A Wave-Length Comparator for Standards of Length: An Instrument for Fine Measurement in Wave-Lengths of Light. With an Appendix on the Use of Wave-Length Rulings as Defining Lines on Standards of Length

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Phil. Trans. R. Soc. Lond. A 1911 **210**, 1-34
doi: 10.1098/rsta.1911.0001

PHILOSOPHICAL TRANSACTIONS.

I. *A Wave-Length Comparator for Standards of Length: An Instrument for Fine Measurement in Wave-Lengths of Light.*

With an Appendix on the Use of Wave-Length Rulings as Defining Lines on Standards of Length.

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Received June 9,—Read June 10, 1909.

The following is a brief account of a new apparatus for fine measurement in wave-lengths of light, designed primarily as a comparator for the measurement in wave-lengths of the difference between a standard of length, either a line or an end measure bar—the Imperial Standard Yard, for instance—and any duplicate or similar bar proposed to be employed as a derived standard. The instrument is also, however, the most perfect instrument yet devised for measurement in wave-lengths in general, and performs its functions so admirably as to render it highly desirable that a description should now be published concerning it. It has been constructed to the designs and under the supervision of the author for the Standards Department of the Board of Trade, and this account of it is communicated to the Royal Society with the permission of the President of the Board of Trade. The principle underlying the instrument is that of the author's interferometer,[*] which has also proved so successful in its application, in the interference dilatometer,[†] to the determination of the thermal expansion of small bodies by the Fizeau method, and in the elasmometer,[‡] to the measurement of the elastic bending of a small plate or bar under a given weight applied at the centre. The essence of the interferometer is that homogeneous light, of a definite wave-length, corresponding to a single spectrum line —isolated with the aid of a constant-deviation prism from the spectrum derived from a cadmium or hydrogen Geissler tube, or a mercury lamp—is directed by an auto-collimation method, ensuring identity of path of the incident and reflected rays, normally upon two absolutely plane surfaces, arranged close to each other, and nearly, but not absolutely, parallel; the two reflected rays give rise, by their interference, to

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[*] 'Phil. Trans.,' A, 1898, vol. 191, p. 324.
[†] 'Phil. Trans.,' A, 1898, vol. 191, p. 313.
[‡] 'Phil. Trans.,' A, 1904, vol. 202, p. 143.

rectilinear dark interference bands on a brilliantly illuminated background in the colour corresponding to the selected wave-length.

In the instrument now described, one of these two reflecting surfaces concerned in the production of the interference bands is carried by, and moves absolutely with, one of the two microscopes employed to focus the fiducial marks, or "defining lines," determinative of the length of the standard, the other surface being absolutely fixed. The movement of either of the surfaces with respect to the other causes the interference bands to move, and the extent of the movement of the surface is equal to half the wave-length of the light employed for every interference band that moves past a reference mark carried by the fixed surface. The movement of the microscope parallel to itself and to the length of the standard bar is thus measured by counting the number of bands and the initial and final fractions of a band which are observed to pass the reference spot during the movement, and multiplying that number by the half wave-length of the light radiation used in the production of the bands. It is only necessary, therefore, in order to compare the lengths of two bars, (1) to place the bar of known length, say, the Imperial Standard Yard, under the two microscopes so that the two defining lines are adjusted in each case between the pair of parallel spider-lines carried by each of the micrometer eye-pieces; (2) to replace the standard by the copy to be tested, so that the defining line near one end is similarly adjusted under the corresponding microscope, then, if the other defining mark is not also automatically adjusted under the second microscope which carries the interferometer

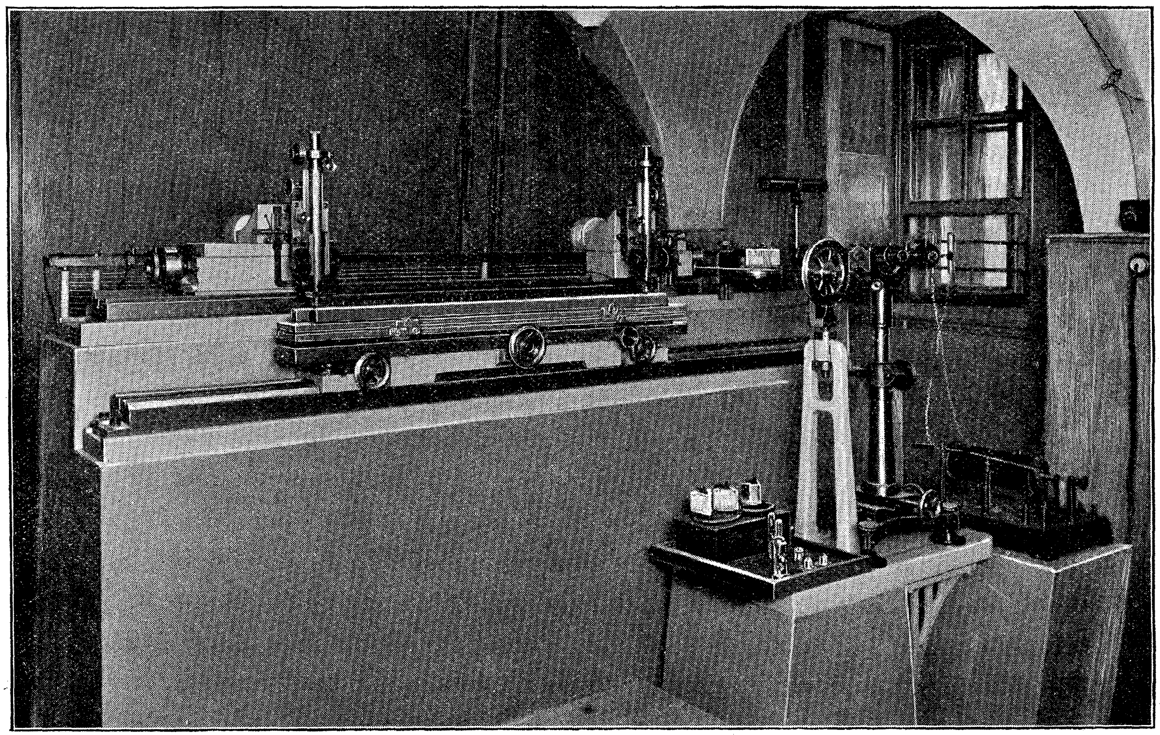

Fig. 1. General view of the comparator.

glass surface, as it should be if it is an exact copy, (3) to traverse that microscope until it is so adjusted, and (4) to observe and count the number of interference bands which move past the reference spot during the process. The product of this number into the half wave-length of the light used to produce the bands thus obviously affords the difference between the two lengths included between the defining marks on the two bars.

The simplicity of the method is one of its greatest recommendations. It appears to have been hitherto thought that the mechanical difficulties involved would render such a method impossible to carry out in actual practice. The experience gained by the author in connection with the elasmometer, however, had shown that Messrs. Troughton and Simms, its constructors, were able to make a fine screw movement to work so exceedingly slowly, and so absolutely steadily, while at the same time driving a considerable weight, that interference bands produced between a pair of glass surfaces, one of which moved with the slider driven by the screw, moved past the reference spot, as seen in the interferometer telescope, with the required complete steadiness and precision and became arrested instantly when the observer ceased to turn the screw.

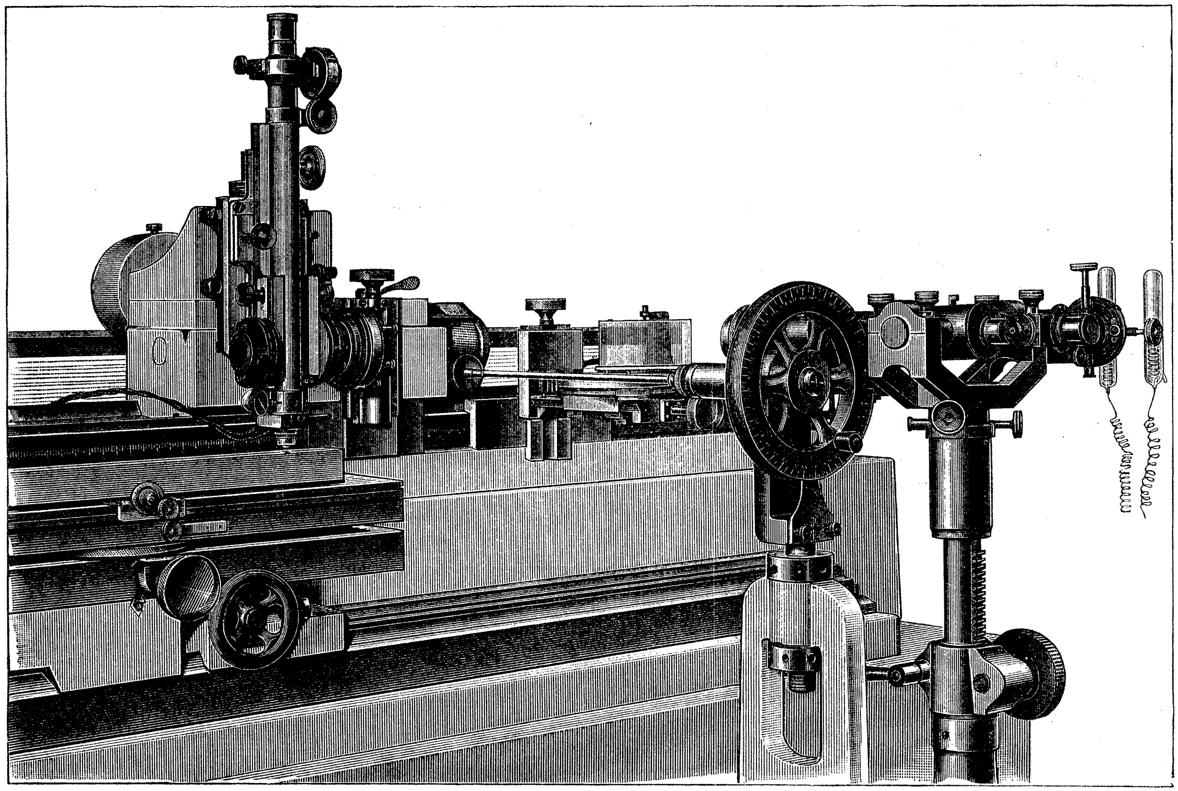

Fig. 2. Central part of comparator, showing interferometer.

This experience has been applied with perfect success to the new comparator. The

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sliders, which carry the two microscopes, have been provided with a slow motion of this description which enables either microscope to be traversed so absolutely steadily that the interference bands, generated between a vertical black-glass surface carried by the microscope and the second colourless-glass surface carried in rigid attachment to the bed on which the slider moves, move with perfectly steady precision, without either rotation or alteration of the width of the bands, and without even the slightest tremor, simultaneously with the movement of the microscope, of which they afford a

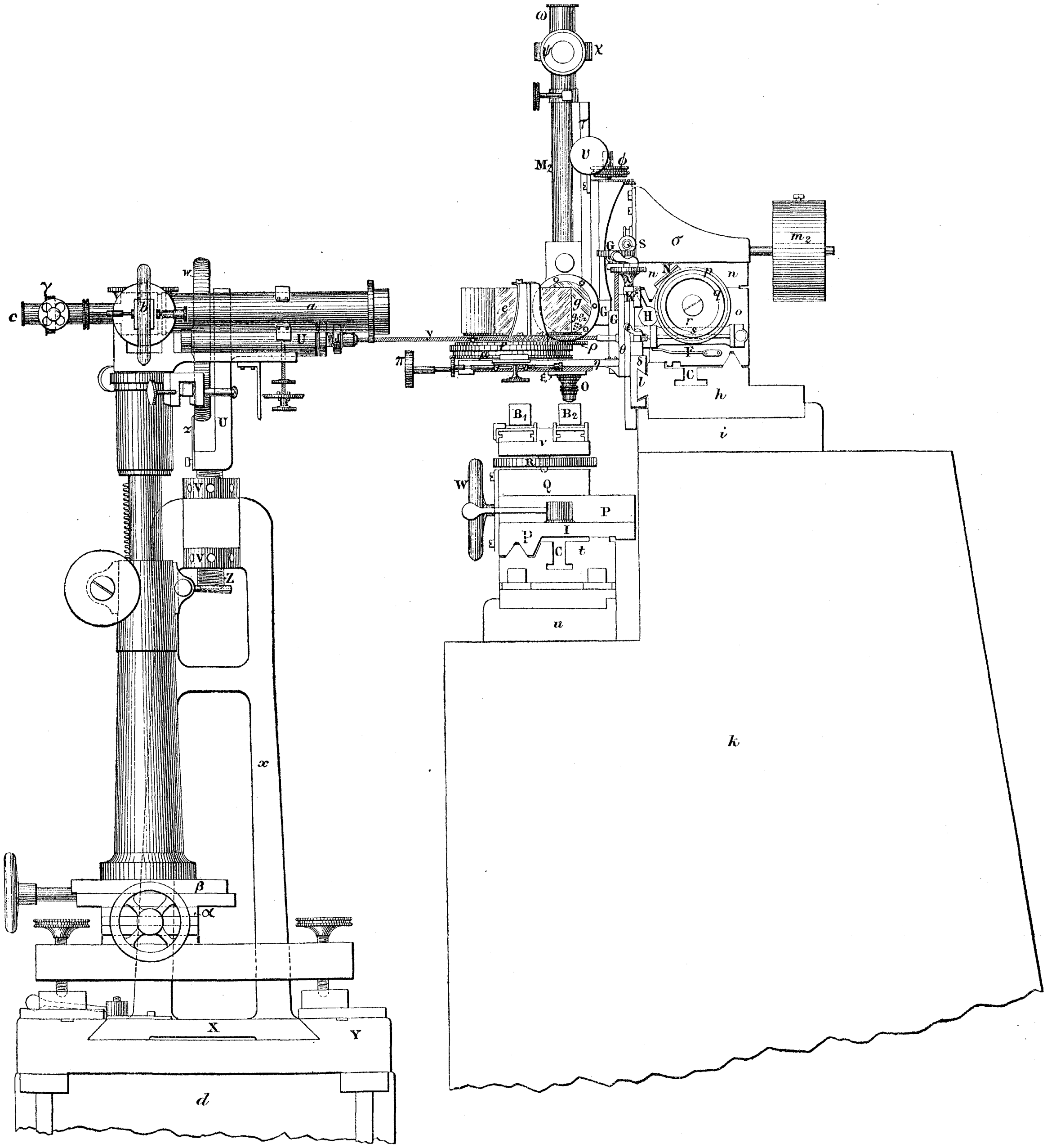


Fig. 3. Right end-elevation.

perfect record. The bands cease to move the instant the screw is released, and each band can thus be adjusted to the centre of the spider-lines, or of the reference spot (the centre of a minute silvered ring carried by the fixed-glass surface), and left there as long as one chooses. The process of counting the bands in such circumstances is a perfectly easy matter.

The instrument is composed of the following seven essential parts, the arrangement of which will be more clearly understood from the accompanying reproductions of photographs, fig. 1 giving the general view, and fig. 2 an enlarged view of the central part; also from figs. 3 and 4, giving the right and left end-elevations :—

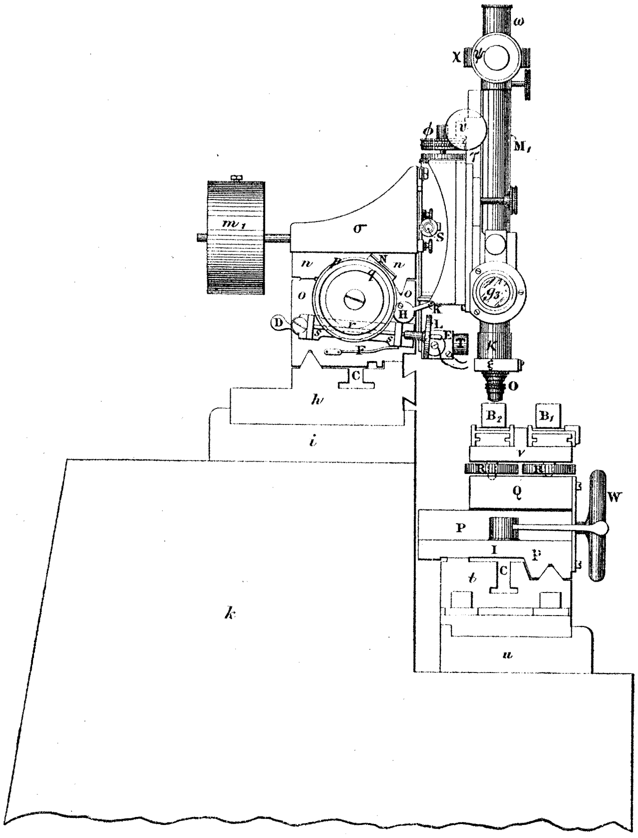


Fig. 4. Left end-elevation.

(1) *The interferometer.*—This consists of (i) an autocollimating telescope, a, with Geissler tube attachment, b, and special micrometer eye-piece, c. Like the interferometer described by the author in connection with the dilatometer and elasmometer, the telescope is mounted on a strong adjustable column provided with levelling tripod, which in turn is mounted on a stone pedestal, d, in front of and isolated from the main instrument, and continued down by means of concrete to the sandy loam foundations. (ii) A dispersing apparatus, e, to select the rays chosen as illuminant, consisting of either a pair of reflecting prisms, or a Hilger constant-deviation prism (shown in position at e in fig. 3 and in figs. 1 and 2), mounted so as to be interchangeable

with the latter on a divided circle, *f*. (iii) An interference apparatus, *g*, consisting essentially of three truly plane glass plates, whose axial line normal to the surfaces is horizontal. Two of them, g_1 and g_2, of colourless glass, are separately referred to under (4), and the third, g_3, of black glass, is carried by the right-hand microscope of the two referred to under (3). All the refracting and reflecting glass surfaces of this optical train are thus vertical, instead of horizontal as in the dilatometer and elasmometer. All are mounted rigidly on (2), except the black-glass disc.

(2) *A* **V***-and-plane bed, h.*—This is constructed of specially chosen cast iron, the casting of which was most carefully carried out. It is 6 feet 6 inches long, and rests in a plinth, *i*, of the same metal, bolted down to the upper surface of a stone block, *k*, with special precautions to avoid strain. The latter, the rigid support for the whole instrument, except the interferometer telescope, is 7 feet 6 inches long, 4 feet 4 inches high above the floor of the room, and 2 feet 2 inches thick at the base; it is vertically upright in front and at the ends, but tapers towards the top at the back of the block away from the observer. This large block of stone rests on a concrete basal continuation, which is carried right down 4 feet below the floor to the sandy loam foundations, with an air space of 6 inches all round, as shown in fig. 5, which gives the foundation plan and two elevations as kindly supplied by H.M. Office of Works. The front facial edges of the cast-iron bed are grooved out to form a dove-tail, *l*, to take the prism-circle fitting and the supports of the glass discs referred to in (1, ii and iii).

(3) *A pair of similar microscopes*, M_1 and M_2.—These are arranged vertically and at the same height, with truly parallel axes, and each is mounted on a relatively very thick fine-movement sliding plate, *n*, of the same cast iron as the bed, 10 inches long, $4\frac{3}{4}$ inches wide, and 1 inch thick. This plate, or slab, in each case moves by manipulation of the all-important fine screw referred to in the introduction, with **V**-and-plane contact, over a similar thicker block, *o*, but, for sake of smooth sliding, constructed of steel, 11 inches long and 3 inches thick. This block slides on the cast-iron **V**-and-plane bed, *h*, referred to in (2). The right-hand microscope, M_2, carries the black-glass disc, g_3, of the interference apparatus referred to in (1, iii), whose outer surface is one of the two truly plane-polished vertical surfaces which reflects the interfering light so as to produce bands which are visible through the interferometer telescope. The fine screw is of $\frac{1}{50}$-inch (0·5-mm.) pitch, and bears a large silvered drum-head, *p*, graduated directly into 1000 parts by the method already described in connection with the author's elasmometer. It also carries both a milled head, *q*, for the direct rotation of the screw, and a fine-adjustment worm-wheel, *r*, of 100 teeth gearing with an endless screw, *s*, manipulated by the control wheel referred to under (7).

(4) *A pair of similar colourless-glass discs*, g_1 and g_2, part of the interference apparatus referred to under (1, iii), 5 cm. diameter and 1 cm. thick. The two surfaces of each disc are polished absolutely truly plane, but are not strictly parallel, being 35 minutes inclined to each other, which is just adequate to laterally displace the reflection from one surface when that from the other is in the centre of the field of

the telescope. These wedge-discs are mounted close together, apparently, but not quite, parallel to each other and to the black-glass disc carried by the microscope. The surface of the colourless disc, g_2, nearest to the black-glass surface, and the latter surface, g_3, are the two surfaces whose reflections are made to interfere. The reflection from the back surface of this colourless disc is got rid of by its 35 minutes of inclination. The back surface of the black-glass disc is ground.

The other colourless-glass disc, g_1, acts as a countervailing wedge to neutralise the slight dispersion introduced by giving the second surface of the first colourless disc, g_2, 35 minutes of inclination. This it does absolutely, being cut from the same large 35-minute slab. It is slightly tilted in a direction 90-degrees to the direction of the wedges, which are placed with the thinner end of one opposite the thicker end of the other. Both discs are carried in a fitting, G, which provides for further separate adjustment by three screws in each case.

(5) *A* **V**-*and-plane bed*, *t*, similar to that of (2), rests $7\frac{3}{4}$ inches lower than, and parallel with, the latter in a step cut for $7\frac{1}{2}$ inches backwards in the stone to replace its top front edge. This bed rests like (2) in a basal plinth, *u*, bolted down to the stone.

(6) *An adjustable table*, *v*, for the support of the standard bars, B_1 and B_2.—This is arranged to slide over the bed referred to in (5), and is provided with both quick and fine adjustments for its horizontal position on the bed, with a transverse motion perpendicular to its length, a fine adjustment for azimuth, and another for levelling. There are three interchangeable table tops. One is merely a truly plane experimental top; a second is fitted with friction rollers in the officially approved manner for the support of line measures; a third provides for the similar support of both line and end bars.

(7) *A fine-movement control wheel*, *w*.—This is supported on a special bearing-pedestal, *x*, near the observer's left hand, and to the left of the telescope. It is used for bringing about the fine movement of the microscope, M_2, which carries the black-glass surface, g_3, relevant to the interference. The wheel has a diameter of 6 inches and a circumference of approximately 19 inches. It is rigidly connected, by means of either a solid or a flexible steel shaft, *y*, with the axis of the endless screw *s* referred to in (3). Each complete rotation of the wheel corresponds to the traverse of the microscope and its black-glass disc for 0·005 mm., which is equivalent to the passage of 15 interference bands of red C hydrogen, or red cadmium light. Hence more than an inch of movement of the circumference of this wheel occurs for the passage of each interference band, thus affording very considerable delicacy of control over the passage of the bands.

Further details essential as elucidating the working of the instrument, or because they involve original mechanical devices, will be given, after a brief account of the foundations and of the thermostat, under the headings of the seven parts, whose main functions have now been indicated.

The Foundations.

The foundations were laid by H.M. Office of Works in a manner which affords the greatest satisfaction. The plan, with two sectional elevations, shown in fig. 5, will render them quite clear. The room which has been set apart for the new comparator is one in the basement of No. 6, Old Palace Yard, the building occupied by the Standards Department of the Board of Trade, which is interesting historically as having been built in 1754 as a residence for the Clerk of the House of Lords, immediately in front of the old Jewel Tower. The latter is also now part of the Standards Office, and is the oldest remaining part of the original Palace of Westminster; it was completed during the reign of Richard II. Moreover, it is believed that the building of 1754 was erected on the basement of a house of some historic interest, formerly existing on the site, and which was only partly removed to make way for the new building. The new Comparator Room was one of the large wine cellars thus left.

The room is rather more than 15 feet square and 9 feet high, the ceiling being arched; the excellently preserved stone walls are upwards of a yard thick. It has one double window and two double doors, each provided with two very efficient ventilators. Between each pair of doors and windows, owing to the thickness of the walls, there is adequate space for the insertion of fans, and for the storage of ice or other means of cooling, if desired on hot summer days when the outside temperature is over 62° F., the official temperature for comparisons. The floor of the room is 10 feet below the street level, and a pit, 11 feet 6 inches long by 5 feet 6 inches broad, and with a front bay extension of 5 feet 6 inches by 2 feet 9 inches, was dug out below the floor for a depth of 4 feet down to the virgin soil, a very compact sandy loam. On this foundation concrete blocks were first laid for the support of the cemented brickwork with which the sides of the pit were made secure. Then two separate solid concrete blocks were laid in the midst as indicated in the three drawings (fig. 5), and perhaps most clearly shown in the third, the section CD. An open air space of 6 inches was left all round the blocks, except where the two approach each other, which they each do on one side (the front of the larger block and back of the smaller one) within $2\frac{1}{2}$ inches.

On the smaller front block of concrete, which reaches to a height of 6 inches below the floor, and which occupies the front extension of the pit, the smaller block of stone, 2 feet by 1 foot 3 inches in basal section and 2 feet 10 inches high, was erected for the support of the interferometer-telescope pedestal. On the larger block of concrete, which rises 1 foot 6 inches above the floor, was laid the larger block of stone, shaped as described in (2) and as shown in the last elevation in fig. 5. The stone is an extremely hard sandstone from Darley Dale, Derbyshire. The floor in the immediate proximity of the blocks, and covering the whole of the pit, is laid in slate slabs supported by rolled-steel joists resting only on the outer brickwork lining the pit;

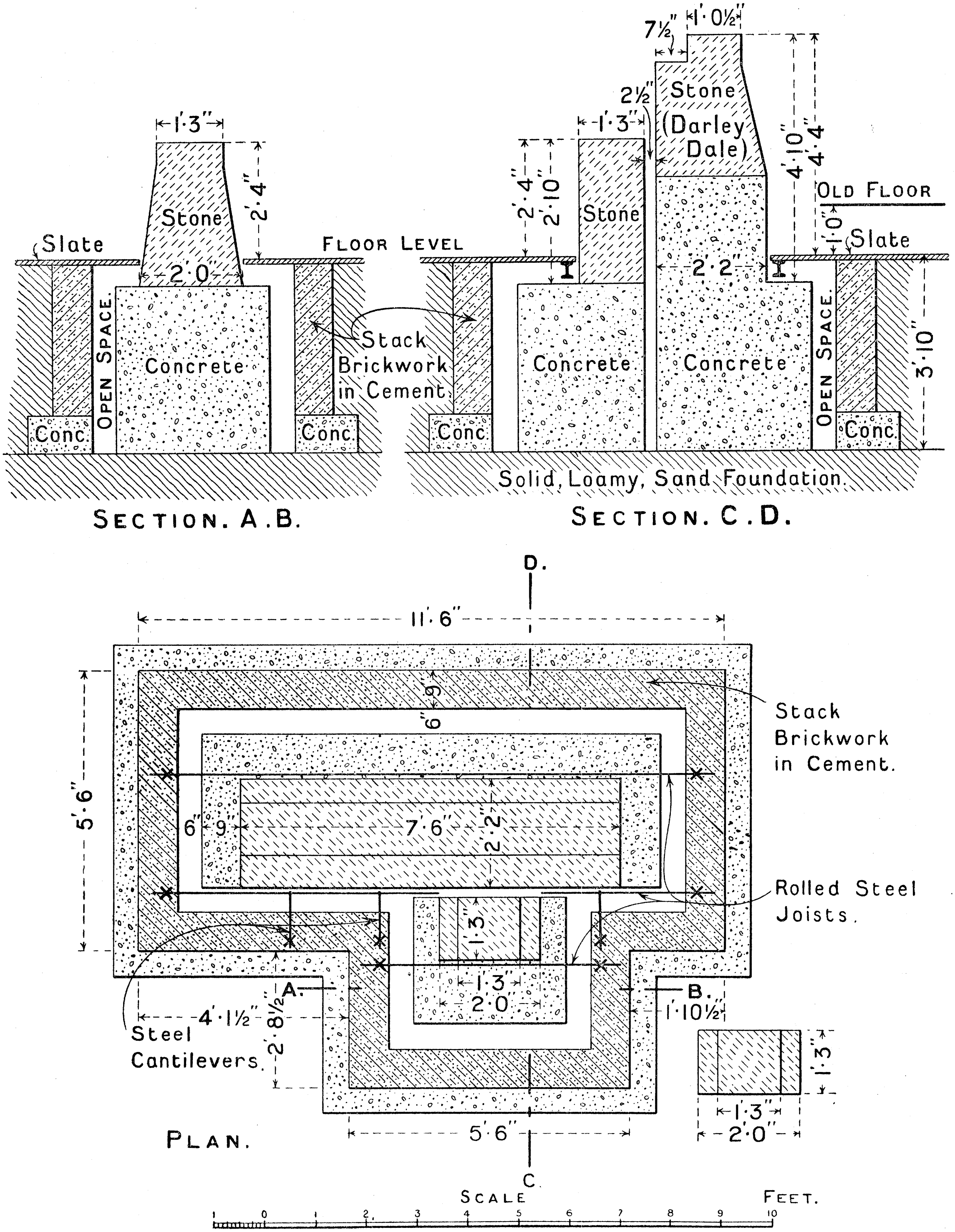


Fig. 5. Plan and sectional elevations of foundations.

the slate, however, does not touch the stone or concrete blocks anywhere, a clear air space of an inch being left. The rest of the floor is concreted and laid with a thick layer of linoleum, which extends to within half an inch of the blocks all round. Hence the stone supports for the two parts of the instrument are absolutely isolated, and in rigid connection only with the foundations.

As a precaution against the condensation of moisture on the solid stone walls they were covered with asbestos, and afterwards matchboarded, leaving an air space of 2 or 3 inches.

The Thermostat.

The temperature of the air of the room is controlled and maintained at the official temperature, 62° F., entirely electrically, and for the sake of security by two different independent methods, one involving the use of a mercury thermometer with platinum contacts, and the other being a resistance-thermometer method. There are five separate electric radiator heating lamps in symmetrical positions in the room, by which all the artificial heating is accomplished; four of these are controlled by whichever thermostat is in use, the fifth remaining uncontrolled, as a reserve for use in the depth of winter.

The resistance method has the advantage of great sensibility owing to the size of resistance-wire-grating adopted. A frame 7 feet 4 inches long by 8 inches high and 3 inches wide holds 200 yards of stretched iron wire open-wound on porcelain insulators. The current used is the 206-volts direct supply from the mains. The zero is constant owing to the bifilar suspension of the galvanometer. Time lag is exceedingly short, and the method adopted gives the average temperature of the whole comparator.

The mercurial thermometers are very large, there being $\frac{1}{4}$-inch length of stem to each degree. The platinum contacts are adjustable, and the whole arrangement has the advantage of simplicity.

If the temperature falls below 62°, two radiator lamps are turned on by either the mercurial or resistance-thermometer thermostat, whichever is in use at the time, the turning on being effected through relays, a separate relay being provided for each lamp. If the temperature rises above 62°, the two lamps normally on are turned off. The arrangements also provide for the automatic adjustment of the speed of an electric fan. The relays and also the galvanometer have been specially constructed, and all difficulty with regard to sparking has been overcome.

Further details, together with drawings, will be communicated later concerning the thermostats, after further experience has been obtained with the various possible methods of working them.

The Interferometer.

As regards the interferometer referred to under (1), the telescope and its supporting pedestal and accessories are on the same model as that of the author's dilatometer and elasmometer, except that there are added at the base of the pedestal, above the tripod, two solidly constructed rectangular movements, α and β, for the adjustment of the pedestal in the right-and-left and front-and-back directions in the horizontal plane. These movements are a great convenience in placing the circular disc of interference bands, that is, the image of the black-glass reflecting surface, g_3, crossed by the bands, centrally in the field of view; and also for adjusting the telescope so as to observe the image in light of different wave-lengths, when employing the pair of refraction prisms as dispersing apparatus. The "comb" or rough scale of the micrometer of the eye-piece is also different, being made adjustable to different heights in the field of view by vertical sliding in a slot, the slider projecting to the necessary slight extent outside (seen at γ, fig. 3), which enables it to be altogether pushed out of the field if desired, leaving the complete circular disc of light vertically crossed by interference bands fully visible.

The actual appearance of the field of interference bands and of the comb is shown in fig. 6. The silvered reference ring occupies the centre of the field, with a band adjusted to its centre, and the spider-lines adjusted on each side of the band.

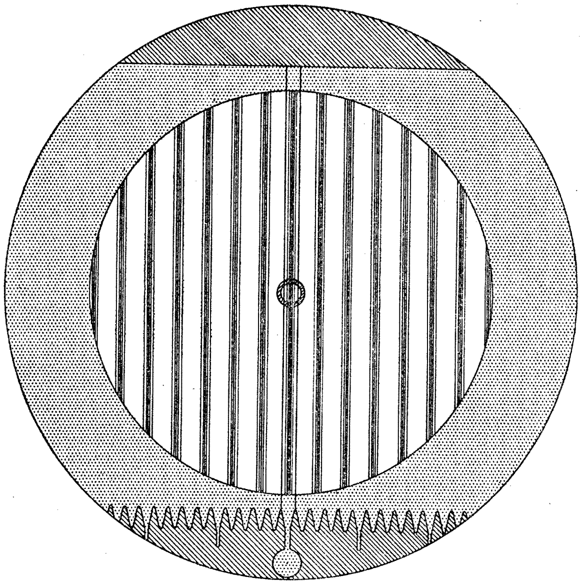


Fig. 6. Field of interference bands.

Provision is made for electrically heating the outer limb of the cadmium vacuum tube, when such is employed instead of a hydrogen tube, by means of a spiral of platinum wire embedded between two jackets of asbestos, the whole being enclosed in an aluminium tube. The arrangement is seen along with the cadmium tube resting on a mahogany tray at the base of the interferometer in fig. 1. When the tube and fitting are in position instead of the hydrogen tube shown *in situ* in the figures, on switching on the current, suitably resisted down to a safe amount by filtration through a special resistance lamp, the platinum spiral becomes sufficiently heated to raise this limb of the tube, which contains a pellet of cadmium, to between 200° and 300° C., when the cadmium spectrum is intensely generated.

With respect to the dispersion apparatus referred to under (1, ii), the use of a Hilger constant-deviation prism, as an alternative to the two refracting prisms employed on the dilatometer, is an innovation. As the plane of the axis of the whole optical arrangement, including the dispersion apparatus, is now horizontal, a constant deviation prism can conveniently be employed and proves very efficient for the purpose; and although the dispersion is not so great as with the two refracting prisms, it is adequate for the purpose of separating and isolating the images of the rectangular stop of the little auto-collimating reflecting prism of the telescope (this stop being considered as the origin of the interfering light), corresponding to the three different hydrogen lines or to the various cadmium or mercury lines. It affords a much readier means of changing from one wave-length to another, mere rotation of the circle carrying the prism being alone necessary, no movement of the telescope at all being required. It is only necessary (a) to move the front lens-combination, which focusses the spider-lines, from the front of the eye-piece, when the brilliant image of the little rectangular stop is seen in the colour for which the bands are adjusted,—red C-hydrogen light, for instance, assuming a hydrogen vacuum tube is being used,—together with a faint continuous spectrum; and (b) to rotate the prism circle so that the faint spectrum moves in the direction of the wave-length to which it is desired to change—that of F-hydrogen light for example—until the brilliant image of the stop in the colour desired (greenish blue in our example) is brought into position in the semi-circular aperture instead of the former image. On replacing the front lens-combination, the field of bands will be seen in the colour desired. The bands are, of course, closer together for F-hydrogen light than for C-hydrogen light, on account of the shorter wave-length. If we again remove the front part of the eye-piece and go on further until the $H\gamma$-violet image is similarly adjusted, on replacing the lens-combination the field of bands in violet hydrogen light will be seen, quite clear and sharp, although, as might be expected, not so brilliant.

The constant-deviation prism is carried on a rotating divided circle, f, which is carried by a fitting, δ, capable of sliding along the front vertical face of the upper bed in a pair of dovetailed grooves, and of being fixed in any desired position by means of a convenient tightening screw manipulated by a lever, ϵ. The circle is divided into half degrees, and reads with the aid of a vernier to minutes. The cone within which it rotates is borne by a stout arm, η, radiating from a vertical slider, θ, in the main fitting, δ, which is adjustable for height by means of a milled-headed screw, λ (which drives the slider), at the top of the fitting; it is also adjustable, as regards its back-to-front distance from the face of the bed, with the aid of the horizontal movement of a slider, μ, carrying the cone along the arm, brought about by means of a milled-headed screw, π, at the extremity of the arm. Thus the sliding motion along the bed front gives one lateral adjustment to the prism circle and the prism which it carries; the back-to-front movement affords the second rectangular horizontal adjusting movement, and the up-and-down motion provides the third necessary adjustment for the prism.

Besides the constant-deviation prism, there are provided two 60-degree prisms for alternative use as in the author's interferometer, and these and the constant-deviation prism are separately mounted and adjusted, each by means of its own tripod screws, on a carrier table, ρ, which drops automatically into position on the circle plate by three pins fitting in corresponding holes in the plate. A third carrier bears an adjusted total-reflection prism for use in adjusting the apparatus. This and the pair of refraction prisms are seen on their carrier plates resting in the tray at the base of the pedestal in fig. 1. All three carriers may be fixed in position on the circle plate by the simple arrangement of a locking plate fitting into grooves in the three pins, and manipulated by a little projecting handle.

The black-glass disc, g_3, whose outer surface, 1 inch in diameter, is polished an absolutely true plane, which reflects one of the rays concerned in producing the interference bands, is mounted on a bevelled slider, a in fig. 7 (which shows the interference discs more clearly and their mounts), on the side of the microscope tube just above the objective, in a vertical correspondingly dovetailed guiding bed, b, so as to be capable of longitudinal adjustment and eventual rigid fixation at the convenient height. The disc may also be adjusted by means of three screws, c, precisely to the vertical plane, perpendicular to the horizontal axis of translation of the microscope on its sliding bed. This is achieved by making the circular mount for the black-glass disc double, the outer part, d, being screwed to the inner, e (which is solid with the slider), by the three screws c, and being maintained pressed outwards by three spiral springs round the screws and compressed between the two metal discs. The outer edge of the disc of black glass is bevelled, and it is attached to the solid mount forming part of the outer adjustable disc d by means of an annulus, which screws on to the mount over the bevel, a disc of thin indiarubber being first laid in the mount, so that when the black-glass disc is placed in position with the ground face against it and the annulus is screwed on to just the right extent, the indiarubber pad between the solid mount and the glass disc maintains the latter and the annulus in rigid connection without straining or bending the glass to even the minutest extent; if any occurred it would at once be detected by curvature of the interference bands. Each microscope

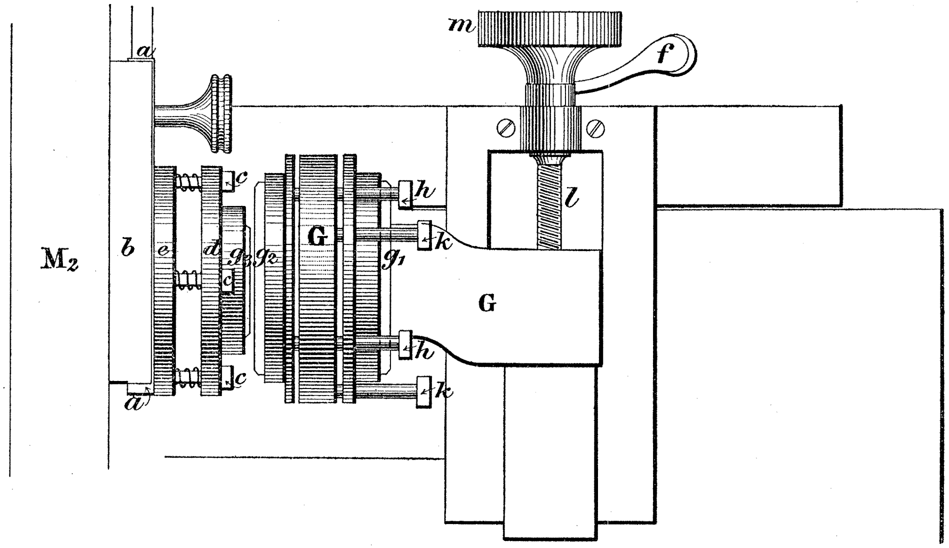


Fig. 7. The interference discs.

has been furnished with a black-glass fitting on each side, which not only renders it symmetrical and evenly balanced on the two sides of the tube, but makes provision for use of the interferometer on either side of either telescope.

The pair of colourless-glass wedge-discs of 35 minutes angle, g_1 and g_2, 5 cm. in diameter and 1 cm. thick, referred to under (4), are mounted in a bracket fitting, G, which is capable of sliding along the same dovetailed grooves in the front of the upper bed as the prism-circle fitting. The fitting is provided with the means of rigid fixation by a lever-handled screw, f, at the position which brings the glass surface of g_2 nearest the microscope within a millimetre of the surface of the black-glass disc, g_3, carried by the latter. The wedge in question and its countervailing duplicate, g_1, are rigidly held in mounts against which they are pressed in each case by a spring, whose force is almost entirely exerted against the cylindrical surface, the normal (unbevelled) edge of the very thick disc, and produces absolutely no bending of the plate, as proved by the perfect linear straightness of the interference bands; and each mount is held in position, one on either side of the annular termination of the fitting G, by three screws and springs, and can be separately adjusted by means of these three screws. All six of the milled heads of these screws are on the outer side of the fitting away from the microscope, and are thus readily manipulated, those h of the principal wedge-disc, g_2, next the microscope being lacquered bright yellow as usual, and those k of the countervailing wedge-disc, g_1, lacquered black for the sake of ready distinction. It is by use of the three bright screws, readily visible in the darkened room, that the interference bands are adjusted, the black-glass disc, g_3, carried by the microscope being never touched after the initial adjustment to the vertical plane.

The Microscopes.

The two microscopes are a duplicate pair which have been specially designed by Messrs. R. and J. Beck with the object of ensuring the greatest possible rigidity and freedom from twist or bending of any kind. They are mounted symmetrically at the inner ends (in order to enable them to be brought as near together as possible) of their respective fine-movement plates carried by the sliding blocks, and counterpoised thereon. The microscope itself is actually fixed to the front of a carrier bracket, σ (figs. 3 and 4), in each case, which is screwed down on the top of the thick fine-adjustment plane, n; the mounting is effected in a manner which permits of adjustment of the optical axis of the microscope precisely to the vertical position, at right angles to the horizontal axis of the fine-movement screw which causes the traverse of the microscope. The counterpoise is a cylindrical leaden weight, m_1 and m_2, adjusted on an arm projecting from the back of the bracket as much as the microscope projects in front. When they are approached as near as possible to each other, the optical axes of the two microscopes are slightly under 4 inches apart, just adequate, in fact, to enable the end marks on a decimetre bar to be respectively focussed by the two microscopes, and a 4-inch bar still more readily. The coarse adjustment is by rack and pinion, moving a very long dovetail slide, τ, which is attached directly to the tube. This can be readily clamped by the milled-headed screw, υ, when set to the approximate focus, so that no motion can take place at this slide. The fine adjustment is by means of a micrometer screw, ϕ, constructed with special care, working a prismatic fitting sliding in a solid correspondingly prismatic-shaped sleeve of great rigidity. This has been constructed on the well-known principle of Messrs. Beck's solid-metal fine adjustment, in which the fitting has no adjustable or spring pieces whatever, but is a long parallel prismatic fitting, solid metal to metal. It is, however, made about double the size of an ordinary microscope fine adjustment, and the result shows that the motion is absolutely free from back-lash; for the bands of the interferometer either do not move at all when the fine adjustment is worked, or if they do very slightly, the movement is regular and can be accurately calibrated, and is due to faulty setting of the mirror g_3, which should once for all be corrected.

The microscopes carry double-motion cobweb micrometer eye-pieces, χ, at the upper end. Each micrometer carries one right-and-left spider-line and two front-and-back parallel spider-lines. There are two drums, ψ, each divided into 100 parts, one of which moves one only of the front-and-back spider-lines, parallel to itself and to the other front-and-back spider-line; the other drum moves both simultaneously, when the distance apart has been regulated by the former. Two eye-pieces, ω, magnifying respectively 8 and 15 times, are provided with each micrometer. The object-glasses, O, for each microscope consist of a low-power for ordinary work, a $\frac{2}{3}$-inch objective, magnifying 150 and 282 times with eye-pieces No. 1 and No. 2 respectively, and a $\frac{1}{15}$-inch dry lens, magnifying 1595 and 2990 times respectively with the two eye-pieces, constructed with as long a working distance as is compatible with the numerical aperture required to give the necessary resolving power for the observation of the Grayson rulings, 40,000 to the inch, referred to in the Appendix. The resolution required to observe lines 40,000 to the inch, which it must be remembered correspond to single wave-length distances of red light, sufficiently well to be able to set any one of them symmetrically between a pair of parallel spider-lines is not less than double that required to actually resolve the lines, and the result attained, which is eminently satisfactory as regards both illumination and definition, may be taken as about the maximum possible with a dry lens involving very perfect corrections of the various aberrations. Both the high-power objectives have been specially calculated and corrected by Mr. Conrad Beck, whose valuable original work on this subject is well known, for the specific purposes of this wave-length comparator, in order to afford a specially clear definition of the Grayson rulings without having to employ an immersion objective, which would be inconvenient. The author is under great obligation to Mr. Beck for the truly excellent definition attained with these wonderfully sharp and clear wave-length rulings.

Their actual appearance as employed by the author will be seen in fig. 13 (Appendix), which also shows the spider-lines of the micrometer (the three single lines in the figure).

The $\frac{2}{3}$-inch objectives are specially designed to focus down into the $\frac{1}{2}$-inch wells in the standard yard bars, at the bottom of each of which a fiducial mark or defining line on a gold plug is situated, without any contact of the objective with the top of the bar; that is, the working distance is just over half an inch. The two objectives of each microscope can be readily interchanged, being screwed not directly into the microscope tube but into a dovetailed slider, which only requires to be pushed home into corresponding grooves in a frame, ξ, carried at the lower end of the microscope tube, until flush with the front of the frame. The slider may then be tightly locked in position by rotating for 180-degrees a little lever pivoted to the frame. Immediately above this terminal frame each microscope tube carries a transparent, thin, and truly plane glass reflector, for the illumination of the object (the rulings or defining line) through the object-glass. The reflector is rotatable about a horizontal diametral axis, parallel to the length of the bar; and opposite the reflector the tube is pierced by two windows, through one of which (the back one) it can be illuminated by the source of light to be employed. Provision is made for the adjustment of the reflector by rotation in the horizontal plane, the whole of this lower portion of the tube, κ, being rotatable in a very stiff manner about the upper portion, as it is carried by an inner tube rotating, without sliding, very tightly in the main microscope tube.

The source of illuminating light for all preliminary work is a miniature electric lamp, E, with a short but thick rectilinear filament, an image of which can be thrown directly across the standard bar at the spot where the defining line or Grayson ruling is situated, which can thus be illuminated throughout its length. The suspension of the lamp, in the space between the microscope tube and the front of the slider-block and upper bed, which are both vertically flush with each other, permits of adjustment for height and for lateral position, the latter movement being provided with a fine-adjustment screw, S. Between the lamp and the back window of the tube opposite the reflector is the short tube, T, carried by an arm projecting from the lamp carrier, and provided with a collimating lens at the lamp end and an adjustable iris diaphragm at the reflector end. These together enable precisely that cone of illuminating light to be produced which is most favourable for the clear focussing of the particular mark which is the object of observation, a great advantage when the latter is a fine Grayson ruling, the thickness of each line of which is less than half a wave-length of red light. By means of the collimating lens the image of the short filament is projected back so that a virtual image is formed at a distance from the object-glass equal to that of the back focus of the eye-piece, and the iris diaphragm controls the angle of the illumination, thus ensuring so-called "critical" illumination for opaque work, and, indeed, as accurately as is given with a sub-stage condenser for transparent objects, the object-glass itself acting as a condenser, and a sharp image of the electric lamp filament being thus projected, as above stated, across the field of the instrument.

The electric lamps are only intended for preliminary work, and in actual measurements each of them is replaced by an image, of the same shape and size as the little straight filament, of a distant powerful source of light, a Nernst lamp. This avoids all possibility of any thermal effect due to the proximity of the lamps to the bars. A small total-reflection prism with rectilinear stop replaces the little lamp, and parallel rays from an adjustable condenser in front of the distant Nernst lamp, filtered and cooled by passage through an elongated cell containing copper acetate solution, are directed upon the little prism, flooding the rectilinear aperture of the stop with brilliant greenish-blue light, the best of all for efficient resolution of the Grayson rulings, and free from all heat rays.

The V*-and-Plane Beds.*

As regards the V-and-plane beds, *h* and *t* referred to under (2) and (5), they are similar in all respects, except that the upper one is $2\frac{1}{4}$ inches wider than the lower one, being continued to this extent backwards, as there is ample space on the top of the stone block-support, while on the step below the width is limited. Each bed has channelled in it from above, between the V and the plane, a ⊥-shaped groove, C, for the purposes of the locking arrangements of the various sliders which have to move over the two respective beds. The sections of the two beds will be clear from figs. 3 and 4. Very special care has been taken with the true planing of the sides of the V, and of the surface of the plane in each case, as it is all-important for interference wave-length work that these should attain the highest refinement of accuracy. The final stage of this planing and the final polishing was done *in situ* on the stone foundations after the best skill had previously been employed on them at Messrs. Troughton and Simms' Works at Charlton. The castings were made under direct supervision at West Bromwich, by Messrs. Kenrick, and were particularly good ones, especially as regards homogeneity, and both were cast from the same melt. Four highly concordant analyses proving this point most satisfactorily, of borings and planings taken from the different parts of each bed, were made by Mr. C. Hobday at Goldsmith's Hall, by kind permission of Sir Walter Prideaux, to whom sincere thanks are due.

The Microscope Sliding Blocks and their Fine Screw.

A few further details of the two steel blocks which slide on the upper bed, and the microscope-carrying slabs whose fine movement over these blocks is the critical point of the whole instrument, will doubtless prove interesting, as they involve several novel features. Each block (*o*, figs. 3 and 4) slides with V-and-plane contact over the $6\frac{1}{2}$-feet bed, *h*, and may be fixed at any position by a novel method of locking a

T-bolt carried below the slider as a stud, which enters the corresponding T-shaped channel, C, running through the whole length of the main bed, as described in the last section; the locking is effected by means of a lever, D, projecting behind from an aperture cut out of the back part of the block, a plate spring being introduced to prevent strain. The sliding of the block is done by hand as this is only the coarse adjustment of the position of the microscope above the bar. Throughout the entire length of each steel block a cylindrical hole has been bored, and ground with great care truly cylindrical and parallel to the length of the block and bed. Within this fits a hard phosphor-bronze cylinder, with adequate nicety to allow free longitudinal motion without the least shake, but keyed to prevent rotation. Into one end of this cylinder is fitted a steel screw of 50 threads to the inch, the length of actual screw thus threaded being 3 inches, affording $1\frac{1}{2}$ inches of fine movement on each side of the normal position. It is maintained in place by a suitable bronze flange screwed to one end of the steel block, and at the other end a strong flexible steel spring is compressed between the cylinder and the plug which closes the boring, in order to prevent backlash; the spring opposes the screw when the latter is turned anti-clockwise. Outside the bronze flange, on the portion of the steel screw which comes through the latter, is fitted the worm-wheel, r, of 100 teeth, already referred to under (3), which is engaged by the endless screw, s, also mentioned in (3), fitted at right angles to it; with the aid of a spring, F, and cam, H, actuated by a lever, K, it can immediately be thrown out of gear when desired, or as readily brought into position. The endless screw has a milled head, L, for direct rotation, and it is also continued with square section sufficiently far in front of the milled head to gear with the shaft, y, of the large wheel-control, w, separately mounted adjacent to the interferometer telescope. One revolution of the endless screw by the milled head of the large wheel obviously advances the fine screw $\frac{1}{5000}$ of an inch or 0·005 mm., which is equal to 15 interference bands of red light.

Outside the worm-wheel the screw shaft carries the silvered drum, p, referred to in (3), which is divided into 100 parts directly; by 100 oblique lines and 10 circles parallel to the first directly divided one, a diagonal scale of 10 further sub-divisions is produced, corresponding to thousandths of the pitch. Each oblique line passes from a division on the directly divided circle on which the hundredths are numbered to the next division on the tenth of the other circles, which had been similarly and exactly parallelwise divided, so that the obliquity is to the extent of a division. An indicating straight line parallel to the axis is carried on a glass plate, mounted in a frame, N, suspended by a bracket over the drum. This enables the thousandths to be read with great ease. At the extreme outer end close up to the drum the shaft terminates in the large milled head q, for direct hand rotation of the fine screw; the endless screw should obviously be thrown out of gear before this is used.

In the centre of the top of this steel slider-block a recess is cut out, exposing the phosphor-bronze cylindrical shaft for about $2\frac{1}{2}$ inches, and on this exposed portion of the slider a tempered steel ring is rigidly fixed, having on the top side a strong rectangular projection with slightly spherical surfaces. This projection engages and brings about the motion of the microscope-carrying inch-thick bed-plate *n*, the all-important cast-iron slider on the steel block (by **V**-and-plane motion) which carries the microscope M_1 or M_2 and its counterpoise m_1 or m_2, and whose fine motion it is the object of the fine screw to bring about. Of all the various movements which the author has tested, for bringing about the movement of the movable glass plate of the two such plates forming the interference apparatus, that of a solid cylinder sliding fairly tightly without rotation in a cylindrical bore—the fitting of the two being very accurate and the length of both adequate to minimise any minute amount of residual play—has always proved the most satisfactory, where a **V**-and-plane could not be used. In this case both are used, the cylindrical motion to push the block carrying the microscope and glass plate along, and the **V**-and-plane as the type of motion of that block itself. Hence a particularly steady movement is employed to bring about by pushing the absolutely steady movement desired. The object is wonderfully well achieved by this arrangement. The projection enters a suitable steel socket with a rectangular recess let in to the underside of the inch slider, and projection and socket are so accurately fitted as to need no further provision for an absolutely free and steady motion.

To facilitate the free motion of this microscope-carrying slider, and to reduce the driving strain on the fine screw, however, it is necessary to relieve some of the dead weight of the microscope and its bracket, σ, and counterpoise; this has been accomplished in a highly satisfactory manner by four spring-pistons let into the lower steel block-slider *o*, the ends of which are fitted with steel rollers. These spring-pistons are so disposed as to relieve the weight to the extent of about two-thirds of the total weight of the inch slider and all that it carries. The two springs at the microscope end of the slider, where the main weight occurs, are considerably more powerful than the other two, the relations being such as to provide for equal facility of motion throughout the whole length of the slider.

This device is found to quite successfully relieve the 50-thread screw from undue strain, and enables an absolutely free and surprisingly steady motion to be given to the microscope. The proof of this is the perfectly steady motion of the interference bands, when the endless screw is rotated, either by hand by means of the milled head or by the large wheel and its attached shaft. The success of this operation, which carries with it the success of the whole instrument, is largely due to the admirable manner in which Messrs. Troughton and Simms have constructed this part of the apparatus.

The Standard-bar Carriage.

A few details concerning the mode in which the bar carriage is moved, so as to bring the bars under the microscopes, involving either their longitudinal or their transverse motion, or both, and which involves certain mechanical novelties, may also be given. The bar carriage is composed of three essential parts, all of the same cast iron as the **V**-and-plane beds, namely, (*a*) a lower part, the main carriage, P, 2 feet 1 inch long, $5\frac{1}{2}$ inches wide, and $2\frac{3}{8}$ inches deep to the bottom of the **V**, and which is the longitudinal slider on the **V**-and-plane bed; (*b*) an intermediate part, Q, 3 feet 6 inches long, $3\frac{3}{4}$ inches wide, and $1\frac{1}{4}$ inches thick, which is capable of transverse motion over (*a*); and (*c*) the upper table *v* already alluded to in (6), of equal length and width to (*b*), and $1\frac{1}{16}$ inches thick, for the support of the standard bars B_1 and B_2; this part (*c*) may be either of the three interchangeable table tops specified in (6).

The main carriage, P, slides on the lower **V**-and-plane bed, by hand as regards its coarse adjustment for position, but as respects its fine adjustment by means of a pair of pushing pistons shown only in fig. 1, and which form a novel feature. Each of these fine-adjusting pistons, 3 inches in length, is carried by a slider-block of similar section to the bar carriage, but only 5 inches long, and which may be locked to the bed in any position by the same **T**-bolt stud device, worked by a projecting lever, which is common to all the sliding blocks traversing both the upper and the lower **V**-and-plane beds, the stud fitting the **T**-groove in the bed in each case. The fine movement is effected by rotation of a relatively large gunmetal wheel facing the observer, which carries at the inner end of its transverse shaft a bevel wheel gearing with another on a short longitudinal shaft, which is really the mother-nut of the central fine screw, whose smooth outer projecting part (about 1 inch long), with spherically rounded end, is the pushing piston. Where the contact with the piston end occurs the carriage end is faced with a hardened steel plate.

The transverse motion is also novel. A cylindrical shaft runs the whole length of the main lower carriage, P, being let into a central channel. In the middle of the shaft a racked quadrant is fixed, which is operated from the front of the carriage facing the observer by means of another large gunmetal wheel, W, which forms the head of an endless screw gearing with the toothed quadrant. Rotation of the wheel rotates the quadrant together with its attached shaft for about 60-degrees. Near the two ends of the shaft are fitted a pair of "tappits," or mechanical fingers; these are furnished with hardened and somewhat expanded spherical ends, which engage in slots in the under side of the intermediate transversely movable carriage, Q, these slots being lined with hardened steel. Each tappit is thus capable of exerting a pushing force in either direction in order to move the intermediate movable carriage transversely backwards or forwards, according to the direction of rotation of the wheel. Absolutely correct and perfectly smooth motion is obtained by two transverse **V**-slides, one near each end precisely at the symmetrical points demanded by AIRY's well-known formula

$$d = l/\sqrt{n^2-1},$$

where d = the distance between the supports, l = the length of the bar (in this case the movable carriage), and n = the number of supports, for the points of support of a bar or elongated plate without flexure. This movement is a particularly steady and easy one, very superior to the transverse movements hitherto given to comparators.

The upper table, v, rests with only $\frac{3}{8}$ inch interval on the transversely movable carriage, Q, by means of three levelling screws, two near the left end and one near the right end, also at the Airy positions; their heads, R, are large milled flat discs projecting outside the width of the carriage just sufficiently to enable the observer to manipulate them easily. The single levelling screw on the right rests in a short longitudinal **V**-groove in a gunmetal slider let transversely into the intermediate carriage top, the transverse sliding motion of which can be brought about by means of a large milled-headed screw in front facing the observer. The levelling screw is thus carried with it, the **V**-slot providing for the slight longitudinal component of the motion which occurs. Of the two levelling screws at the left end the back one is bluntly pointed and rests in a conical depression in the intermediate carriage top, and forms the pivot of the whole operation of this slight adjustment for azimuth. The front left screw has a slightly spherical but almost flat termination, and merely rides on the surface of the intermediate carriage during the operation. These three levelling screws thus provide at the same time the means of levelling, slight raising or lowering, and, with the aid of the milled-headed front screw, for slight azimuth adjustment of the bars. They afford, in fact, all the adjustments required for insuring parallelism of the defining marks on the standard bars and the micrometer spider-lines, and for finely adjusting a defining line to the focus of the microscope, when it is not desired to touch the microscope itself for fear of disturbing its adjustment as a beam compass, in comparing a second bar with a standard bar.

The ordinary table-top, for all experimental purposes, is simply a truly planed surface on which bars, Grayson rulings, or other objects under observation can be directly supported. The second of the three interchangeable table tops is the one which is shown marked v, in figs. 3 and 4. It is specially constructed to support a pair of standard bars independently, each on a pair of friction rollers at the Airy positions, or at any positions officially required. The two bars are thus separately supported in order that, whilst the back one is fully adjusted by the means provided with the intermediate carriage and the three large levelling screws which this table top carries precisely like the first one, the second bar may in addition be independently adjusted for azimuth, level, and longitudinal position, by means provided in the mode of fitting its pair of rollers. This enables two bars of slightly different dimensions, say, as regards shape and size of section and depth of defining-line wells, to be brought so that their four defining lines, two on each bar, are in precisely the same plane. This adjustment also greatly facilitates work with Grayson rulings and high powers of the microscopes. Moreover, exact parallelism of the bars can be obtained, and their defining lines—at any rate those at one end if there are appreciable differences between the bars—can be brought exactly opposite to one another. Further, the pair of friction rollers for each plate can be readily adjusted at any distance apart so as to attain the desired theoretical positions for bars of different lengths, for instance either yard or metre bars. The third table for use with end-measure bars as well as line bars will be described in a further communication. It involves novelties of method and of mechanical device which are worthy of separate treatment.

The Wheel-Control for the Movement of Bands.

The wheel-control is carried on a very rigid pedestal, x, mounted closely to the left of the interferometer-telescope pedestal, on a slider, X, in a longitudinal dovetailed channel in a large cast-iron plate, Y, which forms the basal table on which the tripod of the telescope pedestal rests. The plate rests directly on the stone pillar d, to which it is firmly bolted down. The slide enables the axis of the wheel to be brought exactly opposite to and in line with the fine-movement endless screw s, which operates the worm-wheel r of the all-important microscope traversing screw. The height of the axis has been approximately adjusted in mounting, and the final small amount necessary to render it accurate is given in the following manner :—A stout screw, Z, descends from and is rigid with the axle bearing-bracket U, and passes down freely through the upper looped end of the casting of the two-legged pedestal; the amount of screw which thus projects down into the loop is regulated by means of a pair of locking nuts, VV, which are firmly fixed when the height of the screw, and of the wheel and axle which it carries above, have been adjusted so that the axle is in the same horizontal line with the endless screw s.

The axial bearing carried at the top of the bracket U is adequately strong and well fitting to prevent all trace of wobble on the part of the wheel, while permitting its easy motion; the six-inch wheel itself is massive and very truly balanced, and its face is divided into degrees, an indicating mark being carried on the plate z below the lower limb. Of the three shafts y provided, the author prefers the one constructed of the new flexible steel shafting, for connecting the wheel with the endless screw s of the microscope fine movement, as it avoids all risk whatsoever of strain. The square continuation of the endless screw fits a correspondingly squared brass socket, fitted with tightening spring, carried by the shaft. The wheel end of the shaft carries no socket, but fits freely into a boring in the wheel axle, where it can be gripped tightly by working a milled nut, J, down the split and tapped end of the bored axle. The second rigid shaft provided fits in a similar manner, with the addition of a telescopic arrangement to enable it to be shortened sufficiently to admit it into the axle boring. A third shaft, also rigid and telescoped, but with the addition of a set of gimbal joints at the endless-screw end, is also provided and fits in a similar manner. The first and the third prove most satisfactory on the whole, being safer as regards possible strain, and the first is used for all purposes of adjustment or demonstration, while the third is employed during actual measurements. The endless screw s, as worked directly by hand with the milled head, shows absolutely no backlash or "dead space" on reversal, and the bands follow its rotation perfectly. The flexible shaft shows a little "dead space" due to torsion on reversal, but when once the bands begin to move they follow the rotation of the wheel perfectly and they stop immediately the wheel stops. Neither of the solid shafts show any hesitation on reversal of the wheel's rotation, and the bands stop absolutely when the wheel stops.

The Method of Production and Adjustment of the Interference Bands.

(Fig. 7 will be very useful in following this description.)

The mode of once for all adjusting the interference apparatus is briefly as follows :—

The black-glass disc g_3, carried by the right-hand microscope on its right side, which forms one of the two all-important reflecting surfaces employed for the generation of the bands, has once for all been adjusted to the truly vertical plane, parallel to the axis of the microscope, and perpendicular to the direction of the V-and-plane beds and standard bars. The large total-reflection prism, already adjusted with truly vertical faces on its carrier table, is placed in position on the circle of the dispersing apparatus, dropping automatically by its three pegs into the corresponding holes, and is locked there. The white-light goniometer lamp—a Nernst lamp in an adjustable cylindrical copper tube, with a plate of ground glass to diffuse the light closing its aperture—is placed with the ground glass in front of the collimator instead of the Geissler-tube fitting ; and the image of the little rectangular stop in front of the small total-reflection prism of the autocollimating telescope, as reflected from the black-glass surface, is adjusted in the field of view of the telescope. The common eye-piece only is employed, not the micrometer eye-piece, and the iris diaphragm is left wide open. The visible field is semicircular, the right half of the complete circular aperture being closed by the opaque mount of the little total-reflecting prism, whose left edge is the straight vertical line forming the base of the semicircle.

The two colourless-glass 35-minute wedge-discs g_1 and g_2 are then placed in their spring mounts, the fitting carrying which is already in position. In placing each wedge-disc in position, it is only necessary to hold up the spring, which bears only on the normally ground cylindrical edge-surface of the disc, by a little handle projecting through the mount, and to push the wedge-disc in until it is stopped by the truly planed flange, which occurs when about two-thirds of the thickness of the disc has entered the mount ; and then to release the spring, which maintains the disc firmly pressed in position without chance of movement, and without any bending strain on the all-important surfaces of the disc, any slight strain being only parallel to those surfaces. The disc g_2 should first be thus placed in position, in the left mount, with that surface which bears at its centre the silvered reference ring nearest the microscope, and with the direction of the edge of the wedge horizontal. Each of these wedge-discs is engraved with two dots at the thick end of the diameter perpendicular to the edge of the wedge, and with one dot at the thin end, so that it is only necessary to arrange the disc with the diametral line joining these two marks vertical, say the two dots at the top.

This should be done while the mount-fitting is some little distance away from the microscope, and as soon as g_2 is in position the fitting is pushed along its dovetailed bed until the black-glass disc g_3 and the colourless disc g_2 are just within a millimetre of each other. They should be approximately parallel, and, if this is not the case, g_2 should be adjusted by means of the three brightly lacquered screws h until parallelism is approximately attained. There will be two images of the signal-stop reflected from this plate, one from the important outer surface near to the black-glass surface and another from the back surface within the mount; the one will be immediately under the other, as at B and C in fig. 8, B referring to the surface nearer to the black-glass and C to the back surface, while A refers to the image from the black-glass surface. This latter image will be quite close to B if parallelism of the two surfaces has been nearly attained, and the closer the more perfect the adjustment. At the worst it should not be further away than is indicated by the dotted image A′ in fig. 8.

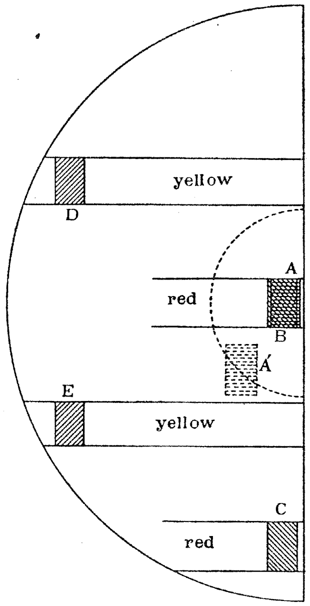


Fig. 8. Positions of signal-images from the five surfaces.

The reason for arranging the images thus vertically separated is, that when they are broadened out into spectra by the dispersion apparatus, the two spectra, being horizontal, will not overlap, as will be clear from the horizontal lines indicating the spectra in fig. 8; whereas, if the images were horizontally separated by placing the line joining the two dots and one dot of the disc horizontal, their spectra would overlap and interfere with each other.

If the images A and B do not already overlap, the images B and C (which move together) should be moved by manipulation of the bright screws until B overlaps A, the relative positions of A, B, and C being then as shown in fig. 8; the image A can readily be distinguished as being that one of the three which does not move when one of the bright screws is gently touched. The countervailing wedge-disc g_1 is then to be similarly attached in the right mount, but with the two dots now below and one dot above, on the vertical diametrical line. On observing the images again, we now see five—the three already referred to, B and C belonging to the colourless disc g_2 and A to the black glass g_3, and A more or less overlapping B—and two new ones, D and E, belonging to g_1. These two latter should be arranged as in fig. 8, by means of the black-lacquered screws k, vertically over each other but to the left, *en échelon* with B and C, the four images forming a rhombus. This arrangement avoids all possibility of the spectra overlapping, as will be obvious from fig. 8, while g_1 corrects for the dispersion introduced by g_2. The full aperture of the iris is just sufficient, with wedge-discs of 35 minutes angle, to enable all four corners of the rhombus to be included in the field.

The image B should then be made to cover the image A to exactly the right extent, for the production of interference bands which shall be precisely vertical in the field of the micrometer eye-piece, and at the same time of the convenient width, equivalent to somewhere between 100 and 200 drum-divisions of the micrometer. This is achieved when the overlapping occurs to the extent and is of the character shown in fig. 8, the displacement being only horizontal. The adjustment is now complete in white light.

The large total-reflection prism is then replaced by the constant-deviation prism, already adjusted with vertical faces on its separate table, which only requires to be dropped into position with its pegs in the holes of the circle plate, and locked there by pulling round the little locking handle-pin projecting through a slot in the table. The position of the circle on its transverse bed will require to be altered to the necessary extent to bring the centre of the receiving face of the prism in the normal line of the interference discs. The telescope may also have to be moved slightly parallel to itself, by means of the right-and-left movement α at the base of the pedestal, to direct it to the proper part of the exit face of the prism. On setting the circle to the reading which is known by preliminary work to approximately adjust the prism for the production of bands of red hydrogen light, the four spectra should be seen in the telescope, still using the common eye-piece, as shown by the horizontal lines in fig. 8.

The goniometer lamp is then removed and the hydrogen Geissler-tube fitting placed in position. The common eye-piece is also removed and the micrometer eye-piece substituted, but without the front lens-combination, leaving only the special single lens in position between the micrometer and the iris diaphragm, in its draw-tube of the correct length for focussing the silvered reference ring of the glass disc g_2. On actuating the Ruhmkorff coil, the four spectra will again be seen as in fig. 8, although the magnification is not so great. But instead of consisting of continuous spectra, as with white light, they will now show only a faint continuous spectrum, but at the positions which the Hα, Hβ, and Hγ bright lines would occupy in a hydrogen spectrum there are images of the rectangular signal-spot in red C-light, greenish-blue F-light, and violet light (near G). Only one set of these images—those in red hydrogen light if the prism has been set for this—will be in the field at once, the dispersion of the constant-deviation prism separating the different sets very considerably, to the extent of several field diameters. The iris diaphragm may now be closed to the extent which is shown by the dotted semicircle in fig. 8, which is a faithful representation of the appearance while the front lens-combination is removed. All but the second spectrum (the double one corresponding to the images A and B) can just be excluded, without impairing the illumination of the double red image required and leaving that alone in the centre of the field; the 1st and 3rd spectra are just out of the field and the 4th considerably so. The very faint traces of continuous spectra of A and B are negligible compared with the brilliance of the sharp A and B images in Hα red and are quite without effect on the bands. A little adjustment may possibly be required to bring the double image in red light (or greenish-blue if the prism has been adjusted for F-light) to occupy exactly the position shown in fig. 8, which is, at the same time, vertically central and quite close to the sharply focussed vertical edge of the semicircular aperture. This is effected, if needed, by slight altitude and azimuth adjustment of the telescope, supposing the prism to have been correctly adjusted at the proper circle reading for the radiation in question, from the knowledge acquired in the preliminary work. On now replacing the front-lens combination, the field of interference bands will be seen in the colour for which the prism has been adjusted.

Its correct appearance is clearly shown in fig. 6. The comb, or rough scale, should be arranged as shown, with the circular image of the black-glass disc g_3 in the red or green light, for which the adjustment has been made, fully exposed. The silvered ring in the centre of the surface of the colourless plate g_2, nearest to g_3, should be sharply focussed if the special single lens of the eye-piece is arranged in the tube of the correct length for this working distance, as already ascertained by preliminary work. If then, however, the focus is not quite sharp, it is because the telescope requires a little adjustment in the direction of its own length, by means of the front wheel, that corresponding to the front-and-back movement β, of the adjusting movements at the base of the pedestal. When the reference ring is sharply focussed, the bands are thereby automatically focussed, as they are actually produced between the two surfaces, g_2 and g_3, which are less than a millimetre apart, and one of which, g_2, actually bears the ring.

The bands may not be quite of the desired width, and they will probably also be very slightly inclined to the vertical, as the adjustment of the A and B images cannot be done to the required fineness to effect these adjustments absolutely. These defects, however, can both be simultaneously remedied by careful slight manipulation of one or possibly two of the three bright screws h which adjust g_2, these adjustments being thus more delicately performed on the bands themselves.

The spider-lines then require to be set at the requisite distance apart by means of the left drum of the micrometer, so that any one band may be clearly adjusted between them as in fig. 6; when the proper width of band is attained, this adjustment of the separation of the parallel spider-lines is such as brings them just within the little silvered ring, a small segment of which should show equally on each side, as also shown in fig. 6. Everything is then adjusted concerning the interference bands.

On now carefully working by hand the milled head of the endless screw s, the microscope and its black-glass interference disc g_3 will move parallel to themselves to an extent invisible to the naked eye, but which is instantly interpreted by the steady movement of the interference bands parallel to themselves, without the slightest twist or alteration of their width; and reversal of the direction of rotation of the screw causes the instant reversal of the direction of movement of the bands.

On attaching one of the shafts to the endless screw and to the large control-wheel, the traverse of the microscope and of g_3 can be equally and much more conveniently and delicately effected and controlled, in the manner already fully described in the last section. The calculated number of bands, namely 15 for red hydrogen light, pass most accurately for each revolution of the wheel, and the steadiness and "dead beat" nature of the motion is very pleasing.

Indeed, the most satisfactory thing about the whole interference method is that the slightest fault, productive of inaccuracy of measurement, is at once visibly indicated by irregular movement, twisting, alteration of width, or complete disappearance of the bands. The fact that during the operation of measuring the difference of length between two bars—involving the traverse of the microscope through the length corresponding to this difference—the bands move with the precision which has just been stated, is the final proof of the success of the method and of the instrument now described.

The author desires to record his appreciation of the most kind help and encouragement invariably received from the Deputy Warden of the Standards, Major P. A. MacMahon, F.R.S., to whose initiative the whole of this advance in fine measurement at the Standards Department is due. Further, to express his deep indebtedness to Mr. F. Stanley Read of the Standards Department, and to Mr. J. Skinner of Messrs. Troughton & Simms, for untiring aid and many excellent suggestions during the design and construction of the apparatus. The author's thanks are in a special manner due to Mr. James Simms, the head of this firm, which has had a long historic connection with the Standards Department, for placing his unique experience and the very highest constructive skill at the service of the Board of Trade in regard to this instrument. Mr. J. H. Agar Baugh and Dr. Drysdale have also afforded invaluable assistance in connection with the unique electric thermostat. Moreover, to the officials of H.M. Office of Works the heartiest thanks are due for very material help in designing the stone foundations, and in the electric installation of the new comparator room, as well as for the admirable manner in which the work has been executed.

APPENDIX.

The Use of Wave-length Rulings as Defining Lines on Standards of Length.

The delicacy of the method of measurement in wave-lengths, described in the preceding communication, calls for a corresponding refinement in the engraved lines which form the defining limits of the length of a Standard Yard or metre or other line-measure bar. The Imperial Standard Yard is shown in fig. 9. It is a bar of Baily's metal, which consists of 16 parts copper, $2\frac{1}{2}$ parts tin, and 1 part zinc. The bar is of 1-inch square section, and is 38 inches long. At positions 1 inch from each end cylindrical holes, $\frac{1}{2}$ inch diameter, are bored for a depth of half an inch, the depth of the axis or "neutral plane" of the bar and position of minimum flexure. In the centre of the base of each of these depressions a gold plug is inserted, the exposed surface of which, lying in the neutral plane, has been truly planed. The defining mark is engraved approximately at the centre of this gold circular surface. Five lines are engraved, two parallel to the length of the bar and three transversely, the appearance of the lines as seen in the microscope being shown in fig. 10. It is the central one of the three transverse lines (vertical in the figure) which is *the* defining mark, and the distance between this mark in the depression at one end and the corresponding mark in the depression at the other end is the Imperial Yard. It is identical, within the two-hundredth part of an inch, with the yard of Henry VII. still preserved in the Standards Office.

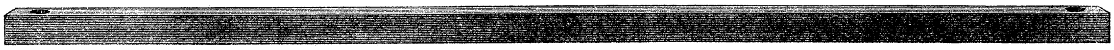
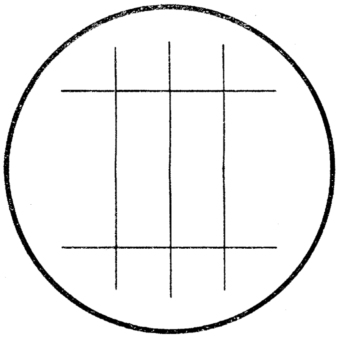


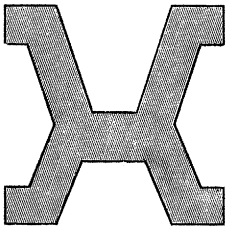
Fig. 9. The Imperial Standard Yard.

Fig. 10.



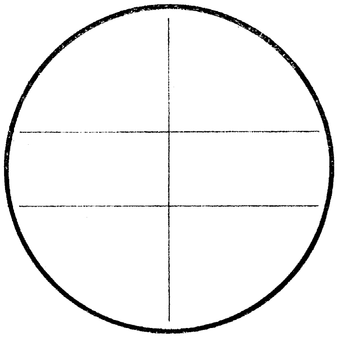
Defining lines on Imperial Standard Yard.

Fig. 11.



"Tresca" section of platinum-iridium yard.

Fig. 12.



Defining line on platinum-iridium yard.

In the year 1902 an official copy of the Imperial Standard Yard was constructed in platinum-iridium (90 per cent. platinum with 10 per cent. iridium), of **X**-shaped

"Tresca" section, shown in fig. 11. The defining lines on this bar are similar to those of the Imperial Standard Yard, except that only one transverse line is engraved instead of three, and the engraving was performed directly on the platinum-iridium, on that one of the surfaces of the horizontal transverse portion of the bar which contains the centre of the section. The appearance of the defining line under the ordinary comparator microscope is represented in fig. 12.

The defining lines on the Imperial Standard Yard were engraved by Messrs. Troughton and Simms, its constructors, and were the finest lines it was considered advisable for the sake of permanency should be engraved. The defining lines on the platinum-iridium yard were engraved at the Bureau International des Poids et Mesures at Sèvres by M. BENOÎT, the Director. They are only one-third as thick as the Troughton and Simms lines, and are similar to those on the French metre employed by MICHELSON.

The lines on the platinum-iridium yard, under a magnifying power of 200 diameters, are observed to have very irregular edges, instead of appearing under this only moderately high power as a broad band of equal thickness with sharp edges. The centre of this line has to be estimated as the actual defining limit of the yard, and it can be well understood how difficult the operation is with any but the lowest-power objectives. Its average thickness is such as includes no less than 15 half wave-lengths of red hydrogen or cadmium light. That is to say, on traversing the microscope of the apparatus described in the preceding communication through the distance covered by the average width of either of the defining lines on the platinum-iridium standard yard, no less than 15 interference bands pass the reference spot in the centre of the field of view.

When the defining lines on the Imperial Standard Yard are similarly investigated, they are found to be much more regular, although three times as thick as the lines just referred to. No less, however, than 45 interference bands pass the reference spot on traversing the microscope through the width of either of these lines.

It will be clearly obvious that defining lines which are considered sufficiently accurate for the degree of refinement of measurement possible to the micrometer-microscope comparator, are very coarse and inadequate for wave-length measurement by the delicate instrument described in the preceding communication. Like the constant struggle between guns and armour-plate, there is a similar struggle going on between fineness of measurement and defining lines, and for the moment refinement of measurement has triumphed. The only weak point in MICHELSON'S wonderfully accurate determination of the total number of wave-lengths of red cadmium light in the French metre is, if the author may be permitted to say so, and as MICHELSON himself states in his book on 'Light Waves,' in the final comparisons between his glass-plate étalons (or the Fabry and Perot étalons) affording the interference fringes, and the standard bar itself, on which the defining lines were similar to those on the British platinum-iridium bar. For the centre of each line has to be estimated, and in view of the degree of accuracy claimed for the whole result, the fraction of an interference band, it is difficult to see how one could be sure of this when as many as 15 whole bands are included in the irregular width of the defining lines, as the author has verified, as regards that on the British iridio-platinum yard, by actually observing these bands to pass while the width has been traversed on several occasions.

Three years ago the author was attracted by a paper by E. M. NELSON in the 'Journal of the Royal Microscopical Society' (1906, p. 521) concerning "The Limits of Resolving Power for the Microscope," in which reference was made to some extremely fine rulings, ranging from 10,000 to the inch to 120,000 to the inch—the latter being on the extreme verge of possible resolution with the highest-power immersion objectives yet constructed—made with an exceedingly fine diamond point on glass by Mr. H. J. GRAYSON of Melbourne, employing a ruling machine of his own construction. The author obtained some of these rulings from Messrs. R. and J. Beck, Mr. GRAYSON'S agents, and was greatly surprised and delighted with their truly wonderful sharpness and the clear, unbroken continuity of their edges. Mr. GRAYSON was approached and most kindly made for the Standards Department a number of experimental rulings on the scales of 40,000, 50,000, and 60,000 lines to the inch on glass, silvered glass, speculum metal, gold, silver, platinum-iridium, Baily's metal, and invar. Each ruling consisted of five of the lines in question, ruled parallel to each other according to one of the above-mentioned scales, together with a pair of "finder" lines parallel with the five rulings, one on each side of them at a suitable interval, and much thicker than these five lines, for the purpose of readily finding the lines under a preliminary low power; and also a pair of lines transverse to the five parallel rulings and crossing them rectangularly for the purpose of identifying a central portion of the rulings.

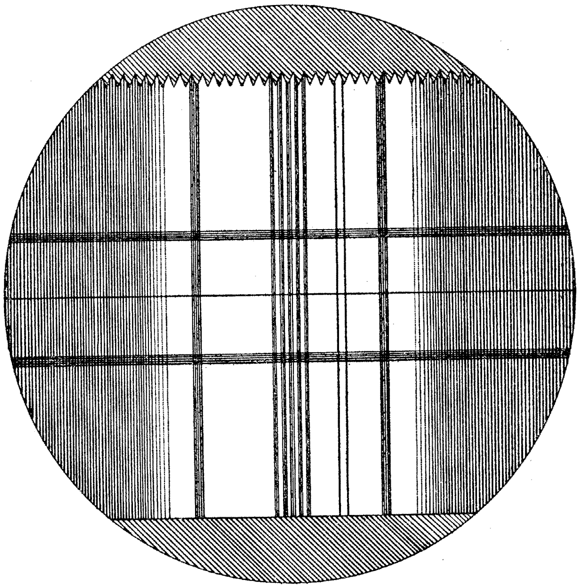


Fig. 13. The location signal.

The appearance of the essential central part of such a series of rulings under the $\frac{1}{15}$-inch dry lens, provided with each of the two microscopes described in the preceding communication, is shown in fig. 13. The author's idea was to constitute the central third line, of the five lines composing such a ruling, *the* defining line. A ruling such as is represented in fig. 13 the author proposes to refer to as a "location signal" to distinguish it from the single defining line hitherto employed.

It may at once be stated that the author found the rulings on speculum metal, on the scale of 40,000 to the inch, satisfactory from every point of view, not only for the purpose in question of an end-defining line on a standard bar, but also for an ulterior purpose which the author had in view; this was the engraving on a standard bar itself of approximately wave-length rulings at stated intervals, which could be used instead of the glass étalons of Michelson and of Fabry and Perot, in a simpler and more direct method of determining the total number of wave-lengths of a particular radiation, red cadmium light in all probability—as the most homogeneous yet known—in the Standard Yard. The surface of the speculum metal was finely polished as truly plane as possible by Mr. Grayson himself before the rulings were engraved by his own uniquely delicate hands, with the aid of his wonderful ruling machine; and for the sake of certainty of preservation of the surfaces they were covered with thin cover glasses.

The results with all the other rulings, of three different finenesses, and on glass and the various metals mentioned, were also more or less satisfactory, particularly the 40,000-to-the-inch rulings. Hence it may be safely taken as quite possible to engrave five rulings on the scale of 40,000 to the inch on glass and on several of the metals employed for standards of length. The rulings on speculum metal, however, are so superior that the author has decided to make detailed experiments with them, and Mr. Grayson has made for the Standards Department a considerable number of such rulings on 20 different small but relatively thick plates of speculum metal, covered as described, and of two types. One type, of which there are 15 similar specimens, consists of a plate 9 mm. square and 2 mm. thick at the base, but bevelled along the edges for insertion in a dovetail in mounting on the bar. Each has ruled upon it a single "location signal" as represented in fig. 13, the five parallel lines being on the scale of 40,000 to the inch. The other type, of which there are 5 specimens, is a plate of equal width and thickness to those just mentioned, but 34 mm. long. On each of these there are ruled location signals at the following intervals:—A zero point, $\frac{1}{32}$ inch, $\frac{1}{16}$ inch, $\frac{1}{8}$ inch, $\frac{1}{4}$ inch, $\frac{1}{2}$ inch, and 1 inch, and also an additional signal at $\frac{1}{8}$ inch on the other side of the zero location signal. The reason for this is that the total interval of 1 inch and $\frac{1}{8}$ is an aliquot part of a yard, which may be reached by a repeated process of doubling; for its double is $2\frac{1}{4}$, the double of this is $4\frac{1}{2}$, twice this is 9, which again doubled gives 18, and finally the double of this makes up the 36 inches of the yard.

These rulings are infinitely superior to those of Nobert. The author is particularly struck with the accuracy with which Mr. Grayson—who has entered into the author's ideas most warmly and put his very highest skill at the disposal of the Board of Trade—has attained the exact spacing of his rulings; for the author has rigorously tested them by direct measurement against interference bands. It is interesting that lines 40,000 to the inch are almost precisely wave-lengths of red light. The exact wave-length of red C-hydrogen light is, in British measure, $\frac{1}{38710}$ inch, and that of the red ray of cadmium is $\frac{1}{39459}$ inch. There was a time, not very long ago, when it would have been considered impossible to see lines only a wave-length apart. On traversing the microscope which carried the black-glass interference plate, from the position in which the first ruling of one of these location signals was adjusted between the parallel pair of spider-lines to that in which the fifth ruling was similarly adjusted—the microscope having thus travelled over four wave-length spaces—exactly eight interference bands (each corresponding to half a wave-length, $\frac{1}{77419}$ inch) in red hydrogen light passed over the reference spot; this was true however many times, and in whichever direction, the traverse was performed, and was precisely the number expected within a very small fraction, if the rulings were truly spaced $\frac{1}{40000}$ of an inch apart.

Thus the interval between two lines ruled $\frac{1}{40000}$ inch apart corresponds to the passage of two interference bands in red hydrogen or cadmium light, past the reference spot in the centre of the field of view of the interferometer telescope, a very convenient fact. The lines themselves are almost as sharp as the spider-lines of the eye-piece micrometer, and there is no trace of roughness of edge; they are also narrower than the white interspaces between the lines, so that the width of a line is less than half a wave-length.

With the $\frac{1}{15}$-inch dry objectives, specially constructed under the direction of Mr. Conrad Beck, the resolution is excellent, and the working distance so relatively great for so high a power as to leave a clearly visible air film between the cover glass and the objective, quite a safe working distance, in fact, for all traversing and adjusting purposes. With an oil immersion objective of the same power the definition is simply surprising.

The lines at 60,000 to the inch are not so satisfactorily resolvable without an immersion lens, which would be inconvenient for the purpose in view; and the rulings 50,000 to the inch are still a little subject to the same criticism. But the 40,000 rulings to the inch are perfect for the purpose, their apparent separation being so considerable that one of the spider-lines of the micrometer eye-piece can readily be placed between two adjacent ruled lines and still leave a clear white space on each side of the spider-line. The sharpness of the edges of any particular line thus ruled on speculum metal is quite comparable with that of the edges of the spider-line itself. All these considerations, combined with the fact that 40,000-to-the-inch rulings are approximately single wave-length rulings (for red light), render the location signals on the 40,000-to-the-inch scale remarkably suitable for defining marks on standard bars, the middle line of the five being *the* defining line. This is equally true whether they are employed in the usual manner merely as end marks, or as interval marks in a scheme of stepping-off by repeated doublings, for the determination of the total number of wave-lengths in the yard or metre. Such a scheme would have the great advantage that the final end-defining marks would be of the same accurate character as all the intermediate ones.

The author has elaborated such a scheme for the determination of the number of wave-lengths of red cadmium light in the British Yard and proposes to check the results obtained with it by comparison with the Fabry and Perot method, to which the apparatus described in the preceding communication lends itself admirably, and which has recently been successfully employed at Sèvres to check the results of Michelson and Benoît for the French metre. The total number of wave-lengths in the $\frac{1}{16}$-inch interval of one of the longer rulings above referred to, corresponding to the transit of about 4200 interference bands, can quite easily be counted as a fundamental base line, and, of course, the $\frac{1}{32}$-inch interval of 2100 bands more readily still, by direct traverse of the microscope of the wave-length comparator described in the preceding communication, from one location signal defining the interval to the other. By the author's scheme of repeated doubling, a full account of which will be published later when the results are described, and which involves the use of two of the larger $1\frac{1}{8}$-inch rulings and nine of the single location-signal rulings, five of the latter mounted on a yard bar and the rest along with the two larger plates on an intermediate $4\frac{1}{2}$-inch bar, the whole yard can be eventually stepped off. Each stage thus replaces one of the stages of Michelson's étalons and each is susceptible of absolute checking of the final fraction of a band by direct observation of the interference bands, if this should be found necessary; as far as preliminary measurements go, the necessity has not proved an imperative one, for practically as great accuracy is afforded with the rulings as with the bands as regards the determination of a fraction of the interval between any two lines or bands.

Sufficient will have been said to indicate the great possibilities before the use of these Grayson wave-length rulings, and the author desires to be allowed to reserve for a time in his hands their fuller investigation for the purposes of metrology with the aid of Mr. Grayson, who, as the man behind the machine, is at present the only person in the world able to produce such magnificent and accurate rulings, delicacy of hand being quite as important and essential a part in their construction as fineness of the diamond point and precision in the ruling machine.

At present there are two difficulties confronting us, which it is hoped may soon disappear. One is that Mr. Grayson is not able to rule a greater length of bar than the $1\frac{1}{8}$-inch strips described in this communication, and, therefore, they cannot yet be ruled directly on the standard bars themselves. This is only a matter of the modification of the ruling machine, however; but, as Mr. Grayson is in Australia and communication is slow, it has not yet been arranged for, but lies with the immediate future. A very satisfactory method of mounting has been arrived at, however, comparable with the mounting of his glass plates by Michelson, so that any criticism on this head is equally applicable to the étalons. The covering by cemented cover glasses, at first looked at by the author somewhat suspiciously, proves on closer acquaintance with high-power microscope work to present no difficulty whatever, or to introduce any error in actual practice, as "critical" illumination is always achieved with great perfection in the instrument described in the last communication.

The second difficulty is only one of degree, and of the perfection of attainment of the constant temperature of 62° F. with the electric thermostat; that is, the fact that the rulings now being employed are on speculum metal. When further experience of these rulings has been gained, however, the author feels convinced that we shall be able to obtain them almost equally satisfactorily on highly polished platinum-iridium, and, therefore, assuming the first difficulty overcome, directly on the bar itself. Gold and invar are not so promising, the former being apparently too soft and the latter too hard.

In conclusion, it may be stated that the author's location signal, of five Grayson rulings on the 40,000-to-the-inch scale, as above described, and as shown in fig. 13 under the $\frac{1}{15}$-inch power, makes a splendid defining line under the $\frac{2}{3}$-inch power employed in observing the Benoît or other coarser ordinary defining marks on standard line-bars. This power is insufficient to resolve the five lines, so that they appear as a single defining line, but of truly wonderful sharpness of edge, as may readily be imagined when their sharpness under the resolving power of the $\frac{1}{15}$-inch objective is remembered. Even if the high hopes at present entertained as to the use of these rulings as stages in stepping-off the total number of wave-lengths in the yard be not fulfilled, the investigation of the rulings will have fully justified itself in giving us a defining mark of the high accuracy and refinement demanded by the wave-length interference method of measurement.

The author desires to record his sincere thanks to Mr. Grayson for the admirable manner in which he has prepared the special rulings described in this communication, and for the enthusiasm with which he has entered into the author's plans. Also to Mr. Conrad Beck for his aid in satisfactorily overcoming the problem of their maximum resolution, illumination, and definition.

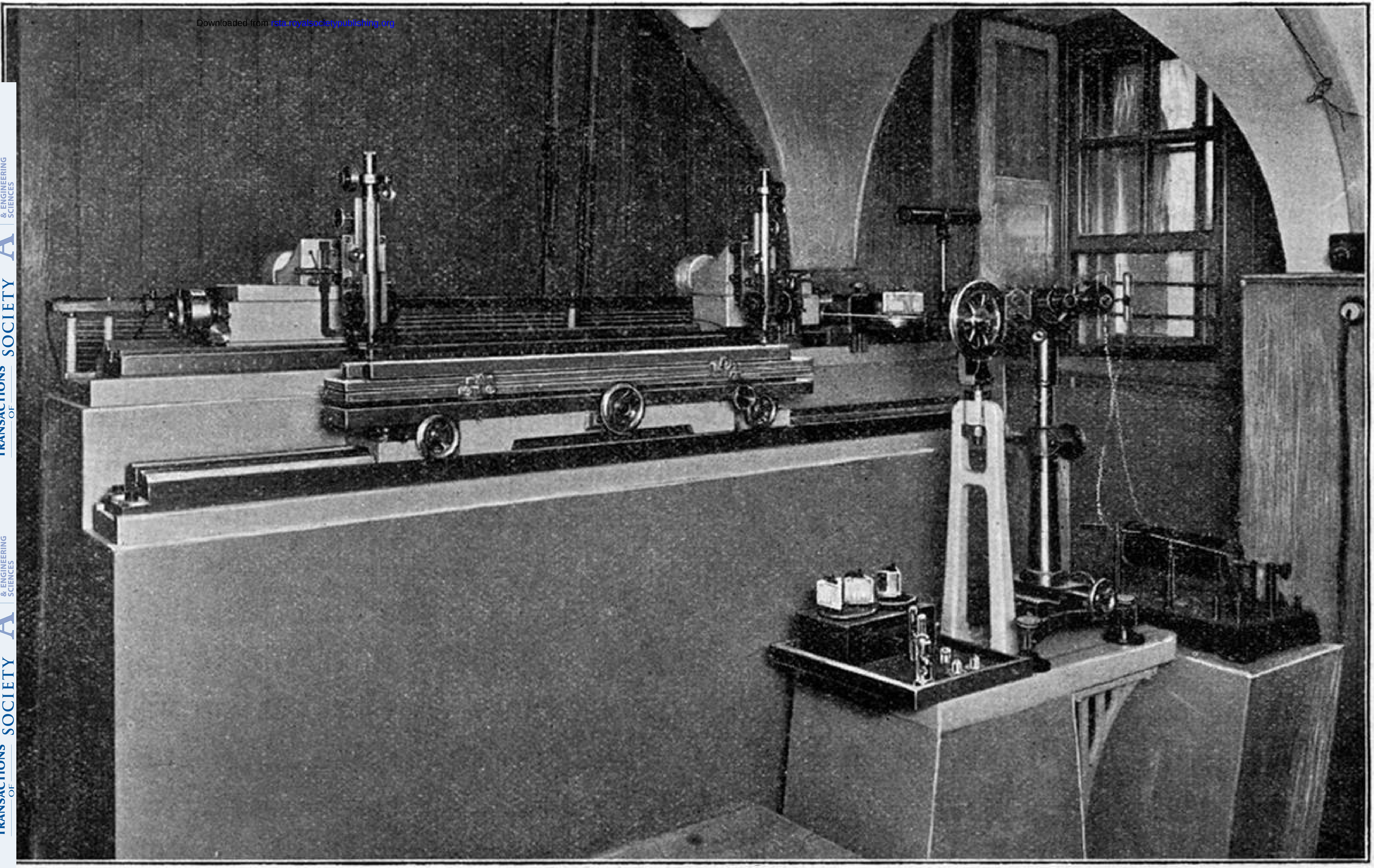


Fig. 1. General view of the comparator.