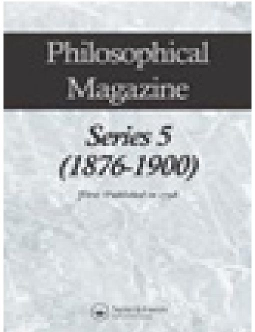

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Philosophical Magazine Series 5

ISSN: 1941-5982 (Print) 1941-5990 (Online) Journal homepage: http://www.tandfonline.com/loi/tphm16

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To cite this article: Silvanus P. Thompson D.Sc. F.R.S. (1893) X. Some notes on photometry , Philosophical Magazine Series 5, 36:218, 120-128, DOI: 10.1080/14786449308620455

To link to this article: http://dx.doi.org/10.1080/14786449308620455

X. *Some Notes on Photometry.*

By SILVANUS P. THOMPSON, *D.Sc., F.R.S.**

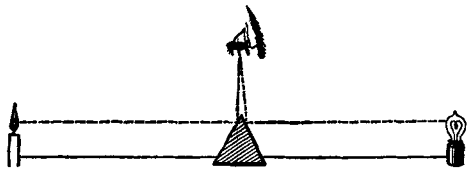
I. *On the use of Two Overlapping Screens as an Isophotal.*

THE employment of two opaque screens placed at an angle with one another, and with the observer's eye, to receive the light from the two sources, was made the basis of a photometric method by the author, in conjunction with Mr. C. C. Starling, in 1881. Their photometer was designed, in the first instance, for electric-light measurements. For this special end any method in which opaque screens are used is to be preferred, in one respect, to those methods in which translucent screens are used; for then it is not necessary to employ coloured glasses when making the comparison, as the opaque screens themselves may be of coloured material, and the choice of opaque coloured material is much more varied than is that of tinted glass.

In the Thompson-Starling photometer the two surfaces for receiving the light met at an angle of about 70°. The pair of screens was constituted by two pieces of card, either white or coloured, or by two surfaces of some brilliantly-tinted fabric mounted on card, each pair being dropped down into position over a wedge-block. The observer, placing his eye opposite the *arête* of the dihedral pair of screens so as to view each surface at the same angle, had to adjust the apparatus until the apparent illumination at the adjacent parts of the two surfaces was equal.

When working with this photometer it was found that the precision of judgment of the eye as to equality of the two illuminations was impaired if by bad workmanship any considerable width of blunted edge intervened between the two

Fig. 1.



surfaces that should have met with precision. There was a similar defect in the original form of the Bouguer photometer, wherein the opaque partition was continued down to the screen and interposed an unilluminated patch equal in breadth

* Communicated by the Physical Society: read June 9, 1893.

to its own thickness between the two illuminated surfaces. In that case the remedy, applied by Foucault in the modified instrument which bears his name, was to shorten the partition so as to permit the two illuminated parts to come just into optical contact. In the case of the oblique opaque screens the author tried to remedy the defect by several modifications, which, though not described at the time, proved useful. In one of these each surface was extended so as partially to overlap the adjacent surface, as indicated in figs. 2 and 3. In

Fig. 2.

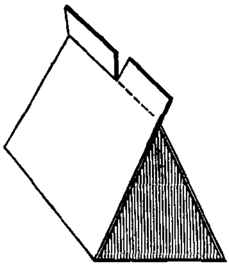
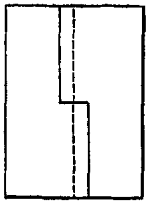


Fig. 3.



another instrument the overlap was given as shown in figs. 4 and 5.

Fig. 4.

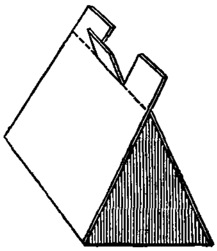
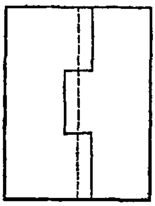


Fig. 5.



The principle of overlap in photometers operating by the diffuse illumination of opaque inclined screens has since been used by Sir John Conroy*, who employed two pieces of white writing-paper, inclined at about 60° to one another. He found, as I did, that 90° is too large a dihedral angle for exact work. Materials such as card and paper are never entirely devoid of specular reflexion. At an incidence of 45° on each surface there is so much specular reflexion of the light as quite to vitiate the observations.

* Phil. Mag. 1883, vol. xv. p. 423.

II. *Periodic Principle in Photometry.*

It is a familiar fact to every person who is accustomed to use the Bunsen photometer that the most convenient way of taking observations is to swing the carriage which supports the screen and mirrors backwards and forwards through a continually-decreasing distance about the position of balance. That position is ultimately found by the eye noting the successive departures from equality produced by rapid small displacements on either side of the position of balance. If these inequalities can be made equal *inter se*, the zero will lie midway; for though the intensity of illumination (assuming the sources of light as points) varies inversely as the square of the distance, the change of intensity for a small change of distance will (irrespective of sign) be the same, to within a small quantity of the next higher order, whether the displacement be toward the standard light or from it. For, taking the initial distance as unity when the illumination is i, then (neglecting small quantities of higher orders), when the distance 1 is made $1+\delta r$, the proportional change of illumination is $\mp\frac{2\delta r}{1\pm 2\delta r}$; or, the change of illumination is approximately inversely proportional to the distance, and is approximately proportional directly, but with contrary sign, to the displacement.

It is a consequence of the law of fatigue that the eye is much more sensitive to small differences of illumination when these are successively produced than when they are constant in amount. Hence it is easier to estimate the true zero position on the photometer by these successive movements than by simply trying to put the carriage at zero. A difference due to a displacement of two millimetres of the stationary carriage might fail to be perceived. But the eye cannot fail to detect the difference when the carriage is quickly swung to and fro over the distance of two millimetres on either side of the zero; and, judging of the two inequalities on either side, and altering the adjustment until the two inequalities are themselves equal, the zero is determined. As a piece of pure physics, this method of successively approximating to a zero, ill-defined in itself, by means of equal errors on either side, may be compared with the method of Joule for determining the temperature of minimum volume of water.

In the researches of Abney and Festing on the photometry of colour, the same principle of estimating the position of balance by producing rapid movements giving successive inequalities on either side of the final position was used; and indeed it constitutes the basis of the method of measuring the illuminating effect of any coloured light at different parts of the spectrum. In this case also the motion was produced by hand, by shifting a lever rapidly to and fro.

Indeed it seems probable that, without any specific recognition of its meaning or importance, the method of roughly producing periodic variations in the relative intensities of the two lights has been quite commonly used by many individuals in their work with photometers.

It has seemed to the author worth while to generalize this principle, and to give definition to it, as a recognized principle in photometry. He has therefore essayed to construct a *Vibration-photometer* in which periodic changes in the illumination are deliberately produced, in order thereby to effect systematically that which has hitherto been done unsystematically and by hand.

There are several ways of arriving at the desired result:—

(1) The "screen" of the photometer may be so mounted on its carriage as itself to vibrate through a small distance, at some convenient frequency.

(2) The standard light may be moved in some periodic way to and fro through a small distance; though in the case of flame-lamps this is inadvisable.

(3) The light of the standard lamp may be made to vary by a small percentage in a periodic manner; one way being by revolving in front of it a fan with narrow arms to obscure periodically a portion of its light; another way being to vary periodically the aperture of a Methven slit.

(4) The light that is to be measured may be made to vary periodically by some known fraction of itself in ways analogous to the preceding.

When any of these things are done the position of balance can be found by simple direct adjustment without the usual delays.

The particular form in which the author has worked out the periodic principle is by mounting upon a spring on the photometer-carriage the paraffin-block translucent "screen" of Dr. Jolly. He finds that a period of $\frac{1}{3}$ of a second is convenient for the purpose. He has also tried an eight-bladed fan, with narrow blades to obscure in passing a fraction of the light. In using with either of these periodic devices the paraffin-block apparatus of Jolly, there is found a curious optical illusion which assists the judgment. As the brightness of the illumination of the two adjacent halves of the divided block passes through the state of equality, from being brighter on the one side to being brighter on the other, the narrow dark line which divides the two luminous portions appears itself to shift, the apparent displacement being away from the more luminous side. Whether this optical effect arises from irradiation, or from any other cause, it certainly assists the eye in its judgment as to the position of balance.

Some further observations with this device are still in progress.

III. *The Electric-Arc Standard of Light.*

In 1878 experiments were made at Chatham by Abney, Cardew, and others upon the electric arc, in the course of which the practical invariability of the intrinsic illumination of the crater-surface of the positive carbon of the arc was established. Abney and Festing, in their researches on the photometry of colour, have since that period used as a standard of white light the light of the crater of the arc. As pointed out by the writer some years ago, this invariability of whiteness, which implies invariability of temperature, is necessarily due to the constancy of the temperature of volatilization of carbon. The introduction into the substance of the carbons of any material having a lower temperature of volatilization, or of any compound which has a temperature of dissociation lower than that of the volatilization of carbon, necessarily lowers the intrinsic brilliancy of the light. This having once been realized, it seemed only natural to suggest as a standard of light the light emitted from a given area of the crater-surface of a pure carbon. This suggestion was made by the author last year when writing from Rome some remarks for the discussion of the paper of Mr. Trotter on the light of the electric arc, read before the Institution of Electrical Engineers. A similar suggestion was independently made by Mr. Swinburne in the same discussion. For some time past the author has been considering the experimental methods for putting into practice the suggestion then made. The only way to secure a constant effective area of crater is to produce a much larger crater than is required, and cover it by an opaque screen pierced with a suitable aperture of standard dimensions. As this screen must be placed very near the arc, it must be kept cool artificially by circulation of water *.

* M. A. Blondel has recently presented to the Société de Physique of Paris an apparatus denominated *arc normale*, in which is embodied this method of carrying out the proposal of Mr. Swinburne and of the author.

As the intrinsic light of the arc is not far from 70 candles per square millimetre, a circular aperture 1 millimetre in diameter will afford a light of about 55 candles. Hence an aperture smaller than this is preferable in a photometric standard for all ordinary photometric work. For the purpose of a special photometric standard with which to compare other arc lamps, a standard light of 1000 candles or some such magnitude is doubtless advantageous. This would require about 14·3 square millimetres of crater-surface, or a circular aperture of about 4·25 millimetres in diameter. For ordinary photometric work an aperture of 0·674 millimetre diameter would give a light of about 25 candles. It is easy to ensure the illumination of the apparent aperture by employing a magnet to deflect the arc to the front face of the carbon.

There is an advantage in using as a standard source of light one whose light is greater than that of the light under measurement. The light under measurement may obviously be balanced either against a smaller light brought nearer to the screen, or against a greater light placed at a greater distance. But if the greater light at the greater distance be employed, there will, for any given inequality of illumination on the screen, be required a greater actual displacement of the moving part, whether screen or light, in order to arrive at the position of balance. Hence any error in reading the scale will be a lesser fraction of the quantity to be measured.

It might have been supposed, *à priori*, that for a given total length of photometric bench (as in a Bunsen photometer from lamp to lamp) the position of the photometric screen which would make errors a minimum would be the position in the centre; balance being sought between two approximately equal lights. Geometrically it is true that a given displacement along the scale produces a minimum change in the difference of the two illuminations, if the point selected be at the centre of the scale. On the other hand, if the total length of the bench be not fixed, it is obvious that the length of bench which will, for a given change in the difference between the two illuminations, yield the greatest actual displacement along the scale will be an infinite length. But in that case, unless infinite lights are used, the two illuminations will both be zero. In fact there is another element to be considered, namely, that in order to make a satisfactory comparison, the eye requires a certain actual brilliancy of illumination in the two surfaces which are to be compared together. Doubtless the habitual patterns of photometer in use have come by natural selection to be of the size that they are in consequence of the absolute magnitudes of the standards habitually employed. If a six-foot bench is the right sort of apparatus to satisfy the needs of the eye when the standard is of one or two candle-power, obviously a longer bench will be right when standards of greater power are employed, as giving, on the average, similar absolute illuminations of the working surfaces. If the degree of accuracy implied in the possibility of reading to within 2 millimetres' length of scale can be attained with a Bunsen or Jolly photometer when the standard is a 2-candle Methven slit, or a pair of standard sperm-candles, an accuracy of five times as great ought to be attainable if there is used as a standard a 50-candle light. The bench need not in this case be five times as long as the ordinary bench: the half length only need be elongated five-fold on one side of the screen, the other half remaining as before. In other words, if the standard is of 25-fold brilliancy, it must be placed 5 times as far away from the screen as before in order to balance a given light at the same distance as before on the other side. And, so far as such standard light is concerned, a five-fold accuracy will be attained, since any error or uncertainty in reading the scale will be now but a fifth part of the whole scale-reading.

All the foregoing points, then, to the use of a brighter standard light and a longer photometric bench than heretofore. Such a standard might well be afforded by an arc crater viewed through a circular aperture 1 millimetre in diameter, giving about 0·7854 sq. millimetre of crater-surface, with a light of about 55 candles. This should be placed at one end of a bench some five metres in length; the graduations of the scale being, of course, reckoned from the edge of the aperture *.

One not unimportant advantage of the use of such a pin-hole standard is that it may with real propriety be treated as a luminous point; whereas no one can maintain that the flame standards habitually used are even approximately points relatively to the distances at which they are set from the screen. For these the law of inverse squares cannot possibly be true; though it is never the practice to make any corrections for the errors arising from the size of the flame.

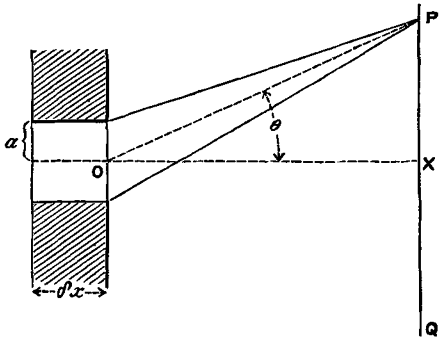
In contemplating the use of circular apertures pierced in metal diaphragms, it becomes necessary to inquire how far

* It is curious to note in this respect that there is usually an erroneous instruction observed with the use of the Methven slit; the distance of the photometric screen being reckoned from the flame behind the slit instead of from the slit itself.

the thickness of the metal will interfere with the illumination of the screen in directions not absolutely in line with the axis of the aperture.

Let the screen PQ (fig. 6) be at a distance $x=\text{OX}$ from

Fig. 6.



the diaphragm at O ; the thickness of the diaphragm being called δx, and the radius of the circular aperture in it a. It is required to find the illumination at a point P on the screen at a distance $\text{PX}=y$ from the point X which is on the axis of the aperture. Let the angle POX be called θ. Then the apparent aperture as viewed from P will be bounded by two portions of ellipses (the front and back edges of the hole viewed in perspective), having each as semi-major axis a, and as semi-minor axis $a \cos \theta$. These two ellipses will overlap, their centres being displaced by an amount equal to $\delta x \sin \theta$. If we represent the ratio of the thickness of the metal to the radius of the aperture as $\delta x/a=\tan \phi$, then we may write the following expression for A, the effective area of the hole, as visible in the direction OP, as follows :—

$$\text{A}=2a^2\left\{\cos\theta.\left[\frac{\pi}{2}-\sin^{-1}(\tan\phi.\tan\theta)\right]-\tan\phi.\tan\theta\sqrt{1-\tan^2\phi.\tan^2\theta}\right\}.$$

Hence, since the real hole has area $=a^2\pi$, the ratio η of the illumination at P to the central illumination at X will be

$$\eta=\frac{2}{\pi}\left\{\cos\theta.\left[\frac{\pi}{2}-\sin^{-1}(\tan\phi.\tan\theta)\right]-\tan\phi.\tan\theta\sqrt{1-\tan^2\phi.\tan^2\theta}\right\}.$$

Case (i). To get some idea of the magnitudes involved, let us take a concrete case. Suppose the aperture to be a hole 1 millimetre in diameter and the diaphragm $\frac{1}{2}$ millimetre thick; so that $\tan\phi=1$. What will the ratio be of the oblique to the central illumination for a point P 2·5 centimetres from the centre X of a screen which is itself at a distance OX = 50 centimetres from the aperture? As a Bunsen disk is seldom more than 5 centimetres in diameter, this is rather an extreme case. Here $\tan\theta=2{\cdot}5\div50=0{\cdot}05$. So $\theta=2^\circ 52'$, and $\cos\theta=0{\cdot}9975$. Whence $\eta=0{\cdot}935$.

Case (ii). Suppose the hole in the diaphragm to be still 1 millimetre in diameter, but the diaphragm to be 2·5 millimetres thick. Here $\tan\phi=5$. Taking θ as before, we get $\eta=0{\cdot}684$.

Case (iii). Suppose, on the other hand, that the hole is made in metal foil only 0·1 millimetre thick, or that, having been pierced through thicker metal the edge has been cut away by countersinking, leaving only a narrow rim 0·1 millimetre in thickness. In this case $\tan\phi=0{\cdot}2$. In the case where thin foil is used there is a considerable risk of the metal buckling with heat: and it would be quite possible, from this cause alone, that the axis of the aperture should become oblique by as much as 10° from the axis of the photometer. Assuming then $\theta=10^\circ$, the ratio of the central illumination, as thus perturbed by the error of centering, to its unperturbed value will be $\eta=0{\cdot}940$.

From all this it may be concluded that unless due care be taken in the selection and proper centering of the diaphragm, errors of several per cent. may arise in the photometric measures executed with its means. The errors arising from thickness of the diaphragm diminish, whilst those arising from defect of centering are increased, as the distance from the photometer-screen to the aperture is increased. In the above investigation no account has been taken of the effects of diffraction, which in the case of very minute apertures might become important.