CASE STUDY OF ELASTOMERIC LENS MOUNTS

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I. Introduction

We were tasked recently with the design and production of an ultra-precision projection lens. The lens performance was extremely demanding, calling for a near diffraction limited MTF and a distortion requirement of ≤1/20%. In addition to the extremely demanding optical performance requirements, the system had to withstand a storage temperature range from -55°C to +95°C, and the lens had to perform over a somewhat smaller range.

The extremely demanding optical requirements required very tight element centration and tilt tolerances, to the point where conventional lens mounting methodologies simply would not be sufficient. With the assistance of Daniel Vukobratovich of the University of Arizona, we developed an elastomeric mounting technique which was employed in the design and which worked extremely well in hardware.

In the following paper we will describe some of the optical challenges of the design, followed by a detailed explanation of the opto-mechanical design and the elastomeric mounting schemes developed herein.

II. Optical Design Considerations

The basic lens requirements are shown graphically in **Figure 1**, and the lens specifications are summarized below.

Parameter	Specification
Entrance Pupil	Telecentric
f/number At Object in Air	9.54 (Object Cone ±3°)
Object Size	1.371 x 1.371 inches
Object Diagonal	±0.9694 inches
Image Size	5.8 x 5.8 inches
Image Diagonal	±4.1012 inches
Lens Length	≤9.0 inches
Image Distance	≥3.5 inches
Spectral Sensitivity	Photopic, Truncated at 420 & 680 nm
MTF	≥0.8 @ 3.4 lp/mm ≥0.4 @ 6.8 lp/mm
Chromatic Correction	0.29 mm maximum chromatic blur
Distortion	≤0.05%

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Uniformity of Illumination	Equal to or better than Cosine 4th Falloff
Transmission	≥90%
Ghost Images	None visible with 120 lumens
Operational Temperature	0 to +60°C
Storage Temperature	-55°C to +95°C

The incredibly low distortion requirement was a significant challenge to the design, especially because of the extremely tight packaging. In order to illustrate the technique used in correcting the distortion to such a low value, consider **Figure 2A** where we show a lens with significant spherical aberration. In **Figure 2B** we show the same lens, however, we extend the rays a long distance to the right beyond the focus position. The input to the lens represents the telecentric chief rays of our projection lens, and the end position of the rays on the right represents the chief rays coming to the final image. The spherical aberration can be clearly seen to manifest itself in a severe amount of distortion. Now consider **Figures 2C and 2D** where we show a lens which is perfectly corrected for spherical aberration, and it can be seen that the final image representation is totally free of distortion. What this suggests is that our lens should, in effect, be well corrected for spherical aberration of the chief rays. While many designs were explored during the project, the final design form is shown in **Figure 3.** There appears to be a thin flat plate just in front of the cemented achromatic doublet. This plate is in reality a Cleartran™ clear zinc sulfide substrate with an aspheric surface which was single point diamond turned. This element permitted correction of the spherical aberration of the chief rays, or in effect the distortion, and it worked extremely well in all regards. The aspheric was intentionally divorced from the rest of the lens, and this turned out to be an extremely advantageous thing to do. A larger scale drawing of the lens is shown in **Figure 4** (there is an apparent edge contact, however there is a small edge separation). It is clear that we have some very steep bendings which lead to extremely tight tolerances.

Figure 5 shows the transverse aberrations of the final lens design, and **Figure 6** shows the residual distortion.

III. Opto-Mechanical Design

The tolerance sensitivities for the system were generated using the CODE V Tor Program. All toleranceable parameters were evaluated, and the position of the lens along its axis was used as a compensator to restore focus. Some of the extremely tight tolerances that were required included air spaces down to ±0.0005 inches, decentrations down to ±0.0005 inches, element wedges down to 0.0001 inches TIR, and element tilts down to 0.0003 inches TIR.

The initial housing design concept, which is shown in **Figure 7** in a preliminary form, was relatively conventional using precision machined lens seats and retainers to support the elements. Two subcells were envisioned in the region where the tolerances were particularly tight.

We can see graphically the effect of element decentrations through temperature in **Figure 8** where we show a -55°C to +95°C thermal change and along with the worst case possible element decentration within an aluminum housing. If we assumed an absolutely zero clearance at the -55°C condition, we see a 0.0001 inch diameter difference which could produce a ±0.0005 inch element decentration at 95°C. The zero clearance at minimum temperature is indeed a serious risk, and more conservatively we would want to leave at least a 0.0005 inch diameter difference at the -55°C temperature. In this case, as shown in the lower part of the Figure, we have a total of 0.0015 inches diameter difference at +95°C which could produce a ±0.00075 inch element decenter if the element were to decenter to the edge of the seat. As some of our decentrations were approaching ±0.0003 to ±0.0005 inches, this is a real problem.

We did consider the option of using alternate housing materials such as stainless steel or titanium. **Figure 9** shows the diameter difference at 95°C between the glass elements and the housing for an aluminum housing, and a titanium housing, including the effect of the glass expansion. Based on this data, it was decided that the housing must be titanium if this housing design concept were used.

IV. Elastomeric Mount Technique

During a visit to our office, we asked Daniel Vukobratovich to review the proposed housing design for the lens. Dan looked at the housing design, and then looked at the required tolerances, and then he looked us straight in the eye and said:

After reviewing the matter in great detail with Dan, a stainless steel housing using subcells for the support of each element or element group was recommended along with bonding each element into its subcell with a compliant bond material. The main housing along with the individual subcells would be of the same material, and stainless steel was the recommended material. The housing was redesigned using the above approach, and the final housing design is shown in **Figure 10**. Note that there is a 0.015 inch annulus bond line surrounding each element. During assembly of each element into its respective subcell, the element was centered to the required tolerance level on a rotary table, and 3M-2216 bonding material was injected using a syringe into the holes as shown in the Figure. The last achromatic doublet on the right and the

Cleartran element were in separate subcells of their own which was then screwed into the main housing. The large achromatic doublet had slightly looser tolerances associated with it, and it was therefore able to be bonded directly into the main housing.

V. Summary and Conclusions

This lens as designed and produced by OPTICS 1, Inc. was extremely demanding from both the optical design standpoint as well as the mechanics.

The optical design called for near diffraction limited imagery with an incredibly low residual distortion. Due to the extremely tight packaging requirements, severe lens bendings were unavoidable. This resulted in extremely tight tolerances on some of the parameters, especially as they relate to element tilt, decentration, and air spaces.

With the guidance of Daniel Vukobratovich of the University of Arizona, a subcell approach using elastomeric bond material was used in order to achieve the extremely tight tolerances required by the lens over the extreme storage range of -55° to +95°C.

The lens was produced, and performed extremely well in all regards. We highly recommend this form of mechanical design and lens mounting when extremely tight tolerances combined with an extreme thermal temperature range exists.

VI. Acknowledgments

The author is deeply indebted to Daniel Vukobratovich at the University of Arizona without whose guidance this project may not have succeeded. Further, Klaus Mattilebach of Von Kampen in Van Nuys, CA, was responsible for the extremely precise machining, and Hal Johnson of Harold Johnson Optical Laboratories provided an extremely high level of optical fabrication for the project.

Figure 1 - Basic lens requirement

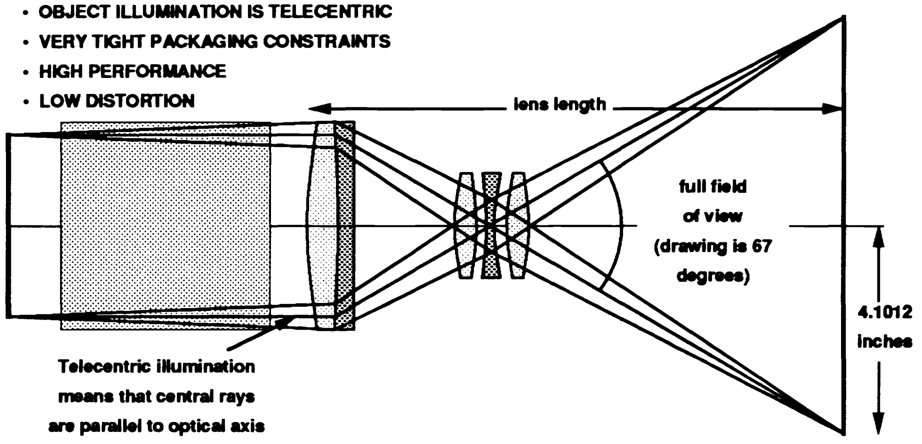


Figure 3 - Final lens design

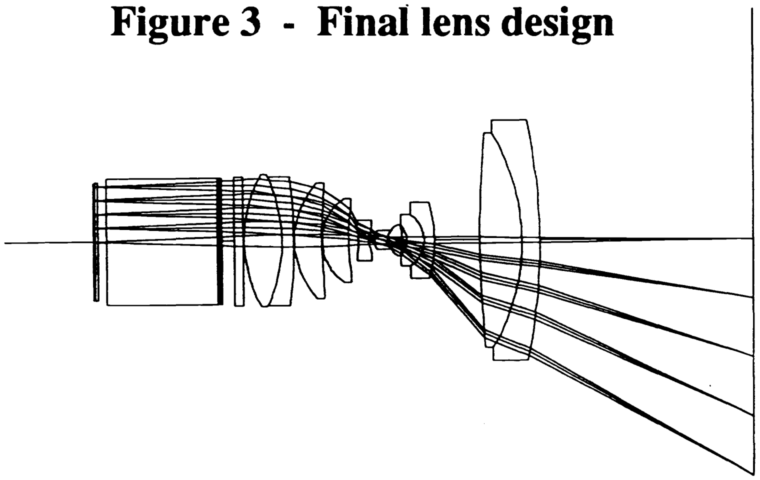


Figure 4 - Detail of lens elements

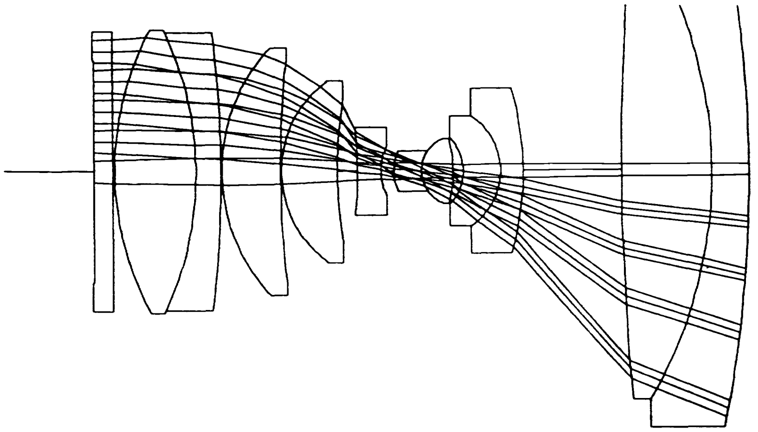


Figure 2a - Lens with spherical aberration

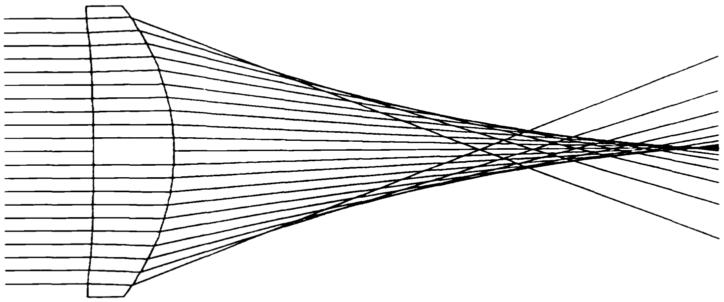


Figure 2b - Above, to screen image

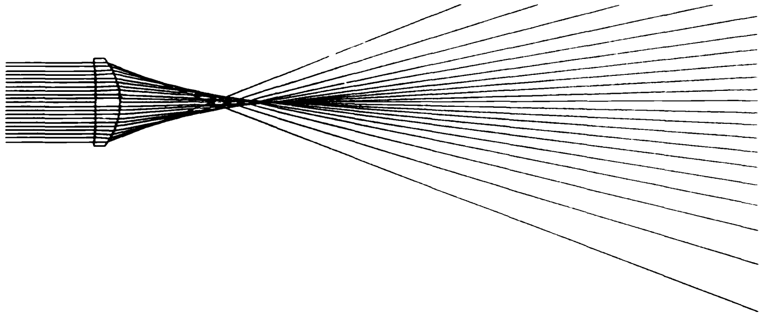


Figure 2c - Lens with zero spherical aberration

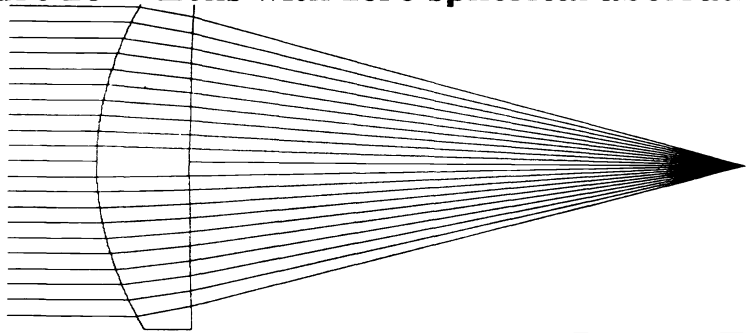


Figure 2d - Above, to screen image

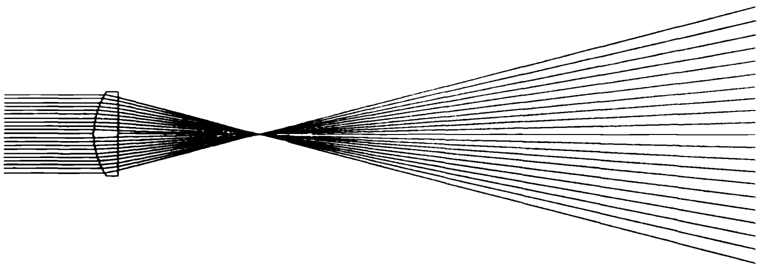


Figure 5 - Transverse ray aberrations, final design

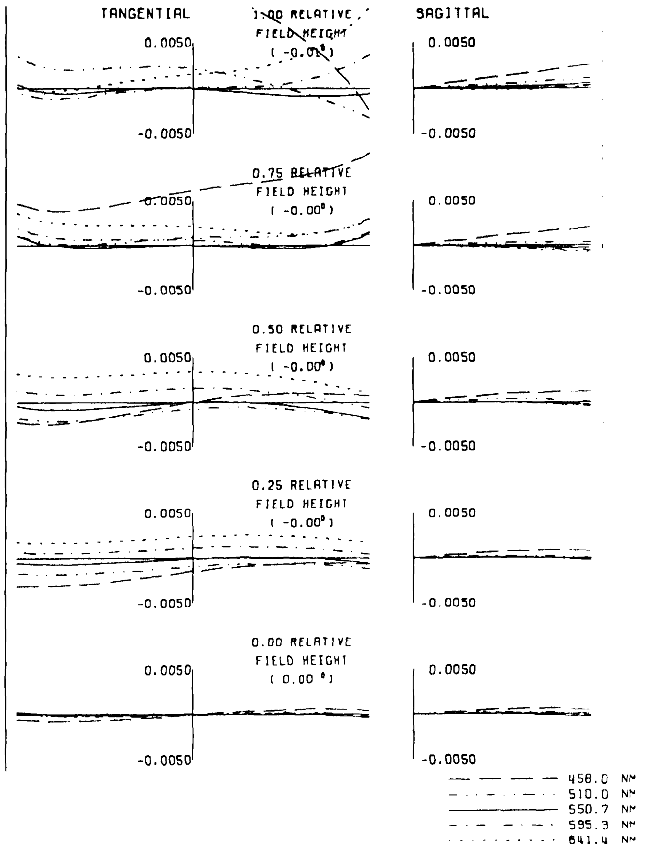
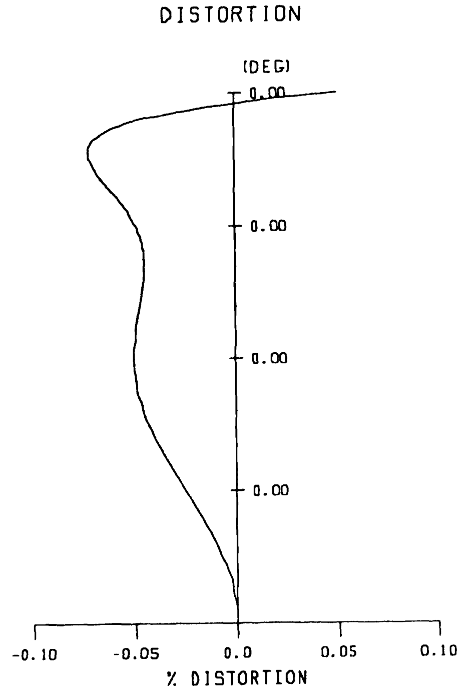


Figure 6 - Distortion, final design



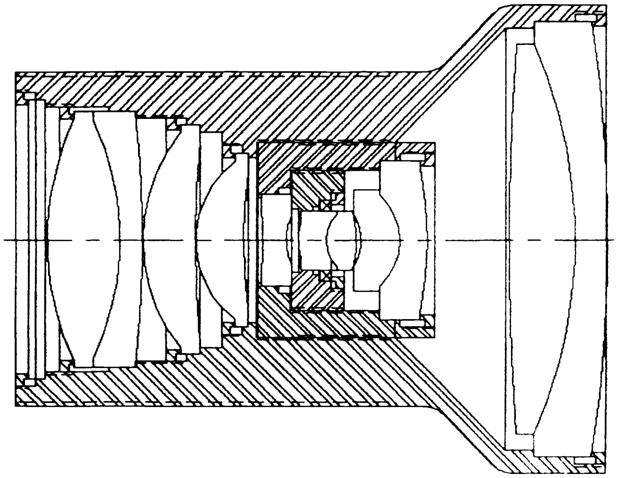
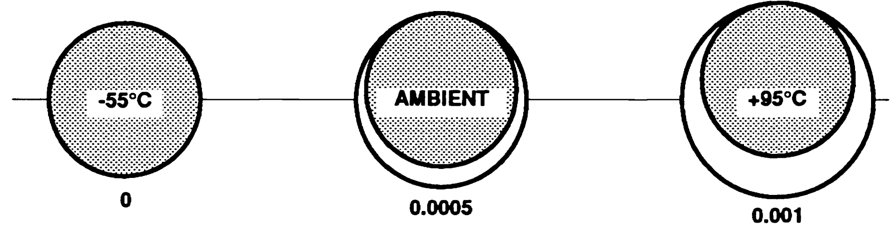


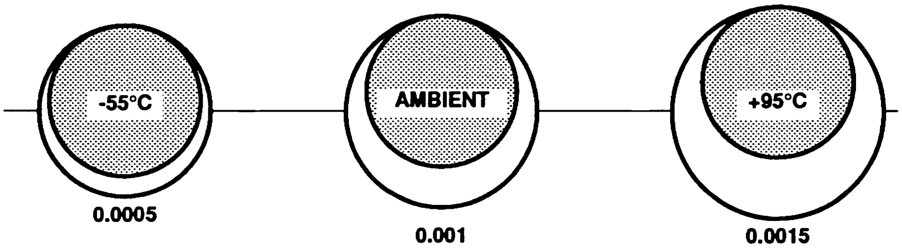
Figure 7 - Initial lens housing concept

Figure 8 - Lens to housing centration scenarios

IF THE WORLD WERE PERFECT (ZERO CLEARANCE AT LOW TEMPERATURE)
DIAMETER DIFFERENCES, INCHES



PRINCIPLE UNKNOWNS: ACCURACY OF MEASURING DEVICES, ROUNDNESS OF LENS & HOUSING, PARALLELLISM OF LENS & HOUSING



ALLOWING FOR 0.0005 INCHES DIAMETER CLEARANCE AT LOW TEMPERATURE

Figure 9 - Diameter difference at 95°C glass to metal (metal is larger)

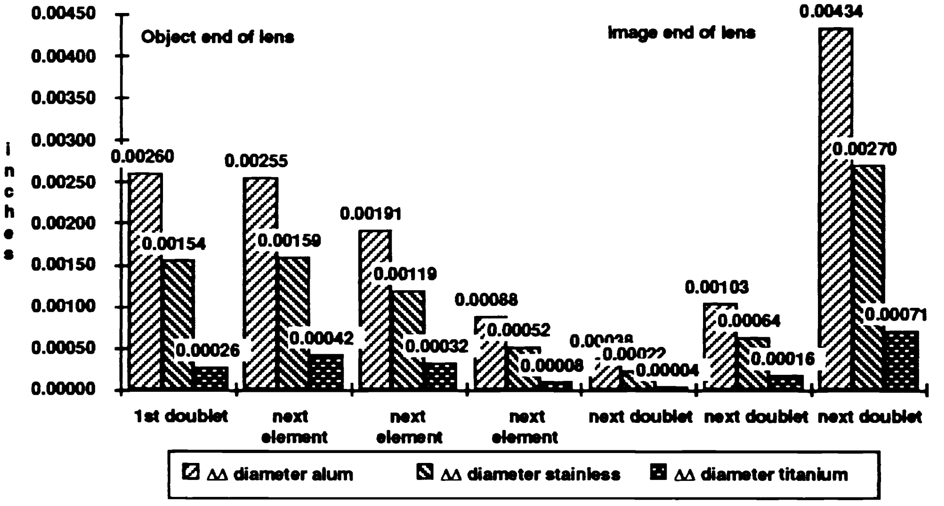


Figure 10 - Final subcell housing design