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Remarks on the Nomenclature of Achromatic Objectives for the Compound Microscope; by Dr. J. J. WOODWARD, U. S. Army.

FOR some years past, while most of the Continental opticians have continued to give arbitrary designations to their achromatic object glasses, such as No. 1, No. 2, &c., or System A, System B, &c., the English and American manufacturers, affecting a higher degree of accuracy, have undertaken to name the objectives they construct by their real or supposed agreement in magnifying power, with single lenses of specified focal lengths. We hear accordingly of inch, half-inch and quarter-inch objectives, &c., by which we are expected to understand combinations agreeing in magnifying power with single convex lenses of the focal lengths named.

At first sight nothing could appear simpler or more exact than such a nomenclature; nevertheless recent articles in the journals would seem to indicate that the general plan is capable of considerable modification in its practical application, and that grave misunderstandings have hence arisen.

Under these circumstances, it appears desirable to give some account of the principles involved, and of the practical difficulties to be considered in their application, particularly as the microscopical text-books contain little or no information on the subject. In fact, the only scientific discussion of the matter with which I am acquainted is the paper of Mr. Charles R. Cross, "On the focal length of microscopic objectives." (Journal of the Franklin Institute, June, 1870, p. 401). This paper gives a reasonable formula for the approximate computation of equivalent focal lengths, and furnishes some other valuable information, but does not discuss all the points at issue. I shall have occasion to refer more than once to this excellent paper, which the reader would do well to examine in connection with the following remarks.

We learn from the elementary treatises on optics that when an object is placed in front of a single convex lens at a distance somewhat greater than its focus for parallel rays, a real image is formed on the other side of the lens, which may be received on a screen. This image will be larger, and formed at a point more distant from the lens, the nearer the object approaches to the focus for parallel rays; and two equations are given which express the relationship of the distances to each other and to the magnifying power, viz:

$\frac{1}{f}=\frac{1}{p}+\frac{1}{p'}$, and $\frac{p'}{p}=m$, in which f is the length of the focus for parallel rays, p the distance of the lens from the object, p' its distance from the image, and m the true magnifying power, that is, the size of the image divided by the size of the object; p and p' are termed the conjugate foci and are variable quantities; f is termed the principle focus, and has an unchangeable value for each single lens.

If now we combine the above equations, representing $p+p'$ or the sum of the conjugate foci by l, we may deduce the formula $f=\frac{m\,l}{(m+1)^2}$ which represents in the case of any single convex lens the relationship existing between the length of the principal focus, the magnifying power, and the distance from the object to the screen. This formula, which I think rather more convenient than that of Mr. Cross, differs from it only in using $m =$ the magnifying power, instead of $n =$ the reciprocal of the magnifying power; it may be deduced from his by substituting for n its value $\frac{1}{m}$ and reducing, or it may be derived directly from the primitive equations. In either shape the formula yields the same numerical results, and if for any single convex lens m and l are given, the accuracy of the value of f resulting, will be limited only by the degree of precision with which m and l have been measured.

If now there were any such actual equivalence between achromatic objectives and single lenses as the nomenclature assumes, it would only be necessary to set up the objective to be rated, in such a manner that the image of a micrometer should be focussed upon a white screen, using of course no eye-piece, to measure the distance from the micrometer to the screen, to determine the magnifying power by measuring the image of the micrometer, and substituting these values of l and m in the working formula to calculate the value of f. Unfortunately, however, if with any compound objective we repeat this operation several times, merely varying the distances, we obtain as many different values for f as there are distances used, instead of obtaining but one value for all distances as we do with a single lens.

Mr. Cross (loc. cit. p. 409) has already pointed out this circumstance which results from the fact that the modern achromatic objective has considerable thickness, from its anterior to its posterior surfaces, and that it has properly speaking no true optical center. He gives two examples, in one of which a change of 5·24 inches in distance corresponded to a change of ·0067 inch in calculated focal length; in the other a change of 6·10 inches in distance corresponded to a change of ·0029 inch in calculated focal length, the objectives used in the experiment being uncorrected ¼ths, so called. If, however, Mr. Cross had used for this purpose lower powers, or had made greater variations in the distances employed, he would have found much greater discrepancies. For example, by measuring the magnifying power first at 25 and then at 50 inches, and deducing the value of f by the formula of Mr. Cross, I obtained in two cases the following equivalent focal lengths. For a so-called 1½ inch, at 50 inches distance, 1·2187 inches; at 25 inches distance, 1·2468 inches; difference ·0271 inch. For a so-called ⅕th, at 50 inches distance, ·1982 inch; at 25 inches distance, ·1893 inch; difference ·0089 inch.

Moreover, since the achromatic objectives of different makers are constructed on different series of curves, and the component lenses placed at different distances apart, it will be found that if two achromatic objectives magnify the same at any given distance, they will no longer do so if the distance is materially changed.

Hence I am compelled to agree fully with the observations of Mr. Cross (loc. cit. p. 401), that the nominal focal length assigned to an achromatic objective can only serve in any case as "a general appellation serving to group together objectives of *approximately* the same magnifying power," and must conclude, therefore, that the English and American nomenclature possesses no real claim to strict scientific accuracy, and especially that the comparison made by some with the case of the celestial telescope is not valid.

But besides the inevitable inaccuracy resulting from this source, there are in the case of the higher powers of modern makers two other sources of much more considerable error. The first of these involves the case of all those objectives which are provided with a screw collar to correct for thickness of cover; the second involves the case of objectives with two fronts, one for wet and the other for dry, or those with but one front which can be used wet or dry by merely changing the correction given by the screw collar.

The correction for thickness of cover is made, as is well known, by changing the distance between the front combination of the triplet and the posterior two combinations. As a consequence, the magnifying power of the objective at any given distance, or with any given eye-piece, is least when the objective is corrected for uncovered, and greatest when it is corrected for the thickest cover through which it will work. The ratio of this change is very different in different objectives. I select a few from my note book in illustration, purposely omitting to name the makers.

	Magnifying power at uncovered.	Magnifying power at covered.
No. 1,	200	225
No. 2,	250	275
No. 3,	300	333
No. 4,	350	500
No. 5,	570	630
No. 6,	900	1100
No. 7,	975	1180
No. 8,	890	1250

These values were obtained by throwing the image of a micrometer on a card board screen, using the objective without an eye-piece, and the distance from micrometer to screen in each case remained the same, the screw collar and the focal adjustment of the objective being modified. Of course, for all intermediate positions of the screw collar intermediate values result. The distance used was 48 inches in some of the cases, 50 in the others. With shorter distances, the amount of the difference is diminished, but its ratio to the magnifying power at uncovered is not materially changed, as any one can convince himself by comparing a stage micrometer, as seen by any corrected objective, with an eye-piece micrometer, first at uncovered and then with the full correction for cover.

Now it is evident that even if, by the formula of Mr. Cross, or otherwise, we could obtain accurate equivalent focal lengths for any one position of the cover correction, the result would not be true for any other position of the cover correction.

We are told by a recent writer that the practice of the opticians is to name the combination at its performance uncovered, that is, at precisely the adjustment least used. If, however, scientific accuracy in the matter is desirable for any purpose whatever, it is evident from the above that at least the maximum and minimum should be furnished by the maker.

It is also evident that the considerations here offered, aside from their bearing on the nomenclature of objectives, have a high practical value to all those who attempt to make micrometric measurements with modern high power objectives; for the practice recommended in the text-books, and too generally pursued, is to give values to an eye-piece micrometer by comparing it with a stage micrometer at a fixed position of the draw tube, and to use these values in subsequent measurements.

Now as these values vary considerably with the cover correction, it is to be feared that the majority of the measurements, made with high powers during the last twenty years are sadly inaccurate.

The difficulties in the way of a nomenclature based upon equivalent focal lengths have been still further increased since the introduction of immersion objectives. The compound objective is usually furnished with two fronts, one for wet and one for dry use. Of these the wet usually gives the greatest magnifying power at any given distance. I have also measured an objective which, when corrected for the thickest cover through which it will work dry, is just corrected for uncovered wet, and by approximating the posterior pair of combinations still nearer to the anterior, corrects for cover wet, thus increasing the magnifying power when the objective is in use wet precisely as if two fronts were used.

The difference in magnifying power resulting from the modifications given to make the objective perform wet is quite considerable, as may be seen by the following extracts from my note book.

	Magnifying power. Dry.		Wet.	
	Uncovered.	Covered.	Uncovered.	Covered.
No. 1,	225	250	250	275
No. 2,	425	490	450	500
No. 3,	700	900	900	1000
No. 4,	770	910	900	1100
No. 5,	790	930	975	1180

Of these objectives No. 1 had but one front, the correction for wet being made by the cover correction; the others had two separate fronts, one for wet, the other for dry.

Now it is just in connection with these complex objectives, with double fronts or other devices to correct for wet and dry, that the greatest diversity of nomenclature exists. In one quarter it is claimed that the system should have two names, one based on its magnifying power at uncovered wet, the other on its magnifying power at uncovered dry; in other quarters the practice has been to give the system but a single name derived from the magnifying power at uncovered dry alone. It is evident, however, that neither of these plans has any pretension to scientific accuracy, and that if the makers will not give at least the maximum and minimum for both dry and wet, the purchaser must learn to measure for himself.

A similar remark applies to the angle of aperture as stated by the makers, for each objective sold. As a rule they give the greatest angle attainable by the combination, which is generally,—not always,—the angle at the correction for thickest cover, their usual practice in this case being the reverse of their usual practice with regard to magnifying power. Now I have seen objectives with an angle of 170° and upward at full cover correction, which did not exceed 140° at uncovered. It is evident, therefore, that the maker should furnish with each glass both the maximum and minimum angle, or the microscopist must measure for himself.

After a full consideration of all the circumstances, I am disposed to think that the best interests of both makers and purchasers would be consulted if the present nomenclature were abandoned altogether, and objectives named instead by their precise magnifying power without eye-piece at some selected distance. It would be well if all the makers could be brought to agree on some fixed distance; but until we obtain this happy uniformity, which perhaps is not to be anticipated, it is only necessary for each maker to state the distance he selects. By this plan objectives without correction for cover would be named by one number, objectives with correction by two, and those with two or more fronts or backs by two or more pairs of numbers.

Thus we should have objectives without cover corrections named precisely 2, 3, 4, 5, 6, 7, 8, 9, and so on up to 100 or more, the number indicating the exact magnifying power, say at twelve and a half inches from micrometer to screen. Objectives with cover corrections would be named 30 to 40, 35 to 46, 75 to 89, 125 to 140, &c., the numbers representing the minimum and maximum magnifying powers at the selected distance. Objectives with wet and dry fronts would require a separate name for each; thus 78 to 95 dry, 98 to 130 wet, &c.

By this plan the real magnifying power of the glass and its limits of variation would be accurately stated, whereas at present even those makers who are most careful about their nomenclature do not hesitate to call a glass an $\frac{1}{8}$th provided its power at uncovered approximates that of a single lens of $\frac{1}{8}$th of an inch focus more nearly than it does a $\frac{1}{6}$th or a $\frac{1}{10}$th. Hence glasses which differ materially in magnifying power at uncovered, receive the same name, and the changes in power produced by the cover correction, are invariably ignored.

If the plan I here recommend be adopted, the precise distance from micrometer to screen which may be chosen does not appear to me to be of very great importance. Many persons would I suppose prefer 10 inches to 12½. I have selected the latter number because many of our larger stands have tubes too long to permit the convenient measurement of low powers with eye-piece and stage micrometers, in the manner I shall presently describe, if the distance be taken at 10 inches, whereas on most stands, with the help of the draw tube, 12½ inches can be used conveniently with all powers from the three inch upward. I do not, however, insist on any particular distance, but only that the distance selected shall be stated in each case until some uniform plan shall be generally agreed upon.

In this connection I may add that the actual plan of the Continental opticians is also unsatisfactory. In the matter of angle of aperture, when they give it at all, they also, as a rule, give only the maximum. In the matter of magnifying power, when they give any information, they attempt, as a rule, to give the magnifying power of the objective with each eye-piece as actually looked through when in use. But as the magnifying power of the combination under these circumstances involves the distance of distinct vision for each observer, it is evident that the figures thus furnished cannot have any practical value.

Pending the adoption of some such system as I have suggested above, it will be necessary for the microscopist to measure for himself the magnifying power of the objectives he uses, whenever he desires to be possessed of the real information concealed behind all the several systems of nomenclature at present in use. Mr. Cross in his paper gives two modes of doing this. I myself have been in the habit of using a dark room, and throwing the image of the micrometer on a white screen, by the direct rays of the sun. Very nearly equal accuracy may be attained, however, by any microscopist who possesses an ordinary glass eye-piece micrometer and a stage micrometer. The glass eye-piece micrometer, it will be recollected, is slipped through the eye-piece in such a manner as to be just in the focus of its eye-glass, that is, in the plane which is occupied by the image formed by the objective when it is seen most distinctly. If now the field glass of such an eye-piece be removed, and the stage micrometer carefully brought into focus, a comparison of the divisions of the eye-piece and stage micrometers will give the magnifying power of the objective alone at the distance actually existing between the two micrometers. Thus, for example, if the stage micrometer is in $\frac{1}{1000}$ths and the eye-piece micrometer in $\frac{1}{200}$ths of an inch, five times the number of eye-piece divisions corresponding to one division of the stage micrometer will be the magnifying power of the objective at the cover correction employed, for the distance selected. We may then apply the following simple rule, derived from the formula of Mr. Cross.

Multiply the distance between the two micrometers in inches and decimals, by the magnifying power, and divide by the square of the magnifying power plus one; the result will be the equivalent focal length (for the given conditions) in decimals of an inch.

It will, moreover, be found in practice that for powers equivalent to those of a $\frac{1}{4}$th or shorter focal lengths a still simpler rule may be adopted, and that the distance between the two micrometers, divided by the magnifying power, will give very nearly the same results as are obtained by the more complex rule, but this of course is not true for lower powers.

It must, however, be constantly borne in mind that the results obtained in any case are true only for the cover correction and distance used.

For the convenience of those who may undertake such comparisons, I append a table in which the real magnifying powers of single convex lenses are given for three different distances. In the treatises on optics the magnifying powers of single lenses are sometimes stated at some given distance from the lens to the screen, but I know of no table which shows their powers at given distances between image and object.

This table is calculated by substituting the numerical values of f and l in the equation $f = \frac{ml}{(m+1)^2}$, when $m =$ the magnifying power remains as the only unknown quantity and is easily computed. I have carried out the values of m to two decimal places only; but in practice the nearest whole number will be found sufficiently accurate.

Table of the magnifying powers of single convex lenses.

Focal length for parallel rays.	Magnifying power at 12½, 25, and 50 inches distance from micrometer to screen.		
	12 1-2 inches.	25 inches.	50 inches.
3 inches, - - -	1·50	6·17	14·59
2 " - - -	4·00	10·40	22·95
1½ " - - -	6·17	14·59	31·30
1 inch, - - -	10·40	22·95	47·99
⅔rds of an inch, - -	16·69	35·47	72·98
$\frac{4}{10}$ths " - -	29·21	60·48	122·99
$\frac{1}{4}$th " - - -	47·99	97·98	197·99
$\frac{1}{5}$th " - -	60·48	122·99	247·99
$\frac{1}{6}$th " - - -	72·98	147·99	297·99
$\frac{1}{8}$th " - -	97·98	197·99	397·99
$\frac{1}{10}$th " - -	122·99	247·99	497·99
$\frac{1}{12}$th " - -	147·99	297·99	597·99
$\frac{1}{15}$th " - -	185·49	372·99	747·99
$\frac{1}{16}$th " - -	197·99	397·99	797·99
$\frac{1}{18}$th " - -	222·99	447·99	897·99
$\frac{1}{20}$th " - -	247·99	497·99	997·99
$\frac{1}{25}$th " - -	310·49	622·99	1247·99
$\frac{1}{50}$th " - -	622·99	1247·99	2497·99

Note.—Since writing the foregoing article, I have read with pleasure a paper on the same subject by Dr. R. H. Ward

("Remarks on uniformity of nomenclature in regard to microscopical objectives and oculars," American Naturalist, March, 1872, p. 136). This paper contains much valuable matter, and should be read by all who are interested in this subject. I learn from it for the first time that the method of determining the magnifying power of objectives by removing the field glass of the eye-piece and using eye-piece and stage micrometer as described above, has already been used by Dr. J. J. Higgins of New York (American Naturalist, Dec., 1870, p. 628), to whom I hasten to give the credit due.

I am very glad to find Dr. Ward indicates the feasibility of the substitution of magnifying powers at a fixed distance as names for objectives instead of alleged equivalent focal lengths. I must, however, differ from him when he recommends that the distance should be measured from some part of the objective to the screen, instead of from the micrometer to the screen; for however desirable this may be made to appear, it is not feasible. Nor can I agree with him in regarding ten inches distance as having anything special to recommend it. To the question he asks at the conclusion of his paper, "at what point of the screw collar adjustment shall the objective be placed for rating its angular aperture and amplifying power?" I reply without hesitation that for each purpose accuracy demands that the maximum should be given as well as the minimum; that the maker should state not merely one limit, but both.

Dr. Ward's paper also contains some interesting suggestions on the subject of the nomenclature of eye-pieces, a matter which will, however, I think, particularly in the case of the ordinary eye-piece, require further discussion. I agree fully with Doctor Ward that eye-pieces should be named by their magnifying power: but the question at once arises, how shall this be accurately measured? To this subject I may recur at some future time.