

Split achromatic doublet problem and lens element centering in a drop-in barrel

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Abstract. A split doublet is more sensitive to aberration because the inner surfaces are typically strong in curvature and can independently misalign. To improve the centering of a lens element, we discuss using a strip of material inserted in the gap between the lens edge and the barrel. This technique has the benefit of relaxing the barrel inner diameter tolerance. Four examples are provided where lens centering was estimated to range between 0.025 and 0.050 mm. © 2022 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.OE.61.10.105112](https://doi.org/10.1117/1.OE.61.10.105112)]

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1 Introduction

Many lens systems in their front lens group use an achromatic doublet to provide optical power and to contribute to the correction of aberration. When the achromatic doublet is split, this is not cemented, the sensitivity to fabrication and assembling errors significantly increases. This is due to the relative strong curvatures of the doublet's second and third surfaces that may contribute undesirable aberration when they are misaligned. In a cemented condition, the effects of the second and third surface substantially cancel. The split doublet then presents a problem in actual fabrication of a lens system that requires diffraction on nearly diffraction limited performance.

Drop-in barrels are desirable because they may need only one retaining threaded ring, the lens elements can be removed if necessary, assembly trials can be performed, and the overall cost of the barrel can be substantially low. However, typically, in a drop-in barrel, the alignment precision depends on the precision of the barrel and lens elements; the higher the precision, the higher the cost might be. When the tolerances are tight to achieve lens alignment, the problem of lens cocking during lens insertion is an issue.

Assuming a small production of lens systems, and for lens diameters in the 25- to 100-mm range, typical achievable tolerances are ± 0.0125 mm in thickness, ± 0 mm/0.025 mm in diameter, and 0.5 to 1 arc min in wedge. Tighter tolerances would likely increase substantially the lens cost. In addition to the lens element fabrication errors, one must consider the lens mounting errors. These can be ± 0.0125 in lens spacing, lens tilt 1 arc min, and depending in the internal diameter of the barrel the lens decenter might be 0.0125 mm to much more. In order words, this set of tolerances are what often a lens designer and opto-mechanical engineer need to work with, in a not mass production environment of lens systems.

For reference, some mass produced photographic lenses for the 35-mm film format were routinely manufactured with gaps between the lens and the barrel of about 0.025 mm. This represents a centering precision of 0.0125 mm.

There are a variety of methods for precision mounting of lens elements.¹⁻⁶ However, precision lens mounting often leads to higher lens system cost when a few systems need to be manufactured. For example, the so called “poker-chip” method³ requires individually mounting and centering the lens elements in sub cells that are precision machined to fit into the lens barrel.

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This method although precise, is expensive and time consuming. Further, self-centering methods⁶ require of precision machining of spacers and/or retaining rings. Often, there is the need to fabricate a few lenses and using off-the-shelf drop-in lens barrels is very desirable. In this situation, counting on a method that can improve lens centering is also very desirable.

In this paper, we discuss the aberrations of the split doublet under misalignment, and a simple but effective method to center lenses in a drop-in barrel.

2 Misalignment Aberrations in the Split Doublet and Aberration Sensitivities

When in a symmetric lens system, the radii and surfaces spacing are perturbed from their nominal values, the main result is a change in focus, magnification, and in the fourth order aberrations⁷ of spherical W_{040} , coma W_{131} , astigmatism W_{222} , field curvature W_{220} , and distortion W_{311} . When the surfaces are tilted, the aberrations that can result are line-of-sight change, uniform astigmatism, uniform coma, linear astigmatism, field tilt, and smile and keystone distortion.^{7,8} Because of the small perturbation uniform astigmatism is usually negligible; however, uniform coma and linear astigmatism usually contribute to limit the image sharpness. If the lens system is optically fast, spherical aberration and uniform coma may be significant; if the field of view is large, then linear astigmatism can also be significant. These three aberrations typically degrade the image sharpness in a perturbed lens system.

Consider the achromatic doublets in Fig. 1, on A, the lens elements are cemented and on B the elements are separated. Tables 1 and 2 provide the prescription data, and Table 3 gives a sensitivity analysis for both doublets. The split doublet is much more sensitive to spherical aberration, uniform coma, and linear astigmatism than the cemented doublet.

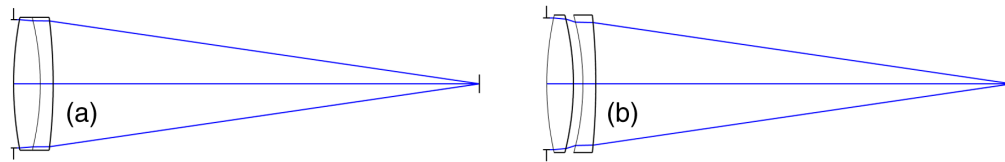


Fig. 1 Achromatic doublets 100 mm in focal length and 25 mm in diameter. Cemented doublet and ray trace on (a), and split doublet and ray trace on (b).

Table 1 Cemented doublet; $f = 100$ mm; $f/4$.

Surface	Radius	Thickness	Glass
1	61.3293	6	N-BK7
2	-45.0476	3	SF-5
3	-130.9572	95.7104	—

Table 2 Split doublet; $f = 100$ mm; $f/4$.

Surface	Radius	Thickness	Glass
1	49.8492	6	N-FK51A
2	-46.3588	2	—
3	-43.9355	3	N-LASF43
4	-104.6834	91.6053	—

Table 3 Sensitivity to aberration in waves.

	Spherical (due to radii/thickness)	Uniform coma (due to surfaces tilt)	Linear astigmatism (due to surfaces tilt)
Cemented doublet	0.049/0.007	0.118	0.019
Split doublet	0.173/0.255 (353%)/(3643% increase)	0.438 (371% increase)	0.032 (69% increase)

Table 4 Monte Carlo analysis of the split doublet.

Maximum element decenter	0 mm	0.025 mm	0.0375 mm	0.05 mm
Wavefront mean value	0.09 waves RMS	0.14 waves RMS	0.19 waves RMS	0.24 waves RMS

Monte Carlo analysis of 100 trials per case. Nominal wavefront RMS value is 0.043 waves. Surface tilts of up to 1 arc min are allowed in each case.

Table 4 gives a Monte Carlo analysis of 100 trials for the split doublet and several misalignments. The nominal RMS wavefront error is 0.043 waves. Allowing surface tilts of up to 1 arc min results in a mean RMS wavefront error of 0.09 waves. Then, adding element decenters of up to 0.025, 0.0375, and 0.050 mm results in RMS wavefront errors of 0.14 waves, 0.19 waves, and 0.24 waves. The diffraction limit⁹ is 0.07 waves RMS, and thus, for the lens to be nearly diffraction limited element decenters of up to 0.025 mm can be allowed but of no more. However, to achieve a maximum element decenter of 0.025-mm tight tolerances need to be specified on the lens diameters and in the inner diameter of a drop-in barrel. In addition, the likelihood of cocking the lens during insertion substantially increases.

Spherical aberration can be adjusted by selecting the thickness of a precisely made spacer in the split doublet. To remove or reduce uniform coma and linear astigmatism, one can improve lens element centering. In this analysis, we have only considered the effects of surface tilt and decenter; other misalignments will contribute to further degrade imaging performance.

In a doublet lens, the inner surfaces typically have strong radii of curvature that are sensitive to aberration. However, in a cemented doublet the axial distance between the inner surfaces is set by the adhesive and there is no sensitivity to spherical aberration. Since the inner surfaces are cemented, and if one is tilted the other is too; therefore, there is aberration cancelation and little sensitivity. In contrast, in a split doublet the sensitivity to aberration substantially increases as the inner surfaces independently misalign. This problem can be mitigated using a precisely made spacer with parallel surfaces.

Although cementing a doublet is desirable, it has the problem of stress developing in the lens elements due to the adhesive, or to the differential coefficient of thermal expansion of the glasses; typically cementing doublets larger than 50 mm is not recommended when they are required to be diffraction limited. The split doublet has the advantage that in addition to chromatic aberrations and spherical aberration, coma aberration can be controlled effectively.

3 Lens Element Centering in a Drop in Barrel

We are interested in prototyping several lens systems that are intended to be nearly diffraction limited, and wish to reduce fabrication cost using a drop-in lens barrel. Methods to improve lens centering in a drop-in barrel are (1) tight manufacturing tolerances on lens and barrel fabrication, (2) use of radial screws to laterally shift a lens, and (3) use of a precision barrel and spacers to bell-clamp the lens elements and achieve self-lens centering.

It is clear from the above Monte Carlo analysis that lenses need to be centered to 0.025 mm or better. To achieve this level of centering without incurring into a costly lens barrel, specifying tight lens manufacturing tolerances, or using undesirable radial screws, we experimented lens centering with a spacer inserted between the lens edge and the lens barrel as shown in Fig. 2. The

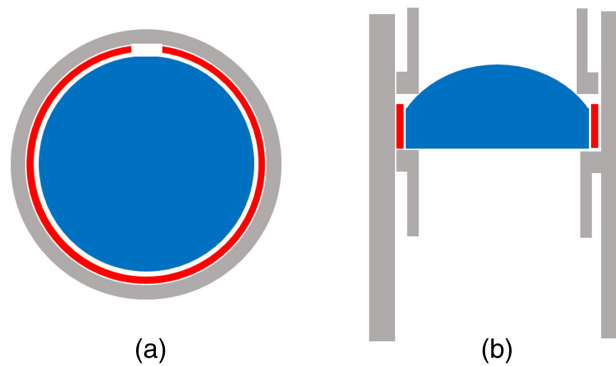


Fig. 2 A strip (in red color) of brass shimming stock is inserted in the gap between the lens and the barrel; Top view on (a), and side view on (b).

barrel inner diameter can be specified to be larger than the outer lens diameter, e.g., by 0.2 mm and with loose tolerances of -0 mm, $+0.05$ mm. Then the actual diameter difference (gap) between the barrel and the lens edge is measured and a strip of brass shimming stock 0.006- to 0.012-mm thinner than half the gap thickness is inserted between the lens and the barrel.

It may be necessary to secure the strip position around the lens; it can be glued once it is inserted. Alternatively, the strip can be constrained in axial movement by lens spacers as schematically shown in Fig. 2(b). Insertion and extraction of the strip of brass shimming stock is shown to be easy in shallow lens barrels as shown in Fig. 3.

There should be a means for extracting the strip; Fig. 4 shows a cut at the ends of the strip that allows it to be lifted at an end to then be pulled tangentially and removed with a pair of tweezers. Because of flexibility brass strips in the range of 0.050 to 0.25 mm in thickness work well. Smaller diameter barrels would require thinner strips, and larger barrel diameter can use thicker strips. A strip 0.025-mm thick is too thin to be inserted because it has not sufficient stiffness. It is possible also to insert two strips to maintain strip flexibility. The advantage of improving lens centering with strips is that cost and time are minimized and that cocking of the lens during insertion is avoided. Other techniques such as using set screws and filling the gap with an

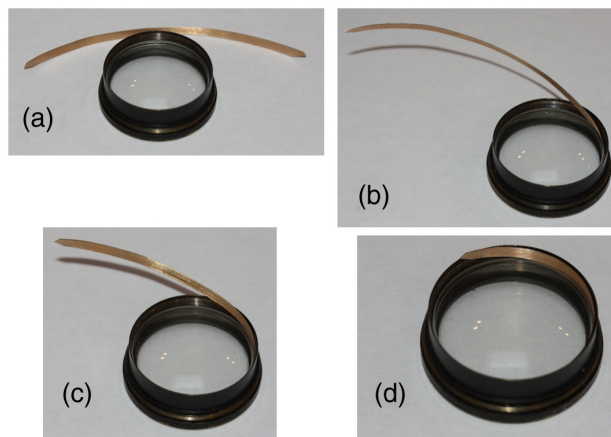


Fig. 3 Sequence illustrating how a brass strip is inserted in the gap between a lens and a barrel of an achromatic split doublet. On (a) the barrel, lens, and strip are shown before insertion. On (b) the tip of the brass strip has been inserted. On (c) one third of the brass strip has been inserted. On (d) almost all the strip has been inserted between the lens and the barrel.



Fig. 4 Cuts at the ends of a strip allow its removal.

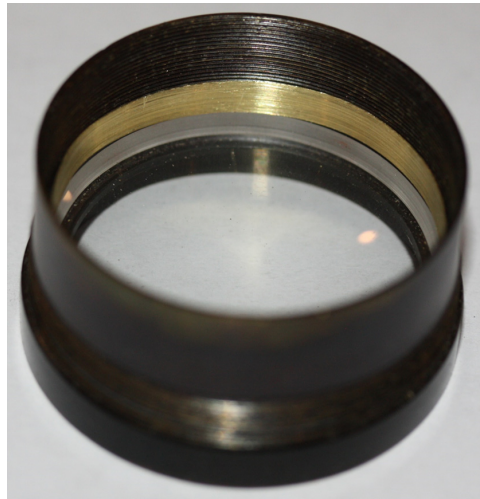


Fig. 5 A strip of brass as a ring is lowered next to a lens.

elastomer require test equipment, highly trained personnel, and are time consuming. There are excellent approaches to center a lens in a barrel but they do require of more elaborated barrels and retaining rings.⁶

If the barrel is not shallow, an alternative method to insert the strip is to insert it as a ring and to lower it to the lens in several steps with a pushing tool. Figure 5 shows a strip of brass lowered to the lens in preparation for insertion in the gap in a sequence of steps.

The strips of shimming stock need to be filed or sanded to remove any burred edges.

It is worth noting that because of lens wedge or tilt, improving lens centering with respect to the lens barrel does not ensure that the lens optical axis is parallel or coincident with the barrel mechanical axis. In addition to lens centering, surfaces tilt must be within tolerances. In a drop-in barrel, one relies on lens seats, spacers, and retaining rings for surface/lens tilt alignment.

4 Examples

To illustrate the use of the method, we present four examples as given in Table 5. We measured the gap between a lens and its drop-in barrel using narrow strips of shims of different thickness. Then, we selected a thickness of a shim strip of half the gap thickness, less clearance ranging from 0.001 to 0.002 in. to center the lens. As given in Table 5, the estimated error in centering ranges from 0.001 to 0.002 in. These estimates are calculated as the difference between the barrel inner diameter and the lens diameter, subtracting twice the strip thickness and dividing by a factor of 2. The results are given in inches because shim brass stock is sold in thicknesses in thousands of an inch; they can be converted to millimeters by multiplying by a factor of 25.4.

The brass strips for centering were cut with a guillotine and then sanded to remove burs. Cleanliness of the strips and barrel is important to remove debris that can interfere with the shim insertion. Example D used an off-the-shelf barrel from Thorlabs¹⁰ with an inner diameter of 1.008 in. The inner wall of the barrel was provided with threads to screw in retaining rings.

Table 5 Examples in inches (± 0.0005).

Example	Lens diameter	Gap	Shim thickness	Estimated centering error
A	1.664	0.017	0.008	0.001
B	1.650	0.007	0.002	0.002
C	2.275	0.013	0.005	0.0015
D	0.985	0.023	0.010	0.002



Fig. 6 A strip of brass is inserted first and rests on a retaining ring that serves as a lens spacer and seat.

The threading did interfere with the insertion of the 0.010 in. thick shim strip. As the clearance between the barrel, shim strip, and lens reduces to 0.002 in. or less, the insertion of the shim strip can be difficult due to debris, lack of circularity of the lens or barrel, inner threading, and friction. In addition, if there is a very tight fit, it may be difficult to remove the lens in case of need. For example D, the shim strip was also divided into two semicircular strips, one 0.010 in. thick, and the other 0.008 in. thick. There was no significant difficulty in inserting these strips into the gap between the lens and the threaded barrel. The setting caused the lens to be decentered by about 0.002 in. This lens decenter can be controlled by the strips difference in thickness and orientation and can be used to control uniform coma aberration if necessary.

Alternatively, brass strips can be inserted first as shown in Fig. 6 for Example D, and then the lens can be inserted. In this case, the conical bevel of the lens helps to push the strip against the barrel inner wall and eases the lens insertion. The strips are first tried in a spare lens barrel and lens to verify that the strips are properly shaped and that they will work. It might be desirable to be able to remove a lens; this can be done by tapping the lens barrel held upside down and by having a clearance of ± 0.002 in. between the lens and the strip. If the remaining gap or clearance is smaller, then lens removal can be difficult. The function of the strip is to help center the lens, and minimizing its width would decrease friction and ease lens insertion and removal.

One mechanism for lens cocking is shown in Fig. 7. When the diagonal of the lens cross section is slightly larger than the inner diameter of a lens barrel there exists the potential for lens cocking.

The lens diagonal D is given by $D = \sqrt{d^2 + t^2}$, where d is the lens diameter and t is the lens edge thickness. For a lens diameter of 25.4 mm with a thickness of 3 mm, the lens diagonal is about 25.58 mm. Friction and debris can also promote lens cocking.

The technique can also be used to center lens spacers instead of centering lenses. If all the lens spacers, the retaining rings, and the barrel itself have no significant manufacturing error, then one can expect self-lens centering in a drop-in barrel by the bell-clamping effect, would help to center the lens elements. This requires the tangent of the clamping angle to be larger than the coefficient of friction between the lens element and the spacer.¹¹

It can be appreciated that the materials needed to practice this shimming method are relatively inexpensive. A technician with some practice can implement this method in minutes. In comparison, precision centering of lens assemblies with other techniques, such as the poker-chip method,³ are typically elaborated and require specialized personnel and precision equipment. Using the shimming method in off-the-shelf lens barrels, the lens centering can substantially be improved.

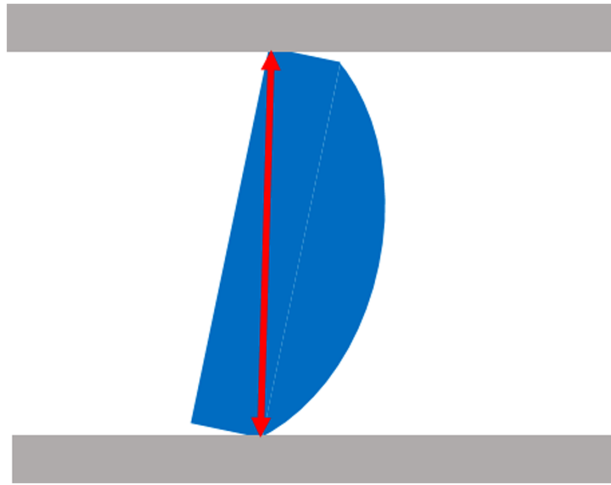


Fig. 7 Lens cocking can occur when the lens diagonal is about or slightly larger than the inner diameter of the barrel.

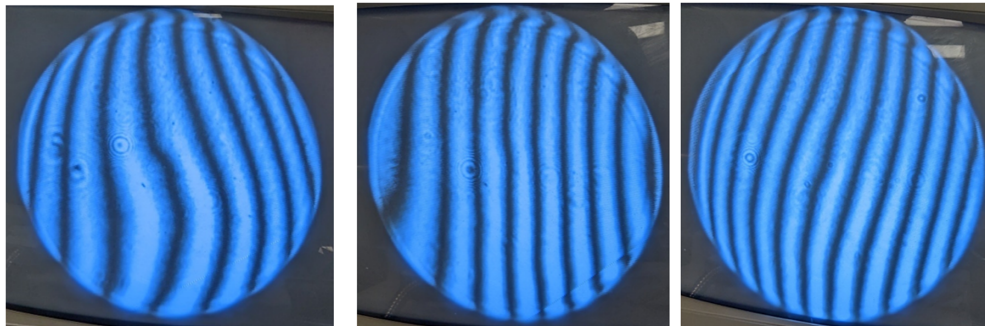


Fig. 8 On-axis interferograms of three assembled lens objective lenses.

5 Objective Lenses

We assembled three objective lenses having each four lens elements with the same diameter. We used Thorlabs¹⁰ 1-inch tube system as lens barrels. The measured gap between the lenses and the barrel was 0.023 in., and shimming stock 0.010 in. thick was used to center the lenses. Figure 8 shows on-axis interferograms in double pass for each of the three objectives. The main error in the interferograms in single pass is coma aberration with an amplitude of about 1/3 to 1/2 of a wave at 632.8 nm. This performance is near diffraction limited and indicates the level of alignment that can be achieved using shimming brass strips.

6 Conclusion

We have pointed out that a lens system that uses a split doublet lens in the first group of lenses, or where the on-axis beam is large, is more sensitive to aberration than when using a cemented doublet. Thus, it is preferable to use cemented doublets whenever possible. To keep cost low in a drop-in barrel, we have shown that lens element centering can be effectively achieved by inserting a spacer in the gap between the lens and the barrel. Insertion and removal of the spacer has been shown to be simple. It is not difficult to center a lens in the range from 0.025 to 0.050 mm provided that the lack of circularity of the lens barrel is negligible. However, as discussed above, the method does not ensure that the lens axis is coincident with the drop-in barrel axis. Like any other technology, this shimming method may be helpful in some lens alignment problems. This methodology is an extension of the well-known shimming method of adjustment

and has the added benefit of losing the barrel tolerance for inner diameter. Here, shimming has been effectively applied to provide a solution to lens element centering. It is likely that in the past this method has been applied, but we are unaware that it has been discussed in the opto-mechanics literature.

Acknowledgment

The authors declare no conflict of interest.

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Biographies of the authors are not available.