MICKLE, WILLIAM JULIUS (1734–1788), son of the minister of Langholm, Dumfriesshire, holds a respectable place among the imitative minor poets of the 18th century. He wrote a poem on *Knowledge*—carefully versified, pointing a moral on the vanity of intellectual pride—at the age of eighteen, entered into business as a brewer at his father's request and against his own inclinations, soon became bankrupt, went to London on outlook for work as a man of letters, solicited patronage in vain, earned a living hardly by writing for magazines, made some impression in 1765 by "a poem in the manner of Spenser" called the *Concubine* (afterwards *Syr Martyn*), was appointed corrector to the Clarendon Press, and finally took a place among the leading poets of that very barren time by a translation of the *Lusiad* of Camoens into heroic couplets (specimen published 1771, whole work 1775). So great was the repute of the work that when Mickle—appointed secretary to Commodore Johnstone—visited Lisbon in 1779 the king of Portugal gave him a public reception. As a translator of Camoens Mickle has been superseded, but he aimed, not at close rendering of the original, but at making a poem which should be worthy of a permanent place in English literature. This ambition he was not capable of fulfilling, though he had great fluency and vigour. It may be doubted whether the fashionable forms which he imitated were the best suited to his natural gifts. He shows delight in lively action, a sense of dramatic effect, and, in the *Concubine*, the substance of which might have been conceived by Crabbe, considerable fulness of detail in coarse realistic painting. Certainly, if the Scottish poem *There's nae luck aboot the hoose* was Mickle's, he mistook his medium. Scott read and admired Mickle's poems in his youth, and, besides founding *Kenilworth* on the ballad of *Cumnor Hall*, was a good deal influenced by him in style. Mickle's prose is lively and vigorous.

MICROMETER, an instrument generally applied to telescopes and microscopes for measuring small angular distances with the former or the dimensions of small objects with the latter.

Before the invention of the telescope the accuracy of astronomical observations was necessarily limited by the angle that could be distinguished by the naked eye. The angle between two objects, such as stars or the opposite limbs of the sun, was measured by directing an arm furnished with fine "sights" (in the sense of the "sights" of a rifle) first upon one of the objects and then upon the other, or by employing an instrument having two arms each furnished with a pair of sights, and directing one pair of sights upon one object and the second pair upon the other. The angle through which the arm was moved, or, in the latter case, the angle between the two arms, was read off upon a finely graduated arc. With such means no very high accuracy was possible. Archimedes concluded from his measurements that the sun's diameter was greater than 27′ and less than 32′; and even Tycho Brahe was so misled by his measures of the apparent diameters of the sun and moon as to conclude that a total eclipse of the sun was impossible.[1] Maestlin in 1579 determined the relative positions of eleven stars in the Pleiades (*Historia Cœlestis Lucii Baretti*, Augsburg, 1666), and Winnecke has shown (*Monthly Notices R. A. S.*, vol. xxxix. p. 146) that the probable error of these measures amounted to about ± 2′.[2]

[1] Grant, *History of Physical Astronomy*, p. 449.

[2] This is an astonishing accuracy when the difficulty of the objects is considered. Few persons can see with the naked eye—much less measure—more than six stars of the Pleiades, although all the stars measured by Maestlin have been seen with the naked eye by a few individuals of exceptional powers of eye-sight.

The invention of the telescope at once extended the possibilities of accuracy in astronomical measurements. The planets were shown to have visible disks, and to be attended by satellites whose distance and position angle relative to the planet it was desirable to measure. It became, in fact, essential to invent a "micrometer" for measuring the small angles which were thus for the first time rendered sensible. There is now no doubt that William Gascoigne, a young gentleman of Yorkshire, was the first inventor of the micrometer. Crabtree, a friend of his, taking a journey to Yorkshire in 1639 to see Gascoigne, writes thus to his friend Horrocks. "The first thing Mr Gascoigne showed me was a large telescope amplified and adorned with inventions of his own, whereby he can take the diameters of the sun and moon, or any small angle in the heavens or upon the earth, most exactly through the glass, to a second." The micrometer so mentioned fell into the possession of Mr Richard Townley of Lancashire, who exhibited it at the meeting of the Royal Society held on the 25th July 1667.

The principle of Gascoigne's micrometer is that two pointers, having parallel edges at right angles to the measuring screw, are moved in opposite directions symmetrically with and at right angles to the axis of the telescope. The micrometer is at zero when the two edges are brought exactly together. The edges are then separated till they are tangent to the opposite limbs of the disk of the planet to be measured, or till they respectively bisect two stars, the angle between which is to be determined. The symmetrical separation of the edges is produced and measured by a single screw; the fractions of a revolution of the screw are obtained by an index attached to one end of the screw, reading on a dial divided into 100 equal parts. The whole arrangement is elegant and ingenious. A steel cylinder (about the thickness of a goose-quill), which forms the micrometer screw, has two threads cut upon it, one-half being cut with a thread double the pitch of the other. This screw is mounted on an oblong box which carries one of the measuring edges; the other edge is moved by the coarser part of the screw relatively to the edge attached to the box, whilst the box itself is moved relatively to the axis of the telescope by the finer screw. This produces an opening and closing of the edges symmetrically with respect to the telescope axis. Flamsteed, in the first volume of the *Historia Cœlestis*, has inserted a series of measurements made by Gascoigne extending from 1638 to 1643. These include the mutual distances of some of the stars in the Pleiades, a few observations of the apparent diameter of the sun, others of the distance of the moon from neighbouring stars, and a great number of measurements of the diameter of the moon. Dr Bevis (*Phil. Trans.*, 1773, p. 190) also gives results of measurements by Gascoigne of the diameters of the moon, Jupiter, Mars, and Venus with his micrometer.

Delambre gives[3] the following comparison between the results of Gascoigne's measurements of the sun's semi-diameter and the computed results from modern determinations:—

	Gascoigne.	*Conn. d. Temps.*
October 25 (O.S.)	16′ 11″ or 10″	16′ 10″·0
,, 31 ,,	16′ 11″	16′ 11″·4
December 2 ,,	16′ 24″	16′ 16″·8

Gascoigne, from his observations, deduces the greatest variation of the apparent diameter of the sun to be 35″; according to the *Connaissance des Temps* it amounts to 32″·3.[3] These results prove the enormous advance attained in accuracy by Gascoigne, and his indisputable title to the credit of inventing the micrometer.

Huygens, in his *Systema Saturnium* (1659), describes a micrometer with which he determined the apparent

[3] Delambre, *Hist. Ast. Moderne*, vol. ii. p. 590.

diameters of the principal planets. He inserted a slip of metal, of variable breadth, at the focus of the telescope, and observed at what part it exactly covered the object under examination; knowing the focal length of the telescope and the width of the slip at the point observed, he thence deduced the apparent angular breadth of the object. The Marquis Malvasia in his *Ephemerides* (Bologna, 1662) describes a micrometer of his own invention. At the focus of his telescope he placed fine silver wires at right angles to each other, which, by their intersection, formed a network of small squares. The mutual distances of the intersecting wires he determined by counting, with the aid of a pendulum clock, the number of seconds required by an equatorial star to pass from web to web, while the telescope was adjusted so that the star ran parallel to the wires at right angles to those under investigation.[1] In the *Phil. Trans.*, 1667, No. 21, p. 373, Auzout gives the results of some measures of the diameter of the sun and moon made by himself, and this communication led to the letters of Mr Townley and Dr Bevis above referred to. The micrometer of Auzout and Picard was provided with silk fibres or silver wires instead of the edges of Gascoigne, but one of the silk fibres remained fixed while the other was moved by a screw. It is beyond doubt that Huygens independently discovered that an object placed in the common focus of the two lenses of a Kepler telescope appears as distinct and well-defined as the image of a distant body; and the micrometers of Malvasia, Auzout, and Picard are the natural developments of this discovery. Gascoigne was killed at the battle of Marston Moor on the 2d July 1644, in the twenty-fourth year of his age, and his untimely death was doubtless the cause that delayed the publication of a discovery which anticipated, by twenty years, the combined work of Huygens, Malvaison, Auzout, and Picard in the same direction.

As the powers of the telescope were gradually developed, it was found that the finest hairs or filaments of silk, or the thinnest silver wires that could be drawn, were much too thick for the refined purposes of the astronomer, as they entirely obliterated the image of a star in the more powerful telescopes. To obviate this difficulty Professor Felice Fontana of Florence (*Saggio del real gabinetto di fisica e di storia naturale*, 1755) first proposed the use of spider webs in micrometers,[2] but it was not till the attention of Troughton had been directed to the subject by Rittenhouse that the idea was carried into practice.[3] In 1813 Wollaston proposed fine platinum wires, prepared by surrounding a platinum wire with a cylinder of silver, and drawing out the cylinder with its platinum axis into a fine wire.[4] The surrounding silver was then dissolved by nitric acid, and a platinum wire of extreme fineness remained. But experience soon proved the superiority of the spider web; its perfection of shape, its lightness and elasticity, have led to its universal adoption.

Beyond the introduction of the spider line it is unnecessary to mention the various steps by which the Gascoigne micrometer assumed the modern forms now in use, or to describe in detail the suggestions of Hooke,[5] Wren, Smeaton, Cassini, Bradley, Maskelyne, Herschel, Arago, Pearson, Bessel, Struve, Dawes, &c., or the successive productions of the great artists Ramsden, Troughton, Fraunhofer, Ertel, Simms, Cooke, Grubb, Clarke, and Repsold. It will be sufficient to describe those forms with which the most important work has been done, or which have survived the tests of time and experience.

Before astronomical telescopes were mounted parallactically, the measurement of position angles was seldom attempted. Indeed, in those days, the difficulties attached to such measures, and to the measurement of distances with the filar micrometer, were exceedingly great, and must have taxed to the utmost the skill and patience of the observer. For, on account of the diurnal motion, the direction of the axis of the telescope when directed to a star is always changing, so that, to follow a star with an altazimuth mounting, the observer requires to move continuously the two handles which give slow motion in altitude and azimuth.

Sir William Herschel was the first astronomer who measured position angles; the instrument he employed is described in *Phil. Trans.*, 1781, vol. lxxi. p. 500. It was used by him in his earliest observations of double stars (1779–83); but, even in his matchless hands, the measurements were comparatively crude, because of the difficulties he had to encounter from the want of a parallactic mounting. In the case of close double stars he estimated the distance in terms of the disk of the components. For the measurement of wider stars he invented his lamp-micrometer, in which the components of a double star observed with the right eye were made to coincide with two lucid points placed 10 feet from the left eye. The distance of the lucid points was the tangent of the magnified angles subtended by the stars to a radius of 10 feet. This angle, therefore, divided by the magnifying power of the telescope gives the real angular distance of the centres of a double star. With a power of 460 the scale was a quarter of an inch for every second.

The Modern Filar Micrometer.

When equatorial mountings for telescopes became more general, no filar micrometer was considered complete which was not fitted with a position circle.[6] The use of the spider line or filar micrometer became universal; the methods of illumination were improved; and micrometers with screws of previously unheard-of fineness and accuracy were produced. These facilities, coupled with the wide and fascinating field of research opened up by Sir William Herschel's discovery of the binary character of double stars, gave an impulse to micrometric research which has continued unabated to the present time. A still further facility was given to the use of the filar micrometer by the introduction of clockwork, which caused the telescope automatically to follow the diurnal motion of a star, and left the observer's hands entirely at liberty.[7]

The modern filar micrometer has now assumed forms of five types. Classification of micrometers

Type A.—Micrometers in which there are two webs, each movable by a fine screw with a divided head. This is the usual English form of filar micrometer.

Type B.—Micrometers in which one web is movable by means of a fine screw with a divided head, and the other by a screw without a divided head. The latter screw, in ordinary use, is only employed to change the coincidence-reading of the two webs, for eliminating the errors of the micrometer screw. This is the ordinary German form of micrometer as originally made by Fraunhofer and since by Merz, and employed by the Struves and other principal Continental astronomers down to the present day.

Type C.—A similar form of micrometer to B, except that the coincidence-point cannot be changed,—there being no second screw to alter the position of the fixed web.

Type D.—A micrometer somewhat similar in general construction to form B, except that, in addition to means of changing the zero point, there is a screw head by which a fine movement can be given to the whole micrometer box, in the direction of the axis of the micrometer screw. This is the modern form of micrometer as constructed by Repsold.

Type E.—Micrometers fitted with two eye-pieces for measuring angles larger than the field of view of an ordinary eye-piece.

The micrometer of type A is due to Troughton; it is represented in figs. 1, 2, 3. Fig. 1 is a horizontal section in the direction of the axis of the telescope. The eye-piece *ab* consists of two plano-convex lenses *a*, *b*, of nearly the same focal length, and with the two

[1] *Mém. Acad. des Sciences*, 1717, p. 78 *sq.*

[2] In 1782 (*Phil. Trans.*, vol. lxxii. p. 163) Sir W. Herschel writes:—"I have in vain attempted to find lines sufficiently thin to extend them across the centres of the stars, so that their thickness might be neglected." It is a matter of regret that Fontana's suggestion was unknown to him.

[3] Quekett in his *Treatise on the Microscope* ascribes to Ramsden the practical introduction of the spider web in micrometers. The evidence appears to be in favour of Troughton.

[4] *Phil. Trans.*, 1813, pp. 114–118.

[5] Dr Hooke made the important improvement on Gascoigne's micrometer of substituting parallel *hairs* for the parallel edges of its original construction (Hooke's *Posthumous Works*, p. 497).

[6] Herschel and South (*Phil. Trans.*, 1824, part iii. p. 10) claim that the micrometer by Troughton, fitted to their 5-feet equatorial telescope, is the first position micrometer constructed capable of measuring position angles to 1′ of arc.

[7] So far as we can ascertain, the first telescope of large size driven by clockwork was the 9-inch equatorial made for Struve at Dorpat by Fraunhofer; it was completed in 1825. The original idea appears to be due to Passement (*Mém. Acad.*, Paris, 1746). In 1757 he presented a telescope to the king, so accurately driven by clockwork that it would follow a star all night long.

convex sides facing each other. They are placed at a distance apart less than the focal length of *a*, so that the wires of the micrometer, which must be distinctly seen, are beyond *b*.[1] The eye-piece slides into the tube *cd*, which screws into the brass ring *ef*, through two openings in which the oblong frame, containing the micrometer slides, passes. These slides are shown in fig. 2, and consist of brass forks *k* and *l*, into which the ends of the screws *o* and *p* are rigidly fitted. The slides are accurately fitted so as to have no sensible lateral shake, but yet so as to move easily in the direction of the greatest length of the micrometer box. Motion is communicated to the forks by female screws tapped in the heads *m* and *n*

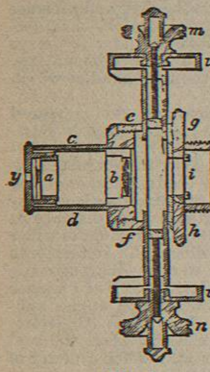

Fig. 1.

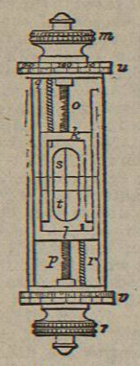

Fig. 2.

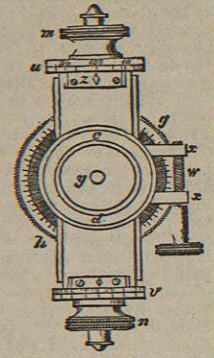

Fig. 3.

acting on the screws *o* and *p* respectively. Two pins *q*, *r*, with spiral springs coiled round them, pass loosely through holes in the forks *k*, *l*, and keep the bearings of the heads *m* and *n* firmly pressed against the ends of the micrometer box. Thus the smallest rotation of either head communicates to the corresponding slide motion, which, if the screws are accurate, is proportional to the amount through which the head is turned. Each head is graduated into 100 equal parts on the drums *u* and *v*, so that, by estimation, the reading can easily be carried to $\frac{1}{1000}$th of a revolution. The total number of revolutions is read off by a scale attached to the side of the box, but not seen in the figure.

Two spider webs are stretched across the forks, one (*t*) being cemented in a fine groove cut in the inner fork *k*, the other (*s*) in a similar groove cut in the outer fork *l*. These grooves are simultaneously cut *in situ* by the maker, with the aid of an engine capable of ruling fine straight lines, so that the webs when accurately laid in the grooves are perfectly parallel. A wire *st* is stretched across the centre of the field, perpendicular to the parallel wires. Each movable web must pass the other without coming in contact with it or the fixed wire, and without rubbing on any part of the brass-work. Should either fault occur (technically called "fiddling") it is fatal to accurate measurement. One of the most essential points in a good micrometer is that all the webs shall be so nearly in the same plane as to be well in focus together under the highest powers used, and at the same time absolutely free from "fiddling." For measuring position angles a brass circle *gh* (fig. 3), fixed to the telescope by the screw *i*, has rack teeth on its circumference that receive the teeth of an endless screw *w*, which, being fixed by the arms *xx* to the oblong box *mn*, gives the latter a motion of rotation round the axis of the telescope; an index upon this box points out on the graduated circle *gh* the angular rotation of the instrument.

The English micrometer still retains the essential features of Troughton's original construction above described. The later English artists have somewhat changed the mode of communicating motion to the slides, by attaching the screws permanently to the micrometer head and tapping each micrometer screw into its slide. Instead of making the shoulder of the screw a flat bearing surface, they have given the screw a spherical bearing resting in a hollow cone (fig. 4) attached to the end of the box. The French artists still retain Troughton's form. Simms (Troughton's successor) and Cooke (of York), for symmetry and more effectual elimination of "the loss of time" (called by the Germans "todter Gang," and sometimes in English "back-lash"), have provided two pins with spiral springs,

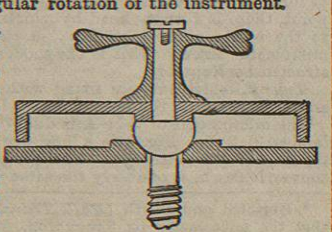

Fig. 4.

[1] This is known as Ramsden's eye-piece; it was made originally by him.

like *q* and *r* (fig. 2), one on each side of the screw which moves each slide.

Grubb of Dublin, with the intention of avoiding the variation of pressure exerted by the spiral springs when the slide is at different distances from the head of the screw, has adopted the following plan. Where the screw enters the slide he has a nut *n* attached to a strong spring *pp* (fig. 5), the pressure of which exerts a constant tension in the axis of the screw, tending to bring the threads into close contact, in opposite directions, with their bearings in the nut *n* and the slide *q*. The pressure of this spring is regulated by the screws *s*, *s*, tapped into the thickened ends of the springs. For maintaining the spherical shoulder of the screw in close and constant pressure on its conical bearing he has attached a conical bearing to the spring *p′p′* (fig. 6). The pressure of this on the upper part of the spherical shoulder is regulated by the screws *s′*, *s′*, passing through elongated holes in the spring *p′p′*, and tapped into the end of the box.

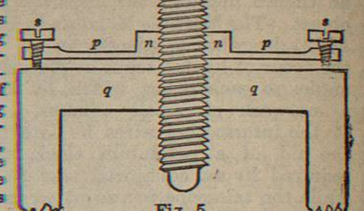

Fig. 5.

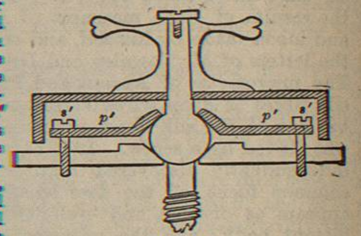

Fig. 6.

The screws of micrometers are generally made with 50 or 100 threads to the inch. Troughton's method of reading the number of whole revolutions by a silver scale is inconvenient, because $\frac{1}{100}$th or even $\frac{1}{50}$th of an inch is too small a quantity to read easily with the naked eye, especially with the faint illumination that it is desirable to use when measuring faint objects. Different methods, including the "comb" (see below) and various kinds of "counters," have been introduced with more or less success; but recently the Repsolds of Hamburg have contrived a plan at once so simple and so efficient that it will be unnecessary to describe those methods which this plan is certain to supersede (see below, type D). Grubb has introduced a modification in the form of the slides with a view to avoid the friction of one slide against the other. On the inner side of the brass plate which forms the bottom of the box (*i.e.*, the side opposite to the eye-piece) four V-shaped furrows are placed (fig. 7); and at each end of the slides are projections (fig. 8, end view) which fit into these furrows. The slides are kept down in their places by springs attached to them, which press upon the inner side of the lid of the box.

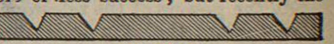

Fig. 7.

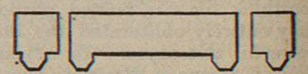

Fig. 8.

Troughton's mode of giving rotation to the position circle is now abandoned. A much quicker motion in position angle than can be obtained without slow motion is often desirable, since, in observing very close double stars, the uncertainty of each pointing may amount to several degrees in the most accurate measurements. The plan of a pinion working in a toothed wheel is often employed, but that also is too slow. Most modern micrometers are now fitted with a clamp and slow motion screw (see fig. 9, type B). This permits observation of position angles of very close objects by simple rotation of the box with the hand; while the slow motion, after clamping, permits the more delicate movements that are required in measuring the position angle of objects farther apart.

The Cookes and Grubb have for years almost invariably transferred the position circle from the micrometer to the telescope tube. The whole eye-end with its focussing arrangements rotates, and its rotation can be measured by a circle attached to the butt end of the tube. There is considerable convenience in this arrangement. One position circle only is required for all the micrometers that may be employed with the instrument; and the orientation of reticulated diaphragms, or the adjustment of the direction of the slit of a spectroscope, may also be accomplished by the same means. But, after a very extended experience of all the various types of existing mountings, the present writer does not hesitate to express a decided preference for a position circle attached to the micrometer and a rigid attachment of the eye-end to the telescope tube,—having never seen an eye-end attached to a position circle on the butt end of the telescope-tube in which, after the wear and tear of a few years,

some looseness or shake could not be detected. This is a fatal fault, especially in those delicate observations of difference of declination which have latterly formed so prominent a feature in refined micrometric research. On the other hand, in some good old micrometers at the Royal Observatory, Cape of Good Hope, that are fitted with attached position circles, there is no trace of shake or wear after fifty years of work.

The micrometer of type B represented in fig. 9[1] is the original Merz micrometer of the Cape Observatory, made on Fraunhofer's model. S is the head of the micrometer screw proper, *s* that of the screw moving the slide to which the so-called "fixed web" is attached, *s′* that of a screw which moves the eye-piece E. C is the clamp and M the slow motion in position angle. L, L are tubes attached to a larger tube N; the latter fits loosely on a strong hollow cylinder which terminates in the screw V. By this screw the whole apparatus is attached to the telescope. The

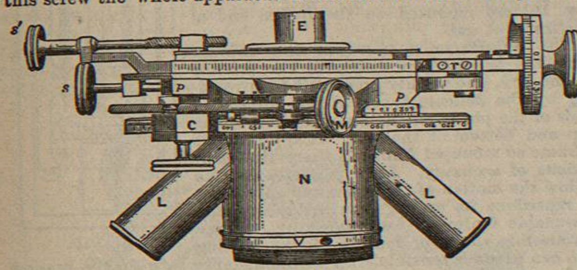

Fig. 9.

nozzles of small lamps are inserted in the tubes L, L, for illuminating the webs in a dark field: the light from these lamps is admitted through apertures in the strong hollow cylinder above mentioned (for illumination, see below). In this micrometer the three slides moved by S, *s*, and *s′* are simple dovetails. The lowest of these slides reposes upon a foundation-plate *pp*, into one end of which the screw *s* is tapped. In the middle of this slide a stiffly fitting brass disk is inserted, to which a small turn-table motion may be communicated by an attached arm, acted on by two fine opposing screws accessible to the astronomer; and by their means the "fixed wire" may be rendered strictly parallel with the movable wire.

The micrometer screw is mounted on the slide which carries the movable web. Fig. 10 shows a plan of this slide; the divided drum of the screw is omitted for sake of clearness. The screw S has a shoulder at κ, carefully fitted and ground to a bearing so as to work sweetly in a hole in the very strong spring $\sigma\sigma$; the other extremity of the screw is formed into a pivot, which fits a hole in the brass piece $\beta\beta$. The end of this pivot—hardened, polished, and slightly rounded—rests on the flat surface of an agate *a*, which is imbedded in the end of the slide, and kept firmly in its place by the brass piece $\beta\beta$. By careful adjustment of the screws θ, θ sufficient pressure may be left upon κ to slightly bend the strong spring $\sigma\sigma$ and thus eliminate all end-shake without preventing easy action of the screw. The screw passes at the same time through the bush B (shown in plan and elevation, fig. 10) attached to *pp* (fig. 9); and there is a fine saw cut, which can be narrowed by the small screw τ, to close the bush upon the micrometer screw with a view of preventing "loss of time." The spider web ω is cemented on the further side of the thin plate $\nu\nu\nu$, the varnish being applied in the countersunk holes shown by the dotted circles μ, μ. The slide is countersunk to about half its thickness within the area indicated by *oooo*, in order to allow the adapter of the eye-piece to come sufficiently close to the webs. The eye-piece was originally moved by a pinion working in a rack *r* (fig. 9); but the screw *s′* applied by Simms was found by Maclear to be more convenient for the purpose. Beyond this, and the graduation of the edge of the circle with more strongly cut divisions than those originally engraved on the face of the circle, the instrument remains and is figured in its original form. Pistor and Martius (Berlin) have also made excellent instruments of the above type. There is a celebrated micrometer of their make, with

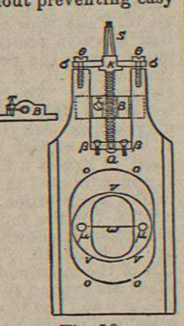

Fig. 10.

Dunsink micrometer. which, in the hands of Brunnow at Dunsink (Dublin), some of the most perfect and refined investigations ever made in practical astronomy have been executed. In this micrometer the screw *s* is mounted on its own slide and has a divided head precisely like the screw S (fig. 9). The plate *pp* is elongated towards *s*, and the corresponding bush B is attached to this elongation. The screw *s′* is shifted to another part of the eye-piece slide, so that it does not interfere with the increased diameter of the screw *s*. Fraunhofer's micrometer in this form belongs to type A, but is quoted under type B for convenience of description.

[1] When it is remembered that the measurements of the Struves, Dembowski, Secchi, the Bonds, Maclear, and of most modern Continental astronomers have been made with Fraunhofer or Merz micrometers, it is not too much to say that fig. 9 represents the instrument with which three-fourths of the astronomical measurements of the last fifty years have been made.

It is not necessary to give a figure representing type C. Such micrometers have been generally constructed on Troughton's type (figs. 1, 2, 3) with the omission of one of the screws, and with one or more of the modifications described in detail under type A. Some have also been made similar otherwise to the Fraunhofer construction, by omitting the screw *s* with its corresponding slide and attaching the fixed wire to a circular plate in *pp*.

Good instruments have been made on type C by Clark (Cambridge, Massachusetts), by Steinheil (Munich), and by the great French artists Secretan, Froment, Brunner, Eichens; and good work has been done with them. But it is necessary that the errors of the screw should be very carefully determined, since, in type C, such errors cannot be eliminated by employing different parts of the screw to measure the same angle. There is a noteworthy description of micrometer that forms a link between types C and D, of which the most famous example (by Clark) is attached to the great Washington telescope. It is essentially a micrometer of type C, with a slide (or fork) and a screw of the English form of construction. But the instrument is provided with a screw as at *s* (fig. 9), which, instead of changing the position of the fixed wire, moves the whole micrometer box in the direction of the axis of the measuring screw. Thus the fixed wire can be set exactly on one star by the screw *s* while the other star is immediately afterwards bisected by the movable wire, and that without disturbing the reading for coincidence of the wires. No one, unless he has previously worked without such an arrangement, can fully appreciate the advantage of bringing up a star to bisection by the fixed wire by moving the micrometer box with a delicate screw-motion, instead of having to change the direction of the axis of a huge telescope for the same purpose. When it is further remembered that the earlier telescopes were not provided with the modern slow motions in right ascension, and that the Struves, in their gigantic labours among the double stars, used to complete their bisections on the fixed wire by a pressure of the finger on the side of the tube, one is puzzled whether most to wonder at the poor adaptation of means to ends or the marvellous patience and skill which, with such means, led to such results.[2] It should be added that Dawes practically adopted a modification of Clark's micrometer by using a slipping piece, and bolting one of the heads of his micrometer (*Mem. R. A. S.*, vol. xxxv. p. 139). His slipping piece gave motion to the micrometer by two slides, one in right ascension the other in declination, so that "either of the webs can be placed upon either of the components of a double star with ease and certainty."

All micrometers used, in conjunction with a microscope, for reading the divisions of transit circles, heliometer scales, &c., are of the type C. The reading micrometer is shown in fig. 11. C is the objective, D the micrometer box, E the graduated head of the screw, G the milled head by which the screw *cc* is turned, A an eye-piece sliding in a tube B, *aa* (fig. 12) the slide,

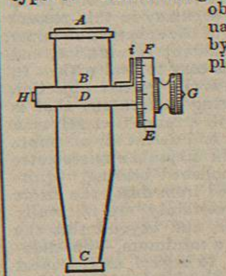

Fig. 11.

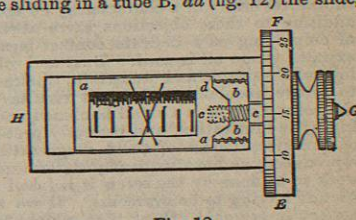

Fig. 12.

and *b*, *b* the spiral springs. The focal length of the objective and the distance between the optical centre of the lens and the webs are so arranged that images of the divisions are formed in the plane of the webs, and the pitch of the screw is such that one division of the scale corresponds with some whole number of revolutions of the screw.

There is what is technically called a "como" inserted in the micrometer box at *d* (fig. 12),—its upper surface being nearly in the plane of the wires. This comb does not move with reference to the box, and serves to indicate the whole revolution of which a fraction is read on the head. In fig. 12 a division is represented bisected by cross webs, and five revolutions of the screw correspond with one division of the scale. In all modern reading micrometers the cross webs of fig. 12 are replaced by parallel webs embracing the division

[2] The late Professor Watson used to say, quaintly and with truth, "After all, the best part of the micrometer is the man at the small end!"

(fig. 13). The means for changing the length of the tube and the distance of C from the scale are omitted in the figure. These appliances are required if the "run" has to be accurately adjusted. By "run" is meant the difference between the intended whole number of screw-revolutions and the actual measure of the space between two adjacent divisions of the scale in turns of the screw divided by the number of intended revolutions. In delicate researches two divisions of the scale should always be read, not merely for increased accuracy but to obtain the corrections for "run" from the observations themselves.

Fig. 13.

Fig. 14 represents an important type of reading micrometer by the Repsolds. Here the web-frame is mounted on the screw itself. The limiting plane of motion is at p, where the end of the micrometer screw bears upon the hardened, flattened end of the screw s, and is kept in bearing against this plane by the spiral spring q. Rotation

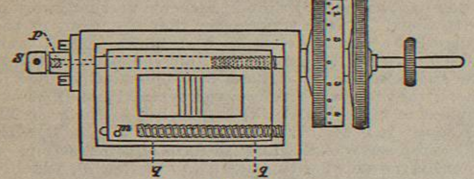

Fig. 14.

of the wire-frame is prevented by the small stud m which passes through the web-frame and projects slightly on both sides of it, just barely touching the inner surfaces of the top and bottom of the micrometer box. The web-frame thus rests solely on the screw and on the point m, and therefore follows it absolutely and accurately.

Micrometer errors.

The comparative merits of the various micrometers are discussed by Lord Lindsay and Mr Gill (*Dunecht Publications*, vol. ii. pp. 53–55, 1877). If the screw of the Repsold micrometer is bent, so that, for example, the end of the frame next the screw-head is raised and that next the end p lowered, a twist will be given to the web-frame, and the centre of the wire will be moved nearer to the micrometer head than it should be, while the reverse effect will follow when the head has been turned through 180°. The effect of a similar error on the other micrometers described would be of a much less amount. They are, however, liable to errors of another character. If, as in Troughton's original micrometer, the shoulder is square, the hole in the end of the box may be left sufficiently wide to allow for a small error in the parallelism of the screw-matrix with the motion of the slide, but the smallest bend in the screw causes the shoulder no longer to bear flat, but to ride on its edge, thus introducing an extremely uncertain form of error. If the shoulder is spherical, fitting into a hollow cone on the end of the box, as in the micrometers of Simms, Cooke, and Grubb, an almost inconceivable accuracy of construction is implied in drilling the matrix of the screw in the slide so that its axis and that of the cone shall be in the same straight line, and both parallel to the motion of a point in the slide. Any departure from perfect accuracy in this respect has the effect of bringing different portions of the spherical shoulder to bear on different parts of the cone for different revolutions, and introduces errors of a character by no means easy to deal with. In addition to these objections there always is the greater objection of employing as a delicate contact-measuring surface one that is exposed where oil is used. Dust and oil will arrange themselves in layers of variable and uncertain thickness and defeat all attempts to secure absolutely consistent results. In Repsold's micrometer the *point d'appui* is a small hardened and polished bearing, requiring little lubrication, and perfectly protected from dust; the errors of the screw (some of them exaggerated, certainly) are faithfully reproduced, and consequently determinable, and beyond this the work to be done by the screw is reduced to a minimum,—no slide-friction having to be overcome. If we are to regard as the most perfect instrument, "not that which has absolutely the smallest errors, but that which reproduces its errors with the most perfect consistency," undoubtedly Repsold's form of micrometer is best.

In order to avoid the exaggeration of the screw-errors produced by the non-symmetrical position of the screw in Repsold's micrometer, Stone, in December 1879, exhibited at the Royal Astronomical Society, and described (*Monthly Notices*, p. 270), a modification of Repsold's instrument. But, both in his statement of the comparative merits of the Troughton and Repsold micrometers and in the new form which he figures, Stone overlooks a strong point in the Repsold form, and in that proposed by Lord Lindsay and Gill three years previously,[1]—namely, the avoidance of all friction of the slide, and the elimination of all error or strain that may occur from a want of parallelism in the axis of the matrix and the motion of the slide. The Lindsay-Gill micrometer will be better understood from the following description. In fig. 15 Ss is the micrometer screw; its cylindrical axis is nicely ground to fit a hole in the side of the box at a;[2] the same axis, but ground to a somewhat smaller cylinder, fits neatly but smoothly a hole in the web-frame at b. A screw, cut on the same axis, is tapped into the web-frame at s, and the axis terminates in a pivot which fits a hole in a brass plate cc. The end of the pivot—hardened and slightly rounded—rests on a flat agate[3] bearing a, which is imbedded in the plate B, and securely held *in situ* by pressure of the plate cc. The plate B is firmly attached to the bottom of the box. q, q are spiral springs mounted on pins. Both springs and pin pass freely through the web-frame at p, p, and the pins (but not the springs) pass freely through the frame at n, n.[4] The parallel webs for observing the division (fig. 13) are mounted on the forked end of the frame at ww.

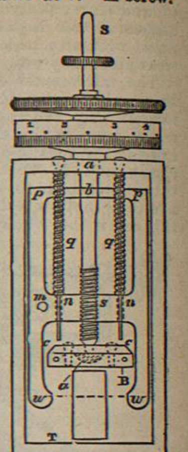

Fig. 15.

The web-frame is narrower and thinner than the breadth and height of the interior of the box, and is only prevented from rotating by the delicate touch of the projecting ends of the pin m on the inner surfaces of the top and bottom of the box. It appears that a frame so mounted fulfils all theoretical conditions of accuracy. It is perfectly free to follow the motion of the screw and accurately to reproduce its errors, notwithstanding any reasonable faults of workmanship; and no permissible shake or fouling of the bearing at a can produce sensible error in the distance between the bearing surface of the agate plane and the spider webs. The motion is produced with the minimum of friction; and the "feel" of the screw is therefore as delicate and perfect as it is possible to make it.

Repsold micrometer

The micrometer of type D shown in fig. 16 has recently been made by the Repsolds for the Cape Observatory. As this instrument combines all their most recent modifications, we describe it in detail. Fig. 17 represents the same micrometer with the upper side of the box removed. The letters in the description refer to both figures.

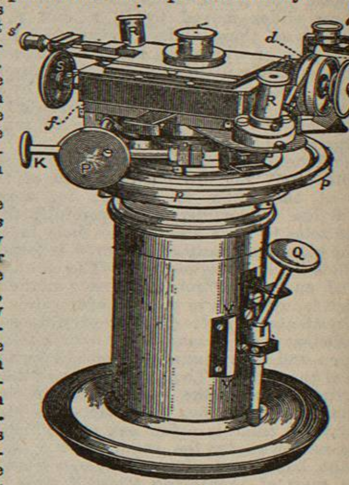

Fig. 16.

S is the head of the micrometer screw, s that of the screw by which the micrometer box is moved relative to the plate f (fig. 16), s' that of the screw which moves the eye-piece slide. K is the clamp in position angle, P the slow motion screw in position angle; pp is the position circle, R, R its two readers. The latter are in fact little microscopes carrying a vernier etched on glass, in lieu of a filar micrometer. These verniers can be read to 1′, and estimated to 0′·2. D is the drum-head which gives the fraction of a revolution, d that which gives the whole number of revolutions, I is the index or pointer at which both drums are read. This index is shown in fig. 17, but only its mode of attachment (X, fig. 17) in fig. 16. The teeth of the pinion z, fig. 17, are cut on the axis of the micrometer screw. The drum d and its attached tooth-wheel are ground to turn smoothly on the axis of the screw. The pinion z and the toothed wheel d are connected by an intermediate wheel and pinion Y; the numbers of teeth in the wheels and pinions are so proportioned that twenty-four revolutions of the micrometer screw produce one revolution of the drum and wheel d. (This is the description of Repsold's counter referred to under type A.) The divisions of both drums are conveniently read, simultaneously, by

[1] *Dunecht Publications*, vol. ii., footnote p. 55. Dunecht, 1877.

[2] There would be some advantage in allowing the screw's axis to pass with a little shake through the hole in the end of the box at a, and then, extending the length of the larger cylinder, transfer the bearing from a to a well-fitting hole in a piece fixed like B to the bottom of the box. This form would also give some facilities of construction, and all the oiled surfaces would be perfectly protected.

[3] Sapphire is better; the agate bearing of such a screw has been found very sensibly worn.

[4] If it is desired to prevent possible contact of these pins with the frame, the ends of the pins may be made to enter guiding holes in cc.

the lens e; at night the lamp which illuminates the webs and the position circle also illuminates the drum-heads (see on illumination below). $aaaa$ is the web-frame (fig. 17), $\beta\gamma$ is a single rod consisting of two cylinders accurately fitting in the ends of the micrometer box, the larger cylinder being at β. There is a hole in the web-frame which smoothly fits the larger cylinder at β', and another which similarly fits the smaller cylinder at γ'. A spiral spring, coiled round the cylinder γ, resting one end on the shoulder formed by the difference of the diameters of the cylinders β and γ and the other on the inside of the web-frame, presses the latter continuously towards γ. Contact of the web-frame of the micrometer with the side of the box at γ would therefore take place, were it not for the micrometer screw. This screw fits neatly in the end of the box at ϵ, passes loosely through the web-frame at ϵ', is tapped into the frame at ζ', and its end rests on a flat hardened surface at ζ. Rotation of the web-frame about $\beta\gamma$ is prevented by the heads of the screws at m; the head of the screw on the lower side of the frame reposes on the plane $\nu\nu$, that on the upper side (fig. 17) touches lightly on the inner surface of the lid of the box. Such rotation can obviously be controlled within limits that need not be further considered. But freedom of rotation in the plane of the paper

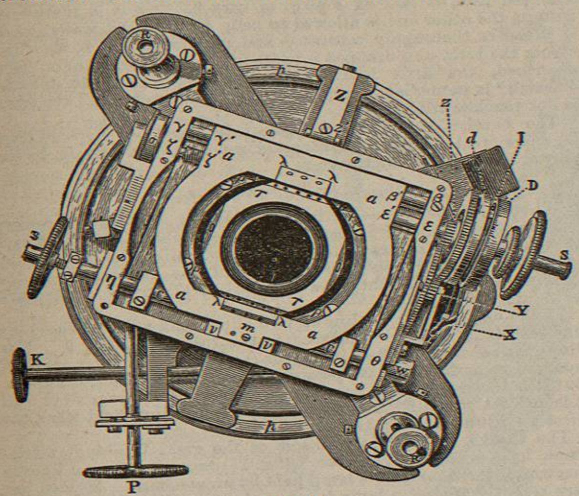

Fig. 17.

(fig. 17) is only prevented by good fitting of the holes β', γ'; and, since the weight of the slide is on one side of the screw, misfit here will have the effect of changing the reading for coincidence of the movable with the fixed web in reverse positions of the micrometer. With the Cape micrometer a systematic difference has been found in the coincidence point for head above and head below amounting to 0″·14. This corresponds, in the Cape instrument, with an excess of the diameters of the holes over those of the cylinders of about $\frac{1}{15000}$th of an inch,—a quantity so small as to imply good workmanship, though it involves a systematic error which is very much larger than the probable error of a single determination of the coincidence point. The obvious remedy is to make all measures on opposite sides of the fixed web before reversing in position angle —a precaution, however, which no careful observer would neglect. In measuring differences of declination, where the stars are brought up by the diurnal motion, this precaution cannot be adopted, because it is necessary always to bisect the preceding star with the fixed web. But in $\Delta\delta$ measures index error can always be eliminated by bisecting both stars with the same web (or different webs of known interval fixed on the same frame), and not employing the fixed web at all. Had the spring q been placed as in fig. 14, and the cylinders β and γ been made to bear like the pivots of a transit on segmental bearings in the frame at β' and γ', it is probable that the difference in coincidence points would not have existed. Such a modification appears advisable, unless this construction, by leaving the end m less free, should make the "feel" of the screw less sweet and perfect. The discordance in zero when known to exist is really of no consequence, because the observations can be so arranged as to eliminate it.

The box is mounted on a strong hollow steel cylinder CC (fig. 17) by holes η, θ in the ends of the box, which fit the cylinder closely and smoothly. The cylinder is rigidly fixed in the studs C, C, and these are attached to the foundation plate f. The cylinder contains towards η a sliding rod, and towards θ a compressed spiral spring. There is thus a thrust outwards of the spring upon the hollow cap W (attached outside the box), and a thrust of the rod upon the end of the screw s. The position of the box relative to the plate f, in the direction of measurement, depends therefore on the distance between the end of the screw s and the fixed stud C. A screwing in of s thus causes the box to move to the left, and *vice versa*. Rotation of the box round CC is prevented by downward pressure of the spring Z on a projection attached to the side of the box. The amount of this pressure is regulated by the screw z'.

The short screw whose divided milled head is σ shifts the zero of the micrometer by pushing, without turning, the short sliding rod whose flat end forms the *point d'appui* of the micrometer screw at ζ. The pitch of the screw σ is the same as that of the measuring screw (50 threads to the inch), and its motion can be limited by a stop to half a revolution.

The five fixed webs are attached to the table $\tau\tau$, which is secured to the bottom of the box by the screws ρ. The three movable webs are attached to the projections $\lambda\lambda$ on the frame aa. The plane surfaces $\tau\tau$ and $\lambda\lambda$ are composed of a bronze of very close texture, which appears capable of receiving a finish having almost the truth and polish of an optical surface. It seems also to take a very clean V cut, as the webs can be laid in their furrows with an astonishing ease and precision. These furrows have apparently been cut *in situ* with a very accurate engine; for not the slightest departure from parallelism can be detected in any of the movable webs relative to the fixed webs. Extraordinary care has evidently been bestowed in adjusting the parallelism and distance of the planes τ and λ, so that the movable wires shall almost, but not quite, touch the surface τ. The varnish to fix the webs is applied, not on the surface τ as is usual, but on a bevel for the purpose,[1] the position of the webs depending on their tension to keep them in their furrows. The result is that no trace of "fiddling" exists, and the movable and fixed webs come sharply together in focus with the highest powers. Under such powers the webs can be brought into apparent contact with such precision and delicacy that the uncertainty of measurement seems to lie as much in the estimation of the fraction of the division of the head as in the accuracy of the contact. It is a convenient feature in Repsold's micrometer that the webs are very near the inner surface of the top of the box, so that the eye is not brought inconveniently close to the plate when high powers are used.

Micrometers of the type E have been invented by Alvan Clark and Grubb. Clark's micrometer was exhibited at the June meeting of the Royal Astronomical Society in 1859 (*Monthly Notices R. A. S.*, vol. xix.). It is capable of measuring angles up to about one degree. It is "furnished with two eye-pieces, composed of small single lenses, mounted in separate frames, which slide in a groove and can be separated to the required distance. A frame carrying two parallel spider lines, each mounted separately with its own micrometer screw, slides in a dovetailed groove in front of the eye-pieces; and by a free motion in this frame each web can be brought opposite its own eye-lens. In using this micrometer, the first step is to set the position-vernier to the approximate position of the objects to be measured. Then the eye-lenses are separated till each is opposite its own object. The frame containing the webs and their micrometer screws is then slid into its place; and the webs, having been separated nearly to their proper distance by their free motion in the frame, are placed precisely on the objects by their fine screws, the observer's eye being carried rapidly from one eye-lens to the other a few times, till he is satisfied of the bisection of each of the objects by its own web. The frame is then removed for reading off the measure by means of an achromatic microscope, on the stage of which it is placed." The advantages which Clark claims are these :—

"1. Distances can be observed with great accuracy up to about one degree, and the angles of position also.

"2. The webs, being in the same plane, are perfectly free from parallax, and are both equally distinct, however high the magnifying power may be.

"3. The webs are also free from distortion and from colour.

"4. A different magnifying power may be used on each of the objects,—which may be advantageous in comparing a faint comet with a star."

It appears to us that the method of removing a slide in order to measure the interval between the webs is liable to objection, not only because of the risk to the webs, but because the taking of measurements of such a different character with a different instrument is inconvenient and troublesome. It is true that the intervals between the webs could be measured by an assistant, and two or more different slides be employed to save time; but astronomers will probably generally prefer the method introduced by Grubb described below. It is understood that Clark has since improved this instrument by an ingenious arrangement of prisms, which permits both webs, even though separated one degree in a large telescope, to be seen in the same eye-piece. The arrangement is not described, and is said to be, as yet, somewhat troublesome to arrange previous to measurement, though when arranged it gives very good results.

Grubb (*Scientific Proceedings of Royal Dublin Society*) thus describes

[1] The marks of varnish so applied will be seen in fig. 17