THE USE OF ACHROMATIC DOUBLETS
BEYOND THEIR DESIGN RANGE

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ABSTRACT

Achromatic doublets are often used in experimental laboratory "breadboards" outside the range for which the lens has been corrected. This investigation examines the use of a commercial 400-mm objective that has been corrected for the visible part of the spectrum, but is being utilized in a laser application at 852 nm. As the theoretical wavefront error at 852 nm is very small, the error attributable to the lens would probably be determined in practice almost entirely by the quality of its construction.
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I  INTRODUCTION

The achromatic doublet is the workhorse of the experimental optical "breadboard." Consequently, one is quite often tempted to use an available objective under conditions that are outside the range for which the lens was designed. It is useful to have an intuitive feeling for the loss of performance that inevitably occurs; of course, the magnitude of such loss will depend on the specific conditions. This investigation is considered to illustrate a rather typical example and, on that account, may be of general interest. However, it is concerned with a lens of aperture f/10 and a design that may be expected to yield high performance up to f/5; in addition, the thickness of the objective is small relative to the focal length. If the lens being evaluated is of this same class, valid conclusions can be drawn; an f/2 doublet of 5-cm focal length (where the thickness is a substantial fraction of the focal length), however, is of another design and uses different glasses.

The specific problem dealt with in our investigation was the deterioration of performance expectable if a commercial [1] 400 mm f/10 objective, designed for minimum spherical aberration at 546.1 nm and achromatism at 478.0 nm and 643.8 nm, were used in a laser application at 850 nm.

II  SOME COMMENTS ON THE DESIGN OF ACHROMATS

Achromats in the form of telescope objectives (object at infinity) have been thoroughly researched during the last 100 years; "good" solutions for special cases are well known. The problem under consideration offers a typical case that has been exhaustively discussed in the literature, so that an adequate selection of glasses for this example can be found in every glass catalogue. The problem is treated in detail by B. K. Johnson [2], who recommends glasses with the following characteristics:
\[ n_1 = 1.51750 \quad V_1 = 60.5 \]
\[ n_2 = 1.69700 \quad V_2 = 30.5 \]

Since both glasses are in contact with air and are subject to chemical attack from handling, it would be prudent to use very stable, resistant glass types, provided we can find them with the required optical constants. This consideration would presumably have influenced the manufacturer's selections; after all, we all follow the same book of rules. Thus, there is a good chance that the design we finally arrive at will be only trivially different from the commercial product.

On looking through the Schott Optical Glass catalogue, the following pair of glasses was chosen as having the required durability:

- K - 5 \[ n_e = 1.52458 \quad V = 59.22 \]
- SF - 52 \[ n_e = 1.69384 \quad V = 30.39 \]

Following the procedures described by B. K. Johnson, we arrive at the following design constants (Figure 1):

\[ r_1 = 204.3 \quad r_2 = -204.3 \quad r_3 = -912.0 \]
\[ t_1 = 4.9 \quad t_2 = 3.1 \]

The refractive indices listed in the Schott catalogue are given in Table 1.
Table 1

Refractive Indices For K-5 and SF-52 Glasses

<table>
<thead>
<tr>
<th>nm</th>
<th>Spectral Line</th>
<th>n K5-522595</th>
<th>n SF52-689306</th>
</tr>
</thead>
<tbody>
<tr>
<td>480.0</td>
<td>F'</td>
<td>1.52910</td>
<td>1.70585</td>
</tr>
<tr>
<td>546.1</td>
<td>e</td>
<td>1.52458</td>
<td>1.69384</td>
</tr>
<tr>
<td>643.8</td>
<td>c'</td>
<td>1.52025</td>
<td>1.68301</td>
</tr>
<tr>
<td>706.5</td>
<td>r</td>
<td>1.51829</td>
<td>1.67843</td>
</tr>
<tr>
<td>852.1</td>
<td>s</td>
<td>1.51507</td>
<td>1.67139</td>
</tr>
<tr>
<td>1014.0</td>
<td>t</td>
<td>1.51257</td>
<td>1.66655</td>
</tr>
</tbody>
</table>

The design was ray-traced as described in Technical Note 215 [3], for the wavelengths of 480.0, 643.8 and 546.1 nm. The axial intercept for these wavelengths is shown in Figure 2, for 852.1 nm and 1014 nm in Figure 3.

In evaluating lens performance the following two criteria are traditional:

Longitudinal Spherical Aberration (LSA)—the tolerance is $4 \lambda / (N.A.)^2$, which corresponds to the Rayleigh tolerance for a wavefront error of $\lambda / 4$. This is discussed by Conrady [4]. In this case the numerical aperture is 0.05, so that at 546.1 nm the tolerance in longitudinal spherical aberration—the spread of the axial intercept—is 0.874 mm. The focal range (depth of focus), for which there is no perceptible deterioration in the axial image, is $\lambda / (N.A.)^2 = 0.219$ mm. Both of these values are wavelength-dependent.
FIGURE 1  THE OBJECTIVE UNDER EVALUATION

\[ r_1 = 204.3 \]
\[ r_2 = -204.3 \]
\[ r_3 = -912.0 \]
\[ t_1 = 4.9 \]
\[ t_2 = 3.1 \]

\[ n_1 \quad n_2 \quad n_1 \quad n_2 \quad K-5 \quad SF-52 \quad 522595 \quad 689306 \]
FIGURE 2 SPHERICAL-ABERRATION CURVES FOR 480.0, 546.1, AND 643.8 NANOMETERS
FIGURE 3 SPHERICAL-ABERRATION CURVES FOR 643.8, 852.1, AND 1014.0 NANOMETERS
Offense Against the Sine Condition (OSC'). This parameter determines how rapidly the image quality deteriorates as one moves away from the axis; it does not necessarily indicate anything about the quality of the axial image, which is determined by the longitudinal spherical aberration. The tolerance for both microscope and telescope objectives that have a field limited to \(1^\circ - 2^\circ\) from the axis is usually taken as \(\pm 0.0025\).

Since the chosen form of design performs very well up to a numerical aperture of 0.1 and since we shall not be exceeding 0.05, the tolerance bounds established present relatively little difficulty--provided a good selection of glasses has been made.

III RESULTS

A. The Design Conditions

The calculations are based on an object distance of 1,000 meters; this yields a convenient incremental angle of 0.0001\(^\circ\) and a maximum value for \(U_0\) of 0.00115\(^\circ\) at the rim of the objective.

The observed back focal distance is 395.96 mm; the value quoted in the catalogue is 395.4 mm. The correction for the object at 1,000 m reduces the calculated value by about 0.2 mm.

The calculated secondary spectrum is 396.07 - 395.86 = 0.21 mm or 1/1900 of the focal length. The catalogue quotes a value of one part in 2,000.

The catalogue states that the foci for the chosen G' and F' wavelengths coincide—which they do in the calculated design.

On the basis of these comparisons it seems fair to conclude that the designed achromat does not differ materially from the commercial product. If this is accepted, the deductions that may be made from the performance curves will probably be valid.
B. Optical Performance of the Calculated Design

As we have indicated earlier, the tolerance for longitudinal spherical aberration is 0.874 mm, the focal range 0.219 mm. If extreme values are taken over the design range from 480 nm to 644 nm, the axial intercept varies by $396.20 - 395.84 = 0.36$ mm. Thus, the design exceeds the tolerance by a large factor.

Offense against the sine condition (OSC') has been calculated for values of $U_0$ of $-0.0003$, $-0.0006$, $-0.0009$, and $-0.0012$ degrees for a wavelength of 546.1 nm, yielding values of $-0.000039$, $-0.000147$, $-0.000320$ and $-0.000544$. The permissible tolerance of $\pm 0.0025$ is almost five times greater than the maximum observed value.

In summary, the design is very satisfactory. The same pair of glasses would almost certainly permit the design of objectives within tolerance up to an aperture of at least $f/5$ (N.A. 0.1).

We can now consider the question that the design was intended to satisfy: how will the lens perform with respect to a spectral line at 852 nm? We observe that the focal length increases steadily with wavelength, while the spherical aberration remains extremely small. At 852 nm it amounts to $397.18 - 397.08 = 0.10$ mm. The LSA corresponding to a wavefront error of $\lambda/4$ is $1600 \times 0.852 \times 10^{-3} = 1.36$ mm.

Assuming that the error caused by the lack of homogeneity in the glass is very small, and that there is no condition of strain from the cement that joins the two components, and provided that the lens has been made with sufficient care—the wavefront error should be as little as $\lambda/10$ and could be as small as $\lambda/20$. 
REFERENCES


