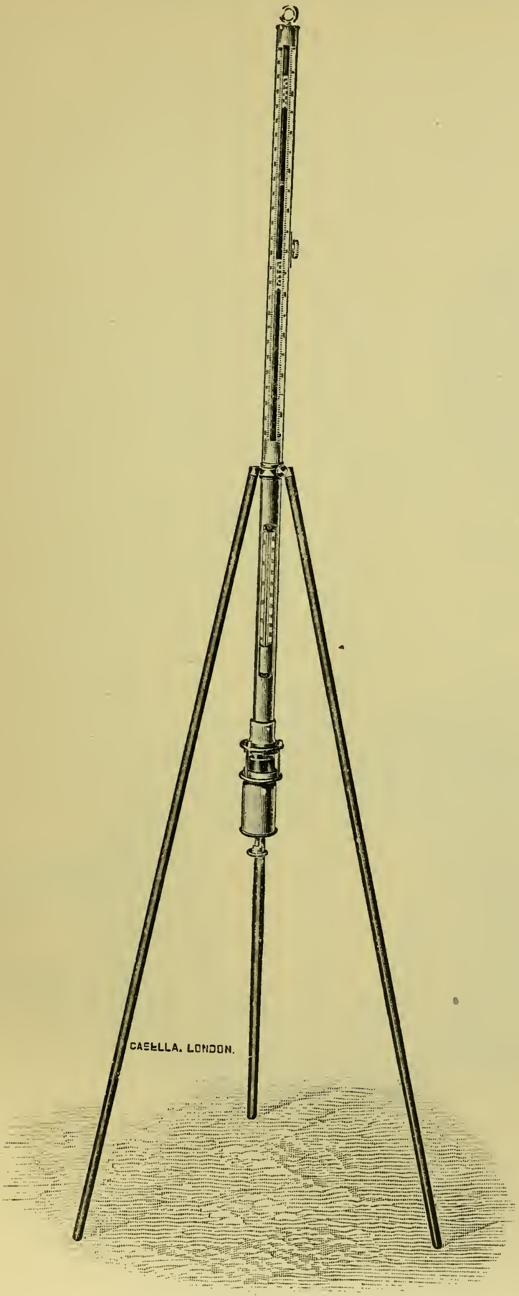


FIG. 231—Mountain barometer on tripod stand

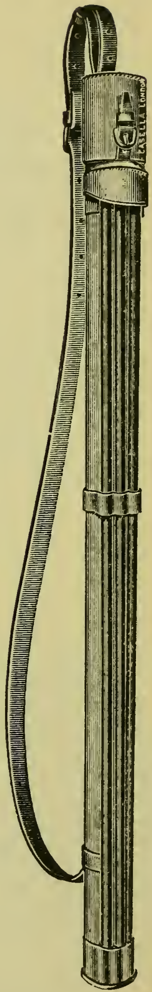


FIG. 232
Case for carrying mountain barometer

short for accurate work. When exact results are required from aneroids, the instruments must be carefully calibrated both before and after the ascent and determinations made of the lag in the readings for rising and falling pressures. This is necessary owing to the fact that it has been found impossible to eliminate hysteresis entirely from the metal chambers or aneroid boxes. Notable improvements in the material used for these chambers have been made in recent years, allowing more consistent results to be obtained, but as so many factors enter into the question it cannot be said that the complete solution of the problem has yet been found.

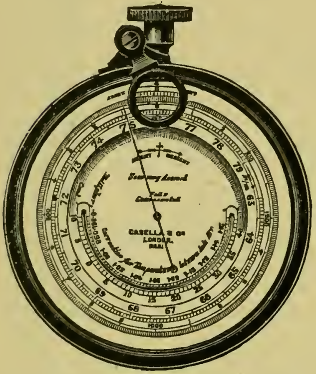


FIG. 233—Aneroid barometer for surveying and mining purposes

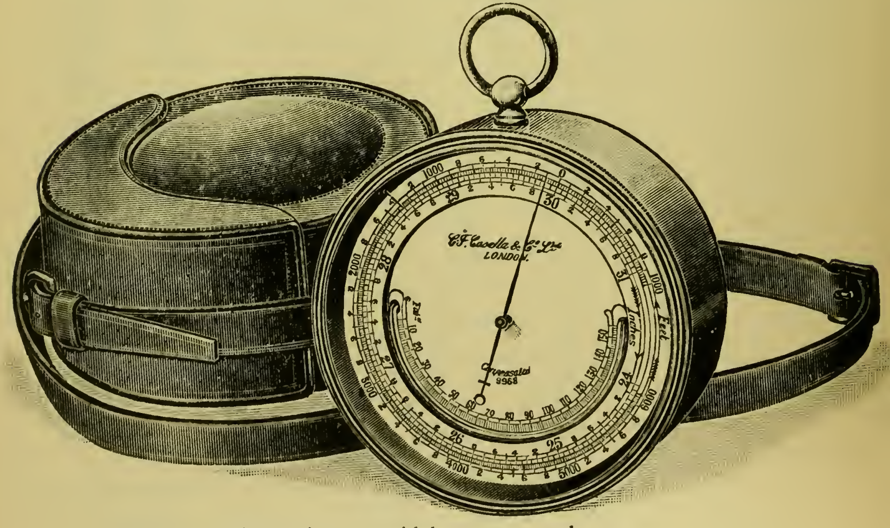


FIG. 234—Surveying aneroid barometer and case

The subject has been very fully treated in a paper* by Dr Filon, to which the reader is referred.

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* *Journal of Scientific Instruments*, Vol. I, No. 1.

Aneroid Barometers

The aneroid barometer was invented by Vidi, of Paris, in 1843, and patented in the following year. It is an extremely ingenious instrument, and has become very popular owing to its portability and low cost as compared with a mercury barometer.

In an aneroid the varying weight of the atmosphere is measured by its effect in altering the shape of a light metal box, the alteration being magnified by levers and conveyed to a hand moving over a suitable dial. The metal box is exhausted of air, as otherwise the expansion and compression of the air sealed in the box, due to the changes of temperature, would affect its shape more than the changes in the atmospheric pressure, and the instrument would tend to become a poor thermometer instead of a good barometer.

Although aneroids in their outward appearance may differ greatly from one another, they are usually very much alike in the construction of the essential working parts—at any rate, to a casual observer. The merit of any particular make lies in the design of the individual components according as they make for robustness and accuracy, in the accuracy of the divided scale, in the treatment, during manufacture, of the vacuum chamber, and, of course, in the quality of the workmanship throughout.

The various parts of which an aneroid " movement " is composed are shown in the illustration, Fig. 235. It is drawn from one of the simpler models for the sake of clearness.

A is the exhausted metal box called the vacuum chamber, made of two thin nickel-silver discs soldered together ; the corrugations are to strengthen its walls and increase its elasticity. As it contains no air and is subject to the weight of the atmosphere pressing upon it (equal to about 15 lbs. to the square inch), the vacuum chamber would collapse unless it was supported in some way. The necessary support is provided by the strong steel spring B, which, pressing upwards, holds the upper disc away from the lower one, which is bolted to the base plate C. The centre of the lower disc being fixed, the movement is confined to the upper one, and, as this is attached to the steel spring, it is finally the movement of the latter which actuates the hand through the system of magnifying levers shown in the illustration. D is an iron plate let into the long brass lever, and its purpose is to correct the effect on the instrument of changes of temperature. Brass expands more than one and a half times as much as iron for a given rise in temperature ; hence, in the case of a compound bar such as this, the effect of the different expansions of the two metals is to cause the bar to curve and its effective length to be slightly reduced, thus neutralizing the expansion due to the rise of temperature. This is called compensation for temperature, and is applied to all the better class of aneroids. E is an arrangement for increasing or diminishing the leverage at that point, and is a workshop adjustment for altering the range of the instrument so as to make the scale of the aneroid exactly equivalent to the mercury barometer scale. The last link in the system of levers is a fine watch-chain F,

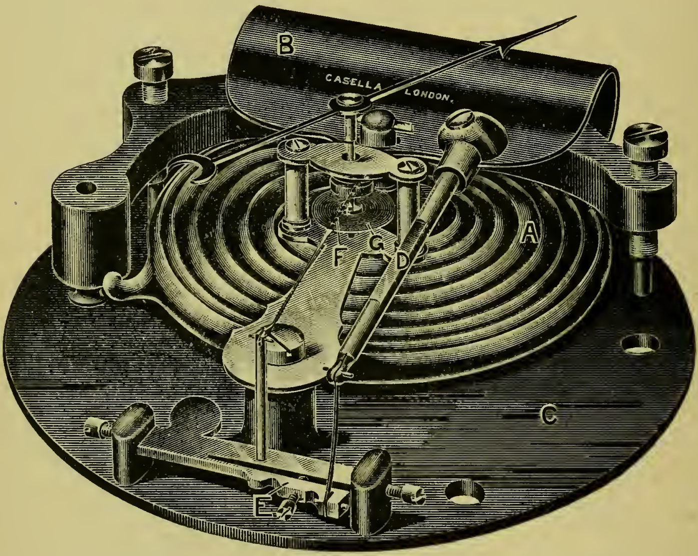

FIG. 235

which is wound round the vertical spindle or arbor and causes it to rotate. The hand is held friction-tight on the arbor and rotates with it, the length of the hand giving an additional magnification to the original movement of the vacuum chamber. G is a hair-spring to take up the fine chain and to move the pointer to the left when the pressure is low. The total magnification in an aneroid is very great, a movement of the wall of the vacuum chamber of one-two-hundredth of an inch may cause the hand to move through more than three inches on the dial.

Aneroid barometers are largely used for reading the heights of mountains, and are very convenient in climbing, travelling, motoring, etc. For this purpose a scale of feet or metres is engraved on the dial in addition to the barometric scale of inches or centimetres. This "altitude scale," as it is called, is preferably a fixed one, but in some aneroids it is made to revolve. The object of a revolving altitude scale is to enable the observer to set its zero opposite to the pointer before beginning to take readings, so that no further calculations are necessary. Although this is very convenient it is not perhaps quite so exact as a fixed scale.

Though they never attain the accuracy of a standard mercury barometer, aneroids possess advantages of their own which render them, for many purposes, equally, or even more, suitable than the former instrument. The peculiar advantages of an aneroid may be summed up shortly as follows :—

(1) It is rapid in action.

(2) It responds to tapping, so that one can see whether its tendency is to go up or down.

(3) It is easily portable, may be carried in any position without fear of injury, and the absence of a long glass tube filled with mercury renders it free from risk of breakage in transport or in use.

Apparatus for Testing and Comparing Aneroid Barometers.—This apparatus consists of a standard barometer, reading down to about 12 inches or 300 mm., connected with an air-tight chamber to hold the aneroid, and an air-pump. The whole is mounted in a very convenient form as shown in the illustration.

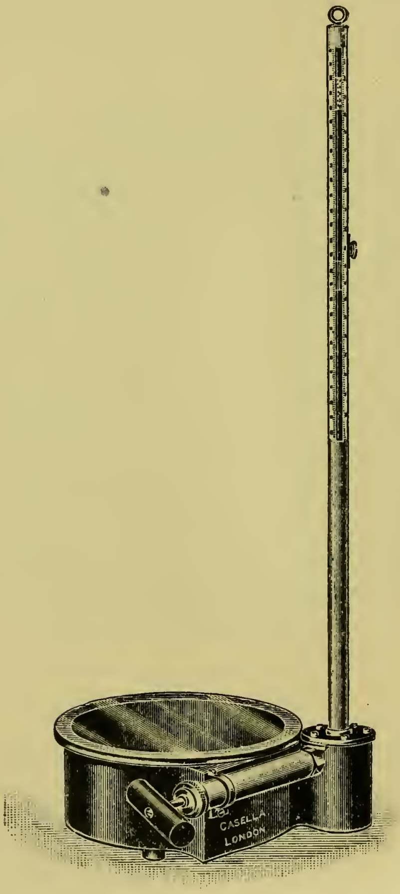

FIG. 236—Apparatus for testing and comparing aneriod barometers.

Hypsometer

The only other method which need be mentioned is that based on the lowering of the boiling point of water under diminished atmospheric pressure. Fig. 236 shows the form which the instrument usually takes. It consists of a vessel for boiling water with a double-walled, telescopic tube in which the thermometer is fixed. The steam from the boiling water fills the chamber and then passes out through a hole at the top, where it escapes into the air. In this way the bulb and the stem of the thermometers are immersed in the vapour. Less than a wine-glassful of water and half that quantity of methylated spirit serve for several determinations. When the instrument is correctly constructed and furnished with a really accurate thermometer it may be made an efficient and handy means of measuring heights in surveying or botanical geography, and it is at all times a reliable test with which to compare an aneroid barometer or similar instrument requiring from time to time to be verified and adjusted.

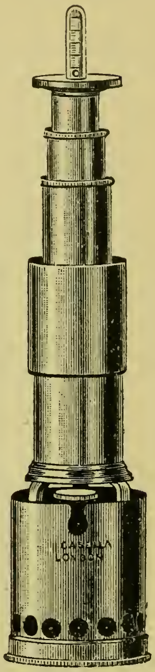

FIG. 237—Small Hypsometer

Though its accuracy is only about one-fiftieth that of a standard mercury barometer, it removes that great anxiety to the traveller—the safe transport of a glass tube, 3 feet long, filled with mercury and encased in a metal frame.

INDEX

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