Triple Cemented Telescope Objectives

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III. *Triple Cemented Telescope Objectives.* By T. SMITH, B.A., and Miss A. B. DALE. (*From the National Physical Laboratory.*)

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THE ordinary telescope objective consists of a crown lens and a flint lens which are not cemented together because the conditions which must usually be satisfied demand a difference in the curvatures of the inner surfaces of the two lenses. For some purposes it is desirable to have a cemented objective, even if this involves some falling off in the quality of the definition obtainable. There are, however, limits beyond which such deterioration may not go, and these depend on the relative aperture and the field of view of the lens. Unfortunately the circumstances in which a cemented objective is required are usually those which also involve large relative apertures and a large field of view. If a triple cemented objective is substituted for a doublet the extra degree of freedom obtained enables the required conditions to be satisfied much more nearly than in the case of the simpler form of objective, even though no additional variety of glass is used for the third component lens. The extent of the advantage thus gained depends upon the magnitude of the outstanding aberrations and upon the magnitude of the curvatures required for the triple objective. A manufacturer will require to have shallower surfaces to grind as a compensation for the additional labour involved in the introduction of two extra surfaces into the optical system, and the performance of the telescope will not be sufficiently improved if the reconciliation of the conditions for the removal of spherical aberration and coma of the first order involves the introduction of greatly increased aberrations of the second order. The object of the investigation described in the present paper is to determine what two kinds of glass should be used in order to obtain a triple telescope objective that is most satisfactory as regards smallness both of curvatures and of second order aberrations.

The commonly accepted opinion is that these two characteristics go hand in hand, so that among otherwise equally good objectives that one will have the smallest second order aberrations which has the least curvatures. This, no doubt, may be taken as a rough guide, but it will be seen from the results detailed below that it is not strictly true, for the series of triple objectives which are best as regards smallness of second

order aberrations have somewhat greater curvatures than another series of triplets which are not quite so satisfactory in this respect.

In the calculation of all objectives thicknesses have been entirely neglected. This course enables the amount of numerical work involved to be reduced to the minimum without causing errors of any consequence in the conclusions drawn from the results of the investigation. A further simplification has been introduced by assuming the refractive index of the flint glass to be 1.6200 throughout the whole series of objectives. With this one exception the results are quite general, as both the refractive index of the crown glass and the ratio of the dispersions produced by the two glasses have been varied over a sufficiently wide range to embrace all the varieties of glass that are likely to be employed for the construction of telescopic objectives.

The objectives considered have in all cases been calculated so that all first order spherical aberration and coma is removed. These are not the conditions that are satisfied in actual objectives, a balance between first and second order aberrations of opposite signs being decidedly preferable. It might be supposed that this would detract from the utility of the investigations; this is, however, not the case. The curvatures of the actual objectives in which such a balance is obtained are almost identical with those of thin objectives free from first order aberrations, and the differences in the magnitude of the second order aberrations must, therefore, be small if the actual objectives are of normal thickness.

The formulæ from which triple objectives are to be calculated have been given in a previous paper by one of the authors.* The triplet is most simply regarded as two doublets cemented together; the aberrations of a triplet then depend upon:—

(a) The minimum spherical aberration for magnification -1 for the doublet, the corresponding amount of coma, and the curvatures of the external surfaces;

(b) The amount of spherical aberration when a plane wave is incident normally on a doublet having its first surface plane;

(c) The Petzval sum.

These quantities are plotted in Figs. 1 to 4, for a varying refractive index of the crown glass and for v ratios of crown to

* "Notes on the Calculation of Thin Objectives." Proc. Phys. Soc., Vol. XXVII., p. 495.

FIG. 4.

FIG. 3.

FIG. 2.

FIG. 1.

FUNDAMENTAL CONSTANTS OF DOUBLETS.

flint of $10^{0.15}$, $10^{0.20}$, $10^{0.25}$ and $10^{0.30}$.* For a doublet with a flat outer crown surface the spherical aberration is A for an object at infinity. When a plane wave is first incident on a flat outer flint surface the spherical aberration is A' . R_1 and R_3 are the outer curvatures of crown and flint components respectively of the doublet which has minimum spherical aberration for magnification -1 , and this spherical aberration is denoted by $4C_0 + 2\pi + 1$. $B_0' - B_0$ is the corresponding amount of coma in this objective, and π is the Petzval sum. A knowledge of the way in which these quantities depend upon the difference in the refractive indices of crown and flint glasses and upon their r ratio is of the greatest importance to the designer of optical systems.

The features of the diagrams which are of most consequence are the following :—

(a) A' is always positive, and the A' curve varies very little in Figs. 2, 3 and 4.

(b) A is practically constant for all refractive indices of the crown component in Fig. 4, but decreases rapidly as the r ratio is diminished.†

(c) $4C_0 + 2\pi + 1$ diminishes with a reduction of either the crown glass index or the r ratio. When both refractive indices become equal, A , A' and $4C_0 + 2\pi + 1$ take the common value $\left(\frac{\mu}{\mu-1}\right)^2$.

It has already been pointed out that the simultaneous fulfilment of the conditions for freedom from spherical aberration and coma in a cemented doublet is dependent upon the choice of a suitable combination of glasses. The classification of triple objectives may be conveniently based upon the cemented doublets which satisfy the same conditions. For a given r ratio there is some one refractive index for the crown glass which will enable a doublet with the crown component leading to be made free from spherical aberration and coma. If now the crown refractive index is slightly altered a doublet can be made to satisfy one condition, while departing slightly from the other. To satisfy both conditions the doublet must

* If the objective is not to be corrected exactly for chromatic aberration these figures represent the absolute value of the ratio of the power of the crown lens to that of the flint.

† Glasses for which A vanishes are those suitable for the construction of symmetrical triplets for magnification -1 . Since A' is always positive there is no possibility of a corresponding symmetrical form with external crown lenses.

be replaced by a triplet, and obviously this triplet will only depart slightly from the doublet form, the additional component being a very weak lens. Evidently two triplets can be found to satisfy the conditions, one consisting of a weak crown component added after the flint lens, and another with a weak flint component placed in front of the crown lens. As greater variations in the refractive index are introduced the departures from the doublet form will become more pronounced, but over an appreciable range of indices it is to be expected that the derivation of these two triple objectives from a doublet with the crown component leading will be evident. In a like manner two series of triple objectives may be derived from a doublet with the flint component leading. The classification adopted here will therefore be as follows :—

Series I. and II.—External Lenses of Crown Glass.

Series I. based on doublet with crown component leading, and therefore tending to have the first crown component more powerful than the second.

Series II. based on doublet with flint component leading, and therefore tending to have the first crown component weaker than the second.

Series III. and IV.—External Lenses of Flint Glass.

Series III. based on doublet with crown component leading, and therefore tending to have the front flint component weaker than the second.

Series IV. based on doublet with flint component leading, and therefore tending to have the front flint component more powerful than the second.

The curves showing any properties of Series I. and III. must necessarily intersect at the position relating to the doublet, since this is a member of both series. Similarly, curves relating to II. and IV. must intersect at the position of the second doublet. It is to be noted that there is no reason why the curves showing certain properties of these allied series should not also intersect at additional points.

Each series is divided by the double points into two parts, and the character of the triplet in these sections is quite distinct. The distribution of the total power of the lenses made of the external glass between the two components varies progressively in the series, and at the double points the power of one of these components becomes zero. If, then, the powers of

both external components are of the same sign on one side of the double point they will necessarily be of opposite sign on the other side. It is to be expected that the curvatures and higher order aberrations of any one series will be greater in absolute value on the latter side of the double point. This side, it will be seen, is that on which the difference of refractive indices of the two glasses is less than for the doublet. From results previously established for double objectives * it follows that the normal glasses now available lie in the region more favourable for small curvatures and higher order aberrations.

If in any region the solution for a series becomes imaginary, the solution for another series must also have the same property. The series associated in this way with one another are obviously those which have the same glass externally, since in such a case the one series must be a continuation of the other. It is found that the solutions to Series I. and II. are always real, but those of Series III. and IV. become imaginary when the difference between the refractive indices exceeds a certain amount depending upon the ν ratio.

Figs. 5, 6, 7 and 8 show the second order aberration coefficients for triple objectives calculated from the data given in Figs. 1 to 4. The full curves show the amount of spherical aberration and the dotted curves the departure from the sine condition. The heavy lines relate to Series I. and III., which approximate to a doublet with the crown component leading, and the lighter lines to Series II. and IV. It will be noted that these two outstanding quantities are always negative. Thus the spherical aberration of the second order always tends in the direction of over-correction. The coma depends upon the difference between the full and the dotted curves, and is thus of one sign for Series I. and III. and of the opposite sign for Series II. and IV. Generally speaking, the amount of coma does not vary very greatly between the various series except near the junction of Series III. and IV., where the coma is small for systems with external flint components. As would be expected from a knowledge of the second order aberrations of achromatic doublets, the spherical aberration is distinctly less for Series I. than for Series II., and for Series III. than for Series IV. The most interesting feature of these diagrams, however, is the way in which the curves for combinations with external flint lenses lie above those with external crown lenses,

* See "The Choice of Glass for Cemented Objectives." *Proc. Phys. Soc.*, Vol. XXVIII., Figs. 1 and 2.

FIG. 8.

FIG. 7.

FIG. 6.

FIG. 5.

SECOND ORDER SPHERICAL ABERRATION AND COMA.

FIG. 11.

FIG. 10.

FIG. 9.

CURVATURES OF TRIPLET SURFACES.

Series III. thus being the best as regards spherical aberration. It is also remarkable that the minimum amount of this aberration left outstanding should vary so slightly over the range of v values covered by the diagrams.

It was originally intended, when this investigation was undertaken, to plot in a diagram, in which the refractive index of the crown glass and the v ratio were the abscissæ and ordinates respectively, contours showing for which glasses the aberrations attained equal values. The four figures shown, however, indicate that this would involve an amount of labour which the results would not justify. For the contours are not in all cases simple closed curves, but are broken up into at least two parts, as may be seen by noting that in Figs. 5, 6 and 8 the curves cross the line -60 , but do not reach it in Fig. 7. The approximate constancy of the position of the highest points of the curves removes the need for accurately plotted contours of the character at first proposed.

The remaining figures show the curvatures of the surfaces. The curvatures of the external surfaces vary between comparatively close limits, and are chiefly determined by the condition for freedom from coma. The curves giving the curvatures of the two cemented surfaces are approximately parallel to one another. The inner surfaces tend to become very strongly curved when the refractive index of the crown lens approaches that of the flint. In Series I. and III., represented by the thick curves, the greatest curvatures are distinctly less than for Series II. and IV., shown by thin lines. In the former two series the cemented surfaces become concave to the incident light, and in the latter two series convex, when the refractive index of the crown glass is only slightly less than that of the flint. The curvature of the steepest surface in Series I. is sometimes greater and sometimes less than in Series III.; but the curvatures of Series I. are decidedly the more favourable when the outstanding aberration of Series III. is least. In the case of greatest practical importance the two conditions are therefore inconsistent. The triple objectives of both Series I. and III. show decided advantages over most doublets, both as regards smallness of curvature and smallness of outstanding spherical aberration. Considerable gain is thus possible by their use for many purposes where the conditions are distinctly difficult of fulfilment with an objective of the ordinary type.

Figs. 9, 10, 11 suggest that for small variations in the μ and ν values of the glasses the principal alterations in the curvatures should usually be carried out on the surfaces indicated in the following table :—

Series.	Variation in μ .	Variation in ν .
I.....	4	3
II.....	1	2
III.....	2 and 3	2
IV.....	3 and 2	3

In all cases a variation in r is chiefly compensated by an alteration of an internal surface. In lenses with exterior crown components alterations for both μ and ν should be carried out on the weak correcting component. The fact that each correction can be carried out on a single surface constitutes an important manufacturing advantage for these two series. If Series I. is adopted, and the only factor likely to vary appreciably is the refractive index of the glass, when objectives of a given focal length are required it should be possible to use with all glass meltings the same standard tools for all the surfaces excepting the last.

ABSTRACT.

The Paper describes the four series of triple cemented thin telescope objectives which can be made from two kinds of glass, and determines their construction when first order spherical aberration and coma are eliminated. The second order spherical aberration and coma are then calculated, and the former found to be of the same sign for all optical glasses when the surfaces are spherical. The best standard attainable varies very little over a considerable range of glasses. Diagrams show the variations in the curvatures as the glasses are varied for refractive index and dispersion. Contrary to the general belief, it is found that the objectives with least second order aberrations (absolute values) are not those with the least curvatures for their refracting surfaces.