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THE PHOTOMETRY OF OPTICAL INSTRUMENTS.

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ABSTRACT. The use of a portable surface-brightness photometer of the polarisation type for the measurement of the fraction of the incident light transmitted by an optical instrument or reflected by a mirror or system of mirrors, and for the measurement of the relative brightness of different parts of the field of view of an optical instrument, is described. The instrument employed is a Wanner optical pyrometer (Cambridge and Paul Inst. Co.) with some modifications to render it suitable for such work. An addition to the instrument is described which removes the danger of error due to polarisation of the incident light.

I. INTRODUCTORY

THE measurement of the percentage of light transmitted by optical instruments, particularly those of relatively complex design, is one of considerable importance. While it is easy to calculate the light loss due to absorption and reflection in the case of simple instruments, it is by no means easy to do so with any precision in the case of those with a large number of optical units without much more precise data than is sometimes available. It is often, therefore, necessary to determine the loss experimentally in order to compare the performance of instruments of similar function but of different design.

The method hitherto used at the laboratory for small instruments, such as binoculars, involves the adjustment of the instrument in relation to a photometer bench, and is unsuitable for instruments such as rangefinders and periscopes because of their size and non-portability, and, also, on account of the lateral separation of their entrance and exit pupils. The method of measurement to be described was evolved primarily for instruments of this type. It has, however, proved to be of considerable general utility for instruments of any size or type, the same apparatus serving not only to measure the percentage light transmission, but also the distribution of brightness in the field of view.

The method depends on the well known principle that the ratio of the intrinsic brightness* of an image to the intrinsic brightness of the object is independent of the magnification, depending simply on the loss of light by reflection and absorption within the instrument producing the image. If a luminous source of uniform intrinsic brightness be placed in the immediate neighbourhood of the exit pupil of a telescope system an image of this is formed at the entrance pupil (objective). The intrinsic brightness of this image divided by that of the source gives at once the proportion of light transmitted by the instrument.

* I.e., the light emitted per unit solid angle by unit area of the surface.

The necessary equipment therefore consists of a suitable light source of which the intrinsic brightness is uniform over an appreciable area, and an instrument for measuring intrinsic brightness.

II. SOURCE OF LIGHT

As regards the source of light it is necessary to employ an illuminated diffusing screen, as there is no source suitable for use directly. After considerable experiment with various devices the arrangement shown in Fig. 1 was found to be very convenient for most purposes. *B* is a cubical lantern of wood or metal in which there are four 30 watt metal filament lamps (only two of which are shown in the diagram). *F* is a conical funnel at the front end of which is mounted the diffusing screen *S*. The interior of the lantern and funnel is painted with a matt white paint and this was found to ensure a sensibly uniform illumination all over the screen *S*. The nature of the screen itself is of some importance. Ground glass is quite unsatisfactory as the intrinsic brightness falls off very rapidly in directions inclined to the normal. The material actually used was Ilford Diffusing Medium. This screen is almost ideal for the purpose, and, when illuminated by a lantern of the type described, is equivalent, within a wide range of angle from the normal, to a self-luminous source of sensibly uniform brightness. Its diameter, as actually constructed, is about two inches. For some purposes a still larger source is desirable. It was found that a sheet of the diffusing medium of half plate size mounted in the long side of a whitewashed box, 40 cm. long, 17 cm. high and 13 cm. broad, containing a row of five incandescent lamps was of sensibly uniform brightness except near the edges.

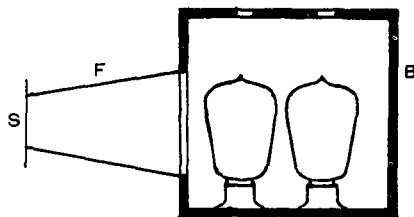


Fig. 1

III. THE PHOTOMETER

The instruments commercially obtainable as surface-brightness photometers were not regarded as sufficiently accurate for the work, and a Wanner Optical Pyrometer, made by the Cambridge Scientific Instrument Co., which is essentially a surface-brightness photometer of the Koenig-Martens polarisation type, was adapted to the purpose. The essential parts of this instrument are shown in Fig. 2.

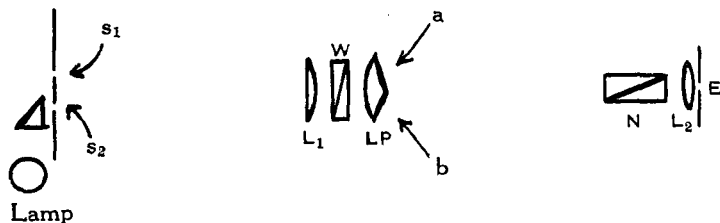


Fig. 2

s_1 and s_2 are two small circular holes in the focal plane of a collimating lens L_1 ; W is a Wollaston double image prism; LP is a combined lens and biprism; N is a nicol prism, which may be rotated about its axis; L_2 is a lens which enables the edge of the biprism to be sharply focussed by an eye placed behind a small circular aperture E .

Consider first light which enters the slit s_1 : it is collimated at L_1 and passes through the double image prism, W , which splits it into two divergent beams polarised in mutually perpendicular directions. These, on reaching the biprism, are again subdivided, those rays which pass through the half a of the prism being deviated downwards (in the diagram) while those which pass through the half b are deviated upwards. The lenticular portion of LP focusses the various beams, so that four images of s_1 are formed in the plane of the aperture E . Of these two are due to light from side a of the biprism and two from side b , while of each pair one is polarised say, vertically, and the other horizontally.

If the aperture s_2 is also illuminated a similar set of four images of this is formed, displaced vertically (in the diagram) from the corresponding members of the other set. The arrangement of the parts is such that an image of s_1 , due to light from side b of the biprism, coincides with the perpendicularly polarised image of s_2 from side a of the biprism, and also with the aperture E . The remaining three images of each set fall on the diaphragm and are not utilised. The eye placed behind E thus receives light from side a which comes from s_2 and is polarised, say, vertically, and receives light from b which comes from s_1 and is polarised horizontally. By rotating the nicol N the relative brightness of the two halves of the field may be adjusted to equality whatever the relative illumination of s_1 and s_2 may be; from the position of the nicol required for equality of brightness the relative intensity of the light entering s_1 and s_2 may be deduced.

In use one of the apertures is illuminated by a small four volt lamp and a right angled prism with matt surfaces, which serves as a standard of brightness.

When the instrument is directed towards a luminous surface rays from different points of it enter the aperture s_1 and reach corresponding points of the field b . Since all the rays intersect at s_1 the arrangement constitutes in effect a pinhole camera, and the brightness of the semicircular field b is proportional to the intrinsic brightness of the luminous surface, i.e., to the amount of light emitted per unit solid angle per unit area, and is independent of the distance of the surface from the instrument. In order that the semicircular field may be filled with light the luminous surface must subtend a greater angle at the pinhole than that subtended by the diameter of the field.

In the instrument as employed for optical pyrometry a deep red filter is mounted in front of the eyepiece, and a cap, in the centre of which there is a lens window, is provided at the other end. The effect of this lens is to focus fairly distant objects in the plane of LP , so that the particular part of a furnace on which the instrument is sighted may be seen distinctly. The circular scale for measuring the rotation of the analysing nicol only extends over a quadrantal arc, the temperature scale being engraved on the opposite quadrant.

In modifying the instrument for the present purpose the red filter and lens window were removed; the scale ring was cleaned and a finely divided scale extending round the complete circle was engraved. The latter alteration enables readings of both index marks (180° apart) to be taken, and settings to be made in the four positions of the nicol in which a brightness balance may be obtained. The mean of such observations was found to be correct when check measurements were made on rotating sectors or filters with known transmission coefficients, whereas readings taken with only one index arm at a time, or for one position of the nicol only, were usually in error.

The instrument as thus modified makes a very serviceable surface-brightness photometer, suitable for many purposes. There is, however, a possibility of more or less serious error arising in circumstances where the light entering the instrument is appreciably polarised, as in the case, for instance, where the light has suffered oblique reflections or refractions. This is a drawback to the use of polarisation photometers, well known to the users of such instruments; but, as far as I am

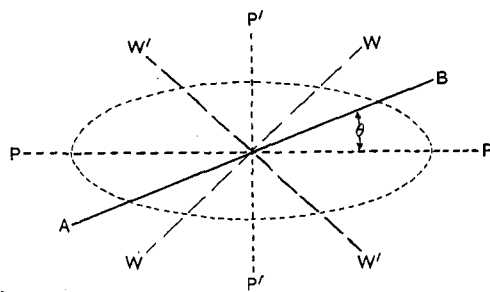


Fig. 3

aware, no attempt to overcome the difficulty has been made. By the simple device of mounting a quarter-wave plate in the front cover of the instrument, and orienting its principal directions to make an angle of 45° with the planes of polarisation of the Wollaston prism, the readings of the instrument may be made practically independent of the state of polarisation of the incident light.

Let AB , Fig. 3, represent a plane polarised vibration of amplitude a and period τ . The displacement of the vibrating particle from its position of rest is given, at time t , by $d = a \cos \frac{2\pi t}{\tau}$, t being measured from the moment at which the displacement is zero. The quarter-wave plate converts this vibration into an elliptic vibration with axes parallel to PP and $P'P'$, the principal directions of the plate.

The position of the vibrating particle in its elliptic orbit is given by

$$x = a \cos \left(\frac{2\pi t}{\tau} \right) \cos \theta,$$

$$y = a \cos \left(\frac{2\pi t}{\tau} - \frac{\pi}{2} \right) \sin \theta = a \sin \left(\frac{2\pi t}{\tau} \right) \sin \theta,$$

where x and y are the components of the displacement parallel to PP and $P'P'$ respectively and θ is the inclination of AB with respect to PP .

This elliptic vibration meets the Wollaston prism and is resolved into two plane polarised vibrations along WW and $W'W'$ at 45° to PP and $P'P'$. We are only concerned with one of these, say that along WW , and the displacement in this vibration is

$$\begin{aligned} d' &= x \cos 45^\circ + y \cos 45^\circ \\ &= a \cos 45^\circ \left\{ \cos \theta \cos \frac{2\pi t}{\tau} + \sin \theta \sin \frac{2\pi t}{\tau} \right\} \\ &= a \cos 45^\circ \cos \left(\frac{2\pi t}{\tau} - \theta \right). \end{aligned}$$

This represents a vibration of amplitude $a \cos 45^\circ$, that is, of intensity $a^2/2$, or half the intensity of the incident light. The orientation, θ , of the plane of polarisation of the incident beam merely affects the phase of the vibration resolved along WW and does not affect its intensity, which is exactly the same as if the incident light were unpolarised.

The adjustment of the quarter-wave plate may be made by trial, the instrument being sighted on a ground glass screen illuminated by polarised light and the plate rotated until the brightness of the screen, as measured on the instrument, is independent of the plane of polarisation.

It greatly facilitates matters, however, if the prism in front of the comparison pinhole can be removed so that both halves of the field are illuminated by light from the screen. The comparison side then receives the component of the elliptic vibration which is resolved along $W'W'$, and which, when the adjustment of the quarter-wave plate is correct, should be of equal brightness to that along WW for any orientation of the plane of polarisation of the incident light. The screen should first be illuminated with unpolarised light and the analysing nicol set to equalise the brightness of the two fields*. The illumination of the screen is now polarised by inserting a nicol prism in front of the source, or by other suitable means, so that the plane of polarisation is approximately parallel to WW or $W'W'$. In the absence of the quarter-wave plate one field would now be black and the other bright. On interposing the plate and rotating it into a suitable position the brightness of the two fields may be brought to equality, and will then remain in equality whatever the orientation of the vibrations of the incident light.

In order to facilitate this adjustment the comparison prism of the laboratory instrument was mounted on a sliding fitting so that it could be pushed into place or pulled out of the way by means of a short rod projecting through the side of the cap. This is necessary, since, if the cap has to be removed after adjustment of the plate in order to put the prism back in position, it is impossible to ensure that the adjustment will be correct after the cap is replaced.

In Fig. 4 two views of the instrument are shown for the information of those who may not be familiar with the Cambridge Pyrometer. In the lower view the

* The reading will be in the neighbourhood of 45° if the scale is in proper adjustment.

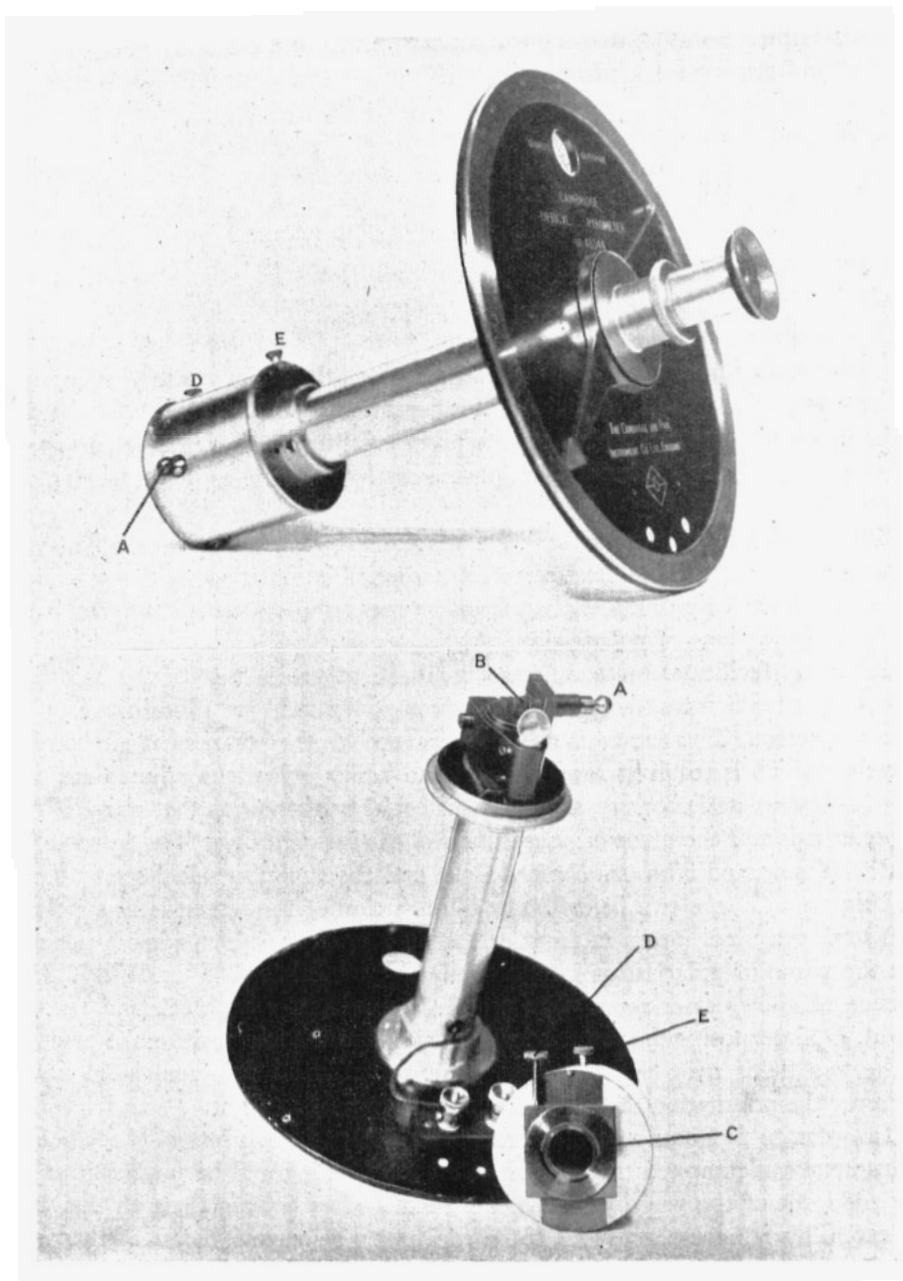


Fig. 4

cap is removed and shown separately. *A* is the projecting rod by means of which the comparison prism, *B*, may be withdrawn from its usual position in front of the second pinhole. The knob in which *A* terminates may be unscrewed to permit of the cap being removed or replaced. *C* is the rotatable mount for the quarter-wave plate, which, when adjusted, is clamped by a tangent clamp *D*. *E* is a locking screw to prevent accidental rotation of the cap.

The phase retardation of a crystal varies, unfortunately, with wave length, so the quarter-wave plate has only the required properties for one colour. For other colours the brightness varies slightly as the plane of polarisation of the incident light is rotated. As a result, when white light is used, a colour difference is set up between the two halves of the field for certain orientations of the plane of polarisation. It is therefore necessary, if the degree of polarisation of the incident light is high, to employ a colour filter to render the light more nearly monochromatic. The centre of the spectral region transmitted by the filter should of course be about the wave length for which the retardation of the plate is exactly a quarter-wave length.

The plate used by the author is of selenite and was taken from a set belonging to an old microscope with polarising accessories. Its retardation is such that when a light green filter (Wratten No. 57) is mounted in front of the eyepiece, the luminosities of the two sides of the field remain equal to within two or three per cent. whatever the orientation of the plane of polarisation of the incident light, although a slight colour difference exists in certain orientations. This is for completely polarised light, so that for the partial degrees of polarisation usually met with in photometric work the instrument is satisfactorily corrected. The use of a coloured filter may appear a disadvantage, but it must be remembered that it is only really necessary with light which is quite appreciably polarised, and in such cases the instrument would not be usable at all without the quarter-wave plate attachment.

In any case, even with completely unpolarised light, it is convenient to use the light green filter, as it is not then necessary to adjust the comparison lamp and the lamp supplying the illumination of the diffusing screen to exact equality of colour. The transmission factor of most optical instruments for green light does not differ appreciably from the value for white light. If it does so the transmitted light is coloured in any case and the "white" transmission factor cannot be measured. It is quite reasonable in such cases to employ for comparison purposes the transmission factor for green light as this, being near the region of maximum spectral visibility, gives a fair value for the luminosity of the transmitted light in the ordinary use of the instrument.

IV. MEASUREMENTS OF TRANSMISSION FACTOR

The procedure in determining the loss of light in an optical instrument by means of the apparatus just described is very simple. Fig. 5 shows the application to an instrument of periscopic type. The illuminated diffusing screen, *S*, is placed

in front of the eyepiece, approximately in the plane of the exit pupil. The photometer is placed in front of the object glass or window and sighted approximately parallel to the optic axis. The brightness of the screen *as seen through the instrument* can then be measured in terms of the comparison light in the photometer head. The lantern and photometer, being both portable, are then moved into the relative positions of Fig. 5 (a) and a direct measurement of the brightness of the screen made.

The ratio of the brightness as measured through the instrument to the brightness as measured directly is the transmission fraction of the instrument for rays approximately parallel to the axis.

It is scarcely necessary to mention that the current through the lamps in the lantern and through the comparison lamp must be maintained constant during the whole determination. The ammeter supplied with the pyrometer is scarcely sensitive enough to give the constancy desirable for photometric work and a better instrument should be employed.

The method just described will be found very convenient for any telescopic instrument such as binoculars, periscopes, rangefinders, etc. provided the angular field of the instrument is not too small. Bearing in mind that the photometer is essentially a pinhole camera it will be clear that the angular dimensions of the beam of light entering the photometer are equal to the angular dimensions of the field of view of the instrument under test *as seen from the objective end*. If those dimensions are less than those of the semicircular field of the photometer, the latter is not filled, and, instead, a pinhole image of the field of the instrument is seen. The photometer can always be adjusted so that this image is partially eclipsed by the dividing line of the photometer field, and the brightness measurements are unaffected by the fact that the illuminated area does not occupy the whole of the available space. If the area is very small, however, the sensitivity of the measurements is very greatly reduced and it is difficult to obtain satisfactory results. The finite size of the pinhole also introduces error when the angular extent of the beam is very small.

This difficulty may be encountered in high power instruments with small fields. In such cases it is convenient to reverse the arrangement of Fig. 5, placing the source of light at the objective end and placing the photometer so that the pinhole is covered by the exit pupil. The angular aperture of the entering beam is now limited by the angular extent of the field of view as seen through the eyepiece and is greatly in excess of what is required to fill the field of the photometer.

If, as usually happens, the exit pupil is too near the eye lens for the pinhole to be placed at it, the photometer may be withdrawn some distance and an auxiliary lens of 10 or 12 dioptries employed to form a real image of the exit pupil on the pinhole. This auxiliary lens should also be interposed between the photometer and

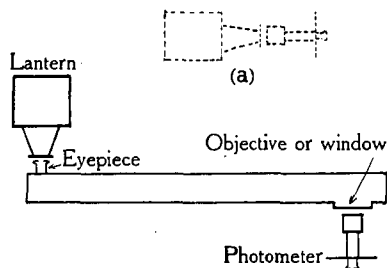


Fig. 5

the source when making the direct measurement of the brightness of the latter; its effect in reducing the intensity is then eliminated. If the instrument has a large entrance pupil the larger source, described earlier, should be employed, so that the effective exit pupil may be as large as possible.

V. MEASUREMENTS OF VARIATION OF FIELD BRIGHTNESS

The relative brightness at different parts of the field of view of an optical instrument has not, as far as I am aware, been experimentally determined. With a photometer of the type here described such measurements can be made with the greatest ease. The method is illustrated in Fig. 6. A luminous screen is placed at the exit pupil as in Fig. 5. It is necessary however that its brightness should be very much greater than is required for transmission measurements. On the other hand it need not be more than approximately uniform, and the most convenient

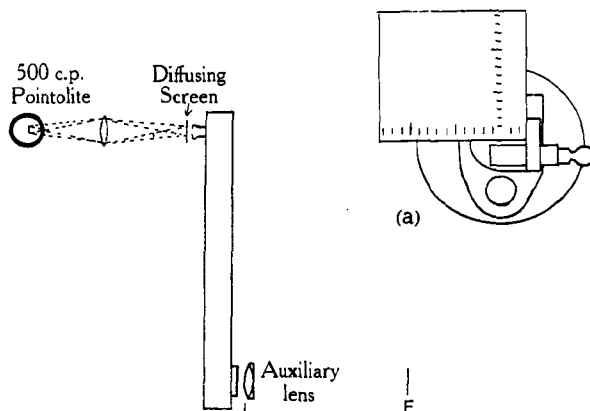


Fig. 6

arrangement is to focus an image of the luminous plate of a 500 candle power "Pointolite" lamp on a piece of diffusing medium situated in the plane of the exit pupil. The magnification should be such that the image is large enough to cover the whole of the area of the exit pupil with something to spare. The diffusing medium acts as a self luminous source emitting light in all directions, so that each point of the field receives light along every possible ray which can pass through the instrument.

An auxiliary object glass of diameter as great as, or greater than, the effective aperture of the instrument is mounted close in front of the latter at *L*, Fig. 6. If a sheet of diffusing medium is placed at *F*, in the focal plane of the auxiliary lens, an image of the field of the instrument under test will be formed on it. The total light falling on any part of this image will be proportional to the total light which reaches the retina from the corresponding part of the field when an observer looks through the instrument at a uniformly illuminated area, say a clear sky or an

extensive cloud, since, for the purposes of the test, we are merely using the instrument the wrong way round, replacing the image-forming parts of the eye by the lens L and the retina by the screen at F . The rays corresponding to any part of the field follow precisely the same path in either case, encountering the various stops, etc. in the same positions though in the reverse order.

Since the screen at F is almost perfectly diffusing, its *intrinsic brightness* at any point is proportional to the *total light* received per unit area of the screen at that point, so if we place the photometer close behind the screen and measure its brightness at different parts of the image we obtain measures of the relative amount of light reaching the retina from different parts of the field in the ordinary use of the instrument.

In order that the measurements may apply to regions as small as possible it is desirable that the pinhole should be close up to the screen. The most convenient arrangement is to remove the cap of the photometer* and attach the screen with plasticene or wax to the face plate containing the pinhole so as to cover the latter. Two scales may be marked off as shown in Fig. 6 (*a*), radiating from the pinhole. Needless to say, no mark of any kind is made at the point occupied by the pinhole which is at the intersection of the base lines of the two scales. The photometer can be placed so that the screen is in the plane F . The image of the field is focussed on the screen, and its diameter in the arbitrary scale units noted. By moving the photometer parallel to itself, either horizontally or vertically, any part of the image may be brought over the pinhole. The positions on the horizontal and vertical scales occupied by the edge of the field serve to locate the point occupied by the pinhole. It is generally sufficient to take measurements at a number of points along horizontal and vertical diameters, as the variation is usually approximately symmetrical with respect to the centre of the field.

The auxiliary objective L should be chosen, if possible, of such focal length that the image of the field formed at F , Fig. 6, is between one and two inches in diameter. If it is larger than this, the brightness of the photometer field is rather low, while if it is smaller there is difficulty in locating the precise part of the field to which a measurement corresponds.

It may not at once be obvious why the screen at F is required and why the photometer pinhole is not placed in the image plane without the interposition of such a screen. If this were done the quantity measured would be the intrinsic brightness of the field at the point occupied by the pinhole, that is the light per unit area per unit solid angle. The brightness of the field as observed in the use of the instrument is not proportional to the intrinsic brightness but to the total light reaching the retina from each unit area, and this depends not only on intrinsic brightness but on the angular aperture of the pencils entering the eye. As a matter of fact the intrinsic brightness varies very little over the field of most optical

* Note that measurements of the kind now under consideration are not affected by any polarisation in the incident light since they are purely relative. Not only so but the diffusing screen in front of the photometer almost completely depolarises light even if completely polarised to begin with. The quarter-wave plate attachment is therefore unnecessary.

instruments, the variations of field brightness being principally caused by variations of effective aperture due to the vignetting of oblique beams by the various stops.

If, however, the diffusing screen is interposed in front of the pinhole, its intrinsic brightness, which is what the photometer measures, is proportional not to the intrinsic brightness of the field of the instrument under test but to the total light reaching unit area of its image at F , or on the retina in ordinary use, that is, to the brightness of the field as observed in practice.

VI. MEASUREMENT OF REFLECTING POWERS

The use of the instrument for measurements of the reflecting powers of mirror surfaces is very simple. The light source of Fig. 1 is first sighted directly and then by reflection in the mirror. This latter need not be plane, since magnification of the virtual image does not affect the measurements. We therefore have a very convenient method of measuring the reflectivity of curved surfaces, a process very difficult to perform by other means.

For such work of course the quarter-wave plate attachment is absolutely essential as most metallic surfaces polarise quite strongly. Silver is an exception, very little polarisation occurring in the reflection from silver or silvered mirrors.

The apparatus lends itself to measurement of the light reflected by a train of similar mirrors in series, since no precise adjustment of the various units is necessary, the photometer being directed towards the source as seen through the last mirror of the train.

Both lantern and photometer may be inclined downwards, so that measurements may be made on a horizontal surface such as mercury.

VII. PREVIOUS WORK ON SIMILAR LINES

A polarisation photometer of similar type to that described here has been used to measure the transmission factor of optical instruments by F. E. Wright* in America. His work was done during the war, but an account of the method did not reach me until 1920, after the methods described here were in regular use in this laboratory. Wright did not use a comparison lamp in the photometer head, but mounted a periscopic prism system a few inches long in front of one of the pinholes. A source of considerable area is required as the procedure consists in sighting the photometer so that light which passes through the instrument enters one hole, exactly as in the author's method, while light which passes over the top of the instrument enters the other hole via the prisms. The arrangement is not suitable for use with periscopes, rangefinders, or any instrument in which there is considerable lateral separation of the entrance and exit pupils. The use of the comparison source in the photometer head as employed in the present method enables the transmission of any instrument whatever to be determined. The disadvantage that the separate light sources require careful voltage regulation is

* *Journ. Opt. Soc. Amer.* 2-3, 65, 1919.

more apparent than real, since such regulation has to be done in most photometric processes and requires no special equipment which is not likely to be found in most optical laboratories where photometric work is performed.

No previous attempt to render polarisation photometers free from errors due to polarisation in the incident light appears to be on record.

DISCUSSION

Mr A. J. Bull said that some time ago he had examined the polar curve of the diffusing medium which the author employed. He found that for a few degrees in the neighbourhood of the normal the medium acted as a self-luminous source.

Instructor-Commander T. Y. Baker thought that the method was very valuable, especially in dealing with cumbrous optical instruments. He had had a number of instruments tested by means of it and the results agreed very well with the theoretical values obtained by taking into consideration the total number of glass-air surfaces.

Mr H. S. Ryland described three methods which he had employed some years ago for comparing the transmission values of various prismatic binoculars. The first was a comparison method enabling a number of instruments to be checked quickly against two standards, an upper and a lower, forming a kind of optical limit gauge. In the second method photographs of the Ramsden discs of the instrument to be tested and of a standard were taken simultaneously and under the same conditions. The third was an autocollimation method of measuring the absolute transmission value of an instrument, part of the light after passing twice through the instrument being compared with the light which had not been transmitted.

The author, in reply, said he was interested to hear that Mr Bull had determined the polar curve of Ilford Diffusing Medium. The efficacy of the source described in the paper depended only partly on the diffusing properties of the screen and more on the fact that the light reached the screen from all directions owing to the high diffusive reflectivity of the white paint in the interior of the lantern and conical funnel. If a perfect paint were available, any kind of screen, e.g. a piece of ground glass, would be so illuminated as to scatter light uniformly in all directions and would be equivalent to a self-luminous source. The paint of course was not perfect, but when its deficiencies were compensated by using a really good diffusing screen, the result was a uniform emissivity over a very large angle from the normal.