

## The testing of photographic lenses

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## THE TESTING OF PHOTOGRAPHIC LENSES.

PAPER BY S. D. CHALMERS, M.A., *Member.**Read at the Optical Society on February 18th, 1904.*

IN a paper read before your Society some time ago your worthy President deplored the absence of any complete accessible account of the various methods of testing lenses; his paper did a good deal to supply this deficiency, but the extent of the subject made it necessary to omit many details which might be interesting to you. This has induced me to give an account of the various methods in use for the testing of photographic lenses, hoping that with a smaller subject it might be possible to refer to matters of detail. With the same idea I

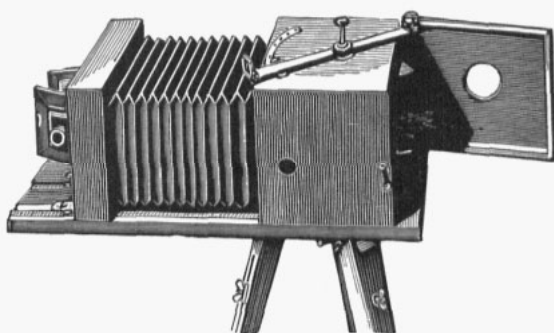


FIG. 1.—THE TOURNIQUET—GENERAL VIEW.

have decided to omit all reference to the testing of defects due to colour, hoping at some future time to be able to deal with that subject in detail.

This paper does not profess to do more than describe the various methods and offer some criticism as to the advantages and limitations of each, suggesting some directions in which progress may be looked for.

The object of a photographic lens is to produce on a flat plate an image of an extended object, every point of which should be well reproduced at the corresponding point of the image plane, and, in general, it is desirable that this image shall be as bright as possible, consistent with the above requirement.

Parts of the object may, however, be at different distances from the lens, and it will be found impossible to form quite sharp images of the points which are in different planes, except by reducing the aperture, and thus diminishing the brightness of the image. But though it is impossible to obtain good images of points at different distances in the one photograph, it would be possible, by adjusting the position of the plate, to obtain in different photographs sharp images of points at different distances. Still, it will be found that there is one distance for which any lens most nearly satisfies ideal conditions.

Photographic lenses may be divided into two classes: those which are designed to give the best corrections for infinitely distant points—the correction being good for any point at a considerable distance from the lens—and those which are designed to give the best results when used at shorter distances—corrected for a distance about three or four times the focal length. In the one case the various points of the object may be regarded as at the same distance from the lens, while in the other they should lie in a plane at right angles to the axis of the lens.

These two classes of objectives require rather different treatment, and it will be found that certain methods and apparatus which are well adapted to one do not apply equally well to the other.

Before proceeding to describe the testing of lenses it would be well to recall, as briefly as possible, the nature of the defects from which the lens system might suffer, as well as the constants which it is desired to measure. In the ideal lens all light proceeding from an object point would pass accurately through one point on the plane of the image.

In the case of a point on the axis (or with light parallel to the axis), the light which is incident on the various zones will in general come to a series of foci on the axis, and the appearance on the image plane will be a number of concentric circles of varying brightness, the defect being known as spherical aberration; when the foci of the central and extreme outside zones coincide this reduces to the less serious defect, zonal aberration.

Again, the magnifications produced by the various zones may not be the same, and hence the image of a

point outside the axis will suffer from the defect of coma. This defect is one which it is extremely difficult to express numerically, but which is very important in lenses of large aperture—fortunately, it is a defect which is almost eliminated in symmetrical lenses of apertures up to about F. 7, the residual amount being practically determined by the correction of astigmatism and the aperture ratio.

For a point some distance from the axis we have the defect known as astigmatism—the pencil of rays passing approximately through two focal lines, except when there is coma or spherical aberration of a serious kind; in this case they can hardly be called lines. It is usual to determine, by observation or calculation, the position

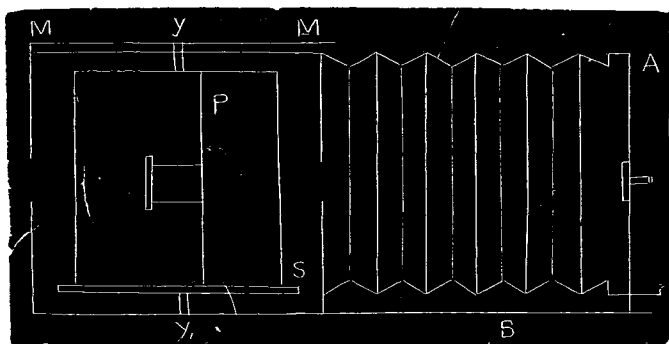


FIG. 2.—THE TOURNIQUET.

of the smallest spot of light, and to consider this as the image position; the various points so found lie on a surface which forms approximately portion of a sphere whose curvature is easily obtained.

But even if there be a perfect image it does not follow that it is in the position corresponding to the object point; the magnification may be increased or decreased towards the outer part of the field, and give rise to the defect known as distortion. It is necessary to be able to measure these various defects and to estimate the loss of light due to the absorption by the lens or reflection at its surfaces. In addition, we require the constants of the lens, its equivalent focal length, the aperture and the field of view throughout which the

image receives light from all parts of the effective aperture.

As the latter is only wanted approximately, it is sufficient to look at the lens from points in the image plane till the light begins to be cut off by the lens mount, and so estimate the field of view. The various tests for effective aperture have been given by Dr. Drysdale, and the various methods used to obtain the equivalent focal length are given in describing the different systems of testing.

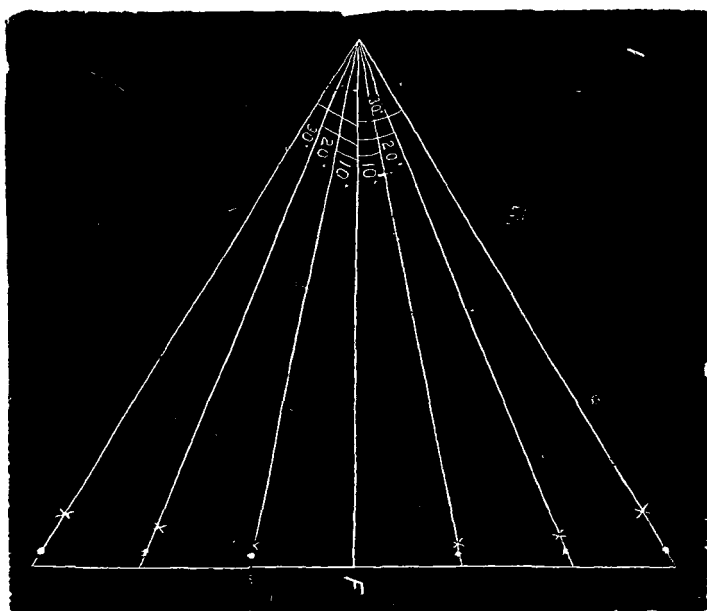


FIG. 3.—TORNQUET DIAGRAM.

The methods of testing for defects may be divided into three, or, rather, four groups, according to the facts which are determined in each case. The first and most obvious method of testing is to obtain an image of small sources of light placed in the positions which the objects photographed would generally occupy, and to examine these images either directly or allow them to be impressed on a photographic plate and subject it to examination.



to photographic tests, and with the usual test the imperfections of the observing instrument—a telescope—are less apparent.

The fourth method is to determine the paths of the various rays through the system and thus to determine the positions in which they intersect the plate. This method is extremely valuable from the point of view of the design of lenses, and has the great merit that it can be applied to an uncorrected, quite as well as to a corrected lens. Its defect in principle is that it only gives the performance of the lens indirectly, but the accuracy and detail are very great.

It now remains to see the methods based on these various principles as they have been actually used, but as most systems of testing make use of more than one of these principles it will be convenient to describe a number of the most common systems.

THE TOURNIQUET.—In this instrument the second principle is almost exclusively applied. The apparatus is shown in the two diagrams; it consists of a hollow cubical box (with openings at the front and back) which is connected by a camera bellows to the carrier A; in the cubical box is mounted a smaller box, with two sides removed, which is capable of a complete revolution about the axis  $y y_1$ ; in this box is a panel P—to carry the lens to be tested—which can be moved forward and backward by the screw S.

The carrier can be racked along the baseboard B, and carries a vernier which determines its distance from the axis  $y y_1$ . In the middle of this carrier are two small hinged panels, one carrying a small framed ground glass, the other a micrometer scale, which can be read by a magnifier; either panel may be brought into position and the image observed on the ground glass or measured against the scale—the latter being capable of rotation, to measure lengths in all directions. The instrument is mounted on a substantial base and is provided with a pointer  $M M_1$ , to measure the rotation of the lens about the axis, and a sighting arrangement to set the axis of the lens in the direction of the small source of light; the latter may be a distant object or an artificial star.

To measure the focal length of a lens, it is mounted in the panel and the image is brought on to the ground

glass, the lens is rotated about the axis; if the image be stationary the focal length can be read off on the vernier. If the image moves, it is necessary to adjust the lens relatively to the axis till there is no motion of the image. For more accurate measurement the position of

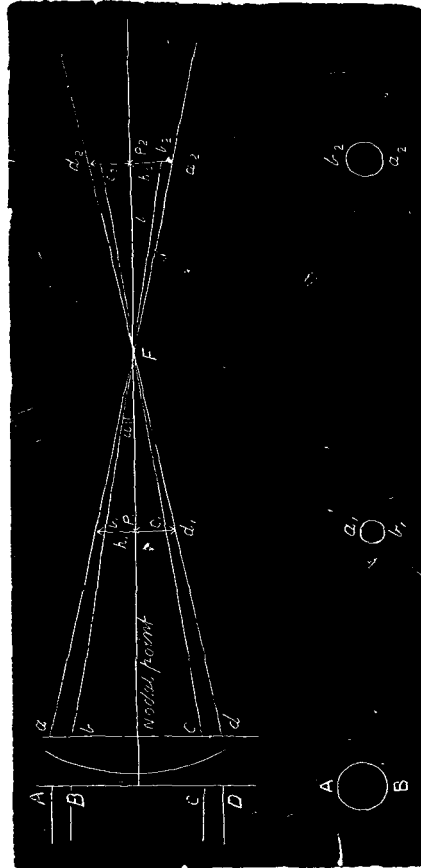


FIG. 5.—DIAGRAM SHOWING PRINCIPLE AND EXTRA-FOCAL METHOD.

the image can be measured on the micrometer scale and any movement readily detected.

To measure the spherical aberration the diameter of the image of the point of light can be measured, or the focusing points of various zones of the objective can be determined.



To determine oblique aberration the lens is rotated through any selected angle about the axis  $y$   $y_1$ , which has been made to coincide with the back nodal point, and the image can be received on the ground glass; if the position of the carrier be adjusted till the image appears successively as a fine vertical line and a fine horizontal line, the distance of the two focal lines from the nodal point are determined, and by the aid of the diagram the curves for the focal surfaces may be drawn. If, in addition to this the shape and size of the smallest disc of light be measured some estimate can be formed of the amount of coma present.

To measure the distortion it is necessary to measure the amount of motion of the image when the lens is rotated through a considerable angle. From this the position of the image may be obtained graphically or by calculation. This instrument might be used simply to determine the size of the image at all points on the image plane, but this would involve much calculation and nice adjustments. Since the source is always at the same distance it is evident that the instrument is unsuited to the testing of process lenses which should be corrected for a flat object with the various points at different distances from the lens.

THE KEW TESTS, AS USED BY THE NATIONAL PHYSICAL LABORATORY.—In the apparatus designed by Major Darwin many of the advantages of the tourniquet have been retained, and the measurements are in general conducted on the same principle. But it is interesting to notice that two tests of defining power have been included. For central definition, a thin, straight strip of steel  $1/10$  inch wide—capable of rotating about the direction of its length, to make it appear, when seen against a bright background, as a thin black line of varying thickness—is employed, and the defining power is measured by the smallest apparent width which can be distinctly seen.

The definition throughout the field is tested with a similar object which is fixed to have a definite apparent breadth, the stop being determined which permits of this being distinctly seen. A test of the transparency of the lens for visual rays is in use, but, unfortunately, this gives little information as to the transmission of much of the light which would be valuable in photography.

**THE BECK BENCH.**—While retaining the advantages of the system of rotating about the nodal point, Messrs. Beck have devised a bench which also permits of a satisfactory test of process lenses. The apparatus consists of a divided bar which carries a number of fittings; one of these carries an axis about which the platform L rotates; on this is another platform which carries the lens holder and is capable of motion by means of a rack and pinion R.

The lens holder consists of a series of screwed rings to take lenses of various sizes. A cross bar slides on the main bar and carries a fitting on which is mounted a microscope to be used for the examination of the aerial image. Thus the microscope can be used—as in the tourniquet—in a fixed position, or can be travelled along the cross bar to examine the images of points not on the axis of the bar. This motion permits of the testing of process lenses under favourable conditions.

But in the case of ordinary lenses it seems to me desirable to reverse the procedure, and, instead of employing a collimator and examining the image by a microscope, to employ a telescope of long focus to examine the image of a fine test object placed in what is usually the image position. The advantages seem to be the greater perfection of the telescope as an observing instrument, and the fact that the errors to be measured are increased in the ratio of the squares of the focal lengths, thus reducing the error in measuring the position of the focus. To obtain the full advantages of this method the object must be arranged to remain always on a plane at right angles to the axis of the lens, and the measurements made by the change in focus of the telescope. The defining power of the combination, when the telescope is focused for infinity, might be made to furnish a simple, yet effective test of the whole performance.

As an additional test, and especially for process lenses, Messrs. Beck employ a test object and examine its image in the position where the photographic image would be received on the plate.

Of the methods based on the first three principles, it remains to refer to the photographic tests, a good example of which is furnished by Rudolph's method; it consists of a test by the first method, *i.e.*, a photograph

of a geometrical design which is placed in a plane at right angles to the axis of the lens, the central portion being focussed and the resulting photograph examined for definition; the remaining portion is a photograph of a number of series of cards, each set being arranged in a spiral with its axis parallel to the axis of the lens, the test being which member of each group is most sharply defined.

In the method used by Dr. Harting, the last object consists of a series of geometrical designs, which is focussed as sharply as possible, and a series of photo-

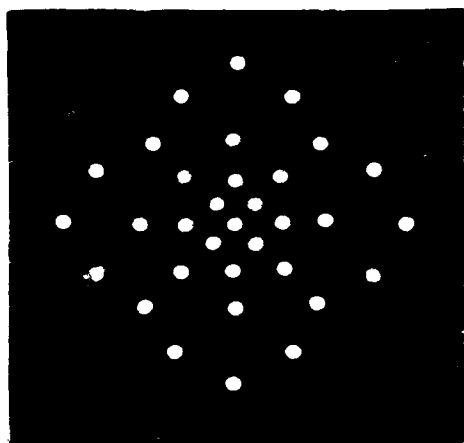


FIG. 6.—A PHOTOGRAPH BY PROFESSOR HARTMANN.  
TELESCOPE OBJECT GLASS, TESTING ZONAL ABERRATIONS.

graphs taken, one in this position and others with the plate in slightly different positions inside and outside the focus.

Such methods are satisfactory in giving an estimate of the general performance of a lens, but are not in general sufficiently accurate to give numerical measures for the various errors. But the great defect of all these methods is that the measures are to a very great extent subjective, and are all, more or less, affected by the personal element in the choice of the best focus. Dr. Harting's method does, to some extent, remedy this, but

it gives practically no numerical estimate as to the performance of the lens.

The fourth principle can, however, be used as the basis of a method which seems to leave no room for possible personal variations, and in addition to this it would seem to be the most desirable from the point of view of the results obtained and the information it furnishes; but at first sight it seems practically impossible of realisation; when sufficiently small pencils of rays are taken to be regarded as approximating to the ideal single ray the intensity of any image formed would be too small to permit of its being observed or focussed for photography.

Even if two small symmetrically placed openings are used, it is practically impossible to determine the point

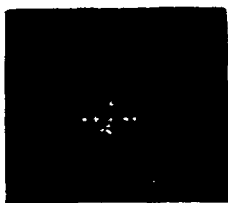


FIG. 7.—TWO  
EXTRA-FOCAL  
PICTURES.  
ANOTHER STOP.

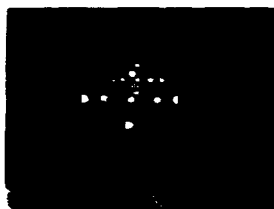


FIG. 8.—THREE EXTRA-  
FOCAL PICTURES, DIFFER-  
ENT POSITIONS OF PLATE.  
SAME STOP.

at which the two images can be brought into exact coincidence. But Professor Hartmann has given a most ingenious method of determining the foci of various small portions of a lens. By the use of photography he has avoided the principal difficulties associated with the small amount of light admitted by very small openings in the plane of the stop. By taking two photographs—one well inside and one well outside the focal plane—he has avoided the necessity of focussing, and with it the possibility of personal error.

Before the lens—for central aberrations—or at the plane of the stop—for oblique aberrations—are placed two small symmetrically situated circular apertures. When a small source of light is photographed we obtain on each plate a reproduction of the stop on different

scales. From the diagram it will be seen that light proceeding from the object point to the point A on the stop will, after passing through the lens, cut the planes  $P_1 P_2$ —where the photographs are taken—in the points  $a_1 a_2$ ; similarly light passing through B C D will meet these planes in  $b_1 c_1 d_1$  and  $b_2 c_2 d_2$  respectively, and thus the pairs of points  $a_1 a_2$ ,  $b_1 b_2$ ,  $c_1 c_2$ , and  $d_1 d_2$ , each determine a definite ray passing through the points A B C D respectively.

If, now,  $l$  be the distance between the planes  $P_1$  and  $P_2$  the intersection of the rays  $d_1 a_2$  and  $d_1 d_2$ , is at a distance from  $P_1 = l \times \frac{a_1 d_1}{a_1 d_1 + a_2 d_2}$ . If  $h_1$  be the height of  $a_1$  and  $h_2$ , the height of  $a_2$ , from the axis, the inclination of the ray  $a_1 a_2$  is given by  $\tan u = \frac{h_1 + h_2}{l}$

Hence, we obtain both the position of the focus and the equivalent focal length for the point A, from these two photographs, and by the use of a number of pairs of apertures this pair of photographs may be made to determine the whole course of the correction for spherical aberration and for coma.

For the testing of astigmatism and oblique aberrations it is only necessary that the object should be in a direction suitably inclined to the axis of the lens; in the case of process lenses the object should remain in one plane perpendicular to the axis of the lens—the plane for which the lens is to be tested. For oblique aberrations generally, it is desirable that the stops used should occupy the position of the effective stop of the system, the apertures should be a series of small openings grouped in two circles—radius of one being  $2/3$  that of the other. A small central hole will serve to determine the distortion.

The practical difficulty is the securing of a sufficiently bright, small source of light which should be practically monochromatic, preferably green or blue. There are two methods which may be used, the best being to employ a collimator of large focal length, at the focus of which is a small opening illuminated by light condensed from an arc lamp, preferably with metal electrodes. This has the defect that any errors of the collimator will affect

the results obtained, and any error in determining its focus will affect the absolute value of the focal length determined. But when the focal length of the collimator is a number of times greater than that of the lens to be tested, the effects of its errors being reduced in the ratio of the squares of the focal lengths, these can be neglected.

The other method is to use an arc lamp at a finite distance with a small aperture in front of it; this has the defect that the photographs only enable us to find the position of the conjugate point directly, but the focal lengths and position of the principal foci can be calculated.

In either case the size of the object will prevent the exact coincidence of the points  $a_1$ ,  $b_1$ , etc., with their theoretical positions, but if the difference is sufficiently great to be appreciable with the source of light used,

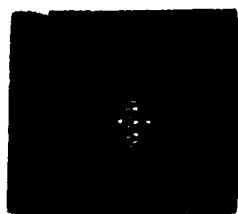


FIG. 9.—TWO EXTRA-FOCAL  
DIFFERENT POSITIONS,  
SAME STOP.



FIG. 10.—TWO EXTRA-FOCAL,  
PICTURES OF ONE  
STOP.

the effect can be eliminated by considering the mean of the values for  $a_1$  and  $b_1$ , and taking this to correspond to the mean of the values of A and B and to that of  $a_2$  and  $b_2$ .

The accuracy of the method is limited only by the accuracy of the measurement of the distance between the two positions of the photographic plate and the accuracy of the measurements of the photographs and stops; the error in estimating the focal length being practically the error of the latter measurement, multiplied by the F number corresponding to the circular aperture which would just include the small portions of the lens considered.

It will be noticed that the accuracy of estimating the differences of focal lengths of the different portions of

the objective is very great, the error in a lens of 250 mm. focus should not exceed .1 mm. Unfortunately, want of time prevents my referring to the application of this method to the determination of chromatic aberrations for which it is singularly well adapted.

One advantage of this method for the purpose of a thorough going test is that the actual measurements are such that they cannot well be influenced by personal considerations, since the observer can hardly know the meaning of the measurement without calculation; this constitutes a defect from the point of view of approximate rapid testing.

In conclusion, I would commend to the Society's notice the necessity for arriving at some standard by means of which the excellence of lenses belonging to different classes, or meeting slightly different requirements, might

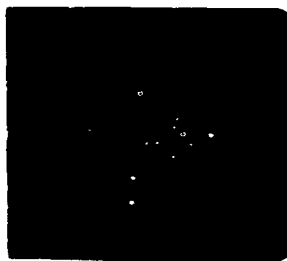


FIG. 11.—TWO EXTRA-FOCAL PICTURES.

be fairly compared; and, also, call attention to the desirability of devising tests which might be useful in locating errors which have arisen by departing from the design, either as regards the glasses employed or the curvatures and thicknesses of the lenses.

One such test I can suggest for such lenses as satisfy the Petzval condition. I have shown that this condition requires that the two focal lines should be at distances from the focal plane which are in the ratio of three to one. As this condition involves only the refractive indices and the curvatures, advantage might be taken of this fact to determine whether the error lies in the thicknesses or not. In making the measurement it is desirable to choose the portion of the field mid-way between the axis and the outside.

I throw this out as a suggestion in the hope that it may induce some of you to devote special attention to devising better tests with this end in view.

### Discussion.

THE PRESIDENT, in opening the discussion, said that Mr. Chalmers' subject was one which must be of the greatest importance to all present. The author had presented it to them in a very interesting manner.

DR. GLAZEBROOK said that the Society was to be congratulated very much on the paper they had listened to. It had been extremely interesting, and would, he was sure, prove of great value. He himself was not thoroughly acquainted with the method of testing lenses that had been described. It seemed to him to be a method requiring very full and very careful investigation, but likely to lead to valuable results. Mr. Chalmers had referred once or twice to the Kew tests, and suggested that he (Dr. Glazebrook) might give some information with regard to them. There were one or two points to which he should like to call attention, if he might be permitted to use the blackboard. He should also like to refer to another method of making tests photographically, which had not been referred to by Mr. Chalmers, but it seemed to him to be worth consideration.

As Mr. Chalmers had said, the principle of Major Darwin's testing apparatus was a modification of the tourniquet method, but it possessed one or two advantages over that method.


[Dr. Glazebrook here illustrated the Kew method on the blackboard by means of diagrams.]

The Kew method, he said, consisted mainly in the fact that there was fixed, in the Kew tourniquet, to the frame carrying the lens a plate at right angles to the lens which moved with the lens. One of the advantages their system seemed to possess was that it was quite easy, by means of a series of measurements, to obtain information as to the focal length of the lens, and other qualities. It was not necessary to measure the distance from the axis of rotation.

With regard to the test of definition, Mr. Chalmers described Major Darwin's test, but that had been found somewhat difficult to carry out, and had not been used. The test at present used at the Laboratory, consisted of



simple observation of two fine lines at right angles, as

shown herewith  The lens was focused for these

lines, and then the whole instrument was turned until the image of these fine lines fell somewhere about half way between the axial position and the extreme edge of the plate. The focus was examined again in that position, and the lens was re-focussed, a wide angle stop being employed. The camera is then turned until the image of the lines comes to the extreme edge of the plate, and the lens is stopped down until the image of the lines is again distinct. With regard to the method of Professor Hartmann, one of the points which struck him was the great length of time necessary to test the lens, so as to obtain, say, the errors of curvature and astigmatism. With the Beck bench, these errors could be obtained in a very few moments.

In a pamphlet he had with him, there was described another method of testing lenses, in which a photographic image of a specially planned object was obtained. He (Dr. Glazebrook) had not seen any allusion to the method in English papers. It was published by Mr. Houdaille in 1894, and the method was what Mr. Chalmers had called the "inverse method" of testing a lens such as the process lens. At Kew, at the present moment, there is practically no method of testing process lenses.

[Dr. Glazebrook here again had recourse to the black-board to describe the method mentioned.]

The point to which he desired to draw special attention with reference to this method of Houdaille was that the experimenter endeavoured to obtain all information about the lens from the photograph of a series of scales arranged in a particular manner, so as to be at slightly different distances from the lens, and inclined at various angles to the vertical. These scales carry as test objects a series of groups of circular dots. In each group there are seven dots, six being at the angles of a regular hexagon, and one in the centre. The dots are  $\frac{1}{2}$  millimetre in diameter, and their centres are  $1\frac{1}{2}$  millimetres apart, so that there is  $\frac{1}{2}$  a millimetre between any two adjacent dots. The bench is arranged to work with  $1/5$  reduction, so that the dots appear as of  $1/10$  mm.

on the photograph, and the spaces between them are  $1/10$  mm. wide.

A lens is defined as having a one-tenth defining power in any direction if it completely resolves such a series of dots. When the photograph is taken, the groups are found to be resolved over a definite area of the plate, and from the size and shape of this area, Mr. Houdaille shows how to determine the properties of the lens. From a single photograph much valuable information is obtained. In conclusion, Dr. Glazebrook again expressed his high appreciation of the value of the paper, and the interest of the method of testing employed.

MR. CONRAD BECK expressed his pleasure at having been privileged to listen to Mr. Chalmers' paper. Professor Hartmann's method was new to him, consequently he was unable to make any remarks upon it, except that it showed promise of being a very beautiful test. He proposed to confine himself to certain tests mentioned in the paper, of which he had had practical experience. The method of measuring the spherical aberrations of the lens, by means of measuring the diameter of the image by a point of light, proved to be in practice of little value, as it was almost impossible to disassociate from the appearance caused by spherical aberration that which was caused by diffraction. Also in certain cases where a small zone of the lens had a different focus to the rest, a general fine haze of light was thrown over the image, whose diameter it was almost impossible to measure accurately. The method of measuring astigmatism by focussing to the focal lines, in practice became equally unsatisfactory.

The so-called focal lines were seldom lines, but were either the figure of 8, or some irregular shape dependent upon coma, etc., the focus of which was difficult to determine. The focussing to gratings, provided a microscope were used, was a perfectly reliable and accurate test of astigmatism. One of the methods adopted of the Beck Lens Testing Bench depended upon the use of a high-power microscope for examining the image. The difficulty of ascertaining the exact position of a focus was very great, if only low magnifying powers were used, owing to the accommodation of the eye. The use of a high-power microscope overcomes this difficulty. In certain cases a ground-glass may be introduced in the focus

of the microscope, as by this means the image became a luminous object, and a wider angle object-glass could be used in the microscope, thus still further avoiding the difficulty experienced in ascertaining the exact position of the focus. But, owing to the ground-glass destroying the definition of the image it could only occasionally be used, and experience showed that a fine layer of wax formed a better screen than ground-glass for this purpose.

A further advantage in the use of the microscope was that monochromatic solutions could be used in the microscope itself, without introducing any error such as would be the case if they were introduced between the photographic lens and its image. He was very much interested in what Dr. Glazebrook had said with reference to the Kew definition test, as his own experience had thoroughly confirmed what he had said on that matter. It was extremely difficult to decide at what position a line was or was not visible, whereas, with gratings or lines that could be divided, it was quite possible with a sufficiently powerful microscope to obtain a distinct opinion on this point.

With reference to the question as to whether visual or photographic tests were the best, the photographic test was invaluable as a check, but he considered that for all lenses for dry-plate photography photographic tests could be replaced by visual tests with proper monochromatic solutions, thereby enabling much better numerical and quantitative data to be obtained. Lenses which were to be used for distant objects could not be satisfactorily tested photographically without unusual opportunities for arranging a series of objects to be photographed at a great distance from the camera. Consequently, most photographic tests resolved themselves into apparatus placed comparatively near to the lens, and were liable to give a totally erroneous idea as to its capabilities for distant work. One department of lenses, namely, those used for process work, required photographic testing, as they are entirely used upon wet plates, which require blue, violet and ultra violet light to be corrected, and it would be a great advantage to Opticians if their chemical friends could produce a fluorescent screen which would render these rays visible.

A further extremely interesting point was how the tests

on photographic lenses should be expressed, and this point required careful discussion. Again, it was not fair to give all classes of lenses the same test, as many lenses were manufactured specially for one purpose. For example, a process lens, to be used with wet plates, should not be submitted to the same test as a lens designed for snap-shot photography or portraiture on dry plates, and a series of different tests was required to truly demonstrate their efficiency for the particular purpose to which they were to be put. The test by means of a collimator, which was suggested by Mr. Chalmers, looked as though it would have very many points in its favour, but without practical experience it would not be safe to predict too much for it.

MR. BLAKESLEY expressed his approbation of the paper. He agreed with Mr. Beck in thinking that somewhat simpler methods than photographic methods should, if possible, be adopted in the testing of photographic lenses. He himself had gone into some of the matters connected with lenses, with a view to accurate testing, and his plan had been to obtain quick results if possible. That would be of great advantage to anybody who had to deal with a large number of lenses. He had lately published a method by which the focal length of a lens could be read off on a scale; in this, he had gone into the subject of lenses generally. He described one of his methods on the blackboard by means of sketches, a method which he had found to be very useful for practically any lens.

MR. HORACE BECK said there was one point about Professor Hartmann's method which seemed to be extremely useful, and that was in cases where lenses were very much out of correction. In many cases, when the spherical aberration in particular was bad, it was extremely difficult to get accurate tests. This method, however, seemed to him to be almost as efficacious in measuring large errors as in measuring lenses which were almost accurate.

MR. SELBY had also been particularly interested in the method described. The objection which had been raised more than once seemed to be the length of time it required. When the system of lens testing was first introduced, one of the considerations taken into account was the expense, and also the time. Photographic

methods were at that time ruled out for this very reason. No doubt, at the present day, that did not hold with quite the same stringency. The lenses made now were made with such accuracy that more extensive and more accurate tests were required, and, consequently, more exact instruments were necessary. But they would all like, before testing, to know something of what a lens was capable of doing, and to have an exact statement about its possibilities. The Kew tests had been of great service to them, having enabled them to obtain an idea of the general purposes of the lens, even though they had scarcely given the lens-maker sufficient information to supply him with all he desires to know in regard to different aberrations.

MR. BULL remarked that with reference to the requirements of process work, three-fourths of the light recorded on the wet plate was invisible to the human eye. He thought that a test which was not photographic would be useless unless the lens was going to be used for either orthochromatic or three-colour photography.

MR. PURSER desired that a comparison of lenses should be prepared for publication, as it would be of very great value to all. It should be made public that, though curvature of the field could be avoided, it might, in very many cases, be of great advantage to the lens.

DR. DRYSDALE thought that there were two points which wanted to be brought out in the discussion. The first was that they required to know the best methods of testing lenses. The second was the very important matter of the expression of the results when they had been obtained. This, he thought, was very important, because the discussion of different methods of testing must, to a large extent, depend on what they desired to measure. Up to the present it was surprising to notice the diversity existing in the manner in which aberrations were expressed. He referred briefly to von Seidel's method. Aberrations might be expressed in four different ways. There were aberrations of focal length; of convergence; they could speak of lateral aberrations; and, finally, there were aberrations of deviation. This last, he thought, was the most important. According to the ordinary Gauss method of treating lenses, all light coming from an object lying in a plane was brought to a focus in the image plane. The light, therefore, gave

perfect focus, and if it departed from the simple path, indicated by the Gauss formulæ, then that departure was the aberration. In dealing with aberrations, they had two further matters to consider. Speaking generally, they might be considered objectively and subjectively, depending on whether the instrument was intended to form real or virtual images. Again, they required to be expressed both absolutely and relatively, in order to compare with other instruments of different focal length, etc. Finally, there was one suggestion about Professor Hartmann's method which he would like to make. Mr. Chalmers had alluded to the difficulty he had experienced in the matter of illumination, and had suggested that there was no harm in making the source of light rather large. Might he suggest to Mr. Chalmers that he might go even further, and adopt the method well known to process workers, *i.e.*, making the source of light so large as to produce an "optical V," by somewhat under-exposing his plate, and reducing and intensifying it, he would probably get a much finer dot with considerably less exposure.

Mr. CHALMERS expressed his great indebtedness to all present for the kind expressions they had made concerning his paper. Some of the work he had referred to, though not original, was quite recent. One special point—the question of visual tests—was very interesting. Professor Hartmann himself always made visual tests for certain colours in examining telescopes, rather than attempting to take photographs on specially prepared plates. With regard to ready methods of examining and testing, Mr. Beck had put forward a suggestion which, though useful, did not exactly give what was wanted for spherical aberration. To get the exact focusing position it would be necessary to take two photographs, one behind the focus, and one in front of focus, with the same stop. Expressing aberrations by means of deviations did not give all one required.

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