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THE TESTING OF OPTICAL INSTRUMENTS.

PAPER BY DR. CHARLES V. DRYSDALE, *Member.*

Read before the Optical Society, May 15th, 1902.

IN bringing before you a paper on the Testing of Optical Instruments, it is evident that it will be impossible for me to do more in the time at my disposal than touch generally upon so large and important a subject, and to mention a few particular details which may appear of special interest. A long treatise might be occupied if the subject were adequately dealt with, but I prefer to deal with it generally rather than with a specific portion, because it is one above all in which general knowledge is necessary among Opticians, and is somewhat difficult to obtain owing to the lack of any connected treatise on the subject. The main object of the paper is to bring to the notice of Opticians concerned in the supply of instruments such as field glasses and telescopes, microscopes, projection lanterns, photographic apparatus, etc., a general idea of the defects to which such instruments are liable and how they may most readily be dealt with. For this reason, I shall not lay so much stress upon very accurate scientific methods of testing as upon those which are readily performed. It must be understood, also, that I only propose in this paper to deal with the testing of defects in the optical portions of instruments and not with those in mechanical construction.

General Principles.

The function of all optical instruments, however diverse they may be in other respects, is finally to produce an image, either real or virtual, of some object, and to produce this image with the greatest possible accuracy of detail in every particular, usually with a certain amount of enlargement or reduction of dimensions. For this purpose, use is made either of plane or curved mirrors, refracting or reflecting prisms, and lenses; and any optical instrument is simply an assem-

blage of one or more of these items. It has been shown that any perfect optical system acts, so far as the production of an image is concerned, as if it were a single lens, having a definite focal length and two definite points on its axis known as the principal points, through which pass the principal planes or planes of unit magnification. Fig. 1 illustrates such a system showing the two principal points and planes, $P_1 P_2$; the two focal planes, $F_1 F_2$; and also the two symmetrical planes, $S_1 S_2$, the latter being such that an object in one of them produces an inverted image of the same size in the other. Any one of the distances, $S_1 F_1$, $F_1 P_1$, $P_2 F_2$, or $F_2 S_2$, represents the equivalent focal length. It is therefore of value, generally, to know the value of the focal length of the system and the positions of these principal points (which are usually coincident with the nodal points). Beyond this, however, we frequently require to know the magnification produced by the instrument, or the ratio of the size of the image to that of the object. Furthermore, we are concerned in knowing the angle of view which the instrument will embrace, or the angle between the extreme rays of light which can or do enter it. Not only, also, is the production of the image in itself of importance, but its brilliancy or illumination concerns us considerably, and in order to know this we must determine what is called the aperture of the instrument. Finally, for some purposes it is of value to know the curvatures of the various surfaces.

It should be remembered, however, that no optical instrument produces a perfect image, and the images produced suffer in clearness from various defects, some of which are due to defective quality of materials employed, others to defective workmanship of the optical surfaces and to faults in their mounting, while a third class of defects are inherent in the optical properties of the surfaces of the lenses and mirrors, and depend upon the proper designing of the system. We may, therefore, divide the defects to be examined into three headings:—

(1) *Due to defects in material.*—Since glass is most extensively employed in optical work, the defects in its constitution are the most serious, and they may be enumerated as existence of veins or striæ and bubbles in the glass itself; want of transparency, either initially or from subsequent chemical action; or strain, consequent on imperfect annealing of the glass during manufacture.

(2) *Defects in workmanship.*—In this class we first have imperfect polishing, causing scattering and loss of light; errors of form, usually

in departure from the plane or spherical form: errors in the parallelism of plane glasses or of the angles or prisms; and, finally, defects in the centering of the different lenses or mirrors in the system.

(8) *Defects due to design.*—Under this heading, we have the usual errors which are well known, viz. :—

- (a) Chromatic aberration, in which different colours are brought to different foci. Fig. 2.
- (b) Spherical aberration, in which the rays of light parallel to but at a distance from the axis are brought to a different focus than those near to the axis. Fig. 3.
- (c) Coma or spherical aberration for oblique pencils, producing a one-sided flare on the image. Fig. 4.
- (d) Radial astigmatism, in which oblique light is focused not at a point but in two focal lines mutually perpendicular. Fig. 5.
- (e) Distortion, in which straight lines in the object appear curved in the image. Figs. 6 and 7; and
- (f) Curvature of the field, in which the best image of a plane object perpendicular to the axis is formed on a curved instead of a plane surface. Fig. 8.

Among the defects due to design may also be mentioned inequality of illumination, generally causing a reduction of brilliancy of the image as we pass outwards from the axis; and that known as flare spot, causing light reflected from the surfaces of the lenses to be approximately focused on the image.

It will be seen from this brief survey of the points involved in optical testing that the subject is an exceedingly large and complex one, especially when we are further concerned in the adaptation of the tests to the very varied types of instruments in use. Notwithstanding this, however, a general discussion on the tests necessary will not be beyond our scope, and will obviate the necessity of doing more than give details in dealing with the specific requirements of different instruments.

Section I.—General.

A. *Determination of the Equivalent Focal Length.*—In the case of mirrors, single thin lenses, or of combinations of lenses, the total thickness of which is very small in comparison with their focal length, the latter may usually be taken with sufficient accuracy as the distance from the surface of the mirror or lens to the principal focus. Where

the combination is convergent the focal length is immediately determinable; if divergent, the focus is virtual and must be found either by neutralisation or by a telescope or range finder, or by combination with a convex lens of known shorter focal length. Little difficulty, however, need ever be experienced in such cases.

Where, however, optical systems are of considerable axial length compared with their focal length, as in most photographic lenses, eyepieces and microscope objectives, the distance between either extreme surface and its corresponding focal point is not the equivalent focal length, but what is technically known as the "back focus," and may be very widely different from the former. In photographic lenses, for instance, the back focus usually roughly corresponds to the camera extension, while the equivalent focal length is greater, indeed in telephoto lenses it may be many times as large.

FIG. 1.—PRINCIPAL, FOCAL AND SYMMETRICAL PLANES.

It would seem unnecessary to give special attention to the testing of the equivalent focal length, but unfortunately even now mistakes seem frequently to be made on this important point, and even some of our recognised text books contain serious errors. An impression which seems to die hard is that the equivalent focal length of a photographic lens is the distance between the diaphragm stop and the screen, but this is only occasionally the case. Another is that if the lens is so set as to give an image equal in size to the object, the equivalent focal length is one-fourth of the distance between them. This is only true if the nodal points are coincident.

There are many well-known methods of truly determining the equivalent focal length, but they divide themselves into three groups. In the first of these the distance between the principal or nodal point and the corresponding focal point is determined to which class belong

the equivalent lens test, and the tests of Sir H. Grubb,* Moessard,† the Kew Observatory,§ and the mirror test of Dr. Clay.‡ In the second class the distance between the focal and symmetrical planes is directly determined ; while in the third class we have the modified method of conjugate foci, and the magnification tests of Dr. S. P. Thompson and Professor T. H. Blakesley.

Of these only two will be described as being probably the most suitable in practice. The first, which I shall term Moessard's method, from its having been brought to perfection by him in his Tourniquet, is very old in principle, and consists of simply rotating the optical system on an axis perpendicular to its own axis, and to find the position by trial when on slightly oscillating the system on the axis the image of a distant object remains stationary. This can only be the case when the axis of rotation cuts that of the system at the nodal

FIG. 2.—CHROMATIC ABERRATION.

point of emergence, and the distance between the axis and the focus is then the equivalent focal length required. Fig. 9 shows a simple method of carrying out the test, in which a lens system to be tested is laid in a trough supported on an oscillating axis. When a clear image of a distant object is formed on the screen, and the trough is given a slight oscillating motion, the image will generally be seen to move. If, however, the lens is moved backwards or forwards over the axis, and the screen is correspondingly moved, a position will readily be found in which a sharp image is produced which does not move for

*R. S. Cole, "Treatise on Photographic Optics," p. 218. Trail Taylor, "Optics of Photography," p. 116.

†P. Moessard, "Etude des Lentilles et Objectifs Photographiques," Paris, 1899. Cole, "Photo Optics," p. 209.

§Leonard Darwin, "On the Method of Examination of Photographic Lenses at the Kew Observatory," Proc. R.S., 1892. Cole, "Photo Optics," p. 224.

‡Dr. R. S. Clay, "Testing of Photographic Lenses," 'Photography,' February 14th, 1901.

small oscillations. The focal length required may then simply be scaled off from the axis to the screen. The test in this form is, of course, only applicable to convergent combinations having a positive focus, but in the case of negative combinations, such as ordinary microscope or telescope eyepieces, or divergent combinations, the writer has modified it in connection with his universal optical bench described before the Society.*

The other method is that by which the focal length is obtained from the distance between the focal and symmetrical planes. In this test as applied to positive convergent systems, a distant object is first focused sharply upon a screen. An object is then brought near the lens and is moved until its image is equal in size to itself and is perfectly sharp. The distance which the screen has had to be moved from the first position to the second is the focal length required.

FIG. 3.—SPHERICAL ABERRATION.

Further reference to this subject will be made in the special sections.

B. *Position of Nodal Points.*—It would certainly be a great convenience in practice if the positions of the nodal points of optical systems were marked on their mounts, as has been done for sometime by M. Moessard, and recently again advocated by Prof. Blakesley. In Moessard's test the position of these points are directly given, while if the equivalent focal length is determined by any other method, and the position of the focal planes is known, the positions of the nodal points can, of course, be found at once.

C. *Determination of Magnification.*—The term magnification is one which is employed in at least three different senses. Scientifically it is defined as the ratio of the linear dimensions of the image to those of the object, and this definition is used when speaking of projection

*A simple universal method of testing spherical and cylindrical lenses. Proc. Opt. Soc., May, 1900.

lenses or microscope objectives, but in telescopes it implies the visual angle which the image of a small object subtends, compared with that which the object would subtend at the same point. With simple microscopes, or with oculars, however, the term magnification has a third meaning, and implies the visual angle subtended by a small detail of the image compared with that subtended by the same detail of the object, the image and object being in each case situated at the distance of most distinct vision, usually taken at 10 ins. or 250 millimeters. The testing of magnification will, therefore, be deferred until the special instruments are dealt with.

D. *Angle of View*.—The angle of view is again a quantity which is variously defined. It may be the angle between the extreme rays which can pass through the system, as in a telescope or microscope; the angle between the extreme rays with which the system is actually used, and which varies with the conditions, as in photography; or the angle between the two extreme directions over which a certain standard of definition is attained, or over which the illumination does not vary by more than a certain amount. The latter definition corresponds to what is called the covering power or angle of a photographic lens, or to the "angle of aplanatic cone" in a microscope condenser.

E. *Determination of Aperture*.—The term aperture has two different significations in the case of telescope or photographic lenses on the one hand, or of microscope objectives on the other. With the former the aperture implies the ratio of the diameter of the emergent pencil of light to the equivalent focal length, while with the latter it is usually taken as the sine of half the angular aperture multiplied by the refractive index of the medium in front of the objective. Both of these quantities can be readily determined and will be described in place.

F. *Curvature of Surfaces*.—Little need be said on this subject. For most purposes the spherometer, especially in Prof. Abbe's form, is suitable, but when the diameter is too small, or curvature too large, the method of testing devised by the writer* may be substituted.

G. *Tests for Defects in Material*.—These tests are well known and need only be briefly referred to. In order to detect veins or bubbles in the glass, the most perfect method is to arrange for a cone of convergent light to pass through the glass and enter the pupil of the eye so that the whole of the glass appears as a brightly illuminated field.

* "A Simple Direct Method of Determining the Curvature of Small Lenses," Proc. Opt. Soc., November, 1900.

If the glass is already ground into lens form it can be used to converge the light, as in fig. 10, otherwise an auxiliary perfect lens may be employed; under these circumstances any such defects are made clearly apparent. The existence of strain or imperfect annealing of the glass may be immediately detected by interposing in the path of the light a pair of ordinary polarising and analysing prisms, set so as to give a dark field, any regular strain of the glass immediately shows as a light or dark cross on the field. Irregular strain is shown by the figure being distorted.

FIG. 4.—COMA.

Defective polishing of the surfaces is, of course, easily detected by examining the surface in a strong reflected light with an ordinary magnifying glass.

The only simple way of testing the transparency of the glass is to compare the piece to be tested with a satisfactory piece of glass, by holding them side by side against a uniformly illuminated sheet of white paper. For accurate testing a photometer should be employed, but apart from the inconvenience of this it should be remembered that the indications of a photometer afford no clue to the transparency for actinic light.

Tests for Errors of Form.

Plane surfaces may be accurately tested in either of two ways, first, by using a telescope which has been focused on some distant object, and afterwards observing the same object by reflection at the surface to be tested. A very slight imperfection of the surface will destroy the sharpness of the image. A more convenient method in the workshop is to have a standard plane surface, either of glass or quartz, and to observe the coloured bands produced on pressing the test surface into contact with it, having previously taken care to thoroughly clean the surfaces. If the surface tested is accurately plane the bands will be very wide and regular, appearing either as straight lines or circles. With the highest possible perfection only one colour will be seen over the whole surface.

The parallelism of plane glasses is frequently a point of considerable importance, particularly where these glasses are to be used in front of

FIG. 5.—RADIAL ASTIGMATISM.

some measuring instrument, as the slightest error from parallelism causes a deviation of the light entering the observing telescope. The most simple test for parallelism is to view a source of light by oblique reflection at the plate tested, when, if the plate is perfectly parallel, the image only will be seen. If, however, the surfaces are not parallel a series of images will be seen, and the greater the angle between the surfaces the further apart will these images be.

A second quick method is to sight an ordinary telescope on a distant object, such as a vertical flagstaff, and to hold the glass to be tested in front of the object glass so that it half covers it; in this case if the glass is parallel the object will appear as before, but should there be want of parallelism the image will appear double in some positions of the glass.

With deeply tinted glasses, such as are used in sextants and other nautical or surveying instruments, some difficulty may be experienced.

A simple expedient in this case is to employ a fixed telescope with cross wires and to accurately focus some object on the wires. If the glass is now rotated in front of the telescope any want of parallelism will be shown by the image also rotating.

The angles of prisms may of course be most accurately tested with the help of the spectrometer or goniometer, but in some special cases it is convenient to test them by a simple internal reflection from the prisms themselves; for example, in prismatic field glasses, and many other cases, right angled prisms are employed, and such prisms may conveniently be tested by looking at the broad face of the prism, in this case an image of the observer's eye will be seen by successive reflection of the two faces, one half of the pupil will be seen on each of the oblique faces. If the angle of the prism is exactly a right angle the pupil will appear to be perfectly circular, but otherwise the two halves will appear to be separated or to overlap, according to whether the angle is greater or less than a right angle. Tests of a similar nature may be made with prisms of other definite angles.

Curved Surfaces.

In lenses and mirrors the surfaces are usually in the form of spherical curves, and it is of the greatest importance that they should be perfectly regular and free from astigmatism. In the workshop the curves of the surfaces are usually checked during construction by the use of test plates ground and polished to the corresponding curves. If the coloured bands formed under these circumstances are perfectly circular and are unaffected by the movement of the surfaces over one another, the glass may be considered to be truly spherical. Where figuring is intentionally resorted to an optical method of test must be employed.

Centering.

The centering of any system of lenses or mirrors is a matter of very considerable importance, as an otherwise perfect instrument will have its definition spoiled by faulty centering. When the instrument is completed the most usual quick test for centering is by Wollaston's method, in which a distant point of light is observed through the system in a darkened room. In this case a number of images will be seen by reflection at the various surfaces, and if by tilting the system all of these images can be brought into one line, the system may be regarded as properly centered, otherwise the tilting or displacement of

FIG. 6.—PINCUSHION OR POSITIVE DISTORTION.

FIG. 7.—BARREL OR NEGATIVE DISTORTION.

any surface causes a corresponding displacement of the image reflected from it. In practice it is usually somewhat difficult to carry out this test, as the image directly seen through the system is often so bright as to mask the other images, and I have found it convenient in performing it not to look directly through the lens system, but to reflect the light into it from a piece of plain unsilvered glass held in front of the eye. Under these circumstances the whole of the images are reflected, and are consequently nearly equally intense, and the test is much easier.

In order to test the centering of the whole of an optical system in its mount, it is sometimes convenient to rest the latter on a couple of V bearings so that when rotated in these bearings the mechanical axis of the mount is stationary. Under these circumstances if an object is viewed through the lens system, with or without an eyepiece, or an image is projected on to a screen by its aid, and the tube is rotated, the image should be perfectly stationary if the centering is perfect, otherwise it will appear to describe a smaller or larger circular path.

Lenses are usually centered in the workshop and edged truly by mounting them on a lathe and observing the reflections from the two surfaces, the lens is moved on the axis until these images appear perfectly stationary as the lens revolves, and the edging is then proceeded with. Lathes for edging lenses have also commonly hollow mandrels, so that the test previously described may also be employed.

In centering lenses which have to be cemented together, the same procedure as in the last case may be adopted, but some optical manufacturers, notably Messrs. Goerz, employ a mechanical method of effecting this, consisting of a lever with a small spherical head at one end touching on the surface of the lens, and a long pointer which shows any variation of the level of this sphere. The lens to be tested is laid on a flat table against two supports so that it may be rotated by hand about a vertical axis, and the lens is adjusted in contact until on rotation no movement of the lever takes place.

The final testing of centering will be described later.

Defects due to Design.

(a) *Chromatic Aberration.*—The tests for chromatic aberration are fairly simple and well known, and little need be said about them. A single lens, of whatever material it is made, always brings the violet

light to a focus at a shorter distance than the red light, intermediate colours being focused between the two extreme positions. The use of a compound lens formed of glasses of unequal dispersive powers compensates for this to a considerable extent. If this correction is insufficiently performed the lens acts like a single one, but in a less degree, and the combination is then said to be under corrected, while if the correcting lens has too great an effect, causing the violet light to be focused at a greater distance from the lens than the red light, the combination is said to be over corrected. It is, therefore, possible to ascertain whether a lens is over or under corrected by finding the positions of the foci for violet and red light, but the correction of the lens may be much more easily tested by observing the disc of light

FIG. 8.—CURVATURE OF FIELD.

produced on a screen, or in an achromatic eyepiece, when a distant source of light is observed and the screen is inside or outside the focus. If the screen is inside the focus and the lens under corrected, the violet light is more refracted than the red, and consequently the extreme edge of the disc of light is coloured with red, while if the lens is over corrected a blue rim will be seen, the reverse effects will, of course, be observed outside the focus. Other tests for chromatic aberration will be mentioned when dealing with the special instruments. It should here be mentioned that chromatic correction of axial light by no means necessarily implies entire correction for oblique light.

(b) *Spherical Aberration*.—The defect of spherical aberration is a very common one in optical systems, and implies that the edge of the lens or lens system has a higher or lower refracting power than its centre. With a single lens the focal length for light passing through the edge of the lens is always less than that for the central light, and with a compound lens it may be either less or greater; in the former case the lens would be under corrected for spherical aberration, in the latter over corrected.

The simplest rough test for spherical aberration is to focus the lens on a screen so as to give the sharpest image possible, using first a stop which covers up all but the middle third of the lens under test, and secondly with a stop in the form of a disc which covers up the centre and leaves the edge free. If the focus remains unchanged with the two stops, spherical aberration is not present to a very large extent, but if any movement of the eyepiece has to be made to restore

FIG 9.—TESTING EQUIVALENT FOCAL LENGTH.

focus when changing stops, it can be easily seen whether the lens is under or over corrected. This test is by no means sufficiently accurate for telescopes or photographic lenses, and more sensitive tests will be described later. The remaining errors of coma, radial astigmatism, distortion, and curvature of the field, are so particularly connected with photographic lenses, that tests for them will be deferred until this section is reached.

We may now pass to the application of the tests to commercial Optical Instruments, and I have selected four classes of instruments for special attention, *i.e.*, Telescopes and Field Glasses, Photographic Lenses, Projection Apparatus, and Microscopic Lenses.

Section II.—Telescopes, Opera and Field Glasses.

In dealing with these instruments, we are very nearly always concerned only with a very narrow angle of view, and consequently the various errors arising from oblique refraction are of comparatively little importance, and, provided the centering is perfect, the points which we are most concerned in testing are, therefore :—

- (a) The centering, or “squaring on,”
- (b) The magnification of the glass,
- (c) Its angle or field of view,
- (d) The illumination of the image,
- (e) The chromatic correction, and
- (f) The spherical aberration of its object and eye lenses.

(a) *Centering*.—The only point we have here to deal with, after what has been said in the general section, is what is technically known as “squaring on.” Telescope object glasses are usually very

FIG. 10.—METHOD OF TESTING STRAIN IN GLASS.

sensitive to tilting, any inclination of the lens causing coma or astigmatism. The test for tilting is very simple, and like all other tests of the optical quality of a glass, is best made on a star or other distant source of light. If this is not convenient, a valuable substitute can be obtained with a “collimator,” which consists of a telescope having an object glass, at any rate, larger and more perfect than any to be tested, and having at its focus a diaphragm with an exceedingly small pin hole. This arrangement serves as an artificial star, since the light emerging from the pin hole is rendered parallel after passing through the lens.

When a real or artificial star is available, the glass to be tested is simply focused on it, and is then racked in and out of focus. If the disc of light which is seen when out of focus is always perfectly circular, the glass is properly centered, but if an unsymmetrical flare is seen, or the disc is oval, the objective is either tilted or is astigmatic.

(b) *Magnification. Double Vision Method.*—The magnification of a telescope may most conveniently be defined as the visual angle which a small object subtends when seen through the telescope, compared with that which it subtends with the unassisted eye. The simplest possible method of testing the magnification is, therefore, to observe a distant scale through the glass with one eye, and to notice how many divisions of the scale seen by the other eye are covered by a single one seen through the glass. If means are provided for holding the glass steadily, this may be fairly satisfactory for low magnifications, but it is unsuitable if great accuracy is required, or if high magnifications are to be measured.

By Measuring Focal Lengths.—It can be easily proved that the magnification is equal to the result obtained by dividing the focal length of the object glass by that of the eyepiece, and in the case of opera glasses of low magnification, this affords a method of testing the magnification. The focal length of both of the lenses can be easily obtained by an optical bench or by neutralisation, and the magnification obtained in this way; the result cannot be expected, however, to give any accuracy with high magnifications, as in that case the eye lens is of short focus, and accurate neutralisation is impossible.

Ramsden's Method.—When parallel light enters the object glass of a telescope or opera glass focused for an emmetropic eye, it is parallel on emergence, and it can be proved that the magnification is equal to the diameter of the entering beam, *i.e.*, the aperture of the object glass divided by the diameter of the emergent beam (sometimes called the diameter of Ramsden's circle), *provided that the light is not intercepted by stops in the interior of the telescope.* This method appears to be very frequently used for determining the magnification of telescopes and field glasses of high magnification, such as prismatic glasses; a distant small source of light is focused in the glass, and the emergent beam of light is allowed to fall on a ground glass or celluloid scale, and the magnification is obtained by dividing the diameter of the object by the diameter of this disc. A further refinement of this test is to measure the diameter of the Ramsden circle by means of an instrument devised by Ramsden himself, known as the Dynameter. In the author's opinion, however, this test is by no means satisfactory, as any stopping down in the body of the glass tends to reduce the size of the emergent pencil, and consequently to give a fictitious high value to the magnification. It is obvious that if a glass, having a certain magnification, were to be provided with a cap on the eyepiece, cutting

down the diameter of the beam to half, the test would apparently give a magnification double the true value.

Author's Method.—None of the methods above described or that seem to have been devised, appear to be altogether satisfactory for universal application, and the author has, therefore, been led to devise one, which, although it requires a little subsidiary apparatus, can be easily set up and is capable of giving directly the magnification of any glass to a fair degree of accuracy. The principle of the method will be easily seen from fig. 11, where A is an ordinary single telescope used as a collimator with a slit which can be illuminated from any convenient bright source of light, and which is adjusted in the focal plane. If a second convex lens of about 50 centimeters focal length is placed in front of the glass with a screen at its focal distance, a sharp image of the slit will be formed on the screen as the parallel light is focused by the lens.

Let us now suppose that we have two slits, or more conveniently that

FIG. 11.—DIRECT METHOD OF TESTING TELESCOPE MAGNIFICATION.

a Maddox double prism is interposed between the slit and the object glass, the result will be to give two beams of light which will consequently be focused by the second lens and will give us two images of the slit instead of one. By sliding the prism nearer or further from the slit, the images formed on the screen may be made to approach or recede from one another, and it is quite easy to set the prism so that the distance between the images is some definite amount, say one centimeter. When this is the case, let any glass whose magnification is required be simply focused on a distant object, and then interposed between the object glass and the lens, the effect of the telescope is to increase the deviation between the two beams of light received by it by an amount equal to the magnification, and consequently the two images of the slit will be seen as before, but they will now be as many centimeters apart as the magnification of the glass. All that is necessary, therefore, is to interpose any glass in the space between the object glass and the focusing lens, and the number of

centimeters distance between the images is the magnification directly, without any calculation. By suitably proportioning the apparatus, it is possible to test magnifications of almost any glass in this way, and the convenience of the method is that it is visible to more than one person at a time, and that, therefore, there is no question of personal error.

(c) *Determination of the Angle or Field of View.*—The angle of view of a telescope or field glass is usually given as the number of degrees or minutes of angle between the two extreme rays which are visible through the glass. The most convenient method of testing this, when a sufficient distance is available, is to set up a scale at such a known distance that the telescope is focused at its ordinary working length, and see how many of the scale divisions are visible in the field. If now the length included between these extreme divisions is divided by the distance between the scale and the object glass of the telescope, it gives the angle of view in radians, and this multiplied by 57.3 gives the angle in degrees, or if multiplied by 3,430 gives the angle in minutes. If much testing is to be done, it is convenient to set the scale up at a distance of 3,430 scale divisions from the object glass; in this case the number of divisions visible in the glass at one time gives the angle directly in minutes.

It is, however, frequently very inconvenient in practice to have to test glasses on a distant object from considerations of space, and here again, a collimating telescope may conveniently be employed. If a properly corrected telescope lens of any convenient focus is employed, as in the test before mentioned, and instead of a single slit in the focal plane a scale is employed, a glass focused for parallel rays will, of course, see the scale clearly, as if it were at an infinite distance, the scale may easily be divided so as to indicate degrees or minutes of angle at the optical centre of the collimator; in the former case, each division being $1/57.3$, and in the second case, $1/3430$ of the focal length. Under these circumstances, the test is subjective, but if used with a projecting lens and screen as before, the divisions will be clearly focused on the screen, and the number of them indicates the field of view. This test is objective and very convenient, the only point is that a sufficiency of light must be allowed for projection. It should not be forgotten, also, with opera glasses of low magnification, that the field of view depends on the diameter and position of the pupil of the eye.

When the angle of view of a Galilean glass is not restricted by

stops in the interior, it may be found from the formula—angle

$$= \frac{p f_1 + d f_2}{f_1 (f_1 - f_2)}$$
 where f_1 and f_2 are the focal lengths of the o.g. and eye lens respectively, p the pupillary diameter, and d the diameter of the o.g., provided that the eye is close to the lens.

(d) *Illumination*.—The illumination, apart from absorption of the lenses or mirrors, is easily found in the case of a telescope, and may be expressed by dividing the diameter of the Ramsden circle by that of the pupil of the eye and squaring the result. The illumination, of course, can never be greater than unity.

Examination for Defects.—It is only proposed here to mention the simpler tests for defects in glasses of low magnifying power, as a discussion of those in larger glasses would take too much time, and is rendered unnecessary by the fact that an excellent little book on the testing of astronomical telescopes has been issued by Messrs. Cooke.*

The best object for detecting any defects in the performance of a telescope, as above mentioned, is unquestionably a star or distant bright point of light. Among Opticians it is customary to test glasses on test types or print at a considerable distance, and this may give an excellent idea of the performance of a glass, but it is almost useless as a guide to determining to what faults any defect in definition may be due. The test types, or similar device, should be always used as a means of judging the capacity of a glass, but if any more detailed information is required as to the defects, the luminous point must be resorted to. For ordinary purposes the collimating telescope may be conveniently employed.

(e) *Chromatic Aberration*.—The simplest test for this has already been described, *i.e.*, of focusing the distant point of light, and then to observe the appearances produced when the eyepiece is pushed in or drawn out beyond focus. If the object glass is under corrected it will show a red ring round the disc when inside focus, and a blue flare if outside; while if the glass is over corrected the appearances will be reversed. With the most perfect double objective, however, as a rule, absolute colour correction is not obtained owing to the irrationality of the dispersion of the two lenses, and in that case the colours of the rings are respectively greenish yellow and “claret coloured.”

Chromatic aberration in the eyepiece on the other hand may be best

*On the Adjustment of Telescope Objectives. T. Cooke and Sons, York. 1896.

detected by turning the telescope so as to view the star almost at the edge of the field. If the objective has been found satisfactory by giving little colour at the centre, and a coloured image is found when viewed through the edge of the eyepiece, the latter is at fault. More refined tests for chromatism are obtained by observing the appearances shown in the diffraction rings with high powers, but this is beyond our present scope.

(f) *Spherical Aberration*.—The simplest test for this has also been alluded to under the General Section, but this is insufficient for telescope work. A more sensitive test is to dispense with the diaphragms and to push the eyepiece nearer the object glass, or to pull it out further, in this case, if the spherical aberration is positive, *i.e.*, the edge rays are brought to a focus at a shorter distance, it will be noticed that the disc of light produced on pushing the eyepiece in is not uniform in intensity, but is brightest at the edge, while if the eyepiece is

FIG. 12.—DIRECT METHOD OF TESTING EQUIVALENT FOCAL LENGTHS.

pulled out beyond focus the disc will be brighter in the middle than at the edge; the reverse is the case if the spherical aberration is negative by over correction. With high power eyepieces diffraction rings are always visible, but the test is conducted in the same way by noticing whether the inner or outer rings are the brighter.

The Knife Edge Test.—An alternative method of testing a telescope objective is by the knife edge method, which, however, does not seem to offer many advantages, and is more difficult both to understand and to interpret. Moreover, the knife edge test is only capable of dealing with defects in the object glass, while the former, or direct focusing method, tests the instrument as a whole, which is a great advantage.

Testing Telescope Eyepieces.—With many larger telescopes sets of eyepieces are provided, both astronomical and erecting. The latter especially are liable to many defects owing to the number of lenses of short focus employed in them. It is convenient where different eye-

pieces are used to find the equivalent focal length of each of them, and the magnification of the telescope with each eyepiece may then be simply found by dividing the focal length of the object glass by the equivalent focal length of the eyepiece. The focal length and performance of eyepieces may be obtained exactly as with photographic lenses.

Section III.—Photographic Lenses.

We now pass to the subject of photographic lenses which are distinct from every other class of lens in that very oblique light is to be focused as well as central rays.

Determination of the Equivalent Focal Length.—This has been fully discussed before in the General Section, any of the tests mentioned being suitable. Where, however, any considerable amount of testing is to be done, the writer thinks that the following method will be

FIG. 13.—DETERMINATION OF FOCAL LENGTH WITH COLLIMATORS.

found most convenient, as it is direct reading and requires no apparatus beyond the ordinary camera. Let two objects A and B, fig. 12, be mounted as far as possible from the camera, which should be fixed in position, and let the distance from A to B be made exactly one half of the distance from the middle point between them to the front of the camera. Under these circumstances if any lens, landscape or combination, is fixed in the camera and the objects are focused, the distance between them when multiplied by two gives the equivalent focal length. For rapid reading a scale reading in half inches or half millimeters may be used. The only drawback to the arrangement is in cases where space is restricted, but this can be easily got over by simply using a pair of collimating telescopes, as in fig. 13, in which case the whole arrangement need not take up a space of more than two or three feet, and the test is perfectly accurate, provided that the lens tested is reasonably free from distortion.

Determination of the Aperture and Values of Stops.—This is of

course a point of very great importance with photographic lenses, and one in which mistakes seem even now to be made. This should not be the case if we had a strict definition of the aperture of a lens, and it may be defined for photographic purposes as the ratio of the diameter of the entrance pupil or largest beam of parallel light which can pass through the lens and stop, to the equivalent focal length of the lens. With single landscape lenses it is of course only necessary to measure the diameter of the stop carefully with a wedge, and to divide it by the distance from the lens to the screen when a distant object is focused. With a combination of lenses, however, two difficulties present themselves, the first being in the determination of the equivalent focal length, which has been already discussed, the second lies in the fact that if a lens is in front of the stop as well as behind it, a larger beam of light can enter the stop than its own diameter, owing to its being converged before reaching it by the front lens. It is of

FIG. 14.—DETERMINATION OF APERTURE : KEW TEST.

course possible to calculate the equivalent aperture of the stop by knowing its actual diameter and the focal lengths of the component lenses, but this is troublesome. The most convenient device if the equivalent focal length is known is that employed at Kew, where a distant object is simply focused on the screen, which is then removed, and has then inserted in its place a plain sheet of metal with a pin hole in it, fig. 14. On allowing light to pass through this pin hole back through the lens, a parallel beam emerges from the front of the lens, and the diameter of this parallel beam is clearly the diameter of the largest beam which can pass through the stop. The value of the stop is then given by dividing the diameter of the beam by the equivalent focal length.

The author, however, ventures to suggest an exceedingly simple method of determining the value of the stops of any lens, whether compound or simple. It does not seem to have been pointed out by anyone

that since the aperture of a stop depends upon the ratio of its equivalent diameter to the equivalent focal length, it is really defined by the angle of the cone which the light makes on reaching the screen. In fig. 15 it is easily seen that the aperture or ratio of the diameter of the parallel beam to that of the equivalent focus is equal to the ratio of the diameter of the cone at any point to the distance of this point from the focus. Consequently it is absolutely unnecessary to know either the diameter of the stop or the equivalent focal length, all that need be done is to focus sharply on the screen some distant bright point of light, to then move the screen in a definite known amount, and to divide the diameter of the disc of light then seen on the screen by the distance moved. To make the thing even more simple the screen may be moved until the disc of light assumes a definite diameter, say 1 in. or 1/10th in., and the distance which the screen moves then gives the value of the stop without any calculation whatsoever. For example, if with a

FIG. 15.—DIRECT TEST FOR STOPS.

certain lens a distant lamp is focused, and it is then found that pushing in the screen 4 ins. causes the disc to expand to 1 in. diameter, the aperture is $f/4$. If with a smaller stop pushing in the camera 2 ins. gives a 1/10th in. disc, the stop is $f/20$, etc. This is much more convenient than the Kew method, as it does not require any special screen, the whole operation being performed with an ordinary camera in a few seconds. Of course in many cases the equivalent focal length has to be determined for other reasons, but in any case the determination of the stops can be most quickly made in this way, and frequently a knowledge of the equivalent focal length is unnecessary.

Angle of View.—The extreme angle which the lens can cover irrespective of definition or illumination is immediately found by seeing how far the lens may be turned before the stop is entirely cut off by the lens mount. The covering power, or angle of view, as generally given, however, implies the greatest angle over which the lens may be used at full working aperture, so as to give a certain standard of

definition. The standard usually taken is that the image of a point shall not exceed $1/200$ th of an inch in dimensions at any part of a flat field.

Only one system of testing photographic lenses, that of M. Moessard, appears to have been devised in which the covering power of a lens is scientifically tested. A special testing camera, known as the Tourniquet, is employed, enabling the lens to be rotated and adjusted to bring either of the nodal points over the axis. The lens is then

FIG. 16.—SAME AS FIG. 5, LARGER SCALE, SHOWING PRIMARY AND SECONDARY FOCAL LINES, AND CIRCLES OF LEAST CONFUSION.

turned at angles of 10° , 20° , 30° , etc., to the axis, and by means of a micrometer eyepiece, the positions within which the standard definition is maintained, are determined and plotted. A full account of this method is given in Cole's 'Photographic Optics,' to which those interested are referred.

Achromatism.—In testing the achromatism of a photographic lens, it must be remembered that none of the ordinary visual tests are of

any value, as visual and photographic achromatism may be widely different.

The simplest satisfactory test is to photograph an object consisting of a number of cards at different distances from the camera. If the card focused is sharpest in the negative, the achromatism is satisfactory, provided that the screen and plate are in perfect register with one another; but if a nearer one appears sharpest in the photograph the lens is under corrected, or if a further one, over corrected.

Spherical Aberration.—The best test for this is to employ an ordinary eyepiece with the lens, and to test it on a distant point of light exactly as with a telescope.

Coma, Radial Astigmatism, and Curvature of Field.—These three errors concern the falling-off of the definition towards the edge of the plate, and may be considered together. In Moessard's test, before mentioned, these errors are at once apparent, as on observing a distant luminous object with the tilted lens, coma is manifested by the usual one-sided flare, and astigmatism by the light being focused in two focal lines, as with a spherocylinder, instead of in a point. The curvature of the field is at once apparent on plotting out the focal lengths in various directions.

At Kew the astigmatism is expressed by the diameter of the disc of least confusion with a certain stop, and the curvature by the movement of the screen necessary to bring the edge of the image into focus after the centre has been sharply focused. A better measure of the astigmatism at any angle is the distance between the focal lines compared with the focal length of the lens.

Distortion.—This defect is, of course, easily recognised by observing the image of an object having vertical and horizontal straight lines at the edge of the field. At Kew the amount of distortion of a lens is measured by the sag of the line.

Definition.—A very useful method of estimating the defining power of a lens is used at Kew, in which a thin strip of steel is set up at a distance from the camera in front of a well-illuminated screen. When this strip is edge on it is invisible, but as it is turned round a point is found at which it is just visible on the screen, and the better the lens the less will the strip require to be turned.

Simple Methods.—The tests above described enable one to test a lens with a fair degree of accuracy, but for ordinary purposes they are somewhat troublesome. It will, therefore, be well to describe one or two methods by which the Optician can get a general idea of the per-

formance of a lens. A common one, as used by English Opticians, is to simply photograph a strip of some printed matter, some simple geometrical designs being included with the lettering; the centre of this strip is carefully focused with the lens, and a photograph is afterwards taken on a large plate. The extreme angle of view of the lens is then indicated by the distance of either side of the centre to which the image extends; the uniformity in illumination by the density of the negative, spherical aberration, distortion, astigmatism, etc., by the quality of the definition, the straightness of the lines, and the ability to see both horizontal and vertical lines equally distinctly. A com-

FIG. 17—COMA.

parison of photographs so obtained with various lenses gives a fair idea of their performance.

The method of testing devised by Dr. Paul Rudolph, of Jena,* is one that seems to be little known over here, and which is unquestionably both simple and capable of considerable accuracy. In it the old device of fixing a number of cards on a spiral round a rod has been

*Über eine Neue Methode zur bildlichen Darstellung der leistungsfähigkeit Photographischer Objective. von Dr. Paul Rudolph. *Atelier des Photographen* 1894 Heft 8.

employed, as in the above described test for chromatic aberration, the centre card being focused, and observation being made of the most sharply defined card in the negative. Dr. Rudolph makes use of a number of such sets of cards spaced out at equal distances horizontally, and having beneath them an evenly divided scale with geometrical designs on it. When a photograph is taken of this arrangement the scale indicates the covering power, etc., as with the test above mentioned, while any curvature of the field is indicated by the fact that different cards of the various sets are focused. By knowing the dis-

FIG. 18.—RADIAL ASTIGMATISM.

tances of the cards apart, etc., it is possible to map out the form of the field with a fair degree of accuracy. This device is one which anyone can easily make up, and the information given by it is exceedingly valuable. Moreover, if two of the marks on the scale are placed at a suitable distance apart with respect to the camera, it will be possible to include in the arrangement the simple test for the equivalent focal length proposed by the author.

Section IV.—Projection Apparatus.

Little need be said about the testing of Projection Apparatus by itself, as practically all that can be said about it has been covered in the section relating to photographic apparatus. The projection lantern consists essentially of two parts, the condenser and the projection lens. The function of the latter is exactly the converse of that of the photographic lens, and consequently it should be tested in the same manner, the only difference being that as a rule the angle of view required with the projection lens is rather less than with the camera. Concerning the condenser, its only function in a good projection lantern is to focus the light proceeding from the radiant as nearly as possible to a point at the projection lens, and it is, therefore, only advisable that it should be as free as possible from chromatic and spherical aberration on the axis. Unfortunately, however, there is hardly any piece of optical apparatus which sins to such a grievous extent as the condenser of a projection lantern. For ordinary slide projection the quality of the condenser is of secondary importance, but if the lantern is to be used for scientific projection work the condenser cannot be too carefully constructed, and the writer has never met with a condenser which even approximately fulfilled the conditions required. The defects of this part of the apparatus are usually so serious as to cause a loss of at least three-fourths of the light in any experiment involving the projection of a small aperture or a slit. It is greatly to be hoped that manufacturers will do something to remedy this state of things.

Section V.—Microscopes.

In entering on the subject of the testing of microscope lenses we are brought face to face with the difficulty at the outset that no definite recognised system of testing seems ever to have been adopted, with the sole exception of the determination of the aperture. It seems curious that in the case of so accurate and costly an instrument as a good microscope objective there should be absolutely no standard by which the attainments of it can be judged. Several methods of testing, notably the mercury test, the grating test, and the Abbe test plates have been in vogue, but all these tests only serve to discriminate between the comparative merits of different objectives under test at the same time, and give no absolute indication of the extent of any errors present. No doubt the extremely short focal length and wide aperture of many objectives make the task of testing appear formidable, but the

writer ventures to think that the problem is not incapable of solution, and to suggest a method by which such results can be obtained.

Before, however, saying anything about a new scheme of testing it may be well to briefly refer to the ordinary methods.

Determination of the Equivalent Focal Length.—No very satisfactory method of obtaining this seems to be given in the books devoted to microscopical subjects. The most common method appears to be by finding the magnification of the image of an object micrometer produced with a known tube length, the difficulty with this in practice is that the tube length ought really to be measured from the nodal point of emergence of the objective, the position of which is not ascertained, and a considerable error may, therefore, result. A modification of the test, devised by the writer, is to insert in the microscope tube, in place of the microscope objective, a telescope of known magnification, and to ascertain the size of the image in the focal plane of the telescope produced by the stage micrometer. In this case, since the rays emerge parallel from the back of the objective, the position of the nodal point is immaterial.

Determination of the Aperture.—This is always effected by the exceedingly beautiful apertometer devised by Professor Abbe, and which is well known. It consists of a semi-circular block of dense glass, on the circumference of which two pointers slide. The straight edge of the block is bevelled at an angle of 45° so as to throw light proceeding from the edge upwards as if it had come from a semi-circular scale lying vertically below the glass instead of to the side of it. The objective to be tested is focused on a small aperture in the centre of the straight edge, either dry or with its appropriate immersion, so that light reaches it from all parts of the semi-circular edge. On withdrawing the eyepiece or inserting a lens into the tube so as to bring the edge of the block into focus, the pointers can be seen, and by sliding them round the block a position is reached where they just appear to be at the edge of a circular field. A scale is provided on the block, the readings of which represent the sines of the angles which these divisions make with the axis multiplied by the refractive index of the block, and which, therefore, gives the values directly of the numerical aperture of the objective. The test is expeditious and very accurate, the only condition required to read conveniently being that the glass block should receive diffused light from all directions, and not from a single source, otherwise the pointers will not be visible.

Determination of Errors.—The most common method of testing a

microscope for defects in this country has been by the mercury test, in which a small globule of mercury is placed on the stage and is crushed with a flat surface so as to split it up into exceedingly small globules, each of which when viewed by reflecting light has a small point of light on its surface, and, therefore, acts as an artificial star.

The tests for achromatism, spherical aberration, etc., can be performed on this precisely as with telescopes. A globule is first taken in the centre of the field and the appearances are viewed when the microscope is either focused downwards or upwards; if in the former case the disc appears with a red fringe, and when outside the focus with a blue flare, the objective is under-corrected. If the opposite appearance is viewed, it is over-corrected, while the appearance when the colour is properly corrected for is the same as with a properly corrected telescope object glass. It must be remembered, if an apochromatic lens is being tested, the test must be performed with its own compensating ocular, and in that case an almost perfectly colourless disc should be viewed either inside or outside the focus. Spherical aberration can, of course, be seen by noticing whether the disc is uniform in brightness or not, as with telescopes.

The same tests may be performed with a globule at the edge of the field, in which case coma or astigmatism may be noticed.

The mercury test is unsuitable, however, for objectives of very small focal length and large aperture, partly from difficulties of illumination and mounting, but chiefly because there is no means of varying the aperture with which the objective is employed. With the exceedingly large aperture of 1.4 which is now reached, even the best objectives fall off markedly in definition with the extreme rays, and it is consequently not always advisable to work with the full aperture.

Professor Abbe has introduced "test plates" in which lines are ruled on a silvered surface, and covered with cover glasses of various thicknesses. These objects are viewed by transmitted light in the ordinary way with a carefully centered condenser, the aperture of which can be varied at will by a diaphragm, and the appearance of the bands noticed on focusing up and down. These plates are particularly suitable for adjustable objectives, enabling one to find the best correction with considerable accuracy. By using also various stops in the condenser so as to give axial or oblique light, spherical or chromatic aberration can be detected.

Suggested New Method of Testing.—This paper is already so long that a few words only will be devoted to a new method of testing

microscope lenses which the author ventures to suggest. It is founded on the principle of auto-collimation, first used by Professor Abbe in his spectrometer, and independently devised by the writer for curvature measurement, and consists in making the light traverse the whole system or any part of it twice. This obviates all question as to centering and makes one independent of the quality of a condenser.

If we use an ordinary microscope, provided with the objective and eyepiece to be tested, and simply fix a small piece of plane, unsilvered glass above the eyepiece, the light from any distant small source of light can be reflected down the system, and will be converged by the objective. If we now use the ordinary Abbe test plates simply as reflectors, the light will be returned by them up the tube, and if the microscope is focused in the ordinary way, an image of the distant light will be seen. The appearances on focusing up and down can now be studied exactly as with an ordinary telescope, with the advantage that every defect is, of course, doubled in its effect. Not only so, but it makes it easy to have an absolute standard of defining power. With the ordinary methods, exceedingly small objects have to be employed on the stage, but this is unnecessary with the method proposed, as the visual angle between the different parts of the object is not altered by its having passed twice through the system. Consequently, ordinary test types may be employed, and with a perfect microscope the visual acuity should be the same as if directly viewed from the same standpoint, provided that the type is sufficiently illuminated to make up for the loss of light.

In order to make this test with the greatest convenience, a special microscope has just been made at the Northampton Institute, which, besides having the reflecting device, is provided with a horizontal axis carrying the objective, with an adjustment for bringing the nodal point on the axis. The objective can then be tilted at any angle, allowing axial or oblique light to be dealt with easily, and, further, allowing the focal length to be conveniently determined. Time has not permitted us to make much use of this instrument as yet, but I am inclined to think that we shall be able by its means to investigate microscope lenses much more thoroughly than by other methods. Further, as the necessity for small objects is done away with, I have some hope that it will enable us to investigate the much vexed diffraction theory more easily and completely.

The auto-collimation principle appears to me to be most valuable in all testing work. It has already been adopted by Dr. Clay for

photographic lens testing, and it might possibly be employed with advantage in telescope work, if a perfectly plane mirror were fixed in front of the object glass.

In bringing this somewhat lengthy paper to a close, I can only hope that in spite of its acknowledged many imperfections, it may be of use to many Opticians and serve as a stop gap until something more complete is available. I also venture to hope that some may be led to study the subject more closely, and to devise new methods or improvements on existing ones, which there is unquestionably good opportunity and necessity for. We shall never be able to ensure the best work in optical instruments until methods of testing are available by which the important quantities and errors of every instrument can be *numerically* stated. Up to the present, hardly anything has been done in this direction, except in the case of photographic lenses, and that only partially. It is much to be hoped that our National Physical Laboratory, or some other recognized institution, will be able to take up this work in the near future.

Finally, I must express my best thanks to Mr. Jolley and Mr. Greenfield, for designing the details of and constructing the testing microscope referred to, and to Mr. Mariner for the great assistance given in the experiments you have seen.