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Final Report - Optical Design of a 1.15:1 Relay Lens NAO=0.245

Optical Research Associates

January 28, 1992

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January 28, 1992

Mr. Keith Hugenberg
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LAWRENCE LIVERMORE NATIONAL LABORATORY
7000 East Avenue
Livermore, CA 94550

Subject: Final Report on the Optical Design of a 1.15:1 Relay Lens $NAO = 0.245$."

References: 1. Final Report "2.5:1 Relay Design $NAO = 0.245$," ORA, dated 04/24/85.
2. Statement of Work for the Design and Analysis of a 1.49:1 Relay Lens, ORA, dated 06/03/92.
3. LLNL Contract B218674.

Dear Mr. Hugenberg:

Enclosed is a copy of the Final Report on the 1.15:1 relay lens. Please review this report and call us with any questions or comments you may have. After review of the two alternative designs, Tinsley Laboratories decided that they preferred the more classical form, and we based the Final Design described in the text on that decision. We have a 100% match to their test plate library, and we have assigned tolerances for manufacture and assembly in two separate listings. We are recommending a recomputation of the lens after the elements are made and measured. This will result in a new set of airspaces for the final assembly. Optical Research Associates (ORA) will provide this service for the fee given in Reference 2 (see Appendix I of the report).

This report completes ORA's work on the Reference 3 contract. Thank you for the opportunity to be of service to you, and we look forward to being of assistance in the future.

Sincerely,

OPTICAL RESEARCH ASSOCIATES

Donald G. Koch
Staff Systems Engineer/Optical Design

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cc: P. Duval/LLNL
C. De Ande/ORA
E. Ford/ORA

enc: Final Report.

- References:
1. Final Report "2.5:1 Relay Design $NAO = 0.245$," ORA, dated 04/24/85.
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1.0 INTRODUCTION

Lawrence Livermore National Laboratory (LLNL) needs a 1.15:1 magnification relay lens that will image a CRT with fiber optics faceplate onto a CCD detector array. Optical Research Associates (ORA) designed a similar lens several years ago with a different magnification (2.5:1 see Reference 1). LLNL had the lens built, and it performed satisfactorily. Now a larger CCD is available, and LLNL needs this new design to have many features of the earlier form except for magnification. Some of these features include virtual telecentricity at both the input and output of the lens, high collection and transmission efficiency, low image distortion, and moderately high MTF at modest spatial frequency in the image. Reference 2 lists the complete set of requirements and goals for an intermediate magnification, and we repeat many of them in Table 1 of this report (Appendix I is a copy of the original Statement of Work (SOW) including the lens specification table). Since ORA wrote Reference 2, LLNL changed the magnification requirement, and we found that the design could not meet some of the former mechanical constraints with the new goal. Table 1 reflects these changes.

During the design process, we found that a lens based on the Reference 1 form (double gauss derivative) was very sensitive to small errors of construction (such as element thickness and centering). We decided to try an alternate design that is less sensitive to these types of errors. We sent a summary of the alternative as well as the design based on the older form to Tinsley Laboratories (LLNL's chosen manufacturer) for review. Despite the lower sensitivity to errors of our revised design, Tinsley chose to build the older form. They thought the centering and thickness tolerances were all within their capability. Consequently, the design described in this report is a modification of the design reported in Reference 1. Appendix II contains a summary of the design, performance, and tolerance sensitivity of the alternative form.

ORA was able to reduce the tolerance sensitivity with additional optimization, but the lens will need to be recomputed after refractive index melt data is available and fabricated element thickness are measured. ORA has offered to do this recomputation for an additional fee if LLNL desires (see Reference 2). This report completes ORA's work on LLNL Contract B218674.

2.0 COMPARISON OF GOALS AND RESULTS

Table 1 compares the requirements and goals with the design results for this lens. Set against the original SOW (Reference 2 - Appendix I) the magnification, critical spatial frequency, and mechanical constraints are different. ORA made these changes at the request of and/or with the cognizance of LLNL personnel. Otherwise, the table shows that the design meets all goals and requirements. In the case of mechanical changes, the substantial change in magnification makes meeting the original goals impossible (especially because of telecentricity - see Item 19).

In Item 14 the relative illumination is slightly higher off-axis until vignetting sets in. This is caused by pupil aberration that is responsible for the higher collection efficiency, reported in Item 13, than a 0.245 numerical aperture would predict (i.e. the NA is greater off-axis).

We were able to match all of the lens surfaces to Tinsley Labs test plates without any significant loss of performance.

3.0 DESCRIPTION OF THE LENS

Figure 1a shows the complete lens cross-section at 0.75 scale from the CRT to CCD face. Figures 1b and 1c show the element cross-sections at full scale in front and in back of the stop. Table 2 lists the lens prescription in millimeters. There are ten (10) elements in the design with three outer field lenses used to maintain telecentricity. The central imaging group has the classical double gauss shape with the exception that one of the doublets is airspaced rather than cemented. The glass surfaces near the image represent windows and cover plate for the CCD. The image surface has a convex spherical shape with a radius of curvature of 2579 millimeters caused by a pressure differential because the sensor package is sealed.

We were able to match every surface in the lens to Tinsley Laboratories test plates. We shall discuss this issue further when considering tolerances below.

4.0 LENS PERFORMANCE

Table 1 specifies several parameters for lens performance. For image quality, the MTF goal at 12 c/mm is 50% or greater measured on the finished lens, and as-built distortion of 0.5% or better. Transmittance must exceed 80%. Relative illumination must exceed 90% across the field,

and the collection efficiency must be greater than 5.0% of the output from the CRT fiber optic faceplate.

Figures 2 and 3 illustrate the aberrations for the lens. In Figure 2, the intercept errors are shown for three (3) field points. These image aberrations produce an MTF illustrated by the curves in Figures 4, 5, and 6. Figure 4 shows the MTF as a function of spatial frequency to 32 c/mm, and Figures 5 and 6 show the through focus functions at 12 and 20 c/mm. The specification extends to 12 c/mm, but LLNL expressed interest in the higher spatial frequencies, and the additional data are for information purposes. The MTF for the nominal design exceeds 80% for the full field at 12 c/mm (minimum value of 83.7%) and 90% on-axis. This is ample margin to meet the 50% goal with tolerances as we will show below in the section on tolerances. Indeed the MTF at 20 c/mm is almost 70% across the image field.

Referring to Figure 3 and the curve marked distortion, the worst case nominal image distortion is less than 0.4% with its extreme value at the edge of the image. This also provides sufficient margin to meet the as-built goal of 0.5% with probability exceeding 0.95.

Table 3 lists the axial transmittance as a function of surface and sampling wavelength. This calculation includes the cover plate and window for the CCD, and when these factors are divided from the total transmittance, the weighted spectral transmittance for the lens is 0.861. This calculation assumed MgF_2 single layers are the antireflection coatings for all surfaces. Using this transmittance and a numerical aperture of 0.245, the collection efficiency should be 5.16%. In fact, the numerical aperture increases for off-axis image points raising the total collection efficiency to over 5.65% for a 40 mm diameter CRT. Figure 7 plots the relative illumination at the CCD surface as a function of radial distance from the center of the image (axial intersection point). In this plot, the center of the image represents the 100% point. Pupil aberrations cause the relative illumination to increase for off-axis points until vignetting takes over toward the edge of the image. The maximum illuminance at the CCD is almost 106% of the center at a point 12.17 mm off center.

5.0 TEMPERATURE CHANGE EFFECTS

Small changes in temperature over a range of $\pm 5.0^\circ\text{C}$ should not cause any noticeable loss of image quality. ORA uses a linear model of temperature change in which we assume aluminum is the barrel material. For this analysis, we applied $+ 5.0^\circ\text{C}$ change using expansion coefficients of the barrel and glass, and the thermal refractive index coefficients for all glasses to find the new

parameters for the perturbed lens. We calculated the MTF for this changed lens without refocusing. Figures 8, 9, and 10 summarize the results. We detect no substantial change in the lens performance by this measure.

6.0 TOLERANCES

There are two sets of tolerances for this lens. The first set, listed in Table 4, is for the allowable symmetrical errors assuming the refractive indices and element thicknesses will be accurately measured and the lens airspaces will be recomputed. The second set, listed in Table 5 gives the allowable measurement error and airspace errors for all of the symmetrical parameters after the elements are made. The centering, wedge, and alignment errors are listed in Table 6.

Comparing Table 4 with Table 5, the radius tolerances after manufacture all assume test plate sag has been accurately measured to an error of 0.5 waves at 550 nm (i.e. a sag error of 0.000011 inches). Most of the manufacturing tolerances for the lens elements and airspaces remain unchanged after fabrication, but the elements and airspaces of the doublets surrounding the stop are especially sensitive. Tinsley Laboratories should give special attention to the stack-up error of the airspaced doublet preceding the stop. The final stackup should be controlled to 0.020 mm or less. Also many of the refractive indices must be measured to tighter tolerances than the default catalog controls (0.001 to 0.002). This is the principal reason the lens should be recomputed after the elements have been made. The glass homogeneity should be good, but special orders for controlled homogeneity will not be necessary.

Tables 7 and 8 list the effect on performance of the final list of tolerances. The worst potential loss is at the edge of the image field for tangential orientation. We estimate a 0.55 MTF or greater at 12 c/mm for this field point with a probability exceeding 0.97 using the recommended tolerance sets. These tolerances also cause a change in the image distortion. Its random component at the image edge has a 2σ value of 0.0194 mm. The nominal distortion is 0.38% or 0.0661 mm. This worst case combination of these two is 0.0854 mm or 0.49% of the edge semi-diameter. We conclude that the lens will meet the distortion requirement with a probability exceeding 95%.

7.0 CONCLUSIONS

ORA has designed a ten (10) element lens that meets all the modified requirements of Reference 2. We have assigned two sets of tolerances for purposes of element fabrication and as-

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sembly. The first set applies to the elements alone, and the second must be applied after the elements have been measured and the airspaces recomputed. The lens manufacturer should pay close attention to errors of fabrication and assembly for elements near the central aperture stop of the lens.

8.0 RECOMMENDATIONS

ORA recommends proceeding with the manufacture of the lens elements and lens barrel design. After making the elements, they should be carefully measured for center thickness. Based on these data and the melt data sheets from the glass supplier, the airspaces should be recomputed to optimize performance. ORA can provide this service for the additional fee discussed in Reference 2.

TABLE 1
DESIGN GOALS, SPECIFICATIONS, AND
PREDICTED PERFORMANCE FOR A 1.15:1 RELAY LENS
(01/28/93)

Parameter	Specification	Predicted Performance	
1. Configuration	Phosphor source, high-speed relay lens, CCD detector at image.	Same	
2. Spectral range	509-654	Same	
3. Spectral weights	P-20 phosphor cascaded with silicon detector, same as in 4/24/85 report	<u>WL</u>	<u>Weight</u>
		654.0	13
		614.8	42
		578.0	86
		542.0	90
		309.2	26
4. Magnification, object to image	1/1.15	Same	
5. Object surface		Same	
i. Active diameter (mm)	40.0	Same	
ii. Shape	Flat	Same	
iii. Type	CRT with fiber faceplate	Same	
iv. N.A. of faceplate fibers	1.0	Same	
6. Image surface		Evaluated to 37.918	
i. Active diameter (mm)	37.783 (Reference)	Spherical	
ii. Shape	Spherical	2579 mm	
iii. Radius (mm)	TBD (convex toward lens) [1]		
7. N.A. at image	Maximize > 0.245 F/2	0.21	
8. MTF at CCD		12.0	
i. Frequency (lp/mm)	12.0	0.55	
ii. Minimum value, as-built	0.5		

[1] Corresponding to a sag of 35 microns at $19\sqrt{2}$ mm diameter.

TABLE 1
DESIGN GOALS, SPECIFICATIONS, AND
PREDICTED PERFORMANCE FOR A 1.15:1 RELAY LENS (CONT.)
(01/28/93)

Parameter	Specification	Predicted Performance
9. Deviation from telecentricity at CCD and object, maximum (deg.)	Less than values in 1985 design (1.4 at object, 1.6 at image)	Object 1.285 Image 1.416
10. Distortion, maximum, as-built (%)	Minimize < 0.5	≤ 0.5 95% probability (nominal = 0.38%)
11. Source radiation distribution	Lambertian	Assumed
12. Transmission	Maximize > 80% goal	86.1% nom (weighted average over spectral band) CCD windows not included
13. Total collection efficiency of lens (%)	5.0 goal	5.65
14. Relative illumination	Maximize > 90%	(0.5% (corresponding to 12.17 mm off-axis)
15. Clearance between lens and CCD enclosure window, minimum (mm)	2.0	> 23.0
16. LLNL CCD enclosure window		
i. Shape	Curved meniscus	Same
ii. Radii (mm)	12,095 (concave toward lens) [2]	Same
iii. Material	BK7	Same
iv. Thickness (mm)	2.0	Same
v. Distance to detector window (mm)	4.7	Same
17. Detector window		
i. Shape	Plane parallel	Same
ii. Material	K50	Same
iii. Thickness (mm)	0.53	Same
iv. Distance to CCD (mm)	0.051	Same

[2] Corresponding to a sag of 26.67 microns at 2 inch diameter.
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TABLE 1
DESIGN GOALS, SPECIFICATIONS, AND
PREDICTED PERFORMANCE FOR A 1.15:1 RELAY LENS (CONT.)
(01/28/93)

Parameter	Specification	Predicted Performance
18. Total track distance, maximum (mm)	305 goal	304 - 738
19. Lens envelope		
i. Diameter	< 71 goal	< 75 [3]
ii. Length	< 140 goal	Vertex to vertex if lens = 278.7 [3]
iii. Guiding principle	Keep element sizes and locations as similar as possible to the 04/24/85 design, to minimize mechanical redesign schedule	This goal could not be met because of the magnification change and other constraints
20. Environment	20°C, 1 atm. $\pm$ 5°C	MTF goal is met without refocusing over the temperature range
21. Test plate fit	As many radii as possible fit to existing Tinsley test plates	100% fit
22. Glass cost (as computed by the CODE V COST program)	Minimize with a goal of the 1985 design value of about \$240	< \$167

[3] Does not meet original goal.

DATE

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END