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Roy W. Esplin
Utah State University

Ronald J. Huppi
Utah State University

Louis R. Fantozzi

Ronald A. Lange

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Predicting the focus of cryogenically-cooled optical systems

Roy W. Esplin, Ronald J. Huppi
Stewart Radiance Laboratory, Utah State University, 1 DeAngelo Drive, Bedford, Massachusetts 01730
Louis R. Fantozzi
Diversified Optical Corporation, Research Optical Systems Division, P.O. Box 585, Farmingdale, New York 11735
Ronald A. Lange
Eaton Corporation, AIL Division, Walt Whitman Road, Melville, New York 11747

Abstract

Results of an experimental study to ascertain how well the focal-plane location of cryogenically-cooled optical systems can be predicted are reported. These results indicate that if the required low-temperature thermal expansion and index-of-refraction data are available, the focal shift caused by cooling to cryogenic temperatures can be accurately predicted by simply computing the shift in the paraxial focus. In this study, the differences between the measured focal shifts and the computed shift in the paraxial focus were less than the diffraction-limited depth-of-focus tolerance. The results of this study also indicate that for off-the-shelf optical systems ray-tracing analysis may not adequately predict the absolute location of the focal plane. Thus, the following method of predicting the focal-plane location of a cryogenically-cooled optical system is suggested: first measure the focal-plane location with the optics at room temperature, and then add the computed paraxial focal shift to the measured location.

Introduction

If the temperature of an optical system is changed uniformily, the radii and thicknesses of its optical elements change according to the linear expansion coefficient of the material used to make each element and the indexes of refraction of its refractive elements change.[1] Also, the spacings between its elements change according to the linear expansion coefficient of the structural mounting material. These optical-parameter changes are relatively large when an optical system is cooled from ambient to cryogenic temperatures, since large temperature changes are involved. Because of these optical-parameter changes, the focus of a typical cryogenically-cooled optical system will shift a significant distance when cooled from ambient to its operating temperature. Compensation for this focal shift can be made by experimentally adjusting the focus of the optical system. However, it is difficult to adjust the focus of a cryogenically-cooled optical system because of the low operating temperature and the insulating vacuum which typically surrounds the optics. Therefore, it is very desirable to be able to accurately predict the focus of cryogenically-cooled optical systems. This paper describes an experiment that was conducted to ascertain how accurately the focal-plane location of a cryogenically-cooled optical system can be predicted when the required thermal expansion and index-of-refraction data are available in the literature.

Experiment Description

The focal-plane location of three plano-convex germanium lenses were measured at both room temperature and at a temperature near that of liquid nitrogen, and the results were compared to predicted values. All three lenses were made to the same optical prescription using standard optical-shop practices; thicknesses were measured with a micrometer, and radii were fit to a test plate whose radius was determined using an electronic spherometer. Each lens was made from a different sample of germanium supplied by Eagle-Picher Industries. Thus, these lenses are representative of what one can expect to get when purchasing off-the-shelf lenses.

The experimental set up used to measure the focal-plane location is shown in Figure 1. The lens under test was mounted on a cold finger in a vacuum cavity of a liquid-nitrogen cooled dewar. This lens was illuminated by collimated infrared radiation from a helium-neon laser emitting at 3.39 μm. This radiation was chopped so that synchronous demodulation techniques could be used to maximize the signal-to-noise ratio. The optical axis of the test lens was aligned parallel to the collimated infrared beam by observing

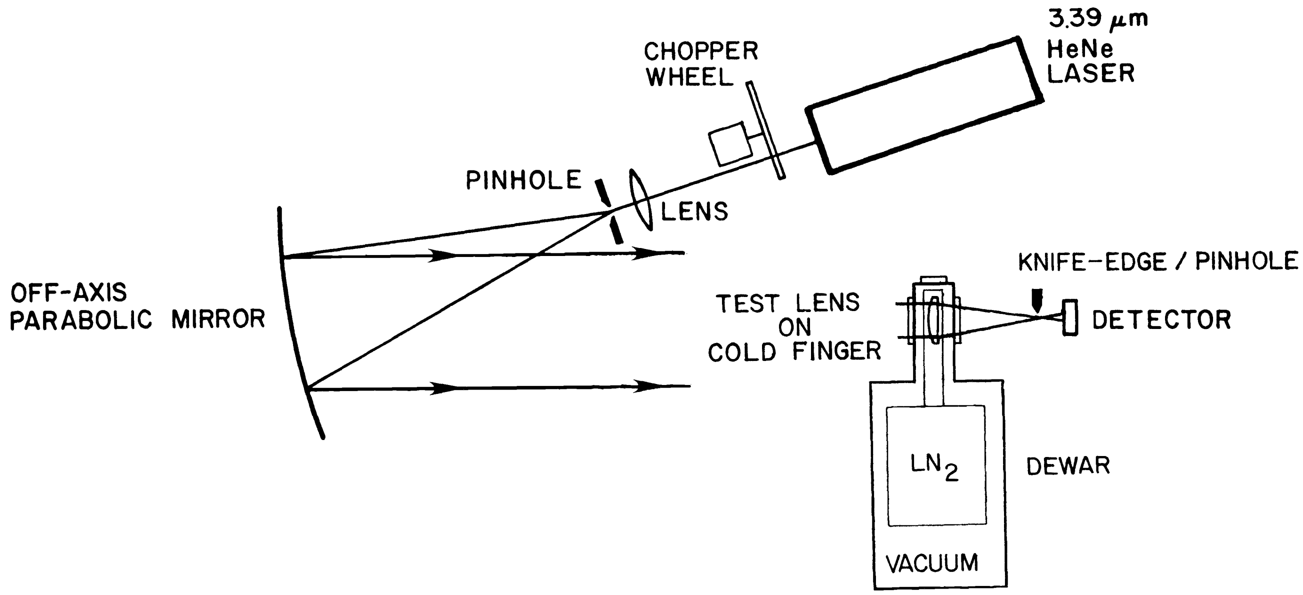

Figure 1. Experimental set up used to measure focal-plane location.

reflections from the front surface of the lens produced by a visible laser coaligned with the infrared laser. Collimated radiation entered the dewar through a calcium-fluoride window, and after being converted to a convergent beam by the test lens, it exited through another calcium-fluoride window. This convergent beam came to focus outside the dewar. Two different methods were used to find the location of the focal plane. For the first method a knife edge was mounted on an X-Y translation stage so that it could be moved throughout the focal region, and for the second method a pinhole was similarly mounted on an X-Y-Z translation stage. For both methods a detector was positioned beyond the focus so that it collected all test rays not obstructed by either the knife edge or the pinhole.

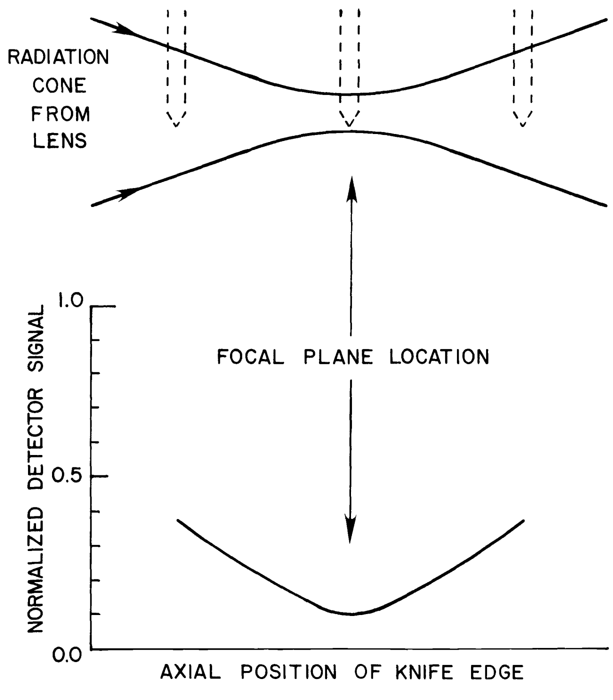

Figure 2. Knife-edge method of measuring focal-plane location.

The knife-edge method of finding the focus is illustrated in Figure 2. In this method, the focus was found by using the following iterative procedure. The knife edge was inserted far enough into the infrared-radiation cone so that a well-defined minimum in the detector signal resulted when the knife edge was translated back and forth longitudinally, that is, parallel to the optical axis. The longitudinal position was then adjusted to the apparent minimum position. Then the knife edge was moved transversely until the detector signal was ten percent of its unobstructed value. This cycle of longitudinal and transverse adjustments was repeated until no further improvements could be made. Typically, only three or four adjustment cycles were required. The ten-percent criteria was selected instead of some other value because it gave the best-defined minimum. For the lenses tested in the experiment, the knife-edge method was repeatable to ±0.01 mm.

The pinhole method of finding the focus consisted of maximizing the detector signal by adjusting the position of a pinhole in the infrared-radiation cone exiting the dewar. The accuracy of this method was maximized by using a pinhole approximately the same size as the lens blur. With a 45-μm

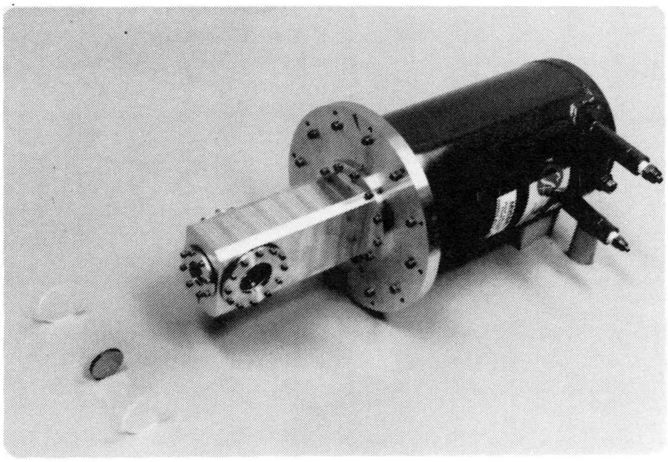

Figure 3. Test dewar.

pinhole this measurement procedure was repeatable to better than ±0.01 mm.

A photograph of the liquid-nitrogen cooled dewar used in the experiment is shown in Figure 3. An extra pair of windows and a test lens are shown in the foreground of this photograph. The larger of the two retaining rings that can be seen in the photograph holds the entrance window; a similar retaining ring on the opposite side of the dewar holds the exit window. The small retaining ring on the end of the dewar holds an observation window that was used to see if cooling caused a longitudinal change in the lens position. A finely inscribed mark identifying the lens location was observed through this window with a microscope as the dewar was cooled. When steady-state conditions were reached, there was no measurable longitudinal shift in the lens position. The estimated accuracy of this measurement was 0.01 mm. Of course, there was a large transverse shift, but this shift had no effect on the accuracy of the focal-length measurements since the entrance and exit windows were large enough so that the 25.4-mm clear aperture of the lens determined the beam size for both warm and cold conditions. A longitudinal shift was prevented by mounting the lens on the axis of symmetry of the dewar. Indium gaskets were used between the mounting surfaces of the lens and the cold finger to insure good thermal contact. The cold steady-state temperature at the lens was 84°K (±0.5°K). This temperature measurement was made using a calibrated diode as a sensor.

Table 1. Nominal optical parameters of germanium test lenses at 297°K and 84°K.

	At 297°K	At 84°K
Index of Refraction	4.0354	3.9625
Radius (mm)	305.05	304.77
Thickness (mm)	3.18	3.17

The nominal optical parameters of the test lenses at 297°K, room temperature, and at 84°K are tabulated in Table 1. The refractive-index data for germanium was computed from the data of Icenogle *et al.*[2] As required for this experiment, the data given by Icenogle *et al*[2] is absolute refractive index data, that is, the refractive index of germanium in a vacuum. The index value for 297°K was computed by first fitting the 297°K data of Icenogle *et al.*[2] to the dispersion equation

$$n = A + BL + CL^2 + D\lambda^2 + E\lambda^4 \quad , \tag{1}$$

where

$$L = \frac{1}{\lambda^2 - 0.028} \quad , \tag{2}$$

and A, B, C, D, and E were determined by a least-squares fit. Then the index value n was computed from this equation for λ equal to 3.39. The resulting index value was checked by comparing it to the value computed using the values for A, B, C, D, and E given by Wolfe[3,4] for germanium in 300°K air. After correcting for air and the 3°K temperature difference, the two values differed by only 4×10^{-4}. This is within the accuracy limit of the data since Icenogle *et al.*[2] give the precision of their data as $\pm 6 \times 10^{-4}$. The index value for 84°K was computed by fitting the 94°K data of Icenogle *et al.*[2] to the same dispersion equation, evaluating this equation with λ equal to 3.39, and finally extrapolating the result to 84°K using a dn/dT of 1.5×10^{-4}. This dn/dT value was obtained by extrapolating the $\Delta n/\Delta T$ vs. temperature data given by Icenogle *et al.*[2] to 90°K. The radius at 84°K was computed using the nominal radius at 297°K and the linear-expansion data for germanium given by Wolfe.[3] Since the coefficient of linear expansion is not constant with temperature, the cold radius was computed recursively using 10°K steps. The same procedure was used to compute the thickness change caused by cooling.

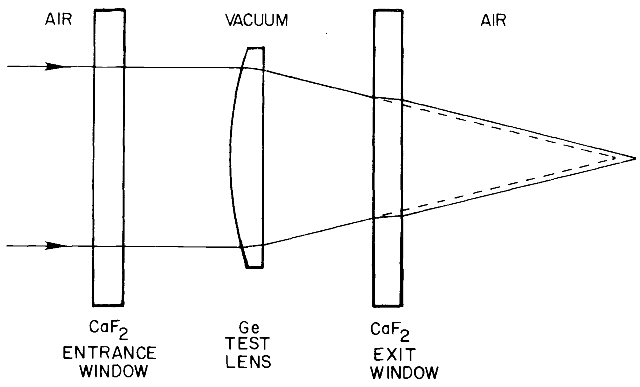

Figure 4. Optical system formed by test lens and dewar windows.

The optical system formed by the test lens and the entrance and exit dewar windows is shown schematically in Figure 4. The focal position of this optical system was measured using each of the three test lenses at both 297°K and 84°K. This optical system was analyzed using the optical-parameter values tabulated in Table 2. Entrance-window data is not included in this table because it had no effect on the analysis. The windows were at room temperature even when the lens was at 84°K. The refractive-index value for calcium fluoride was computed using the dispersion equation given by Wolfe.[3] The refractive index for air was computed using the dispersion and temperature equations given by Jamieson.[1] As can be seen from Figure 4, the test lens was used in its minimum aberration orientation; that is, the flat side of the lens was towards the focus.

Table 2. Warm and cold optical-parameter values used for computations.

		Lens at 297°K			Lens at 84°K		
Surface No	Material	Radius (mm)	Index of Refraction	Distance (mm)	Radius (mm)	Index of Refraction	Distance (mm)
	Vacuum		1.0000			1.0000	
1*		305.05			304.77		
	Germanium		4.0354	3.18		3.9625	3.17
2		∞			∞		
	Vacuum		1.0000	16.97		1.0000	16.97
3		∞			∞		
	Calcium Fluoride		1.41493	3.23		1.41493	3.23
4		∞			∞		
	Air		1.00026			1.00026	

*25.4-mm entrance aperture at surface 1.

Results

It was found that the focal shift caused by cooling could be predicted accurately by a paraxial analysis; the shift predicted from a paraxial analysis was virtually the same as that predicted from a ray-tracing analysis. The ray-tracing analysis predicted that cooling would cause the minimum-blur position to shift 2.38 mm away from the lens. The paraxial analysis predicted that the paraxial focus would shift 2.36 mm when the lens was cooled. The measured focal shifts are tabulated in Table 3; the worst-case error in these measurements is ±0.03 mm. As can be seen, the shift is relatively large. A simple piezo-electric focusing adjustment could not compensate for a shift of this magnitude. Since the nominal focal length was 100 mm, cooling the test lens causes the focal length to increase more than 2 percent. The differences between the computed shift in the paraxial focus and the measured shifts are tabulated in Table 4. The diffraction-limited depth-of-focus tolerance for an f/4 optical system, the f/number of the experiment optics, at a wavelength of 3.39 µm is ±0.11 mm. As can be seen from Table 4, the difference between the shift predicted by the paraxial analysis and the measured shift of all three test lenses was less than the out-of-focus tolerance for a diffraction-limited optical system.

It is interesting to note that the radius change and the index-of-refraction change partially compensated each other; that is, the index change shifted the focus away from the lens while the radius change shifted it towards the lens. However, the shift caused

Table 3. Measured focal shifts caused by cooling test lenses.*

Lens I.D. Number	Knife-Edge Method (mm)	Pinhole Method (mm)
1	2.26	----
2	2.34	2.31
3	2.29	----

*Focal shifts of 2.36 and 2.38 mm were predicted by the paraxial and ray-tracing analysis, respectively.

Table 4. Paraxial focus shift minus measured shifts.*

Lens I.D. Number	Knife-Edge Method (mm)	Pinhole Method (mm)
1	0.10	----
2	0.02	0.05
3	0.07	----

*The diffraction-limited depth-of-focus tolerance is ±0.11 mm.

by the index change was 25 times greater than the shift caused by the radius change.

The focal shift caused by cooling was very accurately predicted, but the absolute location of the focus was not accurately predicted even by the ray-tracing analysis. However, the error in predicting the absolute position of the focus was essentially the same for the lens warm as it was cold. The absolute location of the focus was ascertained by measuring the distance between the flat surface of the test lens and the focus. Measurements of this distance for test-lens temperatures of 297°K and 84°K are tabulated in Table 5. The worst-case error in these measurements is ±0.1 mm; there is a 90-percent probability that the measurement error is less than ±0.05 mm. The ray-tracing analysis predicted that this distance would be 100.12 mm with the test lens at 297°K and 102.50 mm with the test lens at 84°K. As can be seen, both the warm and cold measurements are approximately one mm larger than their respective predicted values. A one-percent error in the radius would account for this one-mm difference. A one-percent error in measuring the radius of the test plate used to fabricate the lens is reasonable since this measurement was made using a spherometer. For a spherometer that measures the sagittal height over a 25-mm diameter, a sagittal error of only 0.003 mm will cause a one-percent error when measuring a 305-mm radius.

Table 5. Measurements of the distance between the flat lens surface and the focus.*

	Lens at 297°K		Lens at 84°K	
Lens I.D. Number	Knife-Edge Method (mm)	Pinhole Method (mm)	Knife-Edge Method (mm)	Pinhole Method (mm)
1	101.26	----	103.52	----
2	101.11	101.33	103.45	103.64
3	101.08	----	103.37	----

*The ray-tracing analysis predicted distances of 100.12 and 102.50 mm at temperatures of 297°K and 84°K, respectively.

Summary and Conclusions

The focal shift caused by cooling was predicted very accurately, but the absolute location of the focal plane was not. The computed shift in the paraxial focus was virtually equal to the shift in the minimum-blur position predicted by the ray-tracing analysis. The error in predicting the focal shift was less than the diffraction-limited depth-of-focus tolerance. However, the error in predicting the absolute location of the focus was nine times greater than this tolerance. An error of only one percent in the value used for the lens radius would account for this error in predicting the absolute location of the focus. Lens-radius errors of this magnitude are to be expected with standard optical-shop practices. The results of this experiment suggest that the focus of any cryogenically-cooled optical system for which low-temperature thermal expansion and index-of-refraction data are available can be accurately predicted by first measuring the focal location with the optics at room temperature and then adding the computed shift in the paraxial focus to the measured location.

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